5G-encode

FINAL COMBINED REPORT

All reports from the project in one document

Mar 2022

Issue Details

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1	Initial issue

ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK's biggest investments in using 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It is designed to validate the idea that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that the UK industry exploits the 5G technology and remains a global leader in the development of robust digital engineering capabilities when implementing complex composites manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (uRLLC/eMBB/mMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-ENCODE project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and SMEs.

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

EXECUTIVE SUMMARY

The 5G ENCODE project was defined to prove the value of 5G to industrial and manufacturing processes. To understand and realise the value of 5G in this context the following objectives needed inclusion:

- Enhanced Mobile Broadband (eMBB)
- Massive Machine Type Communication (mMTC)
- Ultra-Reliable Low-Latency Communication (URLLC)

Demonstrating the above objective in an industrial context required differing use cases, namely:

1. Virtual Reality (VR) & Augmented Reality (AR)
2. Asset Tracking
3. Liquid Resin Infusion (LRI) and Automated Preforming Cell (APC) technologies

The program required multiple partners working in a collaborative manner to deliver the use cases whilst also exploring use cases for:

- Neutral Hosting (NH)
- Network probing and monitoring
- Network visualisation and service management

The program included a feasibility study for:

- Remote Haptics

The project reports are grouped by use case and collaboration partners with Zeetta Networks as program lead assembling this program summary report.

Overall, the 5G Encode programme was a success and met its time, cost, and quality objectives.

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ABBREVIATIONS

Each section contains abbreviations appropriate to that section

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1 INTRODUCTION

The 5G ENCODE project completed with multiple reports for the different activities completed during the project. This document is one document containing all published reports providing a single document for the project.

1.1 Project Closure Reporting

To close the project the following content was created:

- Project Closure
- Lessons Learned
- Benefits Realization – Use Cases
- Benefits Realization – Test Bed Monitoring

This content summarises the project achievements using the content from the detailed reports.

Note: The benefits realization master spreadsheet is not included in this report, it is available as a separate artifact. Summary data from the master spreadsheet capturing key findings has been included in this document.

1.2 Manufacturing Use Cases - Detailed Reporting

The following use cases (UC) were executed within Work Package 3 (WP3) of the project. Each report is prefixed with a WP and UC identity for ease of reference.

- WP3 UC1 Final Report VR Assisted Training
- WP3 UC1 Final Report AR Assisted Training
- WP3 UC2 Final Report In Factory Asset Tracking
- WP3 UC2 Final Report Out Factory Asset Tracking
- WP3 UC3 Final Report APC
- WP3 UC3 Final Report LRI Closed Loop

1.3 Cross Project Use Cases – Detailed Reporting

The following use cases spanned the manufacturing use cases detailed above.
Each report is prefixed with a WP and cross UC (xUC) identity for ease of reference.

- WP3 xUC Final Report Asset Tracking and Neutral Hosting - TUK
- WP3 xUC Final Report Network Probes - Accedian

- WP3 xUC Final Report Single and Multi-Domain Svc Mgt - Zeetta

1.4 Feasibility Study

The following feasibility study was completed to investigate if 5G would be suitable for this manufacturing use case.

- WP3 xxx Final Report Haptics Feasibility Study

1.5 Final Platform Commissioning

The platform commissioning report details the experience creating the mobile private network infrastructure.

- WP2 Final Report Platform Commissioning

2 -- PROGRAM CLOSE REPORT –

3 EXECUTIVE SUMMARY

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4 ABBREVIATIONS

4G LTE	Fourth Generation Long-Term Evolution
5G	Fifth Generation
5GTT	5G Testbeds and Trials
APC	Automated Preforming Cell
AR	Augmented Reality
BMS	Bristol Millennium Square
BR	Benefits Realisation
CR	Change Request
DCMS	Department for Digital, Culture, Media and Sport
DETI	Department of Enterprise Trade, and Investment
eMBB	Enhanced Mobile Broadband
ERP	Enterprise Resource Planning
JOTS	Joint Operator Technical Specification
LRI	Liquid Resin Infusion
LTE	Long Term Evolution
MDO	Multiple Domain Orchestration
mMTC	Massive Mobile Machine Type
MS	Milestone
MTU	Maximum Transport Unit
NCC	National Composites Centre
NH	Neutral Hosting
OEE	Overall Equipment Efficiency
ORAN	Open RAN
PCN	Private Cellular Network
RAN	Radio Access Network

SME	Small and Medium Enterprises
TPO	Total Production Optimization
TUK	Telefonica UK
UoB	University of Bristol
URLLC	Ultra-Reliable Low Latency Communications
VR	Virtual Reality
WECA	West of England Combined Authority

5 PROGRAMME SUMMARY

5.1 Purpose

The 5G-ENCODE Project is a £9 million collaborative project aiming to develop clear business cases and value propositions for 5G applications in manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media and Sport (DCMS) of the UK Government as part of their 5G Testbeds and Trials Programme (5GTT). The project is one of the UK Government's biggest investments in 5G for manufacturing to date and is led by Zeetta Networks Ltd. Other consortia partners include the National Composites Centre (NCC), Telefonica, Siemens, Toshiba, Solvay, Plataine, Mativision, and the University of Bristol while the West of England Combined Authority (WECA) provides additional support through their Department of Enterprise Trade, and Investment (DETI) Programme.

5.2 Objectives

The 5G-ENCODE project will deliver a private 5G testbed within the National Composites Centre (NCC) and demonstrate new business models (neutral hosting) and technologies (network slicing and splicing) and their value proposition to three key digital engineering capabilities for composite manufacturing:

1. Application of AR/VR to support design, training, and advanced Human– Machine interfacing to enhance quality of manual layup of composites
2. Condition monitoring and tracking of time sensitive assets i.e. composite materials to enhance shop floor operational efficiency and compliance
3. Wireless real time in process monitoring inside harsh process environment such as ovens as a steppingstone to full machine autonomy

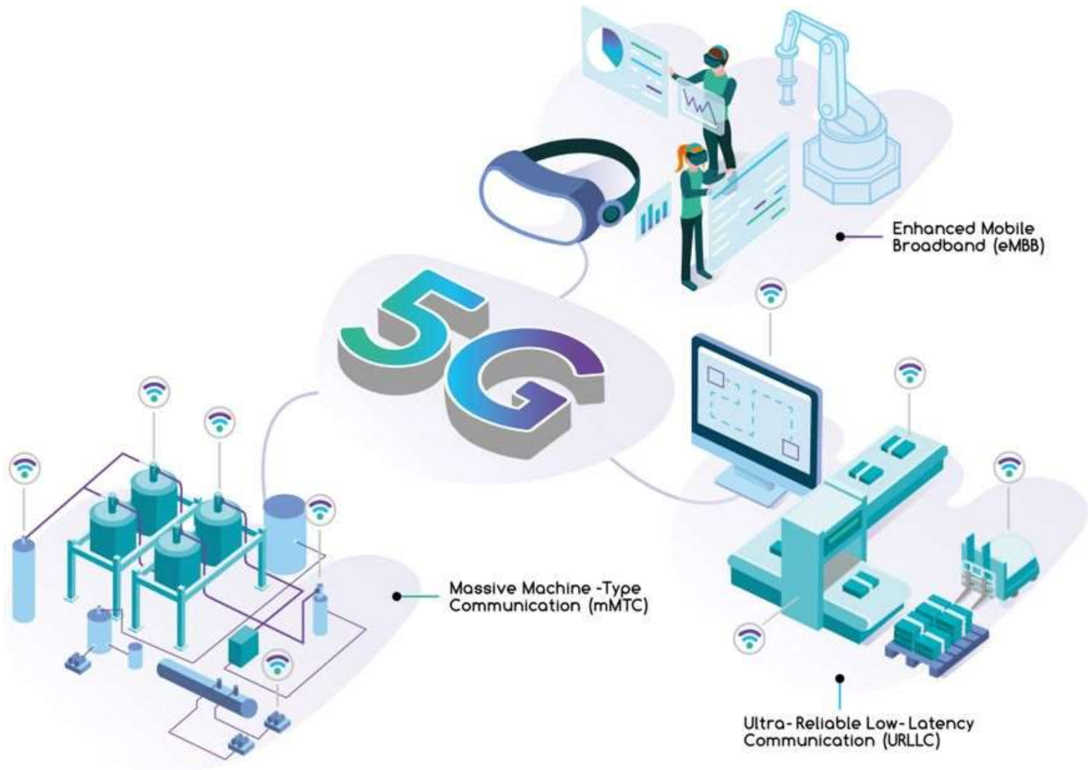


Figure 1: 5G Encode Overview

5.3 Partners and Collaborators

The reports below can all be found on the 5G Encode website https://www.5g-encode.com/media-and-publications.

The collaborating partners worked together as follows:

Work Package	Work Package	Sub-work / Use Case	Use Case Lead	Collaborators
WP1	Program Management		Zeetta Networks	
WP2	Network Design and implementation	LTE network 5G network	NCC	Toshiba, Telefonica & University of Bristol
WP3	Industrial use case	Augmented Reality (AR)	NCC	Mativision
WP3	Industrial use case	Virtual Reality (VR)	NCC	Mativision
WP3	Industrial use case	Asset Tracking	NCC	Plataine
WP3	Industrial use case	Automated Preforming Control - APC	NCC	
WP3	Industrial use case	Multi-sensory, in-process monitoring and analytics - LRI	NCC	Toshiba
WP3	Cross use case	Neutral hosting	Telefonica	
WP3	Cross use case	Out of factory asset management	Solvay	
WP3	Cross use case	Network monitoring using probes	Accedian	
WP3	Cross use case	Single and Multi-Domain Service	Zeetta Network	

		Management (slicing)		
WP3	All Use cases	Benefits Realisation	Zeetta Network	
WP3	Feasibility Study	Remote Haptics Feasibility Study	NCC	

Figure 2: Activity Reports

Collaborator specific additional notes:

Zeetta Networks – as well as collaborating on the service management aspects of the network configuration and visualization, Zeetta Networks are the project lead

Accedian - joined the Encode program during execution. The objective for Accedian was to provide a performance monitoring capability and show that their Skylight solution enables manufacturers to ensure that the performance benefits promised by 5G meet expectation and lead to the successful delivery of the use cases demonstrating the business case for investment in private 5G.

5.4 Scope

The main deliverable of the project is an easily accessible 5G testbed which the UK manufacturing businesses can use for experimentation and new product and services development with minimal risk to their own production facilities. Other key outcomes include:

- Proof of the business viability of 5G private networks targeting the UK manufacturing industry
- Stress-test a carefully selected number of key 5G use cases / proof of concepts (infrastructure, network architecture and information exchanges) across a targeted supply chains to eliminate the risk of implementation for upcoming large-scale UK based future manufacturing programmes
- Combining private and public 5G environments and the seamless transition of goods and services across domains
- Build on existing 5G investment and established testbed by using 5GUK Test Network in Bristol Millennium Square (BMS)

- Exploring the interaction between advanced business models (neutral hosting) and 5G technologies (network splicing and slicing) for better service delivery in a demanding environment

The project meets DCMS requirements as follows:

- Led by private sector, including SMEs: Zeetta Networks is a private SME with specialising in 5G networking technology (network slicing and splicing). Other industry players include Telefonica, Siemens, etc.
- Use of local infrastructure assets: The project makes use of the 5GUK Test Network in Bristol Millennium Square (BMS)
- Explore 5G deployment and industrial use cases in the manufacturing: The project addresses three key industrial use cases
- Seeking involvement from a range of companies: The consortium includes Tier 1 operator, large industrial players, disruptive technology Small and Medium Enterprises (SME), leading 5G research institute and representatives from the high value manufacturing industry

5.5 Achievements / Overall Result

The following sections are taken from the full detailed reports stored the section: 5G Encode - Media publications (5g-encode.com) Case Study Final Reports – Phase 2 introduction of 5G

5.5.1 Use Case - Virtual Reality

Training courses with practical elements are typically carried out by trainers either within their training facilities on-site or at a suitable location at the customer site. Both scenarios have economic and environmental costs related to travel, with most being infeasible within the recent COVID-19 climate. Although there are distance learning options, and internetbased courses available, they are limited to webinar style 2D solutions. The use of 5G and more immersive technologies provides a unique opportunity to engage more effectively with the trainer and the practical elements of the training course.

This use case report evaluates the use of latest 360° video streaming technology, 5G connectivity and VR headgear to demonstrate a fully immersive VR remote learning solution. This solution is used to emulate a physical classroom and allows the user to follow, in real time, the practical course demonstration offered by the NCC in manual composite manufacturing. It relies heavily on 5G's reliable, safe, high bandwidth and low latency connectivity to facilitate uninterrupted high quality two-way communication (3D video and bi-directional audio feeds) between trainer and trainee.

The use case development was split into two testing phases:

The first phase was conducted on 4G Long Term Evolution (LTE) and limited to a controlled setting at the NCC with 4 trainees. 50% of the participants indicated that the solution was an enhancement to a conventional course as offered through an online seminar. Poor streaming quality (due to network capability) was stated as the key reason for negative feedback.

The second phase was conducted using the 5G test bed deployed at the NCC. The testing was extended to an external location and opened to a wider testing group of at least 20 trainees. Even with the expanded scope, 91% of the participants indicated that the solution was an enhancement. The 5G testing phase also showed significant advances to the 4G testing by exceeding 700 megabits per second download speed and around 3 milliseconds latency which significantly improved viewing quality and therefore participant engagement and satisfaction.

The immersive technologies tested in this report are shown to be an effective option for distance learning but only when paired with a reliable, high-performance network as offered by 5G technology.

Further technology development and experimentation are required to ensure solution robustness for application outside of the trial, especially VR hardware development, as direct connectivity to 5G is not yet possible. For wider-scale adoption of the technology, access to operational public or private 5G networks will be a prerequisite.

5.5.2 Augmented Reality

Training courses with practical elements are typically carried out by trainers either within their training facilities on-site or at a suitable location at the customer site. Both scenarios have economic and environmental costs related to travel, with most being infeasible within the recent COVID-19 climate. Although there are distance learning options, and internet-based courses available, they are limited to webinar style 2D solutions. The use of 5G and more immersive technologies provides a unique opportunity to engage more effectively with the trainer and the practical elements of the training course.

This use case evaluates the use of latest AR software, hardware, and 5G connectivity to demonstrate a fully immersive AR remote training solution. This solution is used to guide the user through the manual composite manufacturing process of one of the practical courses offered by the NCC. On-screen text instructions, overlayed 3D graphics, and tutorial videos support the trainees wearing the AR headgear. The work package also relies on 5G's reliable, safe, high bandwidth and low latency connectivity to facilitate high quality two-way communication (video and bi-directional audio feeds) between trainer and trainee.

The use case development was split into two testing phases:

The first phase was conducted on 4G LTE and limited to a controlled setting at the NCC with four trainees across two sessions. None of the participants indicated that the solution was of sufficient quality to justify its use over conventional on-site training. The root cause for this was not found to be the network connectivity, but the initial development of the AR application.

The second phase was conducted using the 5G test bed deployed at the NCC. The testing was extended to an external location and opened to a wider testing group of at least 20 trainees. Even with the expanded scope, almost 79% of users were satisfied with use of the package over on-site courses. The network provided sufficient connectivity to enable the two-way communication function with good quality which was appreciated by all users. Metrics exceeding 700 megabits per second download speed and around 3 milliseconds latency were recorded.

The immersive technologies tested in this report are shown to be a good option for remote training but require high quality digitisation and integration in the process. The 5G technology was shown to be reliable and high-performance with no significant or lasting interruptions throughout the two days of demonstration sessions at Millennium Square. However, the use case was not very heavily reliant on the network because the only feature relying on it i.e., two-way communication, was only used intermittently for relatively short periods of time.

Future developments can include features that increase the use of 5G with the development of online libraries containing interactive digital content. This development should also modularise the solution and improve its adaptability and cross application re-use.

The AR technology must reach a more mature and robust stage before being applied in real world cases. To enable this wider-scale adoption access to operational public or private 5G networks is a prerequisite.

5.5.3 Asset Tracking

5.5.3.1 In-factory

An autonomous asset tracking solution, as the one proposed by this use case, offers the opportunity to effectively track mobile tools and assets such that current unproductive time spent searching for these items is minimised. When applied to time sensitive materials, such as prepreg carbon composites, this solution could also reliably monitor product outlife and a tooling maintenance schedule to minimise material wastage and ensure representative product traceability information, as well as high quality manufacturing standards of components.

This use case evaluates key features, typical of an automated fibre placement process – a high value manufacturing method to produce composite parts, as well as post processing operations (e.g. curing, non-destructive testing, metrology scanning).

The proposed asset tracking solution relies on both software and hardware components, with the existing sensor gates deployed on the NCC factory floor communicating real time data to a live web application via a 4G, 5G or wired power over ethernet (POE) connection.

Based on the 4G asset tracking baseline findings, it was concluded that the performance of the test bed was directly linked to the network stability. 5G technology showed the potential to enhance the asset tracking solution by enabling connectivity to a much wider range of devices and assets simultaneously, without compromising its stability, offering improved speeds and latency.

This digital asset tracking solution showed great benefits in the form of productivity improvement, cost savings and better tooling control. By ensuring easy access to real time asset location information, it is possible to more efficiently plan a manufacturing schedule based on asset availability, minimising the unproductive time spent on searching and locating tooling or materials as production commences. It has been assessed that a 93% reduction in search time per job is possible with the present asset tracking solution, removing the likelihood of rescheduling a production run due to item unavailability.

Another major benefit of the proposed asset tracking solution is the ability to closely monitor stock life and availability, leading to an improved stock management and minimal material wastage, with implicit cost savings of at least £56,000 per year for production facilities similar in size and manufacturing rates to the NCC. Also, by closely monitoring the usage of tooling in production cycles, it is possible to reliably record and schedule maintenance, and, thus, ensure a high-quality standard of production.

The asset tracking technology detailed in the present report showed to be an effective means to wirelessly monitor both item location and material out-life in a production environment, but for a relatively small number of products. It is of interest for this use case to explore further the 5G capabilities for asset tracking and assess how a higher number of assets managed by the system would impact the performance and accuracy of the test bed. Seeking an out-of-factory tracking solution is also a scope of work the NCC would like to trial in the near future; however, access to public or private 5G networks outside production facilities is a prerequisite.

5.5.3.2 Out-of-factory

The asset tracking evaluation work package was delivered in collaboration with Plataine Ltd which provided the Total Production Optimization (TPO) application and the NCC, Bristol which provided the test bed for the private 5G technology evaluation. The NCC test bed was delivered together with Zeetta Networks, Toshiba, Mativision, Plataine, Siemens, Telefonica, Accedian and the High-Performance Networks Group from the University of Bristol as partners.

As a leading supplier of composite materials, Solvay evaluated the potential of the automated asset tracking technology from a material manufacturer perspective. Solvay, based at a site in Wrexham, supplied to the NCC the composite materials required for the evaluation of the automated asset tracking use case from a material manufacturer site to a customer site perspective.

Figure 3: Out-of-Factory Process Flow

The project highlighted the potential benefits of automated asset tracking in terms of waste reduction and Overall Equipment Efficiency (OEE) improvement from a composite materials manufacturer perspective. Potential for full automation of currently manual or semi-automatic quality tasks or Enterprise Resource Planning (ERP) transactions was also highlighted. Solvay has decided to pursue further the evaluation of automated asset tracking technologies following this project.

At this stage the benefits of, in factory, 5G cellular technology to support an automated asset tracking system deployment at the Solvay, Wrexham site compared to a conventional PoE+ approach remains unclear. Further evaluation would be required before any full deployment of automated asset tracking across the Solvay's multiple Wrexham sites.

5.5.4 Automated Preforming Control (APC)

This use case assesses multi-sensory, in-process monitoring and analytics in an industrial use case relating to in-process verification of composite materials using a vision-based system. The main barrier to these types of verification systems being more widely accepted across industry is the significant infrastructure requirements for them to operate effectively. These requirements are driven from the need to process the massive amounts of data generated and the need for low latency feedback, which leads to them needing to be installed in fixed locations with large set up, and integration costs.

This use case aims to demonstrate how a decrease in infrastructure requirements and increased in flexibility offered by exploiting 5G capabilities, can make this technology more accessible for industry.

5G has ultra-fast, high bandwidth, low latency capability enabling large amounts of data to be sent and received wirelessly in near real time. The Gigabit uplink and downlink speeds present an opportunity for this use case as vast amounts of data are generated during each scan. The high throughput ability of 5G combined with the ultra-low latency theoretically lend themselves perfectly to this application as large volumes of data can be communicated in near real time.

To assess feasibility and understand solution architecture prior to 5G network availability, a baseline test was conducted using 4G LTE on a similar vision system. This test proved that vision systems of this nature can communicate data using cellular technology, however low 4G communication speeds led to the scan time being significantly increased while the quality of the gathered data was reduced.

Upgrading the industrial vision system at the NCC to 5G was successful and allowed data to be communicated to a virtual server in near real time, achieving latency values in the region of 14ms. The uplink throughput was still not sufficient to run a scan at the same parameters as the original wired set up but vastly improved compared to 4G. A maximum uplink throughput achieved using 5G was 18Mbps (2.25MBps), far from the 900Mbps seen when using CAT7 cable. The lack of comparative communication speed led to data fragmentation and network instabilities when attempting to pass large volumes of data across the network, often leading to a cease in data flow. The root cause of this has not been fully identified, however, a reduction in uplink data volume, through reduction of Maximum Transport Unit (MTU) size and scan speed, vastly improved the stability of the connection and the quality of the output.

The 5G connection did allow the processing PC to be removed from the system, significantly reducing the weight and footprint of the end effector from 45kg to 3.5kg. This allowed the use of a smaller collaborative robot to accurately position the system reducing robot system cost (~88% reduction) and, in turn vastly reducing the integration cost required to set up when compared to the original deployment (~98% reduction).

The use of industrial 5G for an application such as this is possible but there are trade-offs that must be considered. There is a significant reduction in both robot system cost and integration cost, leading to a much more flexible and easily deployable system. However, until an increase in 5G uplink throughput is possible, the time to scan will be greatly increased to achieve the same quality of output.

5.5.5 Liquid Resin Infusion (LRI)

This use cases assesses multi-sensory, in-process monitoring and analytics in closed loop Liquid Resin Infusion (LRI). LRI is a process used by the aerospace, automotive, marine and several other industries to create composite components. It has many benefits over prepreg, such as cheaper material costs and faster manufacturing times – however is highly dependent on the skill of the operator, is very manual, and often produces many scrap components when developing new parts. There is a need to automate LRI to make parts right-every-time, reduce the environmental impact by generating less scrap, and lower cost and manufacturing time.

The closed loop LRI system utilised 5G and digital technologies to improve the process. The system used a sensor array to monitor key LRI process variables and sent this data to a control model. The model decided how the process should be altered in real time and sent commands to a feedback system that implemented the decisions. A visualisation system used dashboards to display process data in real-time and generated a traceability report for each part. All sensor data and control commands were sent over 5G.

To enable a modern closed loop system to work effectively there are numerous requirements to consider. A high speed, low latency, highly reliable network is needed to transfer process data across. Next, because the amount of data needed to properly model a manufacturing process could be vast, the network needs to be able to handle large numbers of sensors connecting to it. In practice the sensors need to connect to the system wirelessly as attempting to connect a huge number of wired sensors is impractical. Finally, a high-performance computing capability – located on the edge – is needed to run complex models (for instance AI) that will control the manufacturing process. 5G has the potential to meet these requirements through characteristics including Ultra-Reliable Low Latency Communication (URLLC), edge computing, and massive Machine Type Communication (mMTC - allowing thousands of devices to connect to the network at once).

The system was initially tested on a 4G network to establish a baseline, and then tested on a bespoke 5G network to assess if there was a discernible increase in real world performance of the use case. Additionally, the system was tested on a low cost off-the-shelf/open source 5G network; its performance was assessed to understand if this cheaper system could allow smaller companies to leverage the benefits of 5G.

The closed loop LRI system realised numerous benefits. It led to reduced manufacturing labour costs of around 25% while the live dashboards gave engineers a clear view of the process and allowed them to reduce cure cycle time by around 50%. Using wireless 5G communication enabled the system to be flexibly deployed anywhere in the factory. Finally, the automatic generation of the part traceability report saved over 8 hour of engineering time and associated costs.

Overall, the use case was able to operate well over 5G, however network dropouts due to poor reliability caused some data loss – more work is required to enhance device stability on the 5G Standalone Open RAN network (5G SA ORAN).

Reliability issues were also seen with the off-the-shelf/open source 5G network.

There was not a discernible performance increase seen over the 4G baseline. The use case however was a small-scale demonstrator – it is likely that if the system was expanded to a more representative scale (such as an aircraft wing manufacturing process) the advantages of 5G would become visible.

5.5.6 Network monitoring using probes

Accedian, the probe supplier, has been a long-standing provider of network and application performance monitoring to both Service Provider and Enterprise markets and they had recognised the new opportunities that 5G would offer to Industry. Research by the CapGemini Research Institute concluded that "2 out of 3 industrial companies believe that guaranteed quality of service is critical for their digital transformation" and with 5G holding the key to unlocking digital transformation for manufacturers, both in the UK and around the world, monitoring the performance of both the 5G network and the applications driving the 5G use cases of mMTC, eMBB and URLLC, is a critical success factor.

Project Encode provided Accedian with an ideal opportunity to validate the value of its performance monitoring and test generation virtual platform, Skylight Analytics, to in the manufacturing industry by supporting their digital transformation journey and helping companies to realise the performance and reliability benefits of 5G.

Within Project Encode, Skylight was deployed at the National Composites Centre (NCC) and delivered granular and accurate real-time visibility, anomaly detection, and analytics on the performance of 5G-ENCODE's private 5G network and the applications that run over it. Skylight was able to support the project's goal to accelerate the realisation of the benefits of 5G for their key business use cases; in-factory and in-transit asset tracking, virtual 360-degree video training and closed loop manufacturing in Liquid Resin Infusion. The key results being:

1. The simplification of fault identification and resolution to enable non technically skilled staff to identify use case impacting issues and what the issue was and what the possible root cause was.
2. The presentation of highly accurate and granular performance data to enable technical staff to trouble-shoot use case impacting issues to reduce downtime
3. The ability to proactively identify performance degradations that would lead to negative impact on the use cases.

5.5.7 Single and Mult-Domain Service Management (slicing)

5G connectivity services are being explored not only by the incumbent global mobile network operators but also by enterprises looking to have more secure and flexible mobile connectivity solutions for their various connectivity requirements. In an already complex enterprise IT environment, 5G will yet add another level of complexity for those having to manage their networks.

Abstracting away the underlying complexity of provisioning and managing a multi-site and multi-technology enterprise network environment provides great value for enterprises. As Network engineering teams managing these enterprise networks might not have access to the expertise typically required to fully manage this ever-growing complexity, solutions to simplify daily operations are of critical importance.

Zeetta NetOS® and Zeetta Multiple Domain Orchestration (MDO) provide this level of abstraction for the case of single site and multi-site enterprise networks respectively. These tools provide network administrators with a single dashboard for management of various network services - including 5G PCN services - allowing end to end services to be deployed seamlessly across various network infrastructure devices and application servers.

At 5G-ENCODE, Zeetta deployed a cloud based Multi-Domain Orchestrator (MDO) and demonstrated the benefits of using this application by creating a multi-domain end-to-end connectivity slice that was automatically provisioned across different network domains, reducing the time required to enable service connectivity and avoiding manual intervention in the various network devices.

5.5.8 Neutral Hosting

The requirements placed in Telefonica UK (TUK) from the Consortium Agreement included allocation of test spectrum for in-building use if needed, consultancy and SIM cards to support possible public network utilization. The project also asked TUK to investigate the provision of neutral hosting integration, whilst outside the agreed scope of the project TUK agreed to investigate what was possible.

Whilst not included in the original Consortium Agreement, TUK were asked if they could support neutral hosting solution. TUK whilst not contracted to deliver a solution investigated what was possible in the timescales. Following that investigation TUK found that they were unable to support outdoor Use Case 2 (AR/VR) for 5G Encode Phase 2. The project had to find another solution and selected a lower cost core and Radio Access Network (RAN) solution that was available to support the project. TUK had also investigated a Nokia based standalone solution where the RAN and core were supported by TUK, but again the costs were significant and were deemed to be too high.

TUK's analysis clearly showed that connecting private networks to their public network was not possible within the planned project budget and timescale, due to complexity of the integration task, license obligations and security concerns. TUK reviewed three solutions that the project could adopt. The Joint Operators Technical Specification (JOTS) seemed the most realistic, but this was still complex to integrate when the private network supplied by the public mobile operator and with a cost that was beyond the budget of the project. In the end it was simply not possible to deliver a JOTS solution to the timescale of the project, consequently, the integration idea was abandoned.

It should be noted that TUK were only a minor partner in this project from the beginning and never intended to deliver the network solution. And this was reflected in our modest claim for this project.

In the 5G Discussion section of this document the technical and logistical lessons learned are discussed along with recommendations for future projects to consider.

5.5.9 Remote Haptics Feasibility Study

In this work, haptic robot control protocols have been integrated into a teleoperation solution where an industrial robot located at the Bristol Robotics Laboratory is operated from the National Composites Centre.

The teleoperation is cabled to function in this feasibility study with no 5G cellular used in the study. This study was to create a benchmark for use in future projects.

The need for robot teleoperation within the industry remains for use-cases of which the environment is too hazardous for direct human operation and too complex for automation. For further steps to be made in robot teleoperation there need to be intuitive systems designed that allows an operator to control the robot with confidence. A system is proposed that uses hand tracking, haptic feedback, and an immersive experience to actuate a robotic arm from a distance for which optical fibre and network cables are used to facilitate the network needs.

The robotic actuation using the combination of a haptic hand tracking device and a haptic protocol that allows the operator to move the robot by moving his/her hand. The immersive experience using a stereo camera to capture the robot's environment and a Virtual Reality (VR)-headset to make this content visible for the operator. The teleoperation is cabled to function as a benchmark in this feasibility study. The network consists of a combination of optical fibre, CAT 6 Ethernet and universal serial bus cables. The main connections within the network are limited to a 1 Gbps maximum throughput.

During testing of the solution it was measured that the maximum data throughput was 27 Mbps. The current 5G networking capability allows for an uplink of 57 Mbps and a downlink of 410 Mbps. With this it can be concluded that 5G could be integrated within the current solution. To limit the potential project risk an initial study was undertaken where the operation of a robot arm was completely virtual proving that haptic control of an industrial robot arm is indeed feasible. This time around project risk was again mitigated by first testing the network and the solution using a cable. By doing this it was possible to prove the feasibility of 5G in a short time frame.

5.5.10 Detailed Reports

Full reports are stored the section: 5G Encode - Media publications (5g-encode.com) Case Study Final Reports – Phase 2 introduction of 5G

6 MILESTONES & DELIVERABLES

All planned and new milestones were completed as planned or through change requests identified in the change section.

Below is a summary of the Milestones with the detail contained in the fortnightly report to DCMS.

#	Milestone	Delivery status
MS1	MS1: Design for the phase one (i.e. 4G and/or Wi-Fi) network architecture and functional specification is agreed	Completed
MS2.1	MS2.1: Draft benefits realisation metrics recorded	Completed
MS2.2	MS2.2: Benefits Realisation framework	Completed
MS3	MS3.1: ITT is issued for the equipment and services needed in the phase one 4G and/or Wi-Fi network	Completed
	MS3.2: Product descriptions for Use Cases evaluated against network architecture	Completed
MS4	MS4: Final Collaboration Plan	Completed
MS5	MS5: Phase one 4G and/or Wi-Fi network has been deployed	Completed
MS6	MS6: A Case Study about the phase one 4G and/or Wi-Fi network is available to download from the project website	Completed
MS7	MS7: ITT is issued for the equipment and services needed in the phase two 5G network	Completed
MS7.1	MS 7.1 Interim Reports	Completed
MS8	MS8: Phase two (i.e. 5G) network has been deployed	Completed
MS9	MS9: A showcase event is held to share learning from the two innovation use cases that the 5G network has enabled	Completed
MS10	MS10: A final project report is provided to DCMS	Completed
MS11	MS11: A project closure and review meeting is held with the project board and DCMS	Completed
M12	MS13: Collaboration Topic: Project Closure	Completed

Figure 4: Delivery Milestones

7 SCHEDULE

7.1 Planned

The programme was split into three distinct work packages as follows

Work package 1: Programme Management

Led by Zeetta Networks and cover the development and control of an integrated project plan, managing the risk register and financial tracking of the partners.

Work package 2: 5G Network Design, Commission and Testing

Led by Zeetta Networks and included the design, commission and testing and continuous optimisation of the networks.

Work package 3: Industrial Use Cases

Led by the NCC with a focus on developing the industrial use cases with consortium members as demonstrators to prove value of the 5G network.

The requirements of this work package were delivered via 4 sub-Work packages:

3.1 AR/VR application demonstration using materials and resources from NCC and Mativision

3.2 Asset tracking and Monitoring demonstrations using materials and resources provided by Plataine, Siemens, NCC and Solvay

3.3 Multisensory in-process Monitoring and Analytics using materials and resources provided by Siemens and NCC

3.4 Placeholder for additional use cases – TBD post Phase 1

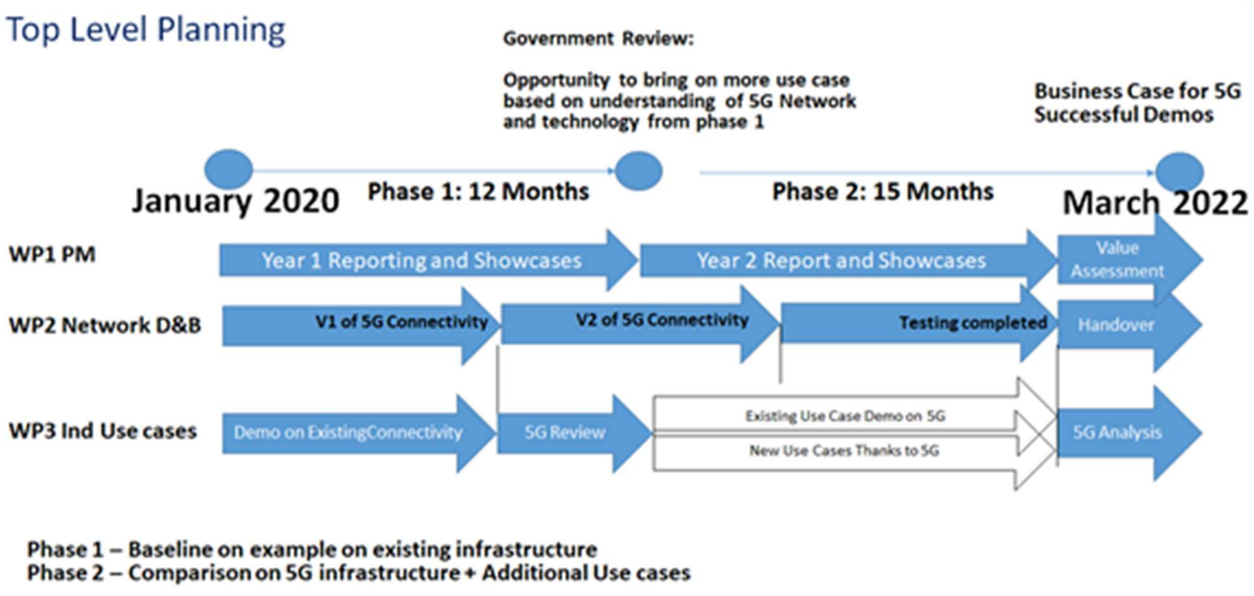


Figure 5: Schedule Baseline

At a top level, the first year will focus on establishing the baseline infrastructure and operational capabilities of the design 5G architecture. Year 2, the networks will be upgrade, extended and optimised and the industrial use cases will be adapted and demonstrated on the available 5G infrastructure and final testing, and demonstrations targeted for January 2022.

7.2 Actual

The overall programme ran to schedule and completed in March 2022 as planned. Within the programme there were several high impact issues related to hardware procurement and network stability that resulted in Milestone Nine (9) being delayed by over a month into November 2021 (Planned Oct 2021), the delay however did not result in a loss of quality for the programme.

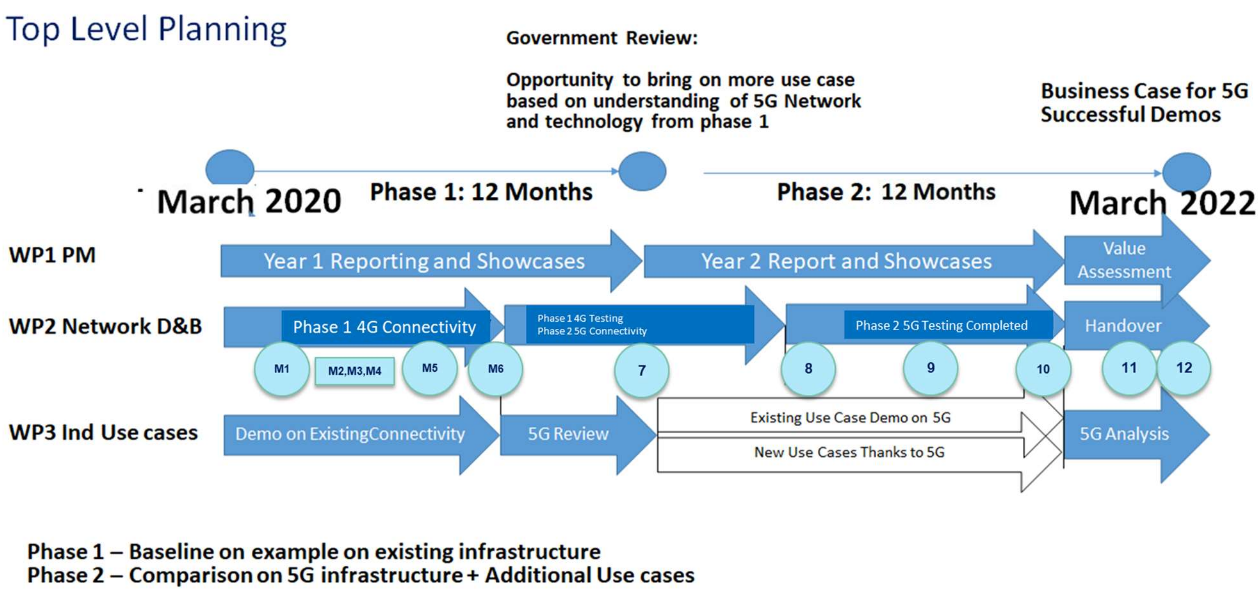


Figure 6: Schedule Actual

8 BENEFITS & LESSONS

8.1 Benefits Realisation

A full benefits realisation was conducted and can be found available for download here: https://www.5g-encode.com/media-and-publications

8.2 Lessons Learnt

As part of the benefits realisation lessons learnt were captured, these are found in the above-mentioned BR document and in a summary available for download here: https://www.5g-encode.com/media-and-publications

9 CHANGES

As part of the project a total of 12 change requests were made and documented in the change log as part of the regular status reporting to DCMS and summarised below

RAG ratings matrix

Red	Very high - materially affects/prevents achievement of the work programme objective or highly damaging impact (e.g., on operational effectiveness or reputation)
Amber/Red	High - significant long-term detrimental effect on achievement of work programme objective.
Amber	Medium - significant short-term damage, and important to outcome of long-term work programme objective.
Amber/Green	Low - affects short term goals within the work programme objective without affecting long term achievement.
Green	Very low - minor and containable impact on achievement of objective.

Req. Number	Description inc. workstream or area	Current Status	Priority
1	Increased our IT overhead costs in Year 1 & Year 2. Moving monies reserved for 5G material spend in Year 2 and also reallocated budget from savings in other categories.	Closed	High
2	Move £225k of budget from year 1 to year 2 due to the following:	Closed	High
3	Change of role for UoB	Closed	Medium
4	Change of role for Telefonica:	Closed	Medium
5	Accession of new partner Accedian to the 5G Encode Project.	Closed	Medium
6	Move all monies, £35,668 within the capital usage pot into materials category. Move £12,500from subcontract pot into materials category.	Closed	Medium
7	Request from DCMS to provide a quarterly status report on the o Network build progress o Use case progress	Closed	Low
8	Changes Requested MS8 – Inclusion of deliverables, D2.3.1, D2.3.2 MS9 - NCC Launch Event – Date Change MS10 – Final Project Report - Date Change Scope change - D3.1.4 will be a feasibility study only.	Closed	Medium
9	Delay to Haptic Feasibility Study	Closed	Medium
10	Return of funds due to programme underspend	In progress	High
11	Change of accountable officer	Closed	Medium
12	£13,500 virement within the University of Bristol's budget	in progress	Medium

Figure 7: Change Log Table

10 KEY RISKS AND ISSUES FACED

The below table summarises the high impact risks and issues faced by the project a full log was kept in the fortnightly DCMS report submitted to the project lead.

ID	Type	Description (inc. consequence & impact on project)	Countermeasure / Risk response (inc. contingency)
030	Risk	Covid19: Government advice could escalate to cancel all necessary travel if situation deteriorates. 14-days quarantine for international travellers to the UK will cause disruptions to partners such as Plataine & MatiVision in respective work packages. Impact is to site survey, installation of equipment, commissioning, testing etc. The project will delay until restrictions lifted and will require a replay	Government guidelines followed and tasks and deliverable completed remotely where possible and onsite where practical
043	Risk	Availability of suitable endpoints is limited for Phase 2. NCC have limited technical knowledge to aid market research and supplier engagement.	Workshops and collaboration space facilitated via UK5G, and initial conversations suggest that there are a number of device options that other projects are investigated so we can leverage those conversations. Final outcome was agreement from DCMS to purchase alternative devices
052	Risk	Ofcom don't grant the spectrum licence	Licence awarded with support of DCMS
040	Issue	NCC, IT have limited ability and scope to support project. During detailed discussions and workshops, it has become clear that any dependency on this department will result in delay. However, we are dependent on them for a minimum set of items such as provisioning remote access	Project has interim remote access solution in place and also a permanent solution ordered from Stordis. Project also has phase 1 network now live and external contractor operational support. Further to this NCC have also recruited additional IT resource to assist project. Considering all of this development I am closing this risk.
046	Issue	Telefonica's process to integrate test networks into their Macro network is time consuming and may not meet the project timescales	Telefonica will adopt the existing 4G core at NCC as their 'Proxy' core and the Zeetta MDO product can be demonstrated using this setup. The approach has been agreed by all parties and is now included in the NW design document. Closing risk.

Figure 8: Risk Management Table

11 OVERALL PROGRAMME PERFORMANCE

Overall, the programme performed well during a period of high uncertainty and disruption caused by the COVID-19 pandemic and the limitations and restrictions put in place to combat the spread, including home working, isolation, and limited travel.

The programme consisting of nine different member organisations worked in a collaborative and professional manner addressing multiple issues associated with researching and transforming manufacturing processes and methods using 5G standalone, ORAN, cellular technology.

The result of the programme was the development, execution, and delivery of 5 x primary key use cases, 4 x supporting use cases and 1 x feasibility study within the manufacturing and engineering environment of the NCC demonstrating the capability or potential capabilities 5G could bring to the industry.

The network splicing use case was not delivered as the neutral hosting network could not be implemented within the project schedule. Network splicing is dependent on neutral hosting. A multi-domain orchestration use case was substituted. Future research is needed to complete this use case.

The use cases showcased at the 5G launch event (Zeetta link and NCC link) held at the NCC in November 2021and attended by Dan Norris, West of England Combined Authority Mayor, with Vassilis Seferidis, CEO, Zeetta Networks, project lead at 5G-ENCODE, and Marc Funnell, Director of Digital Engineering, NCC as the project hosts.

11.1.1 Key stakeholder comment

In the Zeetta Networks news item related to the launch event the following comments are recorded:

Vassilis Seferidis, Founder and CEO, Zeetta Networks, says: "*We are incredibly proud to have hosted this event for our stakeholders showcasing how far the project has come. Launching the network, as planned, in just over 12 months despite the challenges we have faced this past year, is a testament to our partners' hard work. I am honoured to be part of the team building the technology that will revolutionise the manufacturing industry.*"

The NCC's expertise and experience with building, developing, and maintaining testbed environments have been instrumental in keeping 5G-ENCODE on target. The state-of-the-art 5G testbed now underpins the NCC's Digital Engineering offering to market, providing open technology access to a range of virtual and physical industrial testbeds in a secure environment with expert knowledge and skills.

Marc Funnell, Director of Digital Engineering, NCC, added: *"Manufacturers need to develop sustainable, high-performance products with reduced cost and time to market using low carbon processes which can be accelerated using test beds that exploit the power of emerging technologies such as 5G. What we have demonstrated through our manufacturing industry use cases are the potential efficiencies in product, process and productivity through 5G that can enable innovation."*

In support of the progress that 5G-ENCODE has made, **Dan Norris, West of England Combined**

Authority Mayor shares, *"It's a real privilege to have been invited to launch the industrial 5G network at the National Composites Centre. This is a real vote of confidence in our region's brilliance; it's cutting-edge technology which puts the West of England firmly on the map as a digital powerhouse. The 5G-ENCODE project is testing innovations which could revolutionise the UK manufacturing sector, making it more efficient and sustainable. It will create high-skilled jobs right here in our region and bring in investment. It's good news for the West of England and GB PLC."*

12 RECOMMENDATIONS

The 5G-Encode project identified many lessons learned. These are broadly grouped as:

- 5G Network and Infrastructure
- Use Case Challenges
- Project Execution
- DCMS processes

Overall the project was successful and delivered on schedule and to agreed budget.

Many of the items identified in this document were worked around, however some remained unresolved. Recommendations for future research and other projects are included where identified. This document is written from the detailed lessons learned documented by each project collaborator. This document highlights learnings that will benefit other projects.

The 5 x manufacturing use cases, 4 x supporting use cases and 1 x feasibility study were completed as planned, lessons learned were captured for the following topics:

- 5G skills and talent
- Equipment availability and maturity
- 5G spectrum and licensing
- 5G performance and resilience
- 5G ORAN and interoperability challenges
- Neutral hosting and slicing
- Edge compute and data transfer bandwidth and latency

Whilst the project achieved most of the defined objectives the cellular technology is relatively immature and costly. These are limitations and constraints that will be overcome as the 5G cellular products mature.

Detailed recommendations are available in the project lessons leant published here: https://www.5g-encode.com/media-and-publications

Lessons Learned

Final Report

Mar 2022

5G-encode

13 -- LESSONS LEARNED –

14 ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK's biggest investments in using 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It is designed to validate the idea that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that the UK industry exploits the 5G technology and remains a global leader in the development of robust digital engineering capabilities when implementing complex composites manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (uRLLC/eMBB/mMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre (NCC) in the southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-ENCODE project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and SMEs.

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

15 EXECUTIVE SUMMARY

The 5G-Encode project identified many lessons learned. These are broadly grouped as:

- 5G Network and Infrastructure
- Use Case Challenges
- Project Execution
- DCMS processes

Overall the project was successful and delivered on schedule and to agreed budget.

Many of the items identified in this document were worked around, however some remained unresolved. Recommendations for future research and other projects are included where identified. This document is written from the detailed lessons learned documented by each project collaborator. This document highlights learnings that will benefit other projects.

The 5 x manufacturing use cases, 4 x supporting use cases and 1 x feasibility study were completed as planned, lessons learned were captured for the following topics:

- 5G skills and talent
- Equipment availability and maturity
- 5G spectrum and licensing
- 5G performance and resilience
- 5G ORAN and interoperability challenges
- Neutral hosting and slicing
- Probing Edge compute needs for data transfer
- Haptics Robot Teleoperation future feasibility

Whilst the project achieved most of the defined objectives the cellular technology is relatively immature and costly. These are limitations and constraints that will be overcome as the 5G cellular products mature.

16 ABBREVIATIONS

APC	Automated Preforming Cell
AR	Augmented Reality
DCMS	Department of Digital Culture, Media and Sport
eMBB	Enhanced Mobile Broad Band
ATEX	Explosive Atmosphere from French ‘Atmospheres Explosives’
CTIL	Cornerstone Telecommunications Infrastructure Ltd
DU	Distributed Unit
eCPRI	extended Common Public Radio Interface
GPS	Global Positioning System
ID	Identity
JOTS	Joint Operators Technical Specifications
LRI	Liquid Resin Infusion
MCC	Mobile Country Code
MEC	Mobile Edge Compute
mMTC	Massive Machine Type Communication
MNC	Mobile Network Code
MNO	Mobile Network Operator
MPN	Mobile Private Network
NCC	National Composites Centre
NSA	Non-Stand Alone
ORAN	Open RAN
PCN	Packet Core Network
PDF	Portable Data Format
PLMN	Public Land Mobile Network

PTP	Precision Timing Protocol
RAN	Radio Access Network
RFID	Radio Frequency Identification
RU	Radio Unit
SA	Stand Alone
SIM	Subscriber Identity Module
uRLLC	Ultra-Reliable Low Latency Communication
VR	Virtual Reality
WECA	West of England Combined Authority

17 INTRODUCTION

The 5G-ENCODE project created many results. These results include lessons learned. This report includes categorised summaries of lessons learned through the life of the project as recorded by collaborators, suppliers, and project leaders.

The following categories were selected to group lessons learned:

1. 5G network and infrastructure
2. Use case challenges
3. Project execution experience
4. DCMS process efficiency

Each category is further divided into sections that reflect on key discoveries in the program. The categories and sections are intended to capture the most important lessons from the project. A complete list of all recorded lessons is included Appendix A for further information.

18 5G NETWORK AND INFRASTRUCTURE

18.1 Skills

18.1.1 Network design

Cellular networks are becoming increasingly ubiquitous in IT however, the introduction of ORAN and slicing adds new levels of complexity to network designs. In-house IT that are looking to integrate cellular networks into their operations will need to either purchase consultancy or develop in-house knowledge to plan and deploy cellular as part of the network infrastructure. Specific attention to the network design was needed when planning for data volume, network latency and precision timing in the network where required.

18.1.2 General ability to attract and retain talent

The project had to change programme manager twice as the incumbent project managers were resigning either for personal/family reasons (e.g. related to COVID-19) or because they found other more lucrative job opportunities elsewhere. This is an expected result of the demand for 5G-related skills which outpaces supply. When planning a project identify talent management as a risk item and create mitigation plans.

18.2 User Equipment (UE) and Customer Premises Equipment (CPE)

The 5G-Encode project started whilst 5G SA ORAN was still immature. This meant that the range of UE and CPE devices that could be used to connect and pass data through the network were very limited in availability.

Note: The UK government restrictions on Chinese vendors further reduced potentially usable devices although this was not on the critical path of the project.

Note: To mitigate the risk of device availability both Toshiba and the University of Bristol created home-brew device solutions as part of the projects. These solutions used a Quectel RM500Q-GL module to manage RAN connectivity. These were used in the initial stages of the project to support preliminary tests and phased out later in the project.

18.2.1 Engineering mode

All UE devices identified as usable with a 5G SA RAN were in mass production however, each device had to be to put into engineering mode so the device would use the 5G SA protocols to attach and authenticate on the network. This constraint will naturally disappear as 5G SA technology matures and becomes a mainstream technology.

18.2.2 Lab test PLMN

Some UE devices had a further constraint that once in engineering mode (to be usable on 5G SA RAN) that they would only recognise a 5G radio network signal when using a Subscriber Identify Module (SIM) configured with a Public Land Mobile Network (PLMN) identity (ID) comprising of a Mobile Country Code (MCC) of 001 and Mobile Network Code (MNC) of 01 i.e. PLMN ID 00101. Whilst this was not a blocking item, it did require that the Mobile Private Network (MPN) host SIMs with test PLMN ID settings rather than the selected MPN PLMN ID (in this project PLMN ID 99942 was selected for use). Like the need for engineering mode this constraint will naturally disappear as 5G SA technology matures and becomes a mainstream technology.

18.2.3 Scan Mode

To accelerate connection speed for CPE devices, it is recommended that the band scan configuration is in the CPE advanced settings and limited to the band in use e.g. n77 (UK 5G commercial, test and trials band). Updating these settings significantly speeds up the time needed to scan and connect for the device. This was particularly useful in the early phases of network deployment where outages and device reset needs were a common occurrence.

18.2.4 Chinese vendor devices

There are restrictions on use of any technology (including end user devices) from Huawei and ZTE in UK government funded projects. Whilst this reduces the range of devices that can be used in UK projects this is not a blocking item.

18.3 IOT Sensors and Actuators

The range of 5G enabled IOT sensors and actuators is very limited. Further to this manufacturing is often a 'harsh environment' that must comply with strict safety regulations, these topics further restrict and constrain IOT device use.

18.3.1 Harsh Environments

The Liquid Resin Infusion (LRI) process included an oven-bake stage. During this stage the component in manufacture was heated to a very high temperature. The sensors in the oven were temperature hardened sensors reliant on a cabled solution to pass data to the remote processing capability in a private Mobile Edge Compute (MEC) function. The project did not identify any 5G on-board sensors that could be used in an oven; therefore alternatives must be used to pass data in and out of this environment e.g. heat resistant short lengths of cable to a data transfer device outside of the oven. In this project the sensor cabling arrived at a computer outside of the oven that was connected (by ethernet) to a 5G CPE that then passed data to the MEC. As sensors rely on power, they must either be hard wired or battery powered. As batteries are incapable of surviving high temperatures for prolonged periods it is predicted that wired sensors will always be required for processes of this kind. A gateway device on the outside of the oven should act as a conduit to collect the wired sensor data before passing this data to the MEC via a 5G CPE.

18.3.2 Safety constraints

In the out-of-factory asset tracking use case material was tracked from the chemical production facility to the NCC manufacturing plant. Within the chemical production facility additional standards are used to ensure the safe production of materials in a hazardous and explosive environment. The standard in place was Explosive Atmosphere from French 'Atmospheres Explosives' (ATEX). This standard does not recognise compliance of any known cellular network technology or device. Consequently 5G cellular was not deployed at this facility and a Radio Frequency Identification (RFID) solution used instead. To use 5G in controlled production environments requires updates to standards and development of compliant devices.

18.4 IT Network

18.4.1 ISP

The IT in-factory IT network was implemented with 10Gb connections between all devices (fibre and copper). The ISP link was 1Gb. When testing 5G RAN the throughput downlink from the external Vodafone Watford speed test sever 480Mbps downlink speeds were achieved. When testing 2 devices simultaneously on the 5G RAN the ISP link load was measured at 30% consumed, however, it is like that this measure is averaged and that data consumption sporadically peaked much higher. Complaints of poor internet connectivity for other factory applications on test days supported this. There are two recommendations; 1) design the IT network hosting the 5G RAN with a connectivity to support likely 5G peak data needs, in our case a 10Gb network was sufficient, 2) review your ISP connection (enterprise to public network) an consider applying service policies if not already in place to manage 5G consumption.

18.5 RAN

In the project multiple RAN elements required study to determine opportunity and potential created when 5G cellular is used.

18.5.1 Radio Frequency (RF) Planning

In this project RF planning was not conducted in depth. The method for RF planning used for both 4G phase 1 and 5G phase 2 relied on an active connection and continuous ping test from a mobile device to determine the propagation of RF coverage through the building. This approach created a simplistic view of coverage without any signal to noise ratio assessment. The approach whilst very limited in results was very low cost to execute, although, it was predicated on a pre-planning decision to invest in cellular technology with installation, commissioning and integration costs already incurred before any check on coverage could be conducted. It is recommended that projects considering 5G deployment consider investing in an early RF planning service to determine best positioning of Radio Units (RU).

Note: the in-factory interference appeared to be reduced when using 5G and allocated spectrum and bandwidth when compare with the 4G allocated spectrum and bandwidth. These results are unquantified as a detailed RF study was not undertaken.

18.5.2 RF spectrum

The project used licences in the Ofcom trials and innovation spectrum. 8 to 10-weeks of time needs to be planned into the project schedule for the application to be processed by Ofcom. There is no guarantee that trials and innovation spectrum will be available in the proposed location. Applications for spectrum are more likely to be successful if they are a) low power (typically of in-building use), b) shared spectrum (i.e. not in spectrum where the licence had already been sold to a public operator who may not be using the spectrum in the application location and will agree a trial) and/or c) the bandwidth of the spectrum required i.e. 20, 40, 50 or 100MHz (other denominations of bandwidth may be available).

Aligning licensed spectrum with vendor supported spectrum configurations needs to be done during the licence application process. During the project it was learned that centre frequency spectrum allocations could not be exactly matched with vendor supported capability. It is recommended that the proposed RAN vendor provides a range of spectrum supported and the incremental steps within that spectrum that can be used as a centre frequency to avoid any mismatch when a licence is granted.

18.5.3 5G Bandwidth

The 5G SA ORAN network in this project was deployed with a 100MHz bandwidth (maximum bandwidth of the channel). The uplink and downlink maximum data throughputs measured were as follows:

- Downlink ~480Mbps
- Uplink ~50Mbps

These throughputs were typically measured using Ookla's Speedtest application connected to the Vodafone Watford server.

The downlink and uplink throughput are biased in favour of downlink throughput in-line with previous mass consumer experience where download throughput needs are often higher than uplink. In a manufacturing environment the uplink needs can be significantly more demanding than those of a public network hosting mainly consumer end users. In manufacturing there are greater needs to send data to MEC servers for application control of the industrial processes in operation.

Vendor and licence bandwidth alignment

Aligning bandwidth allocation with supported vendor bandwidth configurations needs to be done during the licence application process. During the project it was learned that vendors have constraints on the bandwidths supported in the equipment. To avoid issues of equipment needing more bandwidth allocation than a granted licence permits, check this with the equipment vendor when creating a licence application to Ofcom.

Uplink

Whilst RAN providers and adjust the downlink to uplink transmission ratios there are physical limitations in the RU's and end-user UE's and CPE's that need to be managed. In the project we discovered that high definition 4K and 8K camera support was very limited as the uplink data needs exceeded the capability of the network, even after reducing frames per second to a minimum. This means that very high-resolution cameras deployed when transforming manufacturing processes will need special consideration if they are to rely on 5G RAN uplink for data transmission. In this project the camera issue was not solved, however, alternatives to investigate include, overlapping RU coverage patterns and creating multi-stream connections, using other transfer mediums in preference to 5G cellular and video stream compression.

When executing the Automated Preforming Control (APC) use case the uplink issue was overcome by slowing the overall manufacturing process to create time to transfer data to and from the server, however, the impact was 200 x slower than the pre-modernisation configuration.

Downlink

Using a single radio unit there was sufficient bandwidth to deliver course content to 5 x virtual reality headsets in a common location with good end user experience, however, the bitrate of the streaming server was reduced to the minimum rate of 3Mbps to achieve this.

18.5.4 5G Latency

A key enabler to manufacturing transformation using 5G cellular is the reduced latency offered by the RAN when transferring data. In the 5G SR15 standard, latency expectation is 10ms or less. In the forthcoming SR16 standard the latency expectation is 2ms or less. In this project the RAN vendor was compliant with SR15 meaning low latency use cases needed to be operable with 10ms or less latency.

18.5.5 5G RAN Redundancy

In this project RAN redundancy was not considered. This revealed a finding in the Liquid Resin Infusion (LRI) process that in the event of network failure the process failed and either had to await network recovery or be restarted. This is a significant finding as restarting the process means that any in-process material must be scrapped which is costly. Additionally, when automated systems (such as LRI) rely on a network connection then any drop out can create safety issues. It is recommended that future projects consider RF overlay using RU's from differing cells connected to separate DU and CU elements to create redundancy in the 5G RAN.

18.5.6 5G RAN and multiple device hosting

When selecting RAN vendor, it is recommended that the number of devices inactive and active device connections for RU, cell, gNB and DU are understood. In our project when testing we exceeded the number of simultaneous active device connections on the cell which meant some devices did not work some of the time confusing the testing. It is recommended these parameters are determined prior to starting network integration tests.

18.6 Network slicing and 5G

5G introduced new data service management functionality called network slicing. Slice management in multiple locations requires knowledge of multiple devices and technologies i.e. IP switching and routing as well as 5G Packet Core Networks (PCN). Development of a solution to manage tasks related to slice management within the schedule of this project with the 5G network design not being completed until mid-way through the project was a challenge. It is recommended that, where possible the 5G network design and vendor selections are completed as early as possible so that service tools for network management and orchestration can be adapted and fit within the project schedule.

18.7 Neutral Hosting

A study was conducted to understand the needs of a public Mobile Network Operator (MNO) to host MPN's in their network. During the project it was discovered that connecting MPN to MNO was a complex task. After evaluation the Joint Operators Technical Specification (JOTS) seemed the most realistic solution. Further research is needed to understand and resolve the challenges of integrating MPN and MNO solutions. For this project the neutral hosting was not achieved. The following sub-topics capture some of the challenges to resolve.

Note: a new DCMS programme named FRANC includes a 5G Drive proposal to simplify adoption.

18.7.1 Private Network Hosting

A joint venture with Cornerstone Telecommunications Infrastructure Ltd (CTIL) restricted Telefonica in offering an outdoor mobile private network in the National Composites Centre (NCC) location. This limited the capability of this project to create a private to public mobile seamless network in an outdoor environment.

18.7.2 Interoperability MPN to MNO

To create a neutral hosting solution for new vendors that are not in the MNO list of supporter vendors, the MNO requires processes and solutions in place to adopt and host them.

18.7.3 Cost and practical implications integrating the solution in public MNO networks

The detailed analysis of the cost and effort required to integrate any piece of experimental software (e.g. Zeetta's multi-domain orchestrator) with the public mobile network (Telefonica UK/O2) was grossly underestimated. It was found later in the project that the normal qualification procedures require a considerable higher budget than that allocated to the MNO and takes at many more months of integration and testing than scheduled. For projects where neutral hosting is required it is recommended that a MNO is part of the partnership and that a very detailed study of the effort and activities needed to host a private network within the MNO network is undertaken before project planning is completed.

18.8 Precision Timing Protocol (ORAN specific)

For projects considering a 5G ORAN network (SA or NSA) the Precision Timing Protocol (PTP) design and implementation needs considering early in the project.

18.8.1 GPS Antenna mounting

The PTP grand master clock needs to synchronise with the satellite delivered Global Positioning System (GPS). This typically requires an external roof-mounted GPS antenna. To install such an antenna usually requires several permissions from the building management team and specialist to complete the installation safely. It is recommended that this is planned early so as building changes can take time to plan and execute.

18.8.2 Interoperability

In the ORAN PTP will require that devices from different vendors work seamlessly together to distribute timing through the 5G network. PTP is needed to synchronise the extended Common Public Radio Interface (eCPRI) interfaces connecting the Distributed Unit (DU) and the RU. In the project, it was necessary to bring the disparate skills of different device vendors together to ensure the PTP was synchronised correctly. It is recommended that a similar activity is planned by other projects.

19 USE CASE CHALLENGES

19.1 VR device selection and availability

The VR device market was quite limited when the project started. The VR devices available had the following limitations:

- Costly to purchase
- Overheated when used at high resolution for 45 minutes or more
- Battery life limitations
- Poor quality in-built microphones
- Poor quality imaging
- Poor support for visually impaired users i.e. users that wore glasses
- 5G not built in

When migrating training material to a virtual environment some of the limitations listed above were overcome by:

- Delivering content in sections to reduce failure due to overheating and battery life
- Delivering content in sections to provide adequate end user breaks
- Optimising graphics performance to balance user experience with device heat and power needs
- Simplifying course material to reduce blurring and content obscurity
- Cabling devices to power
- Re-organising content to make it easier to consume as a virtual learner

Not all limitations were overcome during the project, most crucially the headsets used had to use Wi-Fi connectivity from a 5G enabled CPE device. It is recommended that when delivering training in a remote, virtual, environment that the schedule and content is re-organised to deliver it in discreet blocks providing trainees adequate break times from VR devices and to give the VR devices time to cool and recharge.

Additionally, adequate digitisation considerations should be made to effectively present the teaching content in the remote learning solution. Optimising the digital media displayed within the VR headsets and the environment where the trainer is situated could have significant advantages to the overall knowledge transfer of the course.

19.2 AR devices and availability

The AR device market, like the VR device market, was quite limited when the project started. The AR devices and course materials had some limitations:

- Audio output low volume (in noisy environments)
- Poor visual performance in bright environments
- Content needed re-organising to improve the AR experience
- Remote helper function required implementation on another device
- Limited support for visually impaired users i.e. users that wore glasses
- 5G not built into the devices

When migrating training material to an augmented, virtual, environment some of the limitations listed above were overcome by

- Re-organising content to better fit with the new AR device capability introduced
- Connecting AR devices to auxiliary 5G devices (i.e. tethered to 5G enabled UE's)

Not all limitations were overcome during the project. It is recommended that when creating AR content the capabilities of the AR device selected are considered and assistive content re-organised to align with that capability.

Additionally, a sufficient introduction and training (potentially integrated in the course program) is likely to be necessary for new users to get accustomed to the AR training solution.

In the demonstrated AR assisted training solution, the augmented reality environment had three main focal points.

1. The main working area was in the centre of the field of view which had supplementary 3D graphics overlaid on top according to the specific course steps to guide the user.
2. On the left of the working area was the main instructions panel which cycled through text instructions for each step alongside a copy of the technical documentation and drawing.
3. On the right side of the working area was the panel with additional tutorial videos that show the user extra trainer demonstrations of steps that may need further clarification.

The AR environment can have much more content available on-demand which differs to the more traditional practice room environment and as such has potential further benefits for knowledge transfer.

19.3 In-factory Asset Tracking

The asset tracking use case considered the ingress and egress of materials from the facility as well as location of materials and tools within the facility itself. The performance of the RFID tag placement on products revealed some limitations. In general, digitized asset tracking did reduce time to locate materials and assets within the facility.

19.3.1 RFID tag placement

The placement of the tag on the material or asset being tracked is important as incorrect placement may lead to the RFID sensors not detecting the tag resulting in the asset or material location being lost. It is recommended that the material or asset to be tracked is assessed and any tag placement issues identified early to prevent problems later in the project. In this project the material to which the tag was attached on some material blocked RFID detection, consequently RFID tags needed to be placed such that sensors would detect them as material moved through the facility. It is recommended that when using this approach in other projects where the tag is attached is considered to prevent missed detection when materials pass sensors.

19.3.2 Ingress and Egress

The processes to receive materials into the manufacturing facility were file based and manual. These manual processes were not fully considered when planning the project. It is recommended that process workflows are created as early as possible in the project to identify unseen items where digital transformation would benefit the overall process.

19.3.3 RFID gate calibration

When deploying the RFID gates in the NCC shop floor, the calibration of the antenna was a critical operation to ensure the functionality of the asses tracking solution.

Based on the performance of the RFID gates over the past year, it is believed that periodic recalibration of the hardware is required.

For more sustainable and flexible remote working practices, a method to remotely calibrate the RFID antennas is needed. The manual process used involved an operator having to define the coverage area of each antenna using an RFID tag and manually determining if the tag was recognised by the sensor. This is a time-consuming trial-and-error process.

19.4 Liquid Resin Infusion and Automated Preforming Control

19.4.1 Communication protocols

These industrial processes used multiple communication protocols within the network to connect and manage devices. The manufacturing specialists managing these use cases understood these communication methods well, however, they were not specialists in cellular technologies. There were some very specific network needs to support certain protocols. The network specialist had to work with the manufacturing specialist to find a solution to these specific needs. It is recommended that cellular network specialists are made available to support engineers with integration into the network. Additionally, contingency time must be created in the project schedule to overcome these issues.

19.4.2 Network outages

These use cases were very sensitive to network outages or gaps in communication. This finding is captured earlier in this document.

19.4.3 Graphics processing capability in APC

This use case had some specific processing needs to manage and render data for the end user. The demands on the cellular network to transfer high volumes of data needed to be considered as well as the capability of the end user application and hardware to process and render that data upon receipt. It is recommended that specific hardware needs are identified as early as possible in future projects to enable the procurement processes to complete without impact to the overall schedule.

19.5 Haptics Robot Teleoperation Feasibility Study

19.5.1 Virtual Reality Headset devices

There are devices available to use when virtualizing a production environment, however, the wireless link is still quite immature when considering an industrial application meaning workarounds have to be made for certain actions. This will improve as the devices evolve.

19.5.2 Static camera depth of field

In the study a stereo high-definition camera was used to enable the operator to observe the robot arm from the remote location. There is an issue with this approach that that the stereo camera cannot be moved meaning any operator head movement to perceive depth of field cannot be mimicked in the remote location (humans mostly move their heads to gain depth of field without thinking). To fully overcome this limitation a second robotic arm is needed to mimic operator head movement when using a VR headset.

Note: 360-degree cameras are not suitable for looking at a distant robotic arm, they are most suited to being mounted on the active robotic arm.

19.5.3 Transmission latency

Commands sent from the control device to the robot take 1 second to send and receive. The robot has an inbuilt protection mechanism to reduce the opportunity of it damaging itself or something in its surroundings and consequently will only make a movement once it is sure that movement is safe. This results in delayed and jerky movement of the robot arm on the operator's screen making the user experience difficult to work with. This limitation exists in the wired feasibility study and may degrade in future work where a 5G cellular network is used. It is recommended that5G cellular that is SR16 standards compliant (latency <2ms rather than the SR15 standard of <10ms) is considered for use.

20 PROJECT EXECUTION

20.1 Best Practises

The UK 5G UK Innovation Network organisation is ideal for sharing best practises and is a useful resource for new projects to acquire the knowledge required to plan a successful project.

20.2 Project Execution

20.2.1 Structuring project artifacts

Structuring and managing data and documents generated during the project was not very efficient. Partners joining the project struggled to access and acquire clear visibility of the project and its status. There were multiple project manager and technical lead changes throughout the project cycle. It is recommended that a robust, easy to follow, folder structure based on project milestones is created once project scope is agreed.

20.2.2 Managing the communication plan

The communication plan to deliver findings later in the project was not well defined. The intention and audience for communicating results was unclear. The project did have a communications plan that, for the most part, was completed. When communication and publicity management is outsourced, time needs to be assigned and agreed for technical review of materials to be published. In some areas of the project this was not well planned. It is recommended that during project initiation communication deliverables and impact measures are improved.

20.2.3 Change Management

The change management process was easy to understand and use. This benefitted the project as changes and impacts when required could be easily articulated for stakeholder decision. Technical challenges are typically difficult to explain in short and simple terms. The change request forms aided the team in preparing concise change request statements.

20.3 Cost of 5G

At the time of this project the investment required to purchase and deploy a 5G MPN is high. Proving business cases to justify investment will be a challenge until equipment volumes increase and the price reduces. At the time of this project, a private organization considering 5G will need to carefully validate any use case for investment. Examples where investment could be justified include processes when moving to a MEC makes sense and low latency in the network is needed or high bandwidth mobility is needed to support end users.

Note: not all industry 4.0 digitalization use cases require 5G.

20.4 Demonstration days

In the project multiple unexpected conditions occurred in the lead up to use cases and launch event. It is recommended contingency is planned in the schedule so unexpected events do not delay the program.

21 DCMS PROCESSES

21.1 Government Investment Initiatives

The government has multiple initiatives for UK investment in technology. The landscape is complex and can be difficult to understand for inexperienced companies wishing to bid on projects. The initiatives encountered included:

- DMCS
- Innovate UK
- Digital Catapult
- UK 5G

It is recommended that this is simplified.

21.2 Forming a consortium and applying for funding

Whilst this was done by other that subsequently moved on from the project, I understand this process was intense and quite a long activity. For smaller companies the investment in time needed to make an application (successful or otherwise) could be perceived as a barrier to entry. Larger corporates with financial latitude to support such projects have their own internal challenges acquiring approval to bid on projects and whilst their technology maybe superior they may not be as nimble as smaller companies to complete work packages. The application process could benefit from a review to see if the due diligence activities could be accelerated or possibly conducted less stringently to reduce the effort and cycle time needed to form a consortium.

21.3 Project execution

During the project there were adequate processes in place to track progress, ensure funding claims are processed in a timely manner and change requests managed. No significant changes were identified.

21.4 Project Templates

Guidance on how to present project findings was at the discretion of the project lead. The only requirement sent to the project was that the final project report is a single PDF (Portable Data Format) document. Whilst this flexibility is appreciated by the project lead, I would recommend that a simple, unbranded, final report template is constructed to ensure project leads submit quality documents with an element of consistency in the content.

Note: the template used for this report is in a style agreed by the major consortium contributors at the commencement of report generation.

21.5 Project Close out

21.5.1 Benefits Realisation and Lessons Learned template

This is in the form of a MS Excel (.xlsx) file. Some of the sheets in the file contain many columns making them very wide and consequently difficult to navigate.
I think with some thought and consideration of consumer experience and ease of use many of the sheets (tabs) in the workbook could be formatted to fit onto 28-inch monitor running at 1080p (standard office monitor in 2022).
Note: I used 2 x 27-inch identical monitors side by side to create a workable view of some sheets in the workbook. This is not a practical solution for many consumers.

I inherited this file whilst the project was in-flight, so the template may have been changed prior to my engagement on the project. I have not adjusted the template so the examples where simple formatting improvements would make the file easier to work with are from the file I inherited.

- Sheet 'Project information & Employment' columns excessively wide
- Sheet 'TRLs' Columns B and C excessive width, better to make the columns narrower and wrap the content accepting that the table will be deeper rather than wider.
- 'Testbed monitoring' really hard to fill in with column widths as is
- 'Use case monitoring' also hard to fill in with so many columns and the rows often becoming so deep keeping a row in view on screen becomes challenging. I recommend an alternative approach is adopted in another medium e.g. MS Word.
- 'Knowledge creation & dissemination' and 'Lesson learnt' are ok to work with although I would consider narrowing the columns and reducing sheet width.

21.5.2 Asset Register template

This MS Excel (.xlsx) template file contains several bugs as listed in the figure below:

Sheet	Item	Issue
Asset Washup	Header	Cell B4 Project Name not populating
Asset Washup	Project Partners	Cell B5 not populating
Asset Washup	Project start date	Cell B12 not formatted as date
Asset Washup	Project end date	Cell B13 not formatted as date
Asset Washup	Columns	Cannot be resized
Asset Washup	Cannot enter more than 85 rows (17 to 102)	

Figure 9: Asset register xlsx issues

22 APPENDIX A

Lesson Summary	*Challenge (where appropriate)*	Resolution (where appropriate)	Further Detail
General - Enterprise IT departments are not accustomed to dealing with cellular technology and as a result underestimated the level of interaction with the existing LAN and WAN infrastructure and its implications in terms of additional capacity for connectivity and additional requirements such as remote access needs.	The project had complex networking requirements which were not fully understood at the project's early phases. As a result, internal enterprise stakeholders such as IT and Facilities departments did not fully appreciate the requirements of 5G and the implication on existing infrastructure, process and support needs.	Close interworking between the project team and IT has helped to resolve many of these issues and address partner needs for the project from the existing infrastructure. However compromises have had to be made all round to move the project forward. Additional capacity and capability gaps should be identified at an early stage and clear roles and responsibilities agreed between project and support teams.	Some aspects such as link capacity between sites is extremely restricted and the ability of IT departments to support these technologies is limited. Early engagement with these stakeholder groups is essential to ensure proper level of support is in place for the desired use case and business outcome.
General - Enterprises will have varying levels of secure remote access requirements which needs to be considered and planned as part of any potential 5G infrastructure rollout. This can include the need for firewall, DMZ zones, Jump boxes and various trust zones across the network infrastructure. There may also be a requirement to monitor and maintain remote access activity logs for security audit purposes.	Securing remote access to the project infrastructure which meets internal IT requirements	Working with IT stakeholders the project has agreed a number of security improvement measures for the remote access solution including the implementation of a firewall and DMZ. However other measures such as Jump boxes and two factor authentication were deemed by the project to be disproportionate to this initial first phase	NCC now have an isolated environment for anything Digital related and as part of partner engagement, required access to this environment remotely. Due to the nature of this isolated environment widely access via partners across the globe it was necessary to select a solution that is secure & robust. Post implementation of aforementioned solution no issues were observed, and security compliances were addressed.
General - 5G requires new business models such as private cellular networks, neutral hosing etc. in order to facilitate wider deployment.	What models are appropriate for operators, vendors, managed service providers? What are the options available and what are the pros and cons of each of these?	5G Encode has produced a neutral hosting options paper to explore various models with Telefonica and get a commercial operator input into which models make sense from an MNO perspective	UoB team have produced a discussion paper as a reference point for technical discussions with the Telefonica design team for input into the Encode 5G network design. Core integration will need consideration prior to external party/vendor selection for external entities.
General - Enterprises will struggle to deploy private 5G networks by themselves. This needs to be an operator led activity or a managed service from an SI or similar.	Many of the use cases within manufacturing require high quality in-building networks. Who in the ecosystem will deploy these networks, operate and maintain them? Multiple options from	Enterprise likely to seek this as managed service from an existing MNO partner/service provider or alternatively outsource this to a managed service provider. This ensure	Core networking required to deliver 5G platform can be built, managed & maintained by an internal IT professional with

Enterprises are not familiar with cellular technology, nor do they have the skillset internally to this new technology stack.	operators, managed services providers to enterprises themselves. Who is best placed to deploy these networks?	enable them to reap the benefits without having to concern themselves with the design and operations of such networks	relevant skill sets. The vendor selection will determine if the RAN is V-RAN, O-RAN or proprietary and this will determine level of skillset required to take these products to an operate & maintain stage. For example, NCC deployment required a network engineer, an infrastructure engineer, a Linux specialist with knowledge of Kubernetes & knowledge of DELL hardware.
There is a need for easy and simply to use network slicing/splicing and multi-domain orchestration for private 5G networks.	How can industry users easily orchestrate and deploy bespoke network services without the need for specialist skills?	Zeetta Networks is developing it's unique Multi Domain Orchestrator (MDO) solution as part of this programme and plans to demonstrate it during phase 2	
Best Practices for Wireless implementation into Manufacturing systems needs to be developed and agreed at an industry level to hasten the rapid rollout and adoption of 5G in industry.	There is a lack of templated processes, best practices for deploying 5G private networks. This may hinder the speed of deployment and adoption.	Possible update to the Joint Operator Technica Specification (JOTS)?	
There needs to be public connectivity to private 5G networks and MNOs need to explore the various options available to determine suitable options. New tools such as the Zeetta MDO will also be required in order to effectively manage services across these different domains.	Private and public 5G networks need to interface with each other to provide seamless service delivery in a secure manner. How can this be enabled?	Zeetta Networks is developing it's unique Multi Domain Orchestrator (MDO) solution as part of this programme and plans to demonstrate it during Phase 2	
General - More industry engagement required as these benefit messages have not filtered through to the target audience. Training and education on the benefits of 5G technologies for industrial applications. Guidance for Industry for scoping / dimensioning 5G systems.	There is a lack of awareness within industry on the benefits of 5G use cases. At a recent forum many industry partners were still asking why they couldn't utilize standard Wi-Fi for these use cases.	Further forums and events should be held and led by DCMS to help industry understand the benefits of 5G and why they need to start engaging.	

General - The government already has a barrier busting taskforce to address the barriers of public network rollout. Similar effort and task force required for Private 5G solutions.	There are a number of barriers for a wider adoption of private 5G in an industrial setting including a clear business case, lack of end user devices, skills and knowledge. How can these barriers be addressed?	TBD	
General - There needs to be public connectivity to private 5G networks and MNOs need to explore the various options available to determine suitable options. New tools such as the Zeetta MDO will also be required in order to effectively manage services across these different domains.	Private and public 5G networks need to interface with each other to provide seamless service delivery in a secure manner. How can this be enabled?	Zeetta Networks is developing it's unique Multi Domain Orchestrator (MDO) solution as part of this programme and plans to demonstrate it during Phase 2	
VR - No availability of 4G VR headsets	Difficulties in getting the Samsung handsets to connect to the VR headset	Used viewer software on handset to view video stream.	
VR - Wi-Fi tethering shouldn't be used as it interferes with 4G connectivity	Prevention of Wi-Fi tethering made tethering a 4G smartphone to the VR headset difficult.	The player used was further developed to run on smartphone-based VR headsets.	
General - Having knowledgeable experts in networking available or present is crucial to ensuring the installed network is robust and functional. Having this skill base present from the beginning will aid in decision making and reduce delays as a result.	Correctly configuring 4G routers to communicate over a private network is specific knowledge that most individuals will not poses. How can we ensure that a sufficient skill base present?	Recruited the right skill set to deliver this requirement.	
General - A Low level design document will aid in network design & implementation - ensuring the correct hardware is procured and installed.	How can clear and concise communication be ensured when relating to network design? Having multiple organizations and individuals contributing to a design can lead to difficulties and delays from lack of communication.	The presence of a low-level design document containing a clear and concise report on the designed network including protocols and ports will benefit those involved by having everything in one place.	
General - Core features commonly found on networks not just for basic addressing but also secure remote access and the ability for partners to be able to access desktop environments	Having a core understanding of requirements for remote access from partners would be beneficial to facilitate the request in a production infrastructure that can be moulded into requirements for secure remote access and isolated use cases.	Active Directory deployment to manage centralized user access and the ability to leverage WinTel infrastructure to facilitate an RDS farm with isolated session hosts in network segments allowing for use cases to be isolated	Knowledge of a modular development architecture is required to be able to build something more fitting to accommodate each use case

need to be present before commencing use cases.		and worked on across all partners/staff members concurrently.	
General - Open-source hypervisors are unsupported and do not have the modularity required to allow for maximum elasticity and optimization of resources required to facilitate each use case efficiently	Requirements for use cases were unknown at the time of specification but the possible bridging of production networks and development networks would be challenging leveraging open-source hypervisor platforms simply due to security implications.	Purchasing of a widely adopted hypervisor by industry (VMware/Hyper-V) with the correct hardware underpinning it would allow for a much more seamless integration into a production environment with minimal security overheads.	Open-source operating systems have no widely available centralized patching mechanisms making automated patching challenging.
General - Having experts in computer networking available to support the integration of 5G enabled devices into use cases is vital. The engineers who understand the process will often not understand how to properly integrate devices into the system without networking knowledge	How can we ensure that individual's skilled in computer networking are there to support engineers who are seeking to use 5G comms to enhance their process	A network infrastructure engineer was brought in to support with device configuration for the use cases. Wider training in network technologies and specifically Radio Network technologies across both project and support teams will help further.	
LRI - Machines utilize a number of different communication and network methods (such as OPC UA, EtherCat, profinet). To be able to connect these machines to a 5G network to capture their data, experts in machine communication technologies would be beneficial	How can process and data engineers be supported in their goals to connect up machines to 4G/5G networks and use this data to improve manufacturing?	This is still to be resolved	
LRI/General - Dongles have caused challenges in connectivity when using them in tandem with ethernet networks on the same PC. It is recommended that if a PC connected to an ethernet network requires access to the 5G network at the same time, a 5G router (connected to the PC) is used to provide connectivity instead of a dongle to avoid network prioritization issues	Using dongles for 4G connectivity created issues on PCs that already had ethernet connections to other networks. The PC set the ethernet connection as the highest priority and blocked the PC from communicating over the 4G network. Changing the network priority order in the PC settings did not fix this problem.	An industrial CPE device was used to provide 4G network connectivity to the PC instead of the dongle. The CPE was connected directly into the PC via ethernet (and a switch).	Simple infrastructure/methodologies allowed for more efficient use case deployment.

LRI - More information is needed on how to design safe, compliant architecture of automated manufacturing systems that utilize 5G.	How can automation systems built using 5G technology be proven to be as safe as those built using conventional hard-wired (ethernet) connections?	This is still to be resolved	
LRI/General - Industrial 5G devices are still very limited (e.g. 5G routers or 5G enables sensors) making testing of business cases challenging	Procuring 5G enabled devices to test on the 5G network that will be installed at the NCC is proving difficult and reduces the ability of the teams to properly test the businesses cases for 5G	Hopefully as the year progresses 5G enabled devices (such as industrial 5G routers) will become available	
Asset Tracking/General - Interference from other wireless transmission hardware and high voltage electrical equipment have caused issues with consistency and reliability of connection.	The NCC is a finite area and within it there are multiple different wireless communication mechanisms broadcasting on frequencies close to band 3 4G. There are also high voltage pieces of equipment all over the workshop with the backup batteries for the NCC situated right behind one small cell location.	Conduct a full site survey before any installation of wireless hardware is installed - investigating the frequency which is planned for use to ensure interference with signal is kept to a minimum.	Frequency scanner used to visualize the interference and confirm its presence around 1800MHz.
Asset Tracking - UHF RFID tags do not work when in contact with CFRP	When placed on the carbon or the bag holding it the UHF RFID tag is not read. CFRP is conductive and the radio waves do not interact well with the material.	Tags were placed on the box holding the CFRP material as well as the spool itself.	
5G Networks are more than capable of providing AR/VR services with real time interaction between private and public networks sites. However, streaming servers must be capable of providing the required computational power for simultaneous high quality video streaming to many devices.	High quality streaming is essential for AR/VR service provision. Thus, high throughput performance is required between the UE and the RAN network. Streaming high quality video also requires high computational power at the streaming server for video processing purposes. Setting the video quality to a high bitrate caused video stuttering and inconsistencies in the VR service provision, even though the overall UE throughput requirement was much lower than the 5G RAN throughput limit.	The VR video quality was lowered in order to ease the load on the streaming server. The bitrate was tested between 5 – 15 Mbps, only the lowest bitrate being supported by the streaming server's hardware capability.	Various video qualities (bitrates) were tested to find the right one based on the streaming server capabilities.
5G SA provides greater flexibility in configuring the Private or Public networks. However, this solution is not supported by many 5G UE devices as the manufacturers lock 5G SA operation on their devices in countries such as UK, waiting for completion of testing on	Lack of 5G UEs to support the AR/VR services in 5G SA mode. The 5GUK Test Network owns some of the latest 5G-capable flagship phones but the 5G SA operation is locked by the manufacturer. As a result, the phones were not compatible with the 5G SA network configuration of the	In-house built CPE devices were developed and configured by the 5GUK team in order to provide 5G SA connectivity to the UE devices through Wi-Fi 6 'hotspots.	Effort was put into R&D to engineer multiple CPE devices using numerous, readily available as well as custom built components including Single Board Computers (SBCs), 5G Modules, Wi-Fi 6 Access Point

commercial networks. 5G SA has not been commercially tested or deployed in the western countries. Transition from 5G-NSA to 5G-SA may be a barrier with mixed UE capabilities in a network.	5GUK Test Network. A different way to provide network connectivity to the AR/VR devices through the 5G network was required.		Modules, CPE casing, etc.
Most of the recently released Wi-Fi 6 Access Point (AP) Modules are not ready for commercial deployment.	Current WiFi-6 AP modules are not natively supported by Linux-based systems. Module drivers are unstable and do not support the full 802.11ax standard. Module firmware's come with outdated regional channel and transmit power regulations which limits the Wi-Fi performance.	Various Wi-Fi configurations have been tested with the latest drivers. The configuration with best possible performance under the current driver support was selected.	The DL/UL Wi-Fi performance is 1.2/1.9 Gbps, even though the theoretical one should exceed 4 Gbps
Chipsets and modules for Wi-Fi 6 to be designed into a hotspot solution require additional cooling and require drivers for Linux operating system	Supply chain for the parts in making 5G devices are still taking shape in the global market; as we were trying to source and develop our own CPE to enable 5G SA connectivity and creation of WiFi6 to accessories such as headsets.	searched in the global market and found a module that we could programme its driver for the Linux operating system. Also gave feedback to the parts suppliers as how we overcame their design errors for them to improve their product line.	We consider in the next 12 to 18 months the devices with 5G SA capability and Wi-Fi 6 may become mature for industry to depend on their availability of supply.
Asset Tracking - Manufacturing and Material information is not automatically transferred from one software to the another (manual data input between Siemens OpCentre - manufacturing execution system - and Plataine - asset tracking system). The manufacturing process is aimed to have a smooth data sharing process between the systems in real time.	Enabling a smooth and automatic communication between the material tracking software and Manufacturing Execution Software has been particularly challenging.	The task is currently in progress to define correct communication.	Main difficulties were identified in the data transfer process from Siemens OC (MES) to Plataine TPO (tracking software), and vice versa. Based on that, a manual input on each system / software is currently required (data will be populated twice).
Asset Tracking - A digital data handover on goods received (CFRD material rolls) between Solvay (supplier) and NCC (customer) will not be possible to implement. Data / information update on supplied materials will be done manually as the rolls are delivered to the NCC site.	A digital data transfer process between the two organizations would enable an automatic process of recording essential material information as the asset is delivered on site, without requiring an operator to manually input the material details. Solvay could not get an automatic receiving process for October 'In-transit' demo so we will perform a manual receiving process accounting for the associated risks.	Essentially, it is aimed to have a smooth transfer of material information from supplier to NCC.	Solvay to find funding for an automatic receiving process for 1Q 2022. Resolution plan: - October demo - manual receiving process - 1Q 2022 - automatic receiving process

General - There is limited availability of 5G SA network compatible devices as the current technology is still under development, with limited use in a manufacturing setting.	5G SA network has not been deployed yet.	Potentially, it would be of use to identify areas of improvement, as well as current limitations of present 5G technology and work with manufacturers to make it readily more readily available to different industries and business areas.	Complexity of adopting a new 5G ORAN technology impacted deadlines, more contingency time in deployment plans until the technology matures.
AR/VR - Schedule for technology demonstration including contingency	Unexpected technical difficulties can come up with new applications and technologies which can have detrimental effects on the overall demonstration performance or task.	Set out detailed schedule for day to help manage user schedule expectations. Schedule provides structure and clear time to mitigate tasks overrunning and ensure all use cases demonstrations finish having fully showcased capabilities.	
AR/VR - Booster antenna applied to small cell for AR VR use	Small cell connectivity enhancement required ensure a smooth and consistent network connectivity	Increase small cell antenna proven to enhance network connectivity consistency and ease of connection	Consider RF optimization using frequency scanner. Boosters have some effect, but improved performance can sometimes be achieved by moving or re-orientating cell antenna (for omni cells this includes looking for physical obstructions on a radio path e.g. walls, metal etc. and working around them)
AR - Further AR break down of training content to improve user interface	Missing or over simplified steps cause expert helper question queue during AR training	Extra training steps added to composite lay-up AR training to increase scope of AR user applicability to be more suitable for first time composites users	
AR - Improved camera feed management	Camera feed for each user, visible to each user can become confusing for other users and reduce user experience during training. Also, user camera feed requiring handheld user reduces user experience during training	Enhancement to ensure each trainee cannot see other trainee video streams. AR headsets have capability for video feed to be delivered from headset worn by user, rather than video stream from handset; this capability will be utilized	
VR - Mic for VR to improve audio	VR audio can become faint and muffled, reducing user VR experience	Clip-on microphone, worn by trainer, demonstrated to improve audio quality during VR training demonstrations	

AR - How to use equipment introduction for AR	Lack of understanding utilizing new technology such as AR can inhibit user experience during technology demonstrations	Extra content added to ensure users are comfortable and proficient using AR technology will enhance first-time user experience	
VR - Network streaming via VR is found to be highly power intensive and quickly consume VR headset battery life.	Battery life function through whole VR demonstration streamed via network	Ensure all headsets have 100% charge before use in VR demo to minimize chance of battery failure during demo	
VR - Video / audio from 360 camera	Stream has delayed audio because it must run over Wi-Fi	Install camera administration software onto windows 10 laptop to facilitate wired connection to access point	
LRI/General - Interference in manufacturing environments due to machinery and other radiation can cause black spots or sporadic signal drop offs.	Systems that move around a factory and rely on network coverage may encounter black spots and drop offs. A full detailed survey of interference must be done prior to deploying a cellular network, otherwise this could be very costly to rectify once the system is deployed	A thorough interference survey should be done prior to the design and deployment of any private cellular network within a manufacturing environment. The location and type of UE's must be considered to ensure that the right level of signal will be available in the right location	
Asset Tracking - The AT testbed showed great potential not only to closely monitor asset location, but also to remotely record material out life and stock. The user interface showed great flexibility in adapting to different applications, while the 5G network offers reliability and consistency to the asset tracking solution that captures and generates information on the item location, availability, stock and out-life.	Different industrial challenges identified at the NCC, such as monitoring stock, asset out-life and availability.	The asset tracking testbed chowed the capability to address more than one industrial challenge, showing potential to be a reliable solution for more sustainable and efficient means to monitor live material stock and out-life.	Assess the capabilities and capacity of the existing testbed in monitoring stock representative for a production environment (e.g. higher number of assets) - of interest as part of a future study of the 5G asset tracking solution.

Asset Tracking - RFID gate remote calibration	When deploying the RFID gates in the NCC shopfloor, the calibration of the antennas was a critical operation to ensure the functionality of the asset tracking solution. Based on the performance of the RFID gates over the past year, it is believed that periodic recalibration of the hardware is required. It would also be of interest to explore remote means to calibrate the RFID antennas, as the current procedure is mostly manual and highly tedious. The remote calibration procedure involves an operator to define the coverage area of the antennas around each gate manually using an RFID tag, being a time-consuming trial-and-error process.	Periodic calibration of the RFID antennas.	Alternative options are still to be explored in future work.
Asset Tracking - Automation of data transfer	Numerous numbers of steps to capture data and execute operations (e.g. request material for a work order, update stock and monitor material out-life)	By enabling the manufacturing execution system to update material stock and automatically provide part manufacturing data to Plataine TPO, the number of manual steps that are usually completed by the technical authorities or project managers were drastically reduced. It also improved time efficiency as tasks were not delayed and they were completed instantaneously as the work order was completed in Opcentre.	Explore similar automatic exchange between Plataine TPO and other pieces of software (e.g. Polyworks software used to generate metrology scans).
Asset Tracking - Flexibility of asset tracking solution	For this particular use case, the asset tracking solution was demoed for one specific manufacturing process – an automated fibre placement process. The existing system was configured for a linear production flow, using a relatively small number of assets and covering only seven work cells in the NCC factory: Freezer – Thawing – AFP Coriolis cell – Autoclave	The technologies and web solution employed by the use case proved to be easily adapted and customized for any manufacturing environment or process.	Explore the 5G testbed capabilities in a more dynamic production environment, representative of a real case situation - further studies outside the scope of this project.

	– NDT – Metrology – Tool storage. This might not be representative of a production environment.		
VR - 5G headsets currently not available on market	Unable to connect the VR headsets directly to the 5G network and test the full potential of the network during 5G trial on Millennium Square, Bristol.	Have to use a customer-premises-equipment (CPE) device connected to the 5G network and allows the VR headsets to connect to it (to CPE) via Wi-Fi.	
AR - Audio output from AR glasses is quite low volume (hardware limitation)	In a busy and noisier environment the Nreal glasses audio output is quite low volume, so it is more difficult to hear the trainer when using the 'Expert Helper' function.	It is possible to connect the mobile device (OnePlus 8T in this case) to an additional speaker or headphones via Bluetooth. This way the audio output will be through either of those rather than the Nreal glasses. Alternatively, audio could come out of phone speakers also.	
AR - Using AR glasses in bright environments	Viewing content through the AR glasses in a bright environment with significant glare/reflections becomes difficult. The technology is not so well adapted to such environments and users in Millennium Square commented on diminishing visibility when the sun was out.	Turn up brightness control on AR glasses and carry out the AR work in a location with less direct sun glare/reflection.	
AR/VR - Fatigue while using AR glasses and VR headset	Some users commented on fatigue after 15-20 minutes of using the AR glasses or VR headset. Combination of more unusual viewing experience and length of course/necessity to stay in one position.	VR - Possible to modify course structure to include more regular short breaks if necessary. AR - Possible to add prompts from application that encourages users to take more regular short breaks.	
AR - Difficulty for users with prescription glasses to use AR glasses	Users cannot use AR glasses very easily if they also wear prescription glasses. This limited	Nreal glasses can accommodate auxiliary clip-on lenses instead of normal prescription glasses. Or alternatively, users can use contact lenses instead.	Limitation is that user prescription must be known, and specialized lenses made before use. This is difficult if many users have access to hardware and potentially quite costly.

AR/VR - Length of battery life limitations	VR - headsets required charging after every course (every circa 40-50 minutes) AR - dependent on phone battery power (OnePlus8T), so constant continuous usage is limited to a couple of hours	VR - Charging as soon as course ends, ready for next AR - Charging as soon as user finishes, ready for next user	
AR/VR - On-screen media graphics blurry	On-screen media in both technologies were either too small in size or too far away from viewer, so would appear blurry.	If possible, to zoom or get closer to the media, the quality issue would be alleviated. But if not possible, higher resolution images are required or a function to enlarge them within the environment.	
AR - Overall 4G vs 5G comparison	Main feature in the use case that utilizes the network performance is the two-way communication feature called 'Expert Helper'. It allows the user to communicate with the trainer at the NCC HQ in real time with audio and video feeds. The feature was not found to be required by the trainee (or the trainer) very often during the training course and is realistically only used intermittently (when trainee needs assistance) for a relatively short duration (mostly under 5min). As such, there was not a significant quantifiable difference in this feature's performance observed between the 4G and 5G trials. It was operational and usable in both cases.	There are possible developments that can be made to make the use case more reliant on the network performance. These would also improve the use case modularity and usability. The 5G improvements compared to 4G will then become more prevalent. One development is creating an online library containing interactive digital content which can be called upon from the AR device when needed for the course. This will reduce the need to store the AR content offline on the device's local storage and enable quicker creation of a new AR course. Another development is adding a fixed (or 360°) camera at the remote training location (e.g., Millennium Square) which is streaming continuously and allows the trainers to observe the progress being made by the trainees.	

VR - Overall 4G vs 5G comparison	The 360° video streaming on a VR headset use case was significantly improved by the 5G network performance (downlink exceeding 700Mpbs as measured by UoB SIL) in the Millennium Square trial. It allowed for the course to be streamed to a group of sufficient attendance - 5 headsets and at least 3 mobile devices. Additionally, the network capabilities enabled extra media to be shown within the VR environment in the user field of view. As a result, the participant engagement and satisfaction were also improved. On the other hand, in the 4G trial the network performance was not sufficient to enable more than four devices to be used concurrently (2 VR headsets and 2 mobile devices). Even with this many devices the viewing quality had to be prioritized which meant that the additional media could not be enabled. In the end, the user feedback was predominantly negative with key reasons stated as poor streaming quality due to network capability.	Further technology development is required to enable a more comprehensive test of the network capabilities. Specifically, VR headsets which can be connected using 5G directly are not currently available, so a CPE device had to be used which was itself connected to the 5G network but allowed the headsets to be connected to it using Wi-Fi. Additionally, the streaming quality could not be considerably increased from the 360° camera side due to throttling of the streaming server.	
APC - GigE Vision is a layer 2 communication protocol, designed for use with devices on the same network. Communication across networks is possible but not "out of the box" preventing the auto discovery feature from operating.	Testing the architecture for the 4G/5G use cases involved crossing multiple networks, meaning the GigE vision configuration had to be altered to allow this. Fixed ports and IP addresses were required to make use of NAT and port forwarding.	GigE vision uses physical (MAC) addresses to communicate - a custom packet was created containing the MAC address of the router. The camera sent the packet to the router using the MAC address, when the packet arrives the router has a NAT rule to forward any packets from the camera IP onto the server for processing, thus allowing communication.	Without a deep understanding of networking this would not have been possible. GigE vision will be a blocker to industry accepting 5G as a communication standard for these large data volume vision applications until a more appropriate protocol is created.

APC - 5G network struggled with large data volumes and led to connection instabilities.	Sensor application generated large volumes of data to be transmitted across the 5G network leading to fragmentation of data and dropped frames. Connection instabilities observed on the 5G radio when large volumes of data were transmitted. Cause isn't completely known but likely due to network overload and fragmentation of data from slow communication speeds.	Reducing the packet size (MTU size) and slowing down the speed of the robot scan path reduced the data volume going across the network. The result was better data at the server side and a more stable connection.	This limitation in network capacity meant that the time of each scan was greatly increased when compared to a wired solution. The speed of the robot scan path was roughly 200 times slower than the original.
APC - Virtual server adds flexibility and ease of maintenance	Someone with server and network knowledge is required to set up this application.	Hosting the application on a virtual server allows the user to remote desktop into the machine from anywhere in the world with the right permissions. If the server requires maintenance, then the virtual machine can be moved with ease. If the application is hosted on a physical PC and maintenance is required, the effort is much greater and requires a separate PC to run the application - potentially leading to increased downtime.	
APC - Virtual graphics processing is capable of handling these applications and further increases system flexibility.	Someone with server and network knowledge is required to set up this application. Mapping of graphics processing on a virtual server requires an additional licence to work (~£25 per year)	Hosting the application on a virtual server with a vGPU mapped to it meant that all data processing could be done away from the source. This removes the need to have a PC either on the robot or close to it and removes the need for any end users to have powerful PCs. Any device with a remote connection can visualize the data in 3D as all of the compute power is centralized in the server.	Standard comms rooms server equipment can be used for this application - the only specific piece of hardware required for full functionality is a graphics card within the server.
LRI/General - Stability of V-RAN software on the 5G network was poor and often malfunctioned leading to a gap in data collection and posed a risk to automated systems that relied upon network connection. However software always	Availability of CPE/UE devices were limited due to lack of 5G SA NR functionality & availability in the open market. Embedded 5G SA functionality has not been unlocked on most CPE devices and as such specific configurations were required to force NR functionality.	Work with 5G device suppliers to test devices on 5G SA networks and increase reliability/robustness.	

recovered after a few minutes.			
LRI - 5G-native process monitoring sensors do not exist	Due to the lack of native 5G enabled sensors, 5G routers were needed to route sensor data though to the 5G servers for data processing. This limited flexibility the LRI solution that could be developed as it still required a lot of wires.	Work with industry to develop 5G enabled process monitoring sensors	
Stability of Open-Source Open-Air Interface (OAI) software in non-lab conditions.	The stability of the network was affected when devices attempted to roam on the network dues to software bug in the OAI gNB software.	Investigation into stability still on going on Toshiba's lab setup.	During the LRI use-case testing with Toshiba's OAI based NSA network it was noticed that crashes were common when people's phones in the area were set to attempt roaming. Unfortunately this was a breaking bug and caused the network to drop the currently attached devices unfortunately prematurely ending the data logging on Toshiba's network. It has been identified that the PRACH messages received from devices were interfering with the gNB performance on OAI gNB version 2021.w10 which was used during the test. There have since been released newer versions of the software that may address the issue, but this is untested.

Quectel RM500Q-GL Accepted Non-Standalone (NSA) frequency band combinations	The dongle will not connect to an NSA network if the LTE anchor band is Band 40, potentially because it is Time Division Duplex (TDD)	Use LTE anchor band such as Band 3 or 7 which are Frequency Division Duplex (FDD)	When applying for the Ofcom licence Toshiba was given access on Band 40 LTE and Band 77 5G to enable NSA communication. Unfortunately with testing it proved apparent that the Quectel RM500Q-GL dongle that was sourced would not work in the B40 N77 NSA configuration so other configurations had to be used. NCC let Toshiba use a 5MHz portion of their allocated Band 3 spectrum to use for LTE in order to do the NSA handover. This B3 N77 configuration worked without issue for the Quectel RM500Q-GL.
AR/VR - Expand knowledge regarding existing problems in Industrial environments which would benefit from the use of immersive technologies (AR/VR/XR) (MatiVision)	Working with the project partners to identify those areas in industrial environments which can receive the highest benefit from the use of immersive technologies. Expand beyond the specific Use Cases of the project to different processes and procedures in diverse industrial sectors. Manage to properly demonstrate benefits through the execution of focused use cases addressing well-defined industrial problems	At the completion of each Use Case	The industry today shows a very low level of adoption and exploitation of Immersive technologies and applications. Even such low levels of use, aptly and conclusively have demonstrated that such technologies, if applied properly, can bring significant benefits to a wide range of industrial processes, across sectors. It is the intention of MatiVision to seek to demonstrate these benefits more clearly and eventually build a range of solutions which will be easily adopted by different industrial sectors.
AR/VR - There is a need for specialized skillsets (MatiVision) to design, commission and maintain the end-to-end 5G use cases	To allow implementation of case-specific immersive applications in the industry. Adapting and expanding the know-how and experience of existing as well as new personnel (to be recruited) in the specific requirements of diverse industrial sectors as regards immersive technologies and applications	At the completion of each Use Case	MatiVision will aim to provide bespoke solutions for specific industrial problems across industrial sectors, using immersive technologies. The goal is to make the industry aware that instead of each entity addressing internal problems with

			internal teams, reaching solutions that are one-off and seldom (if ever) reused, MatiVision can provide solutions based on field-tested
AR/VR - Prevention of traveling arrangements due to Covid-19 made remote testing of hardware and equipment a necessity.	How can Mativision plan for contingency scenarios where personnel can't access the equipment physically?	Mativision in collaboration with NCC personnel was able to provide remote support and real-time collaboration sessions to test out equipment that Mativision personnel couldn't access.	
AR/VR - Schedule for technology demonstration day	Smooth VR / AR demonstrations day to avoid use case demonstrations overruns and knock-on effects	Setting out schedule for day to help manage user schedule expectations. Schedule provides structure to mitigate tasks overrunning and ensure all use cases demonstrations finish having fully showcased capabilities	
AR/VR - Set-up contingency time for new network and technology	Unexpected difficulties can occur during demonstration days, inhibiting smooth technology demonstration	Allowing at least an hour before any AR or VR demonstration to ensure on-the-day bugs can be resolved ahead of time, mitigating risk of impacting technology demonstrations	
AR/VR - Booster antenna applied to small cell for AR VR use	Small cell connectivity enhancement required ensure a smooth and consistent network connectivity	Increase small cell antenna proven to enhance network connectivity consistency and ease of connection	Consider RF optimization using frequency scanner. Boosters have some effect, but improved performance can sometimes be achieved by moving or re-orientating cell antenna (for omni cells this includes looking for physical obstructions on a radio path e.g., walls, metal etc. and working around them)
AR - Further AR break down of training content to improve user interface	Missing or over simplified steps cause expert helper question queue during AR training	Extra training steps added to composite lay-up AR training to increase scope of AR user applicability to be more suitable for first time composites users	
AR - Improved camera feed management	Camera feed for each user, visible to each user can become confusing for other users and reduce user experience during training. Also, user camera feed requiring handheld user reduces user experience during training	Enhancement to ensure each trainee cannot see other trainee video streams. AR headsets have capability for video feed to be delivered from headset worn by user, rather than video stream from handset; this capability will be utilized	
VR - Mic for VR to improve audio	VR audio can become faint and muffled, reducing user VR experience	Clip-on microphone, worn by trainer, demonstrated to improve audio quality during VR training demonstrations	
AR - How to use equipment introduction for AR	Lack of understanding utilizing new technology such as AR can inhibit user experience during technology demonstrations	Extra content added to ensure users are comfortable and proficient using AR technology will enhance first-time user experience	

VR - Video / audio from 360 camera	Stream has delayed audio because it must run over Wi-Fi	Install camera administration software onto windows 10 laptop to facilitate wired connection to access point	
AR/VR - Error log established	Variety of unexpected difficulties can occur during demonstration days, inhibiting smooth technology demonstration	Error log kept recording each issue and corresponding issue resolution - aiding fast and straightforward resolution on issue recurrence	
VR - 5G (or 4G) headsets currently not available on market	Unable to connect the VR headsets directly to the 5G (or 4G) network and test the full potential of the network during 5G trial on Millennium Square, Bristol.	Have to use a customer-premises-equipment (CPE) device connected to the 5G network and allows the VR headsets to connect to it (to CPE) via Wi-Fi.	
AR - Audio output from AR glasses is quite low volume (hardware limitation)	In a busy and noisier environment, the Nreal glasses audio output is quite low volume, so it is more difficult to hear the trainer when using the 'Expert Helper' function.	It is possible to connect the mobile device (OnePlus 8T in this case) to an additional speaker or headphones via Bluetooth. This way the audio output will be through either of those rather than the Nreal glasses. Alternatively, audio could come out of phone	
AR - Using AR glasses in bright environments	Viewing content through the AR glasses in a bright environment with significant glare/reflections becomes difficult. The technology is not so well adapted to such environments and users in Millennium Square commented on diminishing visibility when the sun was out.	Turn up brightness control on AR glasses and carry out the AR work in a location with less direct sun glare/reflection.	
AR/VR - Fatigue while using AR glasses and VR headset	Some users commented on fatigue after 15-20 minutes of using the AR glasses or VR headset. Combination of more unusual viewing experience and length of course/necessity to stay in one position.	VR - Possible to modify course to include more regular short breaks if necessary. AR - Possible to add prompts from application that encourages users to take more regular short breaks.	
AR - Difficulty for users with prescription glasses to use AR glasses	Users cannot use AR glasses very easily if they also wear prescription glasses. This limited	Nreal glasses can accommodate auxiliary clip-on lenses instead of normal prescription glasses. Or alternatively, users can use contact lenses instead.	Limitation is that user prescription must be known, and specialized lenses made before use. This is difficult if many users have access to hardware and potentially quite costly.
AR/VR - Length of battery life limitations	VR - headsets required charging after every course (every circa 40-50 minutes) AR - dependent on phone battery power (OnePlus8T), so constant continuous usage is limited to a couple of hours	VR – Have ready at 100% and charge as soon as course ends, ready for next AR – Have ready at 100% and charge as soon as user finishes, ready for next user	
AR/VR - On-screen media graphics blurry	On-screen media in both technologies were either too small in size or too far away from viewer, so would appear blurry.	If possible, to zoom or get closer to the media, the quality issue would be alleviated. But if not possible, a function to enlarge them within the environment.	
Restriction on the devices used in the VR Trial	The ability for users to be able to use their own devices was apparent during the trial.	The HTML5 application is cross-platform compatible and was provided to the guest users	

network fluctuations and dependency on P2P low latency streaming	Dependency on the P2P low latency streaming, and network fluctuations cause issues in transferring of data	A second streaming application was provided that didn't rely on the P2P low latency streaming that make the segments easier to be transferred over the network and was less prone to network fluctuations	
The 2 VR overlays produced did not provide satisfactory level of detail	The VR overlays needed more detail.	More than the 2 overlays that were produced were needed for the full scope of the training session.	
Users not completing the course	Most users got up to step 9 of the training course.	The training session needed to be cut back in length in order for users to be able to complete it	
The Training procedure needed to be more detailed	Some steps of the process taught were complicated and were not easy for the trainees to comprehend, leading to mistakes, delays or discontinuation of the training	needed more sub steps to explain better what was needed by the users	The team will consider the possibility of breaking down the procedure to a series of sub-steps which will improve comprehension by the trainees
The AR application is controlled via the phone connected to the AR headset.	Users need to handle the composite materials and the phone at the same time which leads to usability problems.	A gaze to enable controller has been implemented to make it easier for users to control the application.	
A different device must be chosen to run the remote helper application, when multiple users are connected	The remote helper application when running on a phone with multiple users connected scaled each window down to a small thumbnail.	A tablet device will be investigated to make easier the viewing of each user's stream.	
Stability of the 4G network is impacted and signal is interfered due to additional factory equipment located in close proximity to the RFID antennas (Power and RF).	Stabilizing the system - Interruptions with the RFID tags reading as the 4G WIFI signal is interrupted, and packets sometimes get lost on the way, which causes the reader to reset ~13% of the time, making them (and their connected antennas disabled for 1-2 minutes).	NCC reconfigured the core and performed interference testing. Firmware upgrades on readers and time sync between HW elements. Plataine investigated adding tolerance to their system to account for lost packets.	NCC contacted RFID installer to fix the internal RF interference issues. NCC upgraded to a 5G network topology and upgraded 2 stations to compare high interference areas with the 4G technology.

Figure 10: Full list of Lessons Learned

23 BENEFITS REALIZATION – USE CASES

Use Case Number:	Use Case Name:	Measured benefit per user	Cash value (£)	Is this Cash releasing? Yes / Part/ No	Is this a recurring benefit?	5G Dependence
1.1	AR for training and collaborative design	NCC will be able to host composite training without need to travel to customer site	NCC training course typically retail for £1000 to £5000. Trainers will save on overtime, travel and accommodation expenses conducting training remotely rather than on customer site	Yes	Yes	5G has potential to improve two-way communication functionality capabilities with increased bandwidth and better video/audio quality.
1.2	AR for training and collaborative design	NCC will be able to host composite training without need to travel to customer site	NCC training course typically retail for £1000 to £5000. Trainers will save on overtime, travel and accommodation expenses conducting training remotely rather than on customer site	Yes	Yes	5G has potential to improve two-way communication functionality capabilities with increased bandwidth and better video/audio quality.
1.3	AR for training and collaborative design	NCC will be able to host composite training without need to travel to customer site	NCC training course typically retail for £1000 to £5000. Trainers will save on overtime, travel and accommodation expenses conducting training remotely rather than on customer site	Yes	Yes	5G has potential to improve two-way communication functionality capabilities with increased bandwidth and better video/audio quality.
1.4	VR for remote learning and collaborative design	Ease and immersive enhancement of remote learning experience	NCC training course typically retail for £1000 to £5000. Trainers will save on overtime, travel and accommodation expenses conducting training remotely rather than on customer site	Yes	Yes	Would be required to give a better user experience
1.5	VR for remote learning and collaborative design	Ease and immersive enhancement of remote learning experience	NCC training course typically retail for £1000 to £5000. Trainers will save on overtime, travel and accommodation expenses conducting training remotely rather than on customer site	Yes	Yes	Would be required to give a better user experience
1.6	VR for remote learning and collaborative design	Ease and immersive enhancement of remote learning experience	NCC training course typically retail for £1000 to £5000. Trainers will save on overtime, travel and accommodation expenses conducting training remotely rather than on customer site	Yes	Yes	Would be required to give a better user experience
2.1	Asset tracking in-factory and in-transit	-	£76.5 per job (combined operator + machine cost/h)	Yes	Yes	-
2.2	Asset tracking in-factory and in-transit	With this system, we do not need to order more materials as we can revert back to the old project to check remaining materials in the system therefore utilising stock in the freezer. Composite material has a time limit stored in the freezer before it needs to be disposed of to maintain its mechanical performance after manufacture. We can get better understanding of utilisation of project materials/over or under order because we now have that data in past projects, now we can make informed decision on future forecasting/procuring/repeatable tasks.	Estimated £33k annually	Part	Yes	-
2.3	Asset tracking in-factory and in-transit	-	Estimated £58 K annually (saved spending - cost of wasted stock and out-dated material disposal services)	Yes	Yes - annually	-
2.4	Asset tracking in-factory and in-transit	-	£8k for repair ~£200k for replacement	Part	Yes	-
2.5	Asset tracking in-factory and in-transit	-	Estimated £63.6k annually	Yes	Yes	-

Use Case Number:	Use Case Name:	Measured benefit per user	Cash value (£)	Is this Cash releasing? Yes / Part/ No	Is this a recurring benefit?	5G Dependence
3.1	Real-time data acquisition to better control systems at the machine level during infusion process	-	Recording additional variables has allowed engineers to understand the process better, and has already identified areas in the process where the cost to make each part can be reduced.	Part	Yes	4G appeared to be sufficient for this use case, however there were some small issues around signal strength and connectivity. These would likely be rectified with alterations to the location of the small cells (i.e. an improved network coverage set up in the factory) Note: this use case was performed when there were no other loads on the 4G network. Performance characteristics may vary as other services are attached and capacity is shared, meaning 4G may prove insufficient as this use case (and other use cases) grow and increase the demand on the network. 5G would become essential in this scenario.
3.2	Real-time data acquisition to better control systems at the machine level during infusion process	-	Indirect value - the 3 other benefits identified are achievable on any LRI process in the NCC, saving £££ when re-deploying.	No	No	4G appeared to be sufficient for this use case, however there were some small issues around signal strength and connectivity. These would likely be rectified with alterations to the location of the small cells (i.e. an improved network coverage set up in the factory) Note: this use case was performed when there were no other loads on the 4G network. Performance characteristics may vary as other services are attached and capacity is shared, meaning 4G may prove insufficient as this use case (and other use cases) grow and increase the demand on the network. 5G would become essential in this scenario.
3.3	Real-time data acquisition to better control systems at the machine level during infusion process	-	Around £55 per part, however this would grow significantly if the closed loop LRI system was deployed onto a part that was more complex to manufacture	Yes	Yes	4G appeared to be sufficient for this use case, however there were some small issues around signal strength and connectivity. These would likely be rectified with alterations to the location of the small cells (i.e. an improved network coverage set up in the factory) Note: this use case was performed when there were no other loads on the 4G network. Performance characteristics may vary as other services are attached and capacity is shared, meaning 4G may prove insufficient as this use case (and other use cases) grow and increase the demand on the network. 5G would become essential in this scenario.
3.4	Real-time data acquisition to better control systems at the machine level during infusion process	-	Estimated £555 saving per part	Yes	Yes	4G appeared to be sufficient for this use case, however there were some small issues around signal strength and connectivity. These would likely be rectified with alterations to the location of the small cells (i.e. an improved network coverage set up in the factory) Note: this use case was performed when there were no other loads on the 4G network. Performance characteristics may vary as other services are attached and capacity is shared, meaning 4G may prove insufficient as this use case (and other use cases) grow and increase the demand on the network. 5G would become essential in this scenario.

Use Case Number:	Use Case Name:	Measured benefit per user	Cash value (£)	Is this Cash releasing? Yes / Part/ No	Is this a recurring benefit?	5G Dependence
4.1	Increasing the flexibility of high volume data sensor systems.	-	Total cost reduction for integration = £266,333 Equating to 1.99% of original integration cost.	Yes	No	The addition of 5G to this system allowed for a significant reduction in industrial integration cost as data can be transmitted wirelessly to a virtual processing server rather than requiring expensive cabling installations.
4.2	Increasing the flexibility of high volume data sensor systems.	-	Total cost reduction of robot system = £158,489 Equating to 12.23% of original cost.	Yes	No	The addition of 5G removed the need for a processing PC on the end effector, in turn reducing the weight of the end effector from 45kg to 3.5kg. This meant a smaller collaborative robot could be used that was both cheaper and had integrated safety circuits, leading to a significant reduction in system cost.
4.3	Increasing the flexibility of high volume data sensor systems.	-	Original EE volume = 0.432m3 Use case EE volume = 0.012m3 97.2% reduction	No	No	The reduction of the processing PC meant that the end effector was only the FScan sensor, significantly reducing the size.
4.4	Increasing the flexibility of high volume data sensor systems.	-	Total deployment cost reduction = £398,672 Equating to 11.86% of original cost	Yes	No	The flexibility the 5G adds allows for the system to be deployed anywhere in the workshop that has sufficient signal, without the need to fully reconfigure the data lines. This means that the system can be deployed much faster and at a reduced cost.

24 BENEFITS REALIZATION – TEST BEDS

Testbed property type	Specific Property Metric Title	Baseline	Measurement (4G)	Measurement (5G)	Target 1 (4G)	Target 2 (5G)
Use Case 1 - AR/VR Remote Training	0	0	0	0	Phase 1	Phase 2
Network Performance	Camera to Server Bandwidth	20Mbps video stream to the server	2.2Mbps - 6 users supported on VR	~3.0Mbps per user/device - at least 5 users on VR headset and 3 on mobile devices (across 4 sessions, totaling over 20 users)	1 - 10 mbps (4G LTE)	10-100 mbps (5G)
Network Performance	Server to Users Bandwidth (total cell Tput)	20Mbps 360 video stream to reach each user	9.9 Mbps - 6 users supported on VR	16.1Mbps average with 31Mbps peak - at least 5 users on VR headset and 3 on mobile devices (across 4 sessions, totaling over 20 users)	>= 4mps (6 user clients on LTE)	>= 20mpbs per user (12 user clients on 5G)
Network Performance	Server to Users Bandwidth (each user Tput)	20Mbps 360 video stream to reach each user	NA from latest test	3.22Mbps average	>= 4mps (6 user clients on LTE)	>= 20mpbs per user (12 user clients on 5G)
Network Performance	Latency Tolerance	200ms	Range: 4 to 18 mean milliseconds	3.15 milliseconds	200ms	<50ms
Network Performance	Jitter Tolerance	200ms	1.5 to 5.984ms	2.05 milliseconds	100ms	50ms
Network Performance	Packet Loss Tolerance	<1%	140 packet drop rate	0.0012	<1%	<1%
Network Performance	Packet drop - Downlink	See Description	4, 500 packet drop rate	0.0012	>2%	>2%
Network Performance	Packet drop - Uplink	See Description	260, 000 packet drop rate	0	>2%	>2%
Use Case 2 - Asset Tracking - Active tracking of time sensitive assets and asset conditions and maintaining pedigree and traceability	0	0	0	0	Phase 1	Phase 2
Network Performance	Number of Active users (SIMS)	1 SIM per LTE device. 1 RFID reader sat behind it leveraging NAT config.	See Column K & L for comments	4 LTE CPEs + 1 5G CPE (4 Siemens devices, 1 Robustel device) 1 RFID reader sat behind each device leveraging NAT config.	1 Active user to generate some network traffic for this return. It was not possible to capture network traffic on this round of use case testing as the tools were not available at the time.	-> 3 active users
Network Performance	Traffic per SIM (which is one per modem)	None of these metrics readily available on systems installed on site.	See Column L for more info	NCC Capabilities: 450Mbps down 57Mbps up as max values MAX Peak Traffic Up 5000 - 24000 Kb (data from Zeetta)	Peak Traffic GTP-U Octets Received DL = 380kb Peak Traffic GTP-U Octets Received UL = 80kb	Peak Traffic GTP-U Octets Received DL = 380kb Peak Traffic GTP-U Octets Received UL = 80kb
Network Performance	Packet loss	Minimal inconsistent packet loss identified at all locations on 4G network - 300 ping test done with results below: -W1 Freezer: sent= 300 received= 299 lost= 1 (0%loss) -W1 Acclimatisation rack: sent= 300 received= 300 lost= 0 (0% loss) --W1 AFP: sent= 300 received= 300 lost= 0 (0%loss) -W1 PCMM: sent= 300 received= 300 lost= 0 (0%loss) -W2 CIVC: sent= 300 received= 300 lost= 0 (0%loss)	See column L for more info	300 ping test done for 5G with results below: -W1 Acclimatisation rack: sent = 300 received = 300 lost = 0 (0%loss) -WI Acclimatisation rack on 4G: sent = 300 received = 300 lost = 0 (0% loss) Similar results, however more consistent and reliable measurements for 5G (variation of packet loss for 4G between 0 to 11% packet loss, while 5G records consistent 0% packet loss)	0% loss GTP U downlink Packet lost rate is consistent with initial network commissioning results. Air interface PDCP SDU lost rate does peak on one cell as per the graphs below. We do have issue with interference from machinery in and around this cell.	0% Loss
Network Performance	Packet Delay	Latency varied between stations - 300 ping test done with results below: -W1 Freezer: min= 22ms max= 117ms average= 71ms -W1 Acclimatisation rack: min= 23ms max= 116ms average= 70ms -W1 AFP: min= 22ms max= 120ms average= 70ms -W1 PCMM: min= 23ms max= 115ms average= 68ms -W2 CIVC min= 21ms max= 117ms average= 71 ms	See columns L & M for more info	300 ping test done for 5G with results below: - W1 Acclimatisation rack: min = 11 max = 45 average = 25 -W1 Acclimatisation rack on 4G: min= 22ms max= 117ms average= 71ms An improvement of 65% is seen in latency. Improved end user experience - reliable 5G connection and fast location update of asset in Plataine TPO. Interference effects in the area have been avoided as the 5G connection moves the frequency bandwidth higher in the spectrum, away from the interference region (1.8 - 2 GHz where the 4G also acts).	10mS or less on average across the cells	<100ms
Network Performance	Block Error Rate - DL	TCP segment statistic data available when SSH into the 4G router but unsure how to measure BLER.	See Column L for more info	Desired value 2% - No metrics available in current 5G system	Range 5 - 15%	0.02
Network Performance	Block Error Rate - DL	TCP segment statistic data available when SSH into the 4G router but unsure how to measure BLER.	See Column L for more info	Desired value 2% - No metrics available in current 5G system	Range 2-5 %	0.02
Use Case 3 - LRI	0	0	0	0	Phase 1	Phase 2
Network Capacity	Idle to Transmit time	dedicated communication resource	See Column L for more info	0	<500ms	<200ms
Network Capacity	Transmit Time	dedicated communication resource	See Column L for more info	0	<100ms	<50ms
Network Capacity	Latency	dedicated communication resource	81ms (avg)	33ms (avg)	<100ms	<50ms
Network Capacity	Reliability	dedicated communication resource	1	0.857	>99.99%	>99.99%
Network Capacity	Packet Loss	dedicated communication resource	0	0	0	0
Use Case 4 - APC	0	0	0	0	Phase 1	Phase 2
Network Capacity	Latency	dedicated communication resource	Over 19 pings -Max = 1372ms -Mean = 155ms	Over 100 pings - Max = 164ms - Min = 11ms - Mean = 19ms	<100ms	<50ms
Network Capacity	Uplink Throughput	dedicated communication resource	Limited scope - this is for Phase 2.	Maximum observed throughput = 18Mbps Data rate = 2.25MBps	Limited scope - this is for Phase 2.	900 - 1000 Mbps (down link), not relevant for this use case 60-65MBps (Up link)
Network Capacity	Uplink Radio Capacity	dedicated communication resource	Limited scope - this is for Phase 2.	UL - ~70% DL ~2-5%	Limited scope - this is for Phase 2.	(unsure what target value should be - metric added in as deemed important data for these type of applications)
General	0	0	0	0	Phase 1	Phase 2
Network Performance	Ability to support all use case requirements with single RAN system	Network not used.	See Column L for more info	0	Limited scope - this is for Phase 2.	Use case metrics above all supported simultaneously by single network - no impact of use case 1 (high bandwidth) on use case 2/3 operations.

Testbed property type	Specific Property Metric Title	Baseline	Measurement (4G)	Measurement (5G)	Target 1 (4G)	Target 2 (5G)
Toshiba - Ultra Low Latency	0	0	0	0	Phase 1	Phase 2
Network Performance	Latency	Network not used.	See Column L for more info	0	20-30ms (4.5G)	<10ms (5G)
0	0	0	0	0	0	0
Note: The NCC 5G testbed is brand new; therefore, rather than improving the same technology KPIs, the project will perform comparative studies between existing technologies, i.e. Wi-Fi, potentially 4G/LTE Advanced and 5G.	0	0	0	0	0	0

25 VIRTUAL REALITY –

5G-encode

26 ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK Government's biggest investments in 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It also is designed to validate the premise that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that UK industry makes the most of the 5G technology and ultimately remains a global leader in the development of robust engineering capabilities when implementing complex composites structures manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLL/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the Southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and small and medium enterprises (SMEs).

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

27 EXECUTIVE SUMMARY

Training courses with practical elements are typically carried out by trainers either within their training facilities on-site or at a suitable location at the customer site. Both scenarios have economic and environmental costs related to travel, with most being infeasible within the recent COVID-19 climate. Although there are distance learning options, and internet-based courses available, they are limited to webinar style 2D solutions. The use of 5G and more immersive technologies provides a unique opportunity to engage more effectively with the trainer and the practical elements of the training course.

The use case presented within this report evaluates the use of latest 360° video streaming technology, 5G connectivity and VR headgear to demonstrate a fully immersive VR remote learning solution. This solution is used to emulate a physical classroom and allows the user to follow, in real time, the practical course demonstration offered by the NCC in manual composite manufacturing. It relies heavily on 5G's reliable, safe, high bandwidth and low latency connectivity to facilitate uninterrupted high quality two-way communication (3D video and bi-directional audio feeds) between trainer and trainee.

The use case development was split into two testing phases:

The first phase was conducted on 4G LTE and limited to a controlled setting at the NCC with 4 trainees. 50% of the participants indicated that the solution was an enhancement to a conventional course as offered through an online seminar. Poor streaming quality (due to network capability) was stated as the key reason for negative feedback.

The second phase was conducted using the 5G test bed deployed at the NCC. The testing was extended to an external location and opened to a wider testing group of at least 20 trainees. Even with the expanded scope, 91% of the participants indicated that the solution was an enhancement. The 5G testing phase also showed significant advances to the 4G testing by exceeding 700 megabits per second download speed and around 3 milliseconds latency which significantly improved viewing quality and therefore participant engagement and satisfaction.

The immersive technologies tested in this report are shown to be an effective option for distance learning but only when paired with a reliable, high-performance network as offered by 5G technology.

Further technology development and experimentation are required to ensure solution robustness for application outside of the trial, especially VR hardware development, as direct connectivity to 5G is not yet possible. For wider-scale adoption of the technology, access to operational public or private 5G networks will be a prerequisite.

28 ABBREVIATIONS

2D	*Two-dimensional*
3D	*Three-dimensional*
3G	*Third Generation Mobile Network*
4G LTE	*Fourth Generation Long-Term Evolution Mobile Network*
5G	*Fifth Generation Mobile Network*
AP	*Access Point*
APC	*Automated Preforming Cell*
AR	*Augmented Reality*
CPE	*Customer Premises Equipment*
DCMS	*Department for Digital, Culture, Media, and Sport*
DL	*Downlink*
eMBB	*Enhanced Mobile Broadband*
IoT	*Internet of Things*
IP	*Internet Protocol*
Kbps	*Kilobits Per Second*
KPIs	*Key Performance Indicators*
LRI	*Liquid Resin Infusion*
Mbps	*Megabits Per Second*
MEC	*Multi-Access Edge Computing*
MMTC	*Massive Machine-Type Communications*
NCC	*National Composites Centre*
NCC HQ	*National Composites Centre Headquarters*
NCCi	*National Composites Centre – Filton Site*
NR	*New Radio*

NTP	*Network Timing Protocol*
OS	*Operating System*
P2P	*Peer-to-Peer*
PTP	*Precision Timing Protocol*
RAN	*Radio Access Network*
RTMP	*Real-Time Messaging Protocol*
SA	*Standalone*
SMEs	*Small and Medium-Sized Enterprises*
UEs	*User Equipment*
UL	*Uplink*
UoB	*University of Bristol*
UPF	*User Plane Function*
URLL	*Ultra-Reliable Low Latency*
VMs	*Virtual Machines*
VPN	*Virtual Private Network*
VR	*Virtual Reality*
WECA	*West of England Combined Authority*

29 INTRODUCTION

Effective knowledge transfer through training is a core part of people development and is essential for social sustainability. Classroom and workshop training where all attendees are co-located within the same demonstration space are a proven method to facilitate this.

Traditionally, such training courses with practical elements provided by the NCC to customers across the UK have been carried out by trainers either within its training facilities on-site or at a suitable location at the customer site. However, both scenarios can be linked to significant economic and environmental costs due to travel, accommodation, and transportation of equipment. As such, with the continuous drive for sustainability over the past two decades the work developing alternative solutions has become more and more vital.

Additionally, the recent COVID-19 pandemic put extra pressure on training providers and on companies in need of training. This was due to the stringent restrictions put in place such as barring all non-essential travel and gatherings for a significant period.

Though there are distance learning options, and internet-based courses available, the capability to engage effectively with the trainer and demonstrate practical aspects of a course in an immersive way is difficult. As such, more solutions need to be proposed to address this industry challenge.

The VR immersive training demonstrator that is presented in this report will highlight the latest 360° video streaming as an example of an advanced distance learning solution. Demonstration of practical training for the manual lay-up of carbon composite materials, an 'Introduction to Composites' manufacturing training module offered by the NCC, was selected as an example use case.

The solution aims to exploit the capabilities of the 5G technology available to provide distant learning trainees with a real-world experience similar to when on site with the trainer.

29.1 VR Project Objectives

The main project objective was to apply the 360° video streaming VR technology over a fully functional 5G network to improve user experience and training performance from an interactive remote learning solution. The technology was designed to emulate a physical classroom or workshop without the need for the trainers and trainees being physically in the same space.

The use case was created to fill the gap for immersive remote learning solutions. This is particularly pertinent in current times due to the COVID-19 pandemic and sustainability drivers as outlined above. Additionally, this demonstrator can create a work package which has wider implementations in the manufacturing industry for more immersive demonstrations remotely in a variety of scenarios.

One opportunity from a working VR demonstrator is the ability to cascade the digitalisation methodology into other similar courses within the composite manufacturing industry. However, there is also the possibly of applying this more widely within the manufacturing sector as well as outside, as there are various practical courses which could benefit.

The potential benefits for companies of all sizes across the UK as a result of this are numerous. These include:

- Drastic reduction in costs for supplementary activities such as travel, accommodation, and transport.
- Sizeable decrease in emissions as a result of training activities.
- Overall improvements in workforce ability and skill due to more effective training.

29.2 Purpose of 5G in VR Assisted Training

In order to create a comprehensive remote learning experience and achieve an equivalent knowledge transfer as with traditional on-site courses, the internet and any associated internet connection must have sufficient bandwidth to service network traffic created as a result of running an on-line experience.
5G realises this without the need for a wired connection as its radio performance, capacity and flexibility capabilities significantly differ from its predecessor, 4G and conventional Wi-Fi solutions found in industry.

The proposed 360° video streaming VR solution has several specific requirements for the network connection.

- Achieve an average speed which allows for good video and audio quality to be streamed from the trainer to the trainees in the class.
- Provide sufficient bandwidth to enable streaming to multiple devices as a class of trainees will needs to be a specific, minimum size to justify the associated costs of providing training.
- Ensure latency does not affect the stability of the live stream and cause lagging that degrades the trainee experience and hinder delivery of course.

With average speeds theorised to be at least an order of magnitude greater than 4G LTE, 5G has the potential to show a significant improvement. Further, the use of higher frequency bands that have been less widely used thus far, should allow 5G to drastically increase its available bandwidth. As a result, the number of additional devices that can be connected is theoretically much larger. Finally, depending on the location, usage, and maturity of the 5G network, the latency theoretically predicted ranges from below 2ms to 10ms. This is a sizeable difference to the average results of around 20-40ms from 4G LTE, though this can go up to 200ms.

Therefore, it is possible to see that 5G offers significant improvements in all three parameters from the previous generation network and those are the biggest justifications for its use in this work package.

29.3 Use Case Overview and Solution Architecture

The conventional 'Introduction to Composites' practical training course begins with a live demonstration from the trainer on the manual lay-up of a simple flat piece in the form of a coaster using pre-impregnated composite materials.

Trainees then have the chance to try the process for themselves, and though the final product shape is not overly complex, carrying out the process correctly and safely is not a simple exercise. Consequently, the trainer's experience enables a run-through of all the steps in around 45 to 50 minutes, with an expected time allowance for trainees of at least two to four times longer. The process, itself, includes details about working with the different materials and using specific tools alongside theoretical explanations from the trainer which make the visual and auditory cues crucial to satisfactory learning.

The suggested 360° video streaming VR teaching course only focuses on the trainer demonstration section. This is delivered by creating a live broadcast of the practical demo using a 360° camera. VR adds the immersivity for the trainees in the experience and aids with understanding the practical skills shown by having the ability to adjust camera angle and view of the demonstration. Supplementary media is also planned within the VR view in the form of drawings or graphics to improve understanding and knowledge transfer.

Extra functionality also allows for the collaborative training aspect through real time two-way communication, to an instructor offering extra support to trainees and an enhancement of the learning experience as a whole.
Figure 1 below shows the fundamental architecture of the proposed VR solution. The streaming setup is located and controlled from the NCC Headquarters (HQ), while the trainees are based in a remote location with the required hardware.

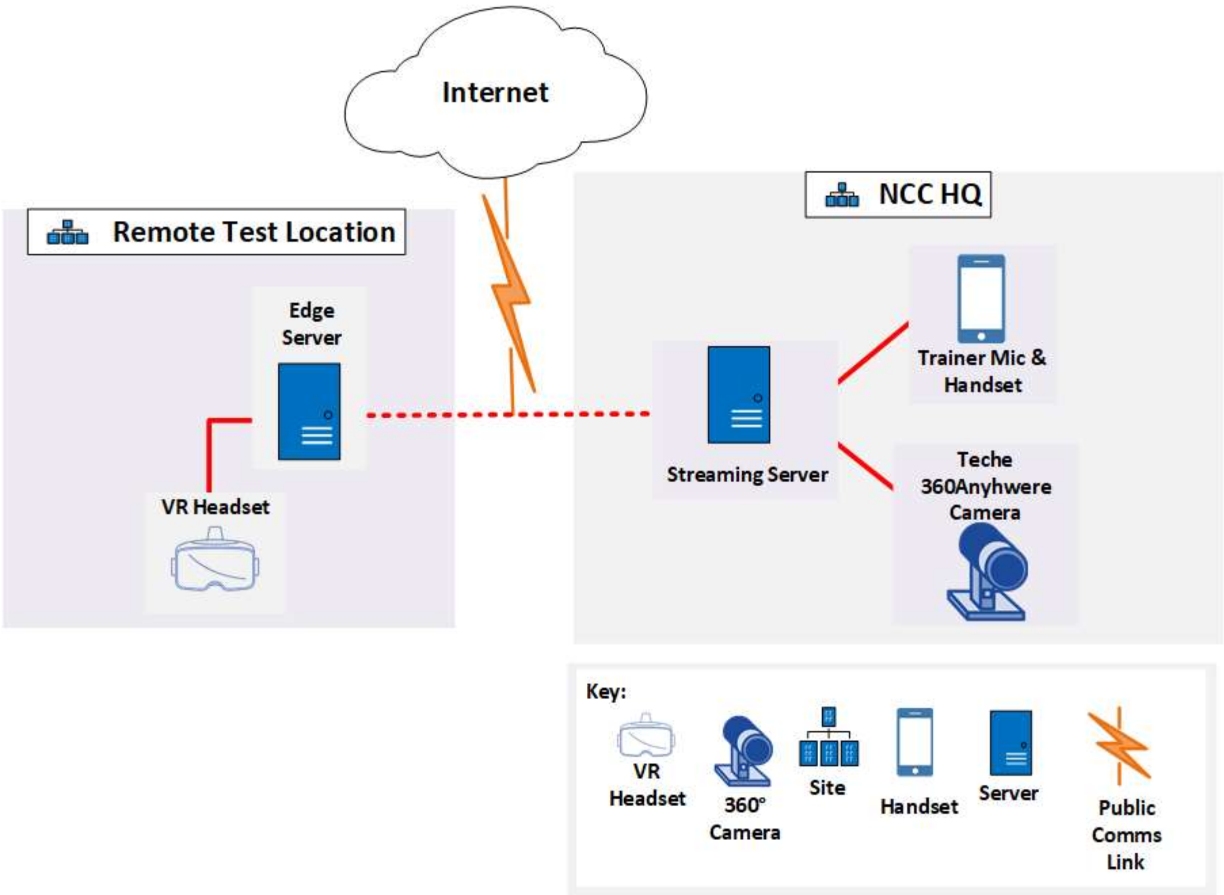


Figure 11 – Fundamental use case architecture

As outlined earlier, in Section 1.2, the use case requires the uplink aspects of the 5G network to be sufficient to support the camera data stream. This is needed to ensure the required quality is maintained throughout the demonstration and there are no gaps in the training.

In order to satisfy all the recognised requirements and overcome any digitisation challenges, MatiVision, an immersive technologies expert company was consulted for support in this use case. Based on their experience, it was possible to integrate the digital features directly and quickly into the solution. From the initial discussions, plans were made to produce the media content required with support from the NCC staff and MatiVision could begin work on the streaming platform which includes two-way communication channels.

29.4 Use Case and Network Metrics

In order to be able to quantify and recognise whether the objectives have been met, two sub-categories have been introduced:

1. Use case monitoring
2. Test bed monitoring

The first sub-category encompasses the user experience of the 360° video streaming VR course and is measured through user feedback. The main points of the feedback are whether the user considers the solution an immersive enhancement on currently available online courses such as a webinar and based on a one-to-five satisfaction grading, rank the experience.

The second sub-category measures the network performance using a selection of metrics collected from the radio network.

Tables 1 and 2 below define all of the measurable quantities for the use case and the test bed, respectively. These are taken from the 'Benefits Realisation' document which contains all requirements defined by the project partners and sponsors at the project inception.

Table 1 – Use case monitoring measurable quantities

Use case metric	Target audience	Measurement type	Unit of measurement
Alternative VR course is an immersive enhancement to conventional webinar courses	Uptake by NCC (and industrial partners)	Feedback from survey after course	Yes / No
Alternative VR course is an immersive enhancement to conventional webinar courses	Uptake by academic institutions	Feedback from survey after course	Yes / No
Quality of 360° live stream experience	All	Feedback from survey after course	1 – 5 Grading* (1 = Extremely dissatisfied, 5 = Extremely satisfied)

* Note – need to score 4 or above to class as a high score.

Table 2 – Testbed monitoring measurable quantities

Network metric	Counter	Description	Unit of measurement
Camera to server bandwidth	Total uplink IP throughput	Total uplink throughput	Kilobits per second
Server to user bandwidth	Total downlink IP throughput	Total downlink throughput (all users)	Kilobits per second
Server to user bandwidth	Total downlink IP throughput	Total downlink throughput (each user)	Kilobits per second
Latency tolerance	E-RAB level IP latency in downlink	Mean IP latency in downlink at the E-RAB level	Milliseconds
Jitter tolerance	NTP mean jitter	Mean value of the jitter estimator between AP and NTP servers averaged over granularity period	Milliseconds
Packet loss tolerance	Downlink PDCP SDU air-interface loss rate	Fraction of IP packets (PDCP SDUs) which are lost on downlink interface	Percentage
Packet drop – downlink	Downlink PDCP SDU drop rate	Fraction of IP packets which are dropped on the downlink	Percentage

Packet drop – uplink	Uplink PDCP SDU drop rate	Fraction of IP packets which are dropped on the uplink	Percentage

29.5 System Requirements and Selection

As described in Section 1.3, the proposed solution is aimed at providing a comprehensive immersive remote learning course which has thus far been difficult at the NCC. This has been the case because of the need to capture the required level of detail in real time with the ability to broadcast it directly to the interested parties.

However, with recent advancements in video recording hardware and software this difficulty is alleviated and there are cameras able to capture all 360° of a relevant space with high quality. An example of this is the TECHE 360Anywhere camera that is capable of live streaming up to 8K video quality. The up-front camera unit cost is high, but this is due to the specific composite manufacturing requirements detailed further in Section 2.3. This can be combined with a comparatively inexpensive clip-on microphone to provide all the additional specialised equipment for the course trainer.

On the user side, to get the full benefit of the 360° video, a VR headset provides the complete package. The Oculus Go headset delivers the necessary functionality, video quality and two-way audio integration for the use case. It is a more cost-effective item than some of the more advanced headsets on the market which have increased functionality and better graphics options. Additional handheld mobile devices can also be used as a backup when accessing the remote course, though these do not provide the fully immersive experience of the headset.

In terms of the stream transmission between the trainer and the trainee the system relies on peer-to-peer (P2P) streaming to keep the latency down to a minimum. A P2P channel is opened between every device. For the video, a P2P channel is opened between the device and the streaming server. For the trainer communication a direct channel is opened between the two devices with only audio streaming enabled so the trainer and trainee can speak to each other in low latency. For the video streaming a mid-range hosting environment is required which can be scaled up for more concurrent users or classes. For the audio streaming the P2P channel is between the two devices, meaning that the server is only used to relay messaging and the actual streaming takes place between the devices themselves. This keeps the hosting requirements to a minimum.

29.5.1 Project Methodology

To gauge the performance improvements of a 5G network and understand the capabilities of an already proven and tested network, the use case testing was split into two testing phases:

- Phase 1 – implement a 4G LTE network architecture to capture baseline data of the performance of the setup.
- Phase 2 – implement a 5G network architecture to test the capabilities of the newer technology and make an analysis of performance when compared with the 4G technology.

The Phase 1 results and discussions were presented in an earlier report but will be briefly summarised within this report for completeness and ease of reference.

Sections 2.4.1 and 2.4.2 describe the approach for delivering each phase of the use case.
Sections 2.5.1 and 2.5.2 detail the relevant phase results and discussion.
Sections 3.1.2 and 3.1.3 document previous 4G network testing results and outcomes.
Sections 3.1.5 and 3.1.6 present 5G network testing results and outcomes.

30 USE CASE DEVELOPMENT AND INVESTIGATION

30.1 Use Case Architecture

The system setup of the use case was split across two locations:

1. NCC Headquarters (HQ)
2. Remote test location

The equipment and connections within the NCC HQ side did not change through both Phase 1 and 2. These included the TECHE 360Anywhere 360° video camera and a mobile device which the trainer used to control of the media content on the video stream. The mobile device was connected wirelessly to a 4G small cell in Phase 1 and 5G small cell in Phase 2, while the 360° camera used a wired connection.

The live video stream from the camera was transmitted to a streaming server via a wired network connection. The streaming server managed the live video feed and transmitted it to a caching server which received the live video stream in a one-to-one relationship and managed the calls to view overlays on the video stream. The most main differences between the two testing phases related to the remote test location side of the setup and will be described in further detail in Sections 2.1.1 and 2.1.2.

30.1.1 Phase 1 – 4G LTE Architecture

Phase 1 – 4G LTE used two sites: NCC HQ and a remote test location at NCC, Filton called NCCi. NCCi is located around 5 miles away from NCC HQ. The specific hardware used for the trials at NCCi included two Oculus Go VR headsets alongside two handset devices and a master control device. A 4G small cell provided the 4G connection and transmitted the video streaming data from the caching server to the handset devices, the master control device, and a customer premises equipment (CPE) device which produced a Wi-Fi connection to the VR headsets. Figure 2 below combines and visually summarises the architecture described in Section 2.1 and 2.1.1.

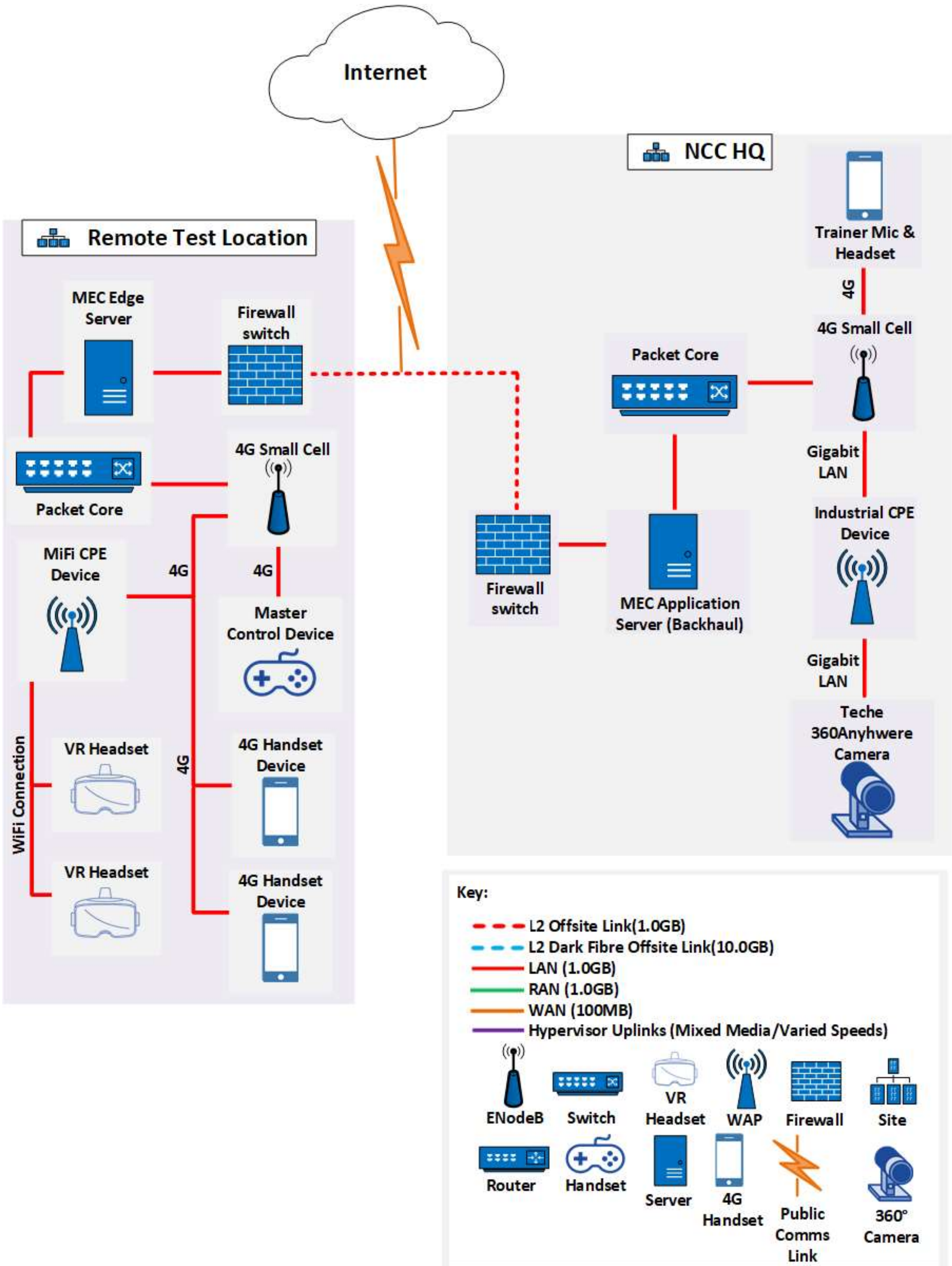


Figure 12 – Phase 1 - 4G LTE trials architecture map

30.1.2 Phase 2 – 5G Architecture

Phase 2 – 5G trials used NCC and a location in Millennium Square, Bristol; located approximately 8 miles from one another. The hardware for the trial increased to five Oculus Go VR headsets, three handset devices and a master control device. The VR headsets and handset devices were split between two CPE devices and connected over Wi-Fi while the CPEs were linked to a 5G small cell over a Nokia 5G connection. Figure 3 below combines and visually summarises the architecture described in Sections 2.1 and 2.1.2.

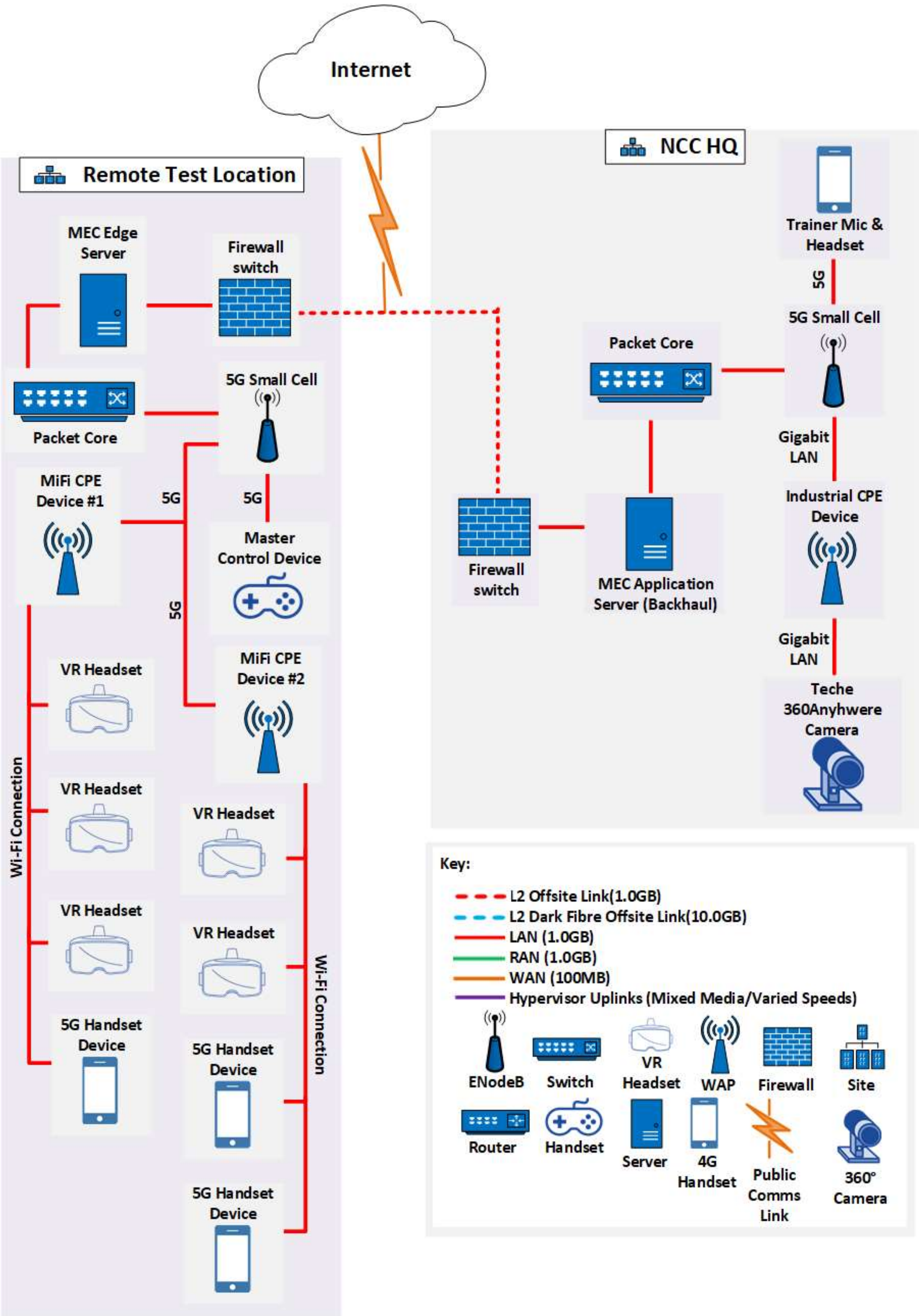


Figure 13 – Phase 2 - 5G trials architecture map

30.2 Use Case and Network Benefits

With a successful outcome from the project the use case will offer significant benefits for similarly positioned work packages that can implement 360° video streaming VR technology and a 5G network.

30.2.1 Use Case Benefits

Being able to effectively digitise practical training courses unlocks a range of similar use cases across a variety of industry sectors not limited to manufacturing.

This will be significant in the development of remote working packages and will improve the training outreach throughout the UK. A functional VR solution will reduce the need for travel, accommodation, and transport of equipment to and from provider and customer sites. This will be crucial in decreasing the overall financial as well as environmental costs associated with these services. As a result, the products will experience long-term cost reductions that will make them more affordable to SMEs.

As mentioned above an effective remote working solution such as this one will contribute to the overall environmental sustainability goal of enterprises such as the NCC by using less energy in a more efficient capacity. This will lead to a sizeable carbon footprint reduction that will be a further contributing factor. In time these benefits will be able to cascade down into the wider manufacturing and advanced engineering fields and have a greater effect on the UK net zero strategy overall.

The use case can also have social sustainability benefits as well. A matured solution has the potential of improving the training experience and knowledge transfer to the trainees and thus producing a more skilful workforce.

30.2.2 Network Benefits

Based on the predicted capabilities of a 5G network, the use case can specifically benefit from the lower latency, the higher bandwidth, and faster average speeds.

The wider bandwidth available in 5G will enable a much larger amount of data to be transferred from one location to another at any one time by single and multiple devices. As such, larger cohorts of trainees per course are achievable or, alternatively, enhanced quality of video and audio for a smaller cohort. For other use cases this can aid large amounts of data acquisition and transfer from various sensors to a processing unit. This is crucial in the automated pre-forming cell (APC) end effector upgrade use case within the 5G-Encode project and more details can be found regarding this in that final report.

The shorter latency of 5G allows for real-time communication with the trainer which can improve the trainee experience and understanding. The lower latency can also improve the capabilities of time sensitive signals such as those in precision machine control applications. This is pertinent in the liquid resin infusion (LRI) use case within the 5G-Encode project and more details can be found regarding this in that final report.

The speed itself will improve the video and audio quality achievable by the stream to the trainees. Additionally, for other use cases it can increase efficiency due to a better productivity overall. This will specifically aid the asset tracking use case within the 5G-Encode project and more details can be found regarding this in that final report.

30.3 Use Case Decisions and Developments

In order to ensure that the hardware presented throughout Section 1.6 and the ancillary software work effectively for the specific use case, certain decisions and developments had to be made over the project timeline. These were as follows:

- 360° camera protection rating:
  The TECHE 360Anywhere camera is rated at IP66 which combines the highest dust protection with a very high protection against water ingress. This was necessary because composite materials manufacturing processes may sometimes release fine carbon dust particles which can be harmful to any electrical equipment.

- <u>360° camera cooling system:</u>

  The TECHE 360Anywhere camera uses a passive heatsink instead of a fan as part of its cooling system. This is a feature that falls under the IP66 rating and as such has a reduced chance of any carbon dust being taken into the camera internals and damaging the equipment.

- <u>Streaming server industrial compatibility:</u>

  For the streaming functionality, a custom application was created that supports ingest via a real-time messaging protocol (RTMP) from the 360° video camera. This is converted to a low latency streaming protocol and a connection is established between the streaming server and a device.

- <u>HTML5 player application:</u>

  A custom HTML5 application was developed with low latency streaming capabilities for video and the custom streaming application. The application also implements the low latency audio streaming between trainer and trainee devices.

- <u>Handset operating system (OS):</u>

  The handsets that could be used as a backup for the VR experience or as supporting equipment were limited to solely Android OS devices. This was due to the safety protocols included in the Apple iOS which would not allow stand-alone licenced software/servers and would only trust ones with public licences.

- <u>VR headset functionality:</u>

  The chosen VR headsets – Oculus Go, are a more cost-effective headset with slightly less functionality than the latest devices available, e.g., only 3 degrees of freedom rather than 6. However, this is somewhat advantageous for the use case in question because the only necessity is the access to the stream and the headset audio integration. Additional capabilities only introduce extra setup steps which could lead to technical difficulties during the training course. Unfortunately, as all VR headsets currently are for the leisure consumers it is not possible to fully restrict them for the proposed industrial application.

- <u>Course trainer setup:</u>
  For the use case proof of concept stage, it was found to be useful to have two members of staff on the trainer side. This was so there would always be someone to support the trainer with the streaming setup and broadcast. However, with more practice and experience it may be possible for the trainer to facilitate the entire process and make it more resource efficient overall.

30.4 Use Case Testing

In both Phase 1 and Phase 2 the testing programme was the same. A demonstration was carried out by the NCC trainer live and broadcasted to several devices. The number of devices differed based on the network capabilities and the location of the trainees changed between as outlined earlier in the report. Further details and the results of the trials are presented in the following sections.

30.4.1 Phase 1 – 4G LTE

As described in Section 2.1.1 the Phase 1 trials were carried out within the available NCC premises between the HQ and the NCCi site at Filton. The trainer setup for the course demonstration at NCC HQ is shown below in Figure 4.

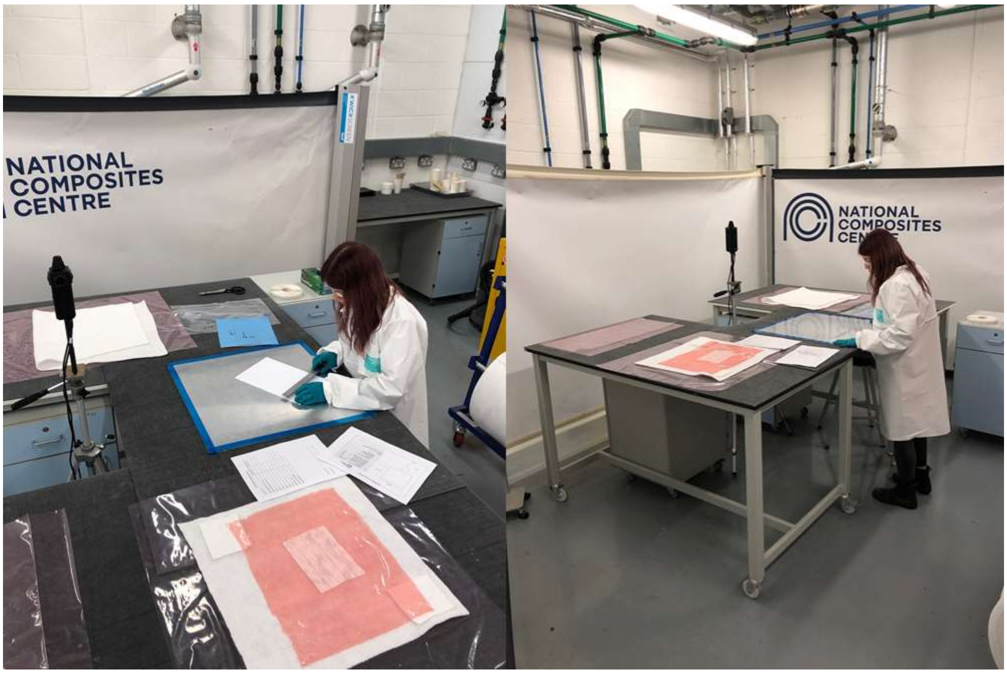


Figure 14 – Phase 1 trainer setup for course demonstration

During the initial Phase 1 tests the attempt was to create a mobile data access point on a Samsung 4G handset and tether the VR headset to that. However, this was not achieved due to difficulties with the VR tethering and the test users during those trials were only able to observe directly using the mobile handsets. This meant the experience immersion was limited but it was useful to test out the streaming server settings and setup. Figure 5 below shows the trainees watching the training course demonstration live on the mobile devices.

Figure 15 – Phase 1 trainees watching training course demonstration on mobile devices

A second test was organised for Phase 1 during which the VR headsets were connected to a CPE device over Wi-Fi as shown in Figure 2 while the CPE itself has a 4G connection to a small cell. This was effective and allowed the immersive stream to be viewable within the headsets. Figure 6 below shows the trainees using the VR headsets.

Figure 16 – Phase 1 trainees watching training course demonstration on VR headsets

The user feedback from the Phase 1 trials was consistent across the two sessions described above. Figure 7 below presents the results regarding the satisfaction of the trainees with the live stream experience, while Figure 8 shows how many would use VR instead of on-site training. The total number of trainees in the data was four.

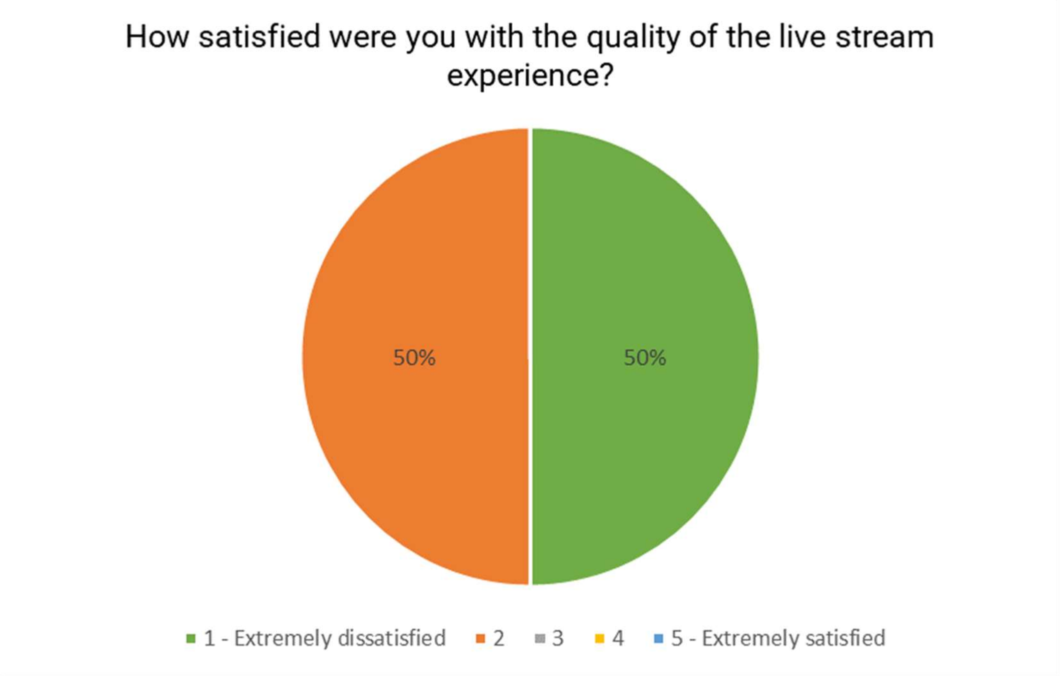


Figure 17 – Phase 1 user feedback regarding satisfaction with live stream experience

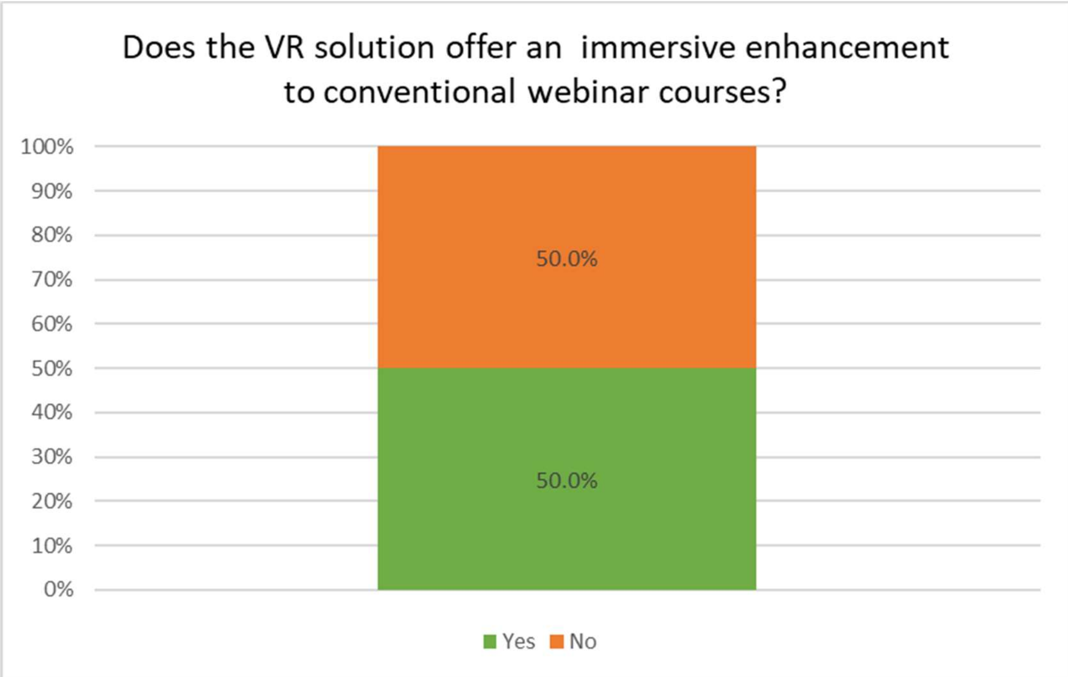


Figure 18 – Phase 1 user feedback regarding the enhancement of the VR solution over a conventional webinar course

The feedback forms included more questions to aid the understanding and development of the use case which were detailed in the previous case study report and thus will not be repeated here. The results from these have been included in Appendix A.

30.4.2 Phase 2 – 5G

The Phase 2 trials as outlined in Section 2.1.2 were carried out on Millennium Square in the Bristol City Centre as part of a two-day continuous demonstration made up of four separate user sessions. The number of devices that were run simultaneously was increased, however the trainer setup at NCC HQ was similar to that used in Phase 1 as it was found to be working, as necessary. This is shown in Figure 9 below.

Figure 19 – Phase 2 trainer setup for course demonstration

The trial setup itself consisted of five workstations and this is shown below in Figure 10.

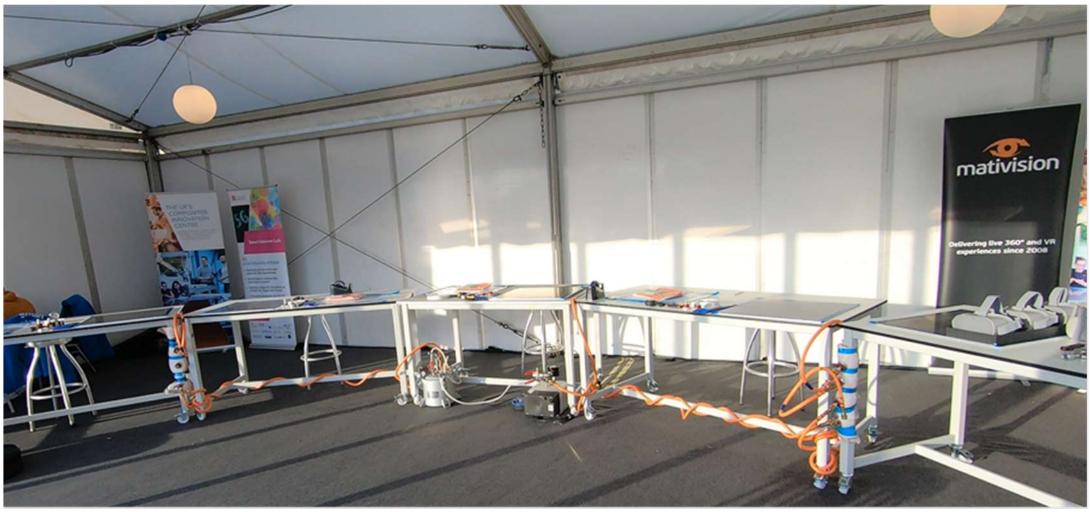


Figure 20 – Phase 2 trial setup on Millennium Square, Bristol

For the Phase 2 trial the VR headsets were once again connected via Wi-Fi to CPE devices as outlined in Figure 3 which in turn were connected to a small cell through 5G. This way of connecting the VR devices proved to be more robust than attempting to tether to mobile devices which were themselves connected through 5G and as a result the workstations in all test sessions could be filled, as shown in Figure 11 below.

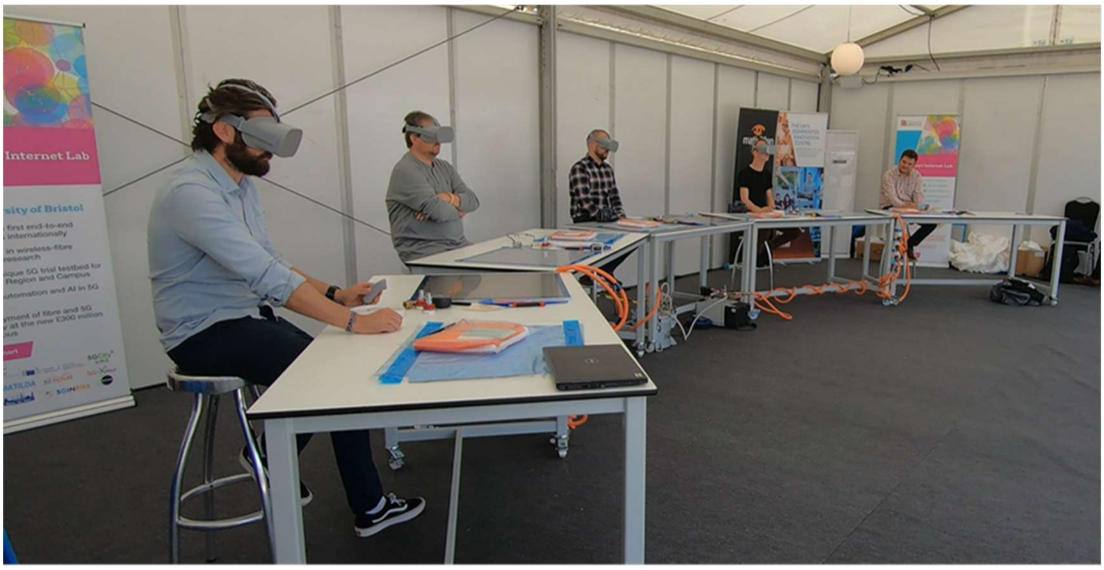


Figure 21 – Phase 2 VR session with all workstations occupied

Over the course of the demonstrations, it was possible to record more footage of the VR experience as captured by the 360° camera and viewed by the trainees through the headsets. Snapshots of these are shown in Figures 12 and 13, respectively.

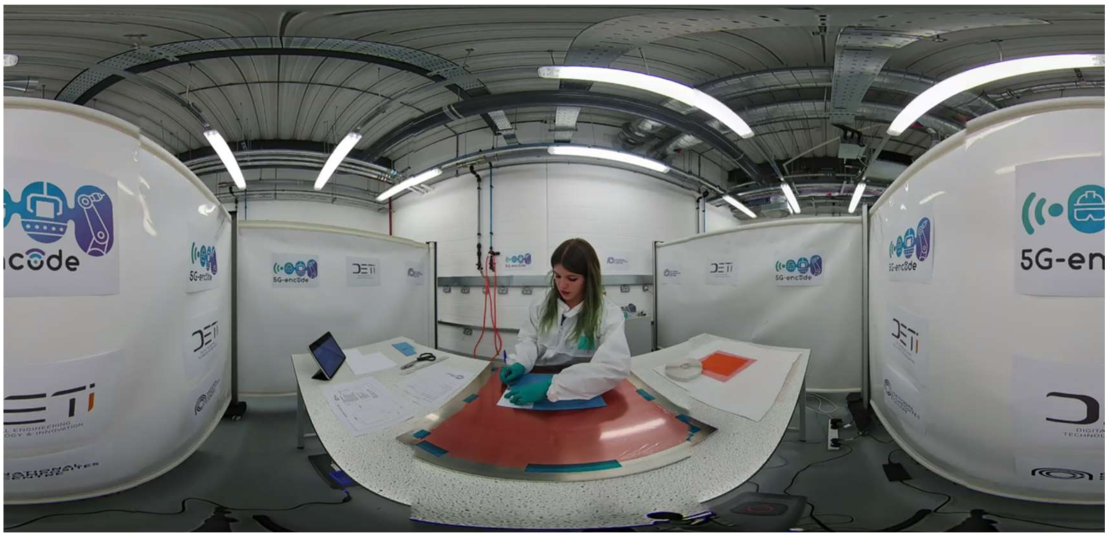


Figure 22 – Phase 2 view from 360° camera

Figure 23 – Phase 2 field of view of VR user

As part of the Phase 2 trial, additional graphics were included within the 360° video stream that would aid the trainees with understanding the technical drawings and paperwork required for the training course demonstration. This has been shown in Figure 14 below.

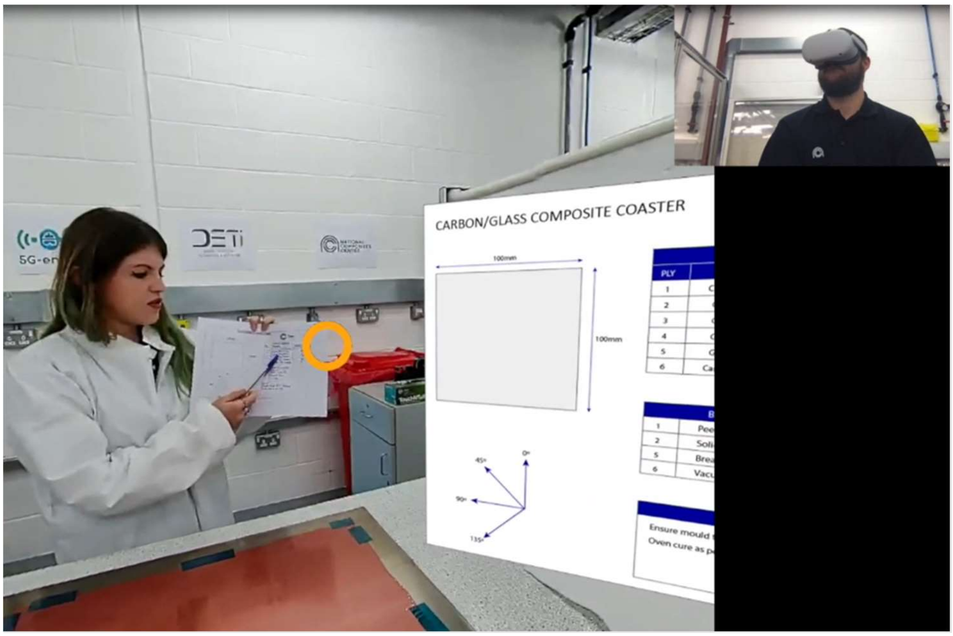


Figure 24 – Phase 2 additional graphics displayed with 360° video stream

Similarly, to Phase 1, user feedback was collected from all of the VR sessions within the Phase 2 demonstrations and upwards of 20 sets were collected which resulted in a more comprehensive view of the experience. Figure 16 shows the latest results on the satisfaction of the users with the VR experience, while Figure 16 presents the percentage of users who would use VR over on-site training.

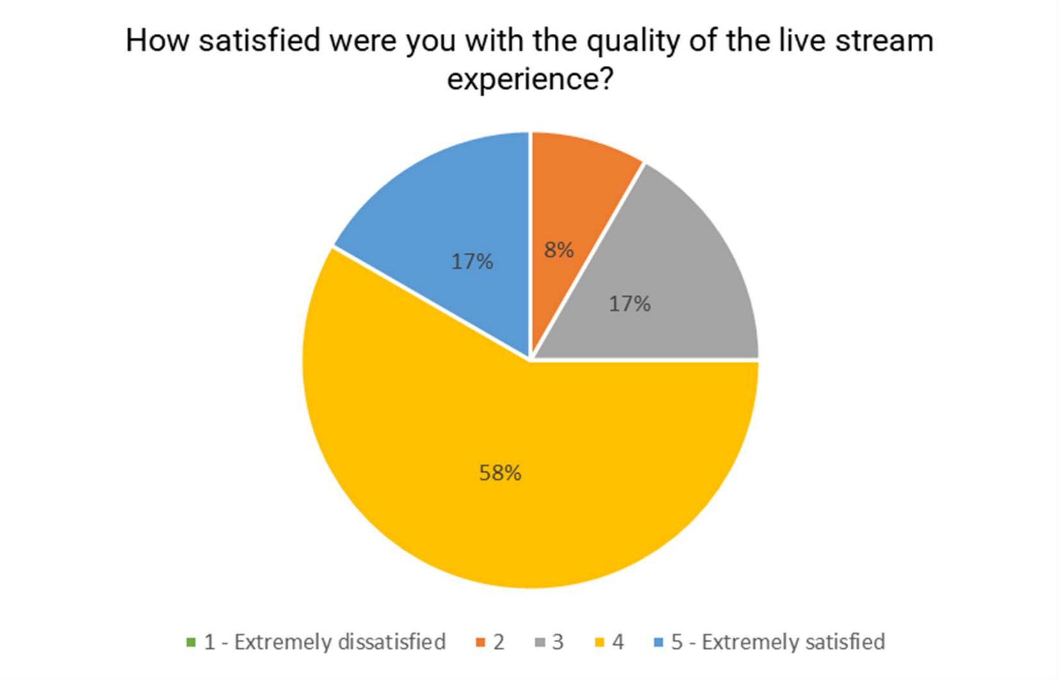


Figure 25 – Phase 2 user feedback regarding satisfaction with live stream experience

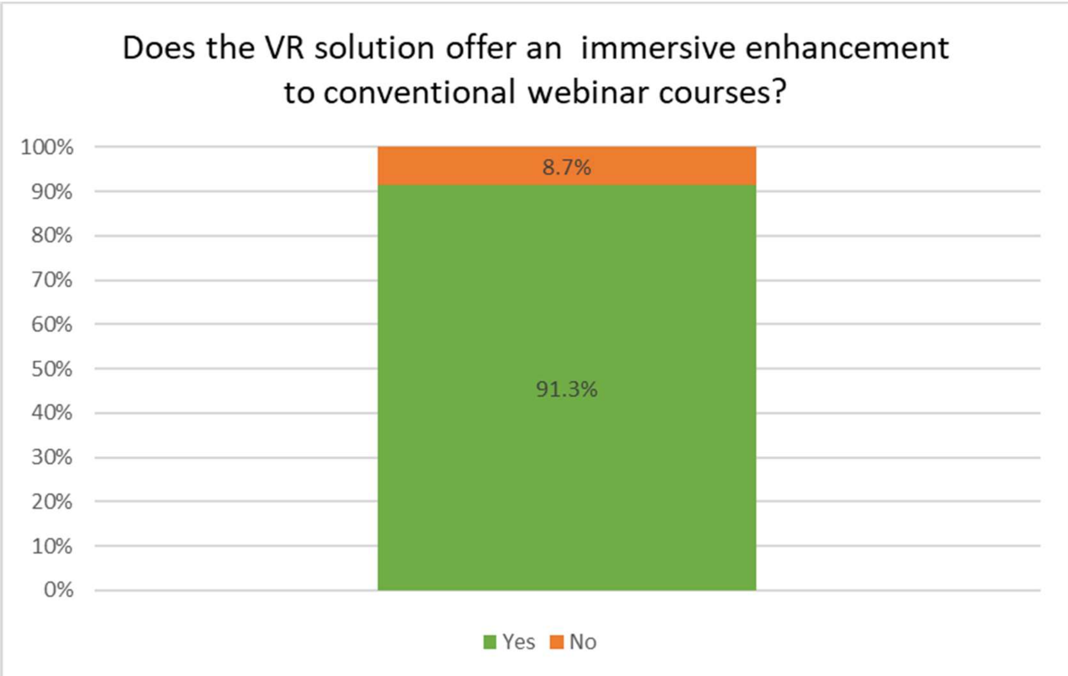


Figure 26 – Phase 2 user feedback regarding the enhancement of the VR solution over a conventional webinar course

Further user feedback from the Phase 2 VR trials has been presented in Appendix B.

30.5 Use Case Discussion

30.5.1 Phase 1 – 4G LTE

From the results of the user feedback presented in Figures 7 and 8 as well as the additional figures in Appendix A it was clear that the experience in the 4G trials was not of a satisfactory level. This can be explained by the screenshots taken of the video stream from the trials, which have been reproduced in Figure 17 below.

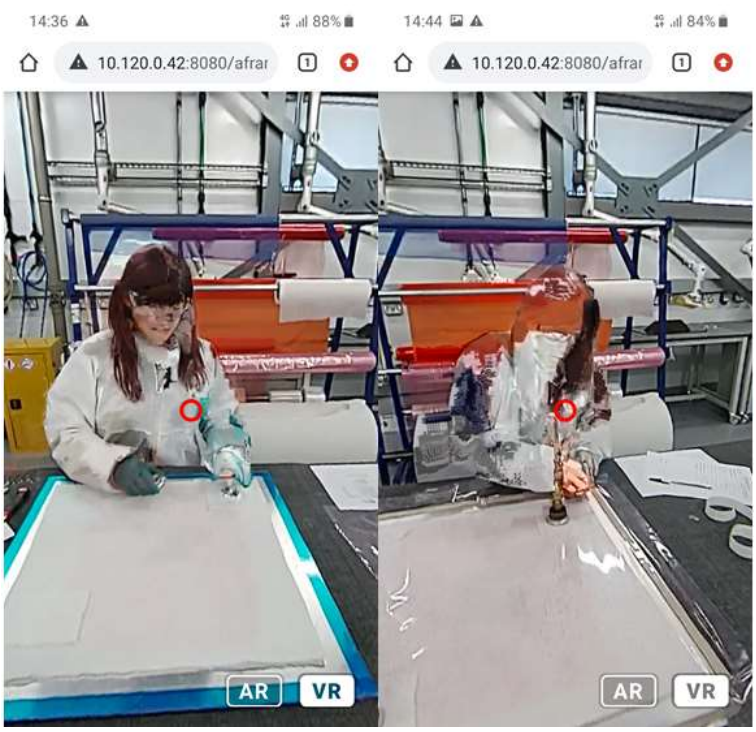


Figure 27 – Phase 1 video stream quality

Deficient performance of the network resulted in limitations in the picture quality (interpreted as elevated levels of latency) and that negatively affected the users' experience, the knowledge transfer efficiency, and the communication with the trainer. Additional graphics to support user engagement were also not possible in Phase 1 tests as it would severely impact the quality and reliability of the video stream.

As such, unfortunately, the benefits expected from the use case could not be fully experienced in Phase 1. However, the potential and the novelty features of the service were acknowledged by the users, which suggested when the network performs better with the 5G technology and the service is more stable and robust, then the experience will likely have a different impact.

One lesson learnt from this trial was regarding the connectivity of the Oculus Go VR headsets to the network. Since the headsets are not directly able to connect to the 4G network it is necessary to have an intermediary device such as a CPE to provide Wi-Fi from a 4G connection. This could then be applied to the Phase 2 trial to reduce the troubleshooting time and make the time used more efficient.

30.5.2 Phase 2 – 5G

Using the 5G connection, visual improvements were experienced in the video quality as seen in Figures 12 to 14. As such, the issues with a degraded quality video stream as seen in Figure 17 were resolved.

This is further supported by the results from the user feedback presented in Figures 15 and 16, as well as the additional ones in Appendix B. Specifically, 75% of the users who attended the VR sessions were very satisfied with the experience and gave high scores of 4 and above. While over 91% of all users would choose the VR training over the conventional on-site training in the future based on their experience. As per the project objectives, data was recorded separately for this statistic depending on uptake – i.e., industrial, or academic. This total percentage was made up of around 82% positive response from the industrial users and almost 100% from the users with an academic background.

Furthermore, 65% of users stated sufficient to high level of knowledge transfer obtained by the VR course. This was qualitatively supported by the users on Millennium Square during the AR training course in WP3.1.3, where comments were made on the benefits of having the VR teaching demonstrator prior. Finally, 17 of the users identified the technology as immersive and captivating which is extremely promising and clearly works towards reaching the overarching objective for the use case.

Even with these optimistic findings, the demonstration was extremely useful in highlighting several limitations or areas for development. These are as follows:

- Course organisation – This needs to be considered to reduce end user fatigue experienced by several the trainees. This could be done by re-structuring the demonstration to introduce additional question and answers sections or breaks to segment the course.
- Camera type and positioning – Implementing a multi-camera setup which can provide additional vantage points for the trainees to utilise. This can be made up of 360° cameras or combination of fixed cameras. The aim for this is to improve the immersive experience by providing more flexibility for the trainees.
- VR hardware – This was showing its limitation with cooling difficulties over the length of the course. This could potentially be improved by introducing more regular breaks or trialling out different headsets with better cooling systems.

The trial also allowed for several lessons to be learnt and put in the protocols for future demonstration or developments of the use case.

- Workstation design - Providing sufficient workstation space for each user allowing them to naturally space out in the room. This will help reduce any interference that may occur between the VR headsets.
- Trainer camera placement - From the qualitative user feedback, it was found that the 360° camera placement in relation to the trainer workstation is critical. This is because there are areas near the base of the camera where blind spots occur due to the separate lenses stitching together their feeds to form a continuous image. In the future, test runs of the setup prior to the official session can ensure that no information is lost by the local blind spots that occur in the image capture.

One challenge that is outstanding after the latest trials using the 5G architecture is the specific stream configuration implemented in the demonstration. There are two options:

1. Segmented streaming – Transmitting video recording in packets of a few seconds each from streaming server to a caching server where it is collected and then sent out to the relevant viewing devices. Inherent delay of circa 8 seconds is present due to the time taken to collect packets and transfer data from server to device.
2. Low latency streaming – Transmitting data directly from the streaming server to the viewing devices by-passing the segmentation stage. Allows for much lower delays between video capture and viewing feed but may induce jitteriness or lag.

The first option would allow for smooth high-quality streaming at a high bitrate thus improving the user experience. However, the function to communicate with the trainer in real-time will have a diminished effect due to the larger delay introduced.

The second option would allow for full exploitation of the two-way communication between trainer and trainee. But will introduce issues with the bitrate used from the 360° camera and resulting jitter in feed to viewing devices.

30.6 Use Case Conclusions

The use case development outlined within this report presents a significant amount of progress in terms of the performance of the package and the experience achieved for the users. It is recommended that this progress be considered alongside the progress made in the Augmented Reality (AR) use case. A summary of this is included in Appendix C. As a result, the objective of producing an immersive and comprehensive remote learning course through 360° video streaming in VR can be considered completed at this stage. However, the set of trials carried out thus far have identified numerous improvements that can further enhance the course. Additionally, to permit a direct comparison between the conventional training course and the 360° VR one, another trial is required which runs them in series to a control group of trainees.

Nevertheless, from the results presented in Sections 2.4.1 and 2.4.2 it is possible to draw several conclusions. Firstly, the use case proved its viability by enabling a sizeable group of users to proficiently progress through the practical training course remotely. The immersive experience demonstrated that it could transfer knowledge efficiently and this was supported by the user feedback regarding the use of 360° VR courses instead of conventional ones.

The above was made possible by the much greater bandwidth offered by the 5G network which clearly significantly improved the stream quality from the baseline 4G LTE trial. This meant that the trainees of the course could experience a more immersive environment and extract much more from the content as a result. This is supported by the positive user feedback collected from Phase 2 and specifically the proportion of users who were satisfied with the quality of the course and the viewing.

Lastly, the additional functionality of two-way communication within the training course can fulfil all of the requirements for an emulated classroom style scenario. However, this will require further testing once the streaming configuration is finalised as per the discussion in the previous section.

31 5G INDUSTRIAL ASSESSMENT

31.1 4G LTE and 5G Network Testing

As described earlier, to make a reasonable comparison of a 5G against an existing network technology, a trial was run using 4G LTE which acted as a baseline. The use case testing itself was fundamentally the same which ensured the improvements from the different trials could be identified. Apart from the developments within the use case scenario itself, data was recorded from the trials to analyse the network performance also and these will be outlined within the following sections.

31.1.1 4G LTE Test Setup

The 4G LTE system setup was as outlined in Section 2.1.1. There were several networking issues identified during the configuration of the infrastructure which delayed testing:

- Extended time required to configure Dynamic IP addressing on 4G network to allow 360° camera to be assigned an IP address.
- Configuration of Virtual Machine on multi-access edge computing (MEC) server to enable video stream output to reach trainee devices.
- Remote working across a virtual private network (VPN) access point.

As the VR use case requires quite a sizeable portion of the network bandwidth for multiple users, the trial was carried out independently from other use cases i.e., no other use cases were active on the 4G network during execution of the VR use case. This ensured that the available bandwidth was maximised enabling the best possible presentation for the experience as well as ensuring network level statistics captured related to the VR use case.

31.1.2 4G LTE Network Metrics

Network performance was reviewed for the day of the VR Phase 1 trial. The VR demonstration was conducted between 11:30 and 14:00. The ip.access 4G RAN network was configured to accumulate metrics for 60 mins and then send a log at the end of each hour to the log server. This logging characteristic is reflected in the charts presented in this section.

Figure 18 below displays the 'Total Uplink IP Throughput', and this measurement provides the total uplink throughput in kilobits per second (kbps). The uplink throughput in kbps was calculated by dividing the count of the total volume of uplink data received in kbits, by the time taken to receive the data in seconds. The maximum measured uplink throughput and target ranges for this measurand are displayed in Table 3 below.

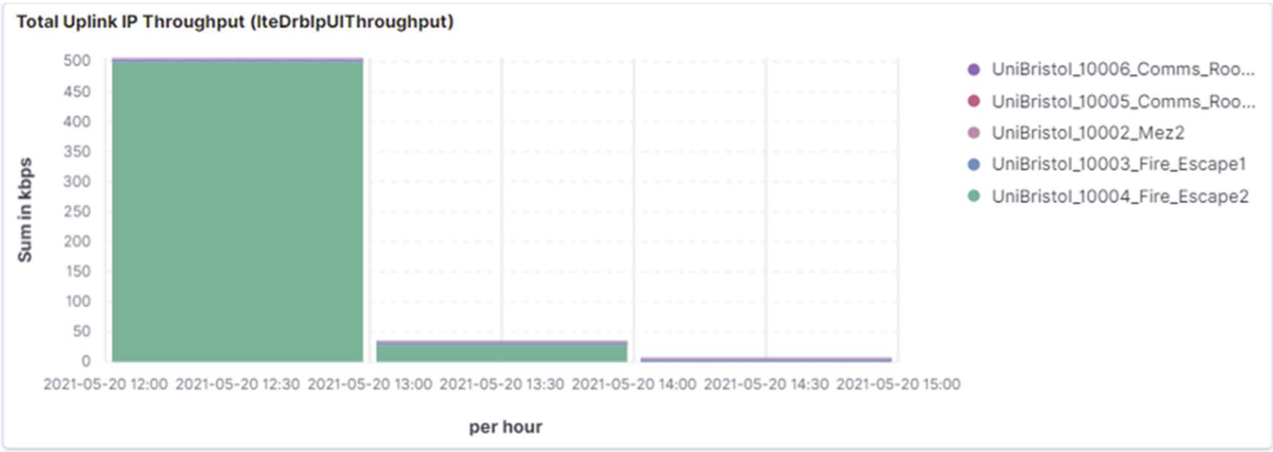


Figure 28 – Phase 1 total uplink IP throughput

Table 3 – Total uplink IP throughput Phase 1 measurement and targets

	Maximum Recorded (kbps)	Phase 1 Target (kbps)	Phase 2 Target (kbps)
Total Uplink IP Throughput	~500	1,000 – 10,000	10,000 - 100, 000

Figure 19 below displays 'Total Downlink IP Throughput', and this measurement provides the total downlink throughput in kbps. The downlink throughput in kbps was calculated by dividing the count of the total volume of downlink data received in kbits, by the time taken to receive the data in seconds. The total measured downlink throughput and target statistics for this measure are displayed in Table 4 below.

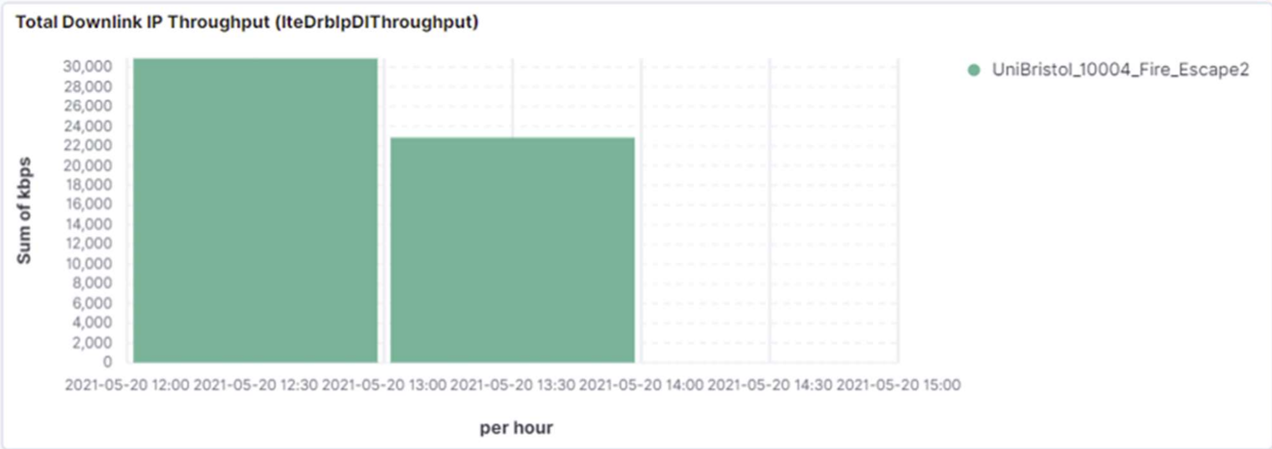


Figure 29 – Phase 1 total downlink IP throughput

Table 4 – Total downlink IP throughput Phase 1 measurement and targets

	Total data throughput recorded between 12:00 and 13:00 (kbps)	Phase 1 Target (kbps)	Phase 2 Target (kbps)
Total Downlink IP Throughput	~30,000	>= 4, 000	>= 20, 000

Figure 20 shows the measure of IP latency in the downlink for each radio unit passing data to support the use case. Latency between devices communicating over the network had a mean of around 8 ms. As such, in the benefits realisation specification, the measured latency is significantly less than stated.

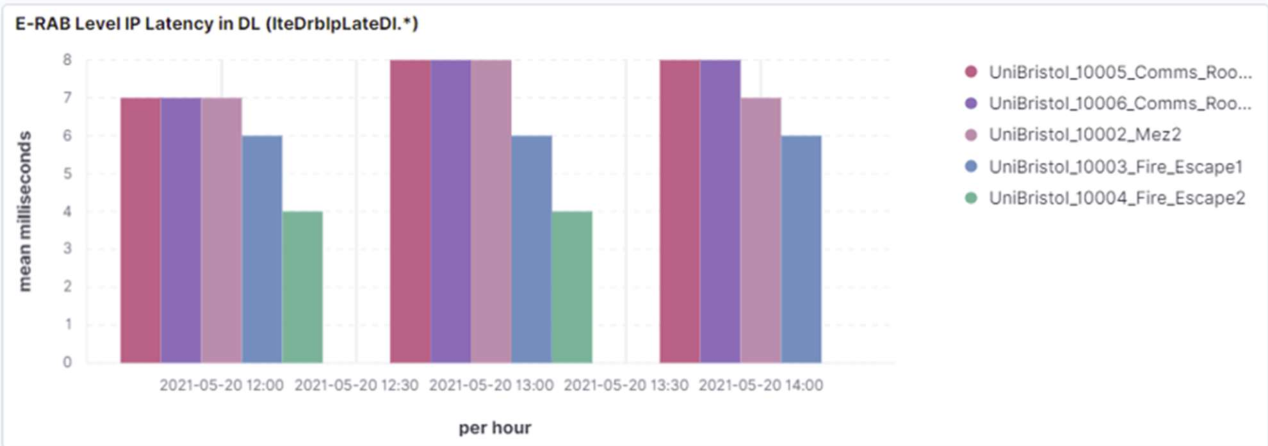


Figure 30 – Phase 1 IP latency downlink

Figure 21 shows mean packet jitter experienced during the use case Phase 1 test. In the benefits realisation specification packet jitter is specified in milliseconds, this relates to measurements possible in a wired network. Referring to Section 2.4.1 in the 4G/5G Network Performance Evaluation Guideline, packet loss and jitter are defined with the following statement:

"The main factors that cause packet loss and jitter are signal quality over the air interface, eNodeB load, and packet loss or jitter on the transport network. Poor air-interface signal quality may increase the packet error rate, which results in more packet retransmissions and segmentation. As a result, the number of lost packets and jitters increases."

Thus, the metric generated was measured in mean packet jitter not milliseconds as documented in the benefits realisation guide.

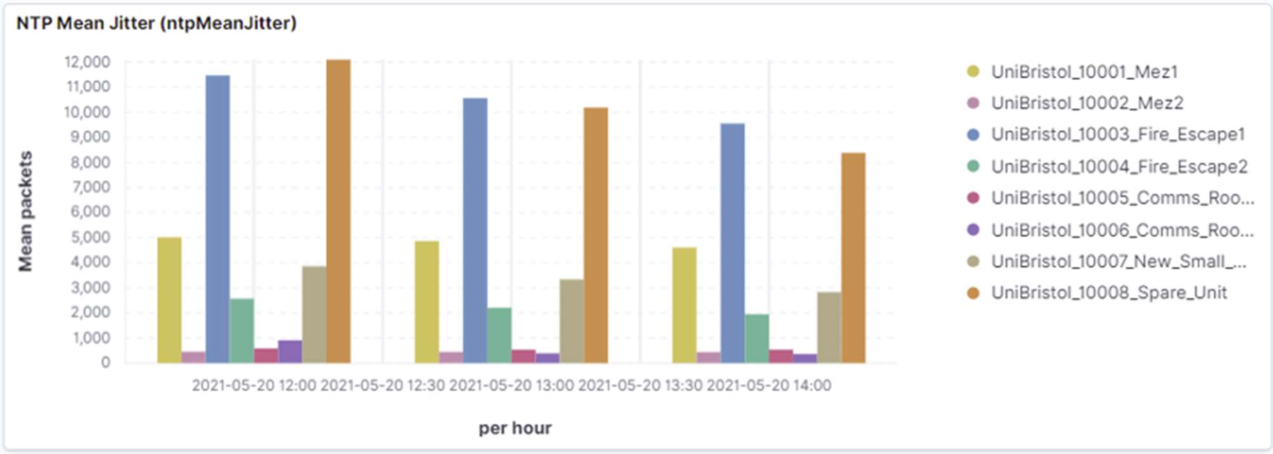


Figure 31 – Phase 1 NTP mean jitter

Additional metrics were also captured from the streaming server application. This was able to monitor the data coming into the server from the 360° camera and data going out of the server to the trainee devices. Figure 22 below shows this data with the orange set representing the camera upload (i.e., 4Mb/s bitrate) and the green set representing the downloads (i.e., a multiple of the bitrate depending on devices connected).

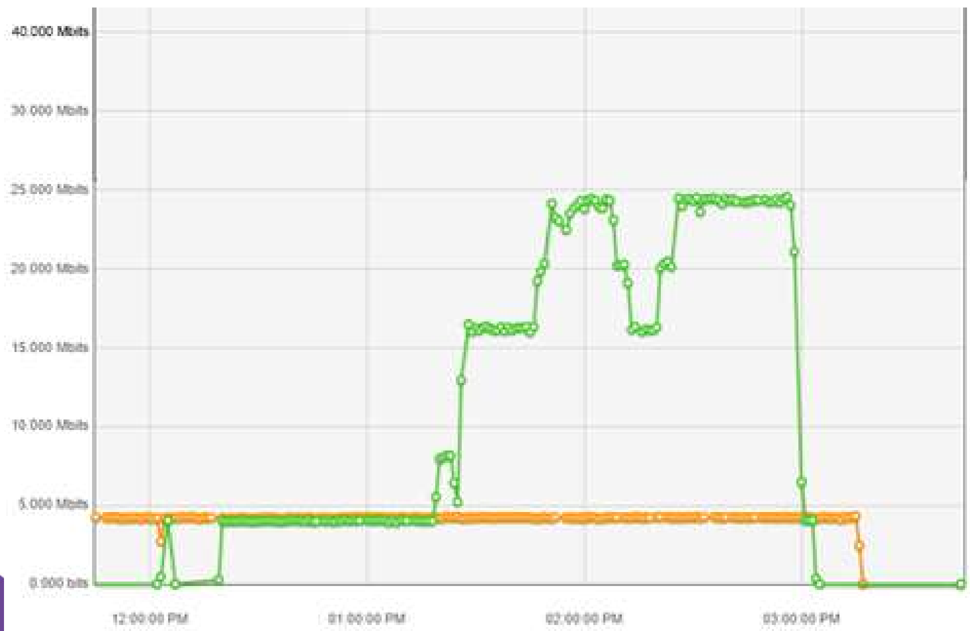


Figure 32 – Phase 1 4G LTE streaming server application recorded metrics

31.1.3 4G LTE Outcomes/Shortfalls

The maximum 'Total Uplink IP Throughput', recorded in Figure 18, was approximately 50% of the lower bound of the target value (Actual ~ 500 kbps, Target = 1,000 to 10, 000 kbps). However, the main device, which was uploading data, i.e., the 360° camera had a wired connection and did not use 4G. As such, it would not be reasonable to expect the target to be reached.

The maximum 'Total Downlink IP Throughput', recorded in Figure 19, was an increase of 650% to the target value for the initial phase (Actual ~ 30,000 kbps, Target = 4, 000 kbps). Two VR headsets and two mobile handsets downloaded the video stream; data suggests that for the initial phase these were sufficient to evidence fulfilment of network downlink requirements.

The 'IP packet latency downlink' in mean milliseconds, recorded in Figure 20, was 96% lower than the target value for the initial phase (Actual ~ 8 ms, Target = 200 ms). This measurement was taken with no other traffic on the 4G radio network.

The 'NTP Mean Jitter' in mean packets, recorded in Figure 21, was in packets and does not match the target value specified in milliseconds for the initial phase. This measurement was taken with no other traffic on the 4G radio network.

The data in Figure 22 shows that after the main portion of the trial (around 2pm and after) extra devices up to a total of six (i.e., two VR headsets and four mobile handsets = 24Mb/s total) were connected to the network. This data combined with the evidence of the poor streaming quality in Figure 17 presents the main shortfall of the 4G LTE network. The end user experience suffered degradation of quality to the point where content was unintelligible when more than four devices were connected.

Based on the bandwidth available this limit was taken as a total of two VR headsets alongside two mobile handsets. However, even with this number of devices, the video and audio quality had to be prioritised, and thus any additional functionality such as two-way communication and on-screen media had to be disabled. Therefore, a 360° video streaming VR training course with 4G connectivity could not be justified as a viable alternative to on-site training.

31.1.4 5G Test Setup

While 5G is already known to provide much higher throughput performance and lower latency compared to 4G LTE, it also provides the required network and data isolation by deploying network slicing as a standard (3GPP Rel.15/16). By doing so, the data arriving at the end-destination of the Independent (Public) networks can be effectively controlled and monitored, along with the network resources and equipment which can also be managed/orchestrated accordingly.

Based on the latency requirements of a use-case, the 5G Core and edge compute capability allow the user data plane (UPF) and application services (VMs, servers, applications, etc.) to run locally at the edge (closer to the end-users), significantly reducing the latency while minimising the backhaul throughput requirements. The high throughput on the downlink (DL) along with the very low latency enable the provision of VR and AR services while also providing a large degree of freedom in terms of video quality and number of connected users.

When analysing network metrics consideration was required for the differing technologies, vendor implementation of statistics and in the case of 5G, the vendor software maturity to support statistics.

An example of a technical difference is the clocking used in 4G which is Network Timing Protocol (NTP) based and 5G which is Precision Timing Protocol (PTP) based.

For the radio technologies, 4G was created using an ip.access solution and 5G created using an Airspan ORAN solution. In 5G statistics there are no measures in place to directly measure PTP, this impacts the capability to monitor, view and report on timing related latency and jitter.

The 5G-ENCODE network architecture between the Private Network (NCC), and the Satellite (NCCI) and Independent (UoB) networks for the VR/AR demonstration is shown in Figure 23 below. From a cellular network perspective, the independent network hosted by the UoB 5GUK test network, represents the public network and acts as an extension of a private network, i.e., NCC network.

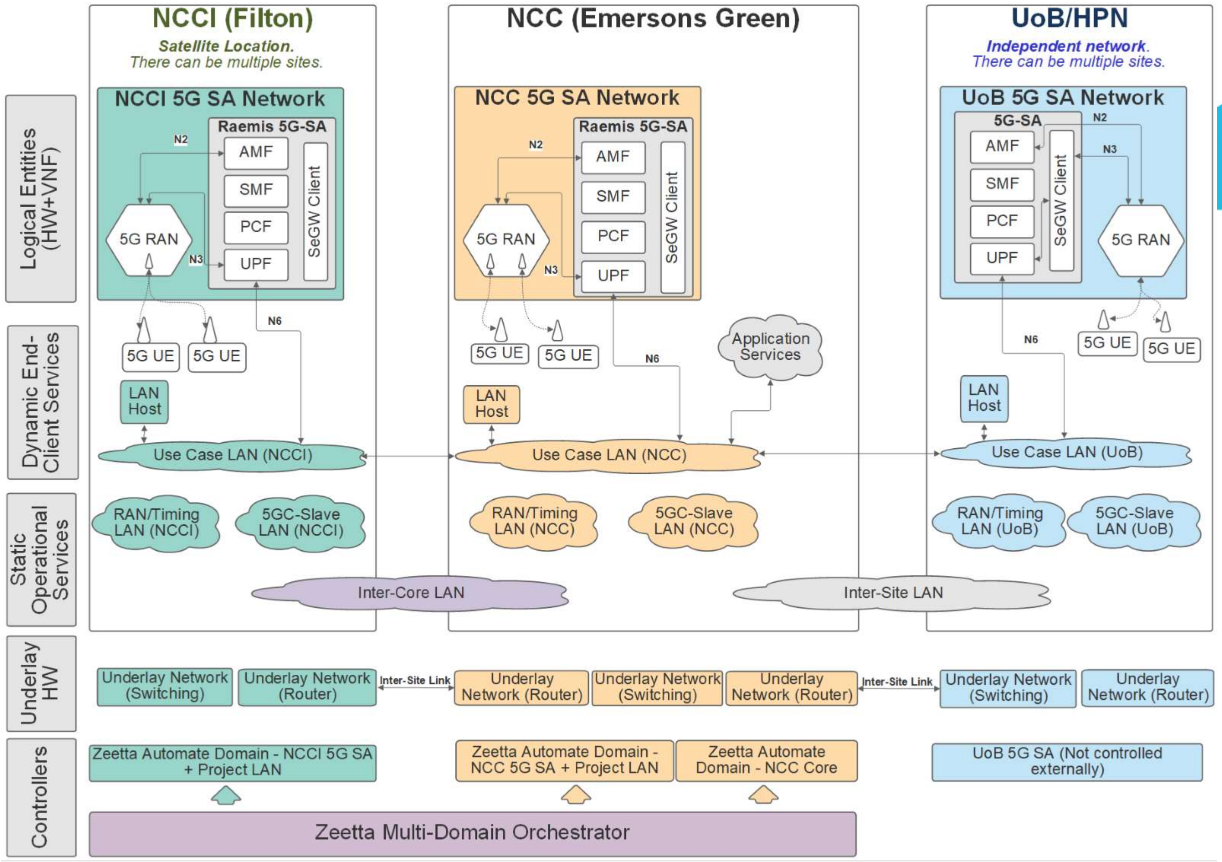


Figure 33 – 5G Encode network architecture

31.1.5 5G Network Metrics

Network performance metrics were collected during the final AR/VR demonstration at Millennium Square and are shown in Table 5 below as KPIs (Key Performance Indexes).

Table 5 – Phase 2 5G measured network metrics

Measured KPIs	Value	Unit
Camera to Server Bandwidth (Total uplink IP throughput)	~3	Mb/s
Server to Users throughput (i.e., Total Cell Throughput) – Total Downlink IP Throughput.	16.1	Mb/s
Server to Users throughput (Individual User Throughput) – App-based DL Throughput on each end-user.	3.22	Mb/s
DL Latency Tolerance – Downlink IP Latency.	3.15	ms
DL Jitter Tolerance – Standard Deviation of the app-based latency.	2.05	ms
% DL Packet Loss Tolerance – Downlink PDCP SDU Air-Interface Percentage Loss Rate.	0.12	%
% DL Packet Drop Rate – Downlink PDCP SDU Percentage Drop Rate.	0.12	%
% UL Packet Drop Rate – Uplink PDCP SDU Percentage Drop Rate.	0	%

These KPIs were derived from a variety of metrics collected from the 5G network (5G Core – open5gs) and the UEs (User Equipment – Android devices/CPEs). The overall network performance was found to be satisfactory. The AR/VR service provisioning showed no problems or interruptions throughout the demonstration.

The total cell DL throughout was 16.1 Mbps on average, reaching a peak of 31Mbps, as shown in Figure 24 below. It should be noted the supported cell capacity was much greater than the one achieved during the demonstration. The wireless link between the 5G NR (New Radio) and the 5G CPE devices was tested before the demonstration, exceeding 700Mbps in DL. Consequently, the stress on the network during the AR/VR demo was well below its throughput limit. It is worth noting that there was a small packet drop in the DL due to some initial inconsistencies between the 5G CPE and the 5G NR. The number of packets dropped was negligible. No dropped packets were detected on the uplink (UL).

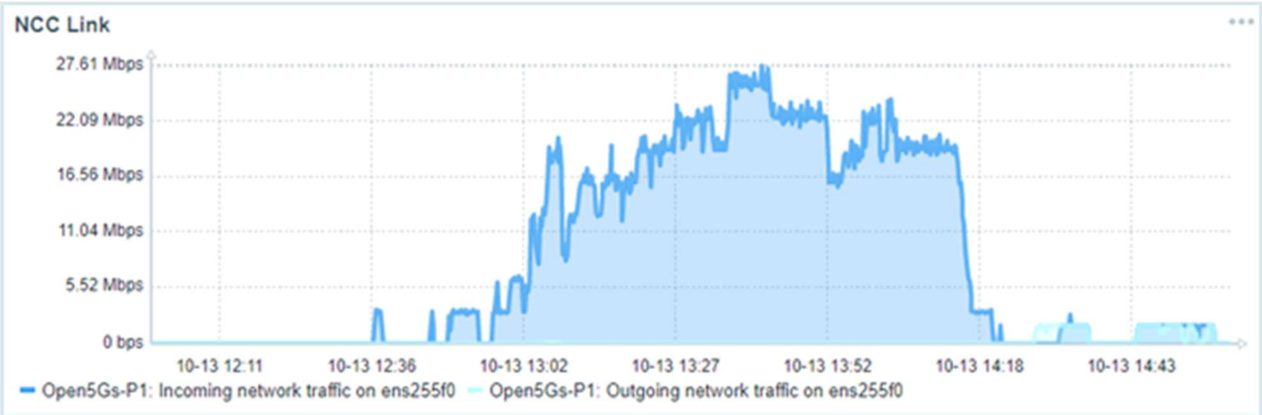


Figure 34 – Phase 2 5G downlink throughput

The average DL latency and jitter between the 5G CPE and the streaming/video server during the AR/VR service provision was measured at 3.22 ms and 2.05 ms, respectively. Hence, the latency performance of the 5GUK Test Network was also satisfactory in terms of end user experience. However, advanced optimization on the 5G network and 5G CPE devices could potentially drop these figures even further.

Metrics were also collected from the streaming server application similar to the Phase 1 trials. Figure 25 below shows the data going into and out of the server – orange representing the upload from the camera and green the downloads to the trainee devices.

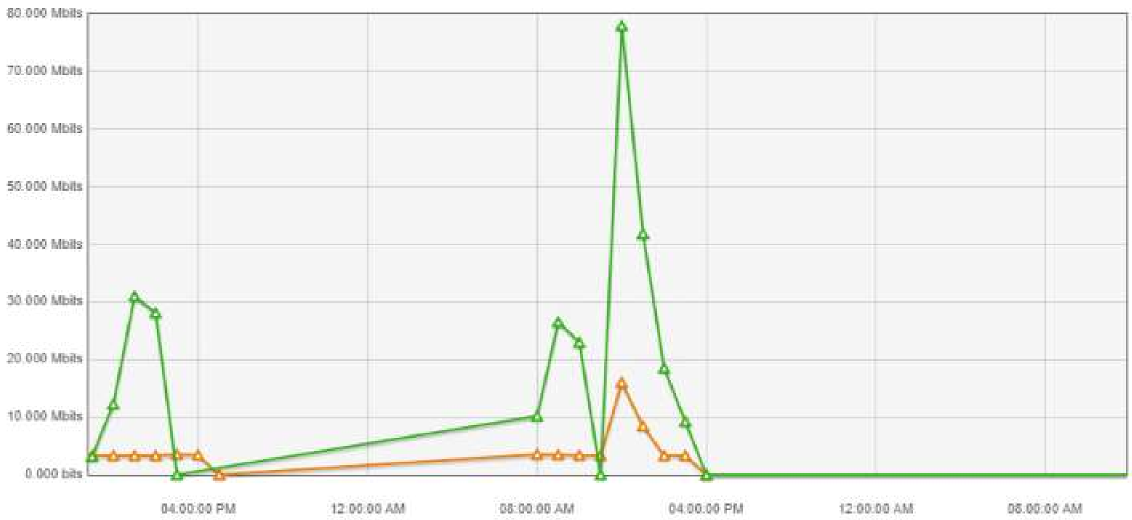


Figure 35 – Phase 2 5G streaming server application recorded metrics

31.1.6 5G Outcomes/Shortfalls

The total uplink IP throughput was not focused on during the network measurements. This was because the 360° camera was again the main uplink contributor and was connected by wire to the internet on the NCC HQ side.

As described above the total downlink IP throughput was on average 16.1Mb/s as the main training devices were the five VR headsets. However, the maximum of 31Mb/s was experienced when up to five additional mobile devices were added. It was promising to see that all of these were able to have consistent and satisfactory video and audio quality. The 5G also enabled the additional functionality such as on-screen media to enhance user experience and improve the knowledge transfer.

To again test the limits of the network, the bitrate of the 360° camera was increased to 15 Mb/s. With five devices downloading this data, as shown in Figure 25, around 75Mb/s was the maximum throughput experienced by the streaming server application during the trial. This effectively brought the streaming server to its limits (i.e., video processing capability) with the VR service characterised by video stuttering and glitching. This highlighted that this part of the system needs further development as the end-to-end link between the server and the 5G CPE could support more than 700 Mbps on the DL.

The 5GUK Test network was stable throughout the demonstration and without any issues. During this demonstration one of the three inhouse developed CPEs presented instability with its network connectivity due to a malfunctioning SIM card. However, the 5GUK team was able to resolve the problem and restore the service for the duration of the demonstration.

31.2 5G Discussion

31.2.1 Benefits of 5G

The benefits recorded by the Phase 2 trials based on the 5G connectivity have been outlined throughout the report but in summary:

1. Data capacity due to available bandwidth (exceeding 700Mbps downlink):
    - Showed significant increase in concurrent devices that can be used with good video and audio quality.
    - Enabled additional functionality such as on-screen media.
    - Highlighted limiting factor in system – i.e., streaming server application, which needs further development for use case.
2. Average speed to each connected device:
    - Ensured good video and audio quality of stream.
3. Low latency (sub 10 milliseconds):
    - Improved trainee experience by decreasing delays between video and audio feeds.
    - Showed potential of two-way communication with minimal delays.

A 5G network within the industrial setting of the NCC HQ also has the potential to facilitate different training courses by increasing mobility of the streaming setup around the factory. A matured and robust system would allow for the 360° video streaming setup to be moved and connected throughout the factory as needed.

31.2.2 Limitations of 5G

A significant limitation in the 5G setup for the particular use case arose from the required hardware. In the current point of time the VR technology has not developed sufficiently to include headsets that allow for direct 5G connections. As a result, the connection had to be over Wi-Fi which can originate from a 5G small cell as described within Section 2.1.2.

However, this introduces additional latency and limits the management of the devices by the core as they are hidden behind a Wi-Fi network; hence limiting the use case architecture which did not allow the benefits from the 5G network to be fully realised in this demonstration.

Also noted most of the 5G-capable devices currently on the market do not support 5G SA operation (disabled on software level), i.e., operating on a pure 5G cellular network without the anchoring 4G cells. 5G Networks and devices are not yet mature enough to support a fast and easy deployment of AR/VR services. Vendors have been slow to implement and support the basic 5G SA functionality, even to their most recent and flagship devices.

To overcome the limited support for 5G SA, the 5GUK engineering team of Smart Internet Lab has developed multiple in-house-built 5G CPE devices. By doing so, 5G SA connectivity could be established and demonstrated between the 5G CPEs and the 5G network, while enabling the provision of 5G services to the AR/VR devices through Wi-Fi 6. These devices are not planned for mass production.

The current inhouse development at Smart Internet Lab is hampered as Wi-Fi services are still pending their integration with the developed CPE devices. The chip-crisis around the world makes it very difficult and expensive to purchase Wi-Fi 6 Access Point (AP) Modules in small numbers (for creation of a Wi-Fi hotspot). Hence, external Wi-Fi 6 APs were connected to the ethernet ports of the CPEs, and traffic was diverted from 5G, to ethernet, then Wi-Fi.

31.3 5G Conclusions

Several conclusions can be drawn regarding the 5G network based on the user feedback and data collected from the Phase 2 trials.

Firstly, the greater bandwidth available and the faster speeds achieved in comparison to 4G LTE significantly improved the use case performance. The video and audio feeds were consistently of a satisfactorily high quality. The number of concurrent devices used was sufficient to justify the VR training course. Most of the users confirmed the immersivity of the experience and were impressed by the quality and knowledge transfer of the course.

However, the trial was unable to fully investigate the capabilities of the 5G network setup by the UoB team. This was because of the highlighted limitation of the streaming server application. Any attempts of significantly increasing the 360° camera bitrate and thus improving quality caused the server to throttle. This resulted in a poor streaming quality observed on the trainee devices. As such the trial was inconclusive in identifying the maximum devices that can be used simultaneously to follow the live stream.

Further, the limitation in the technological advance of the VR headset devices meant that the system could not be fully connected using 5G. This introduces uncertainty in the specific effects of the network. The overall performance is likely to be diminished due to the Wi-Fi connections between the CPEs and the headsets/mobile devices.

Nevertheless, the metrics recorded suggest that the 5G network has the capability to achieve all network targets set out for the project. The downlink exceeding 700Mbps as well as the 3ms and lower latency values were an impressive display for the technology. Based on further testing and optimisation the 5GUK team are optimistic that further improvements can be made to these.

Though as identified in Section 3.2.2, it is important to note that there are difficulties in setting up a 5G SA network. This may impede the introduction of 5G to the wider market of SMEs in the manufacturing sector and beyond until systems are more mature and simpler to install.

The benefits experienced by the use case from the 5G network allowed the project to reach its main objective. The experience was immersive and useful for the users and has the potential of being a viable innovative remote learning solution. Yet, there are still several technological developments that need to be made before this is a matured and robust system. These developments are within the hardware and software on both the use case and the 5G side.

32 APPENDIX A – FURTHER PHASE 1 USER FEEDBACK

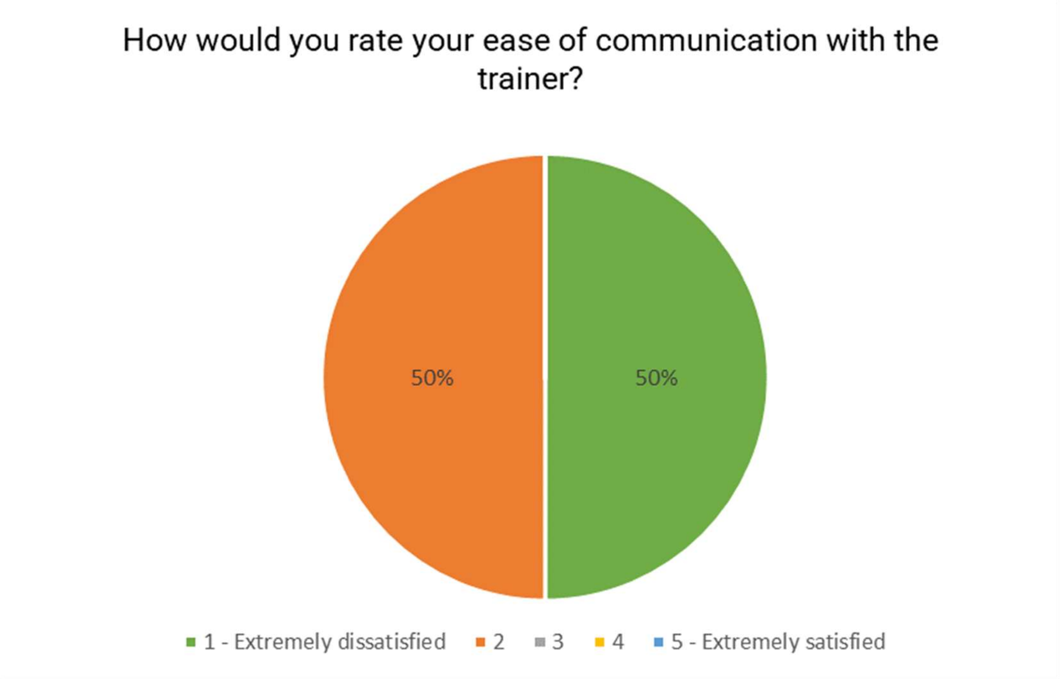


Figure A1 – Phase 1 user feedback regarding ease of communication with trainer

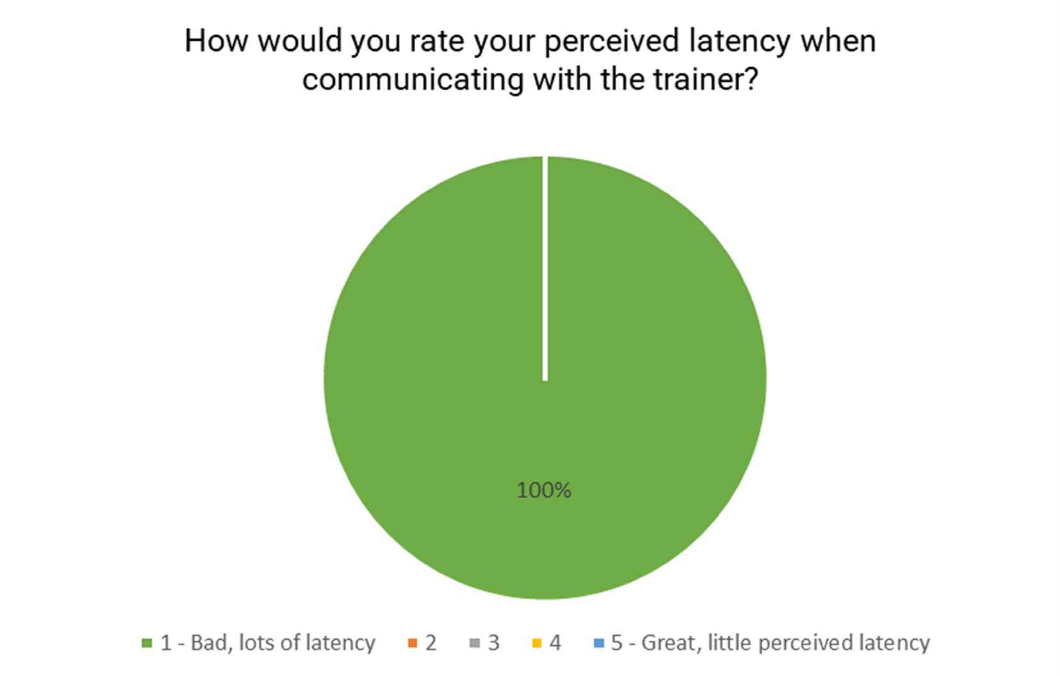


Figure A2 – Phase 1 user feedback regarding perceived latency during communication with trainer

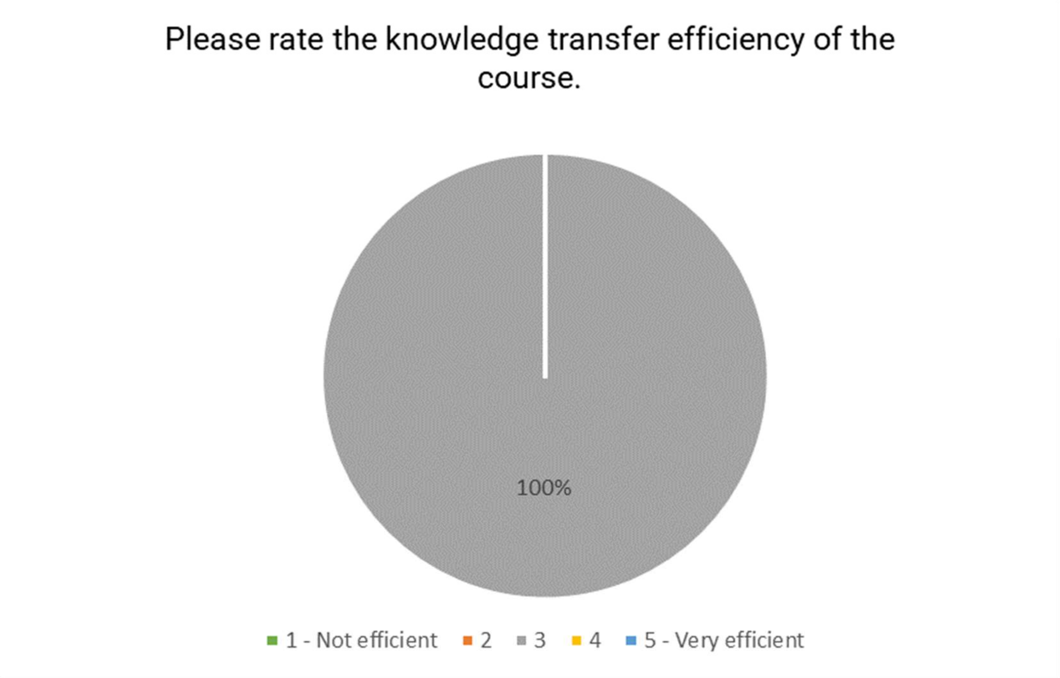


Figure A3 – Phase 1 user feedback regarding knowledge transfer efficiency

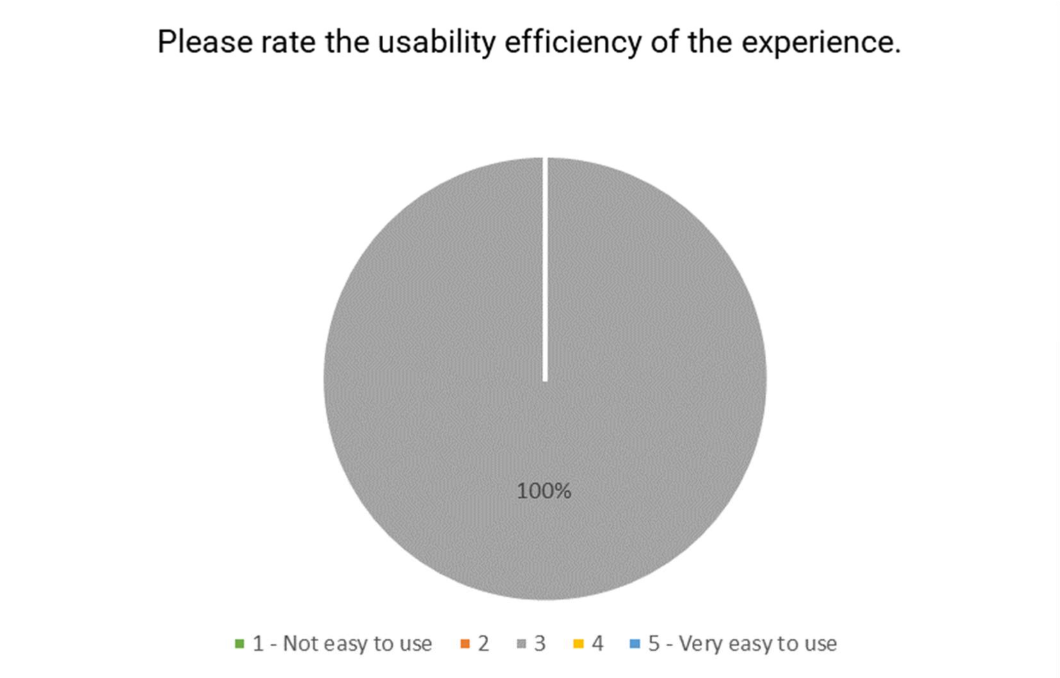


Figure A4 – Phase 1 user feedback regarding usability efficiency

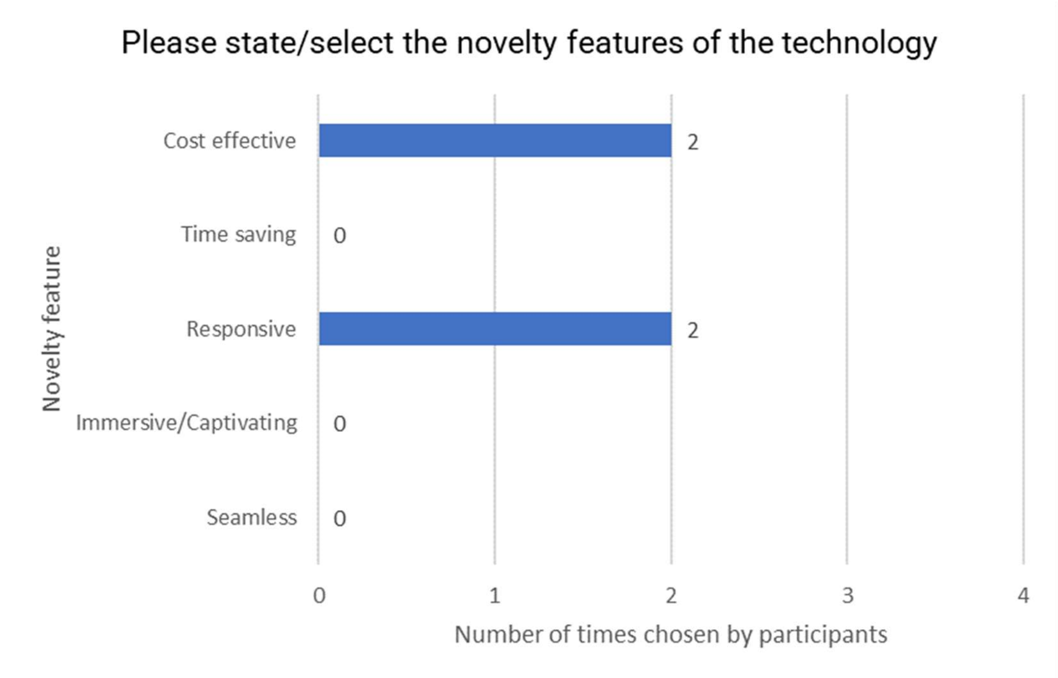


Figure A5 – Phase 1 user feedback regarding novelty features of technology

33 APPENDIX B – FURTHER PHASE 2 USER FEEDBACK

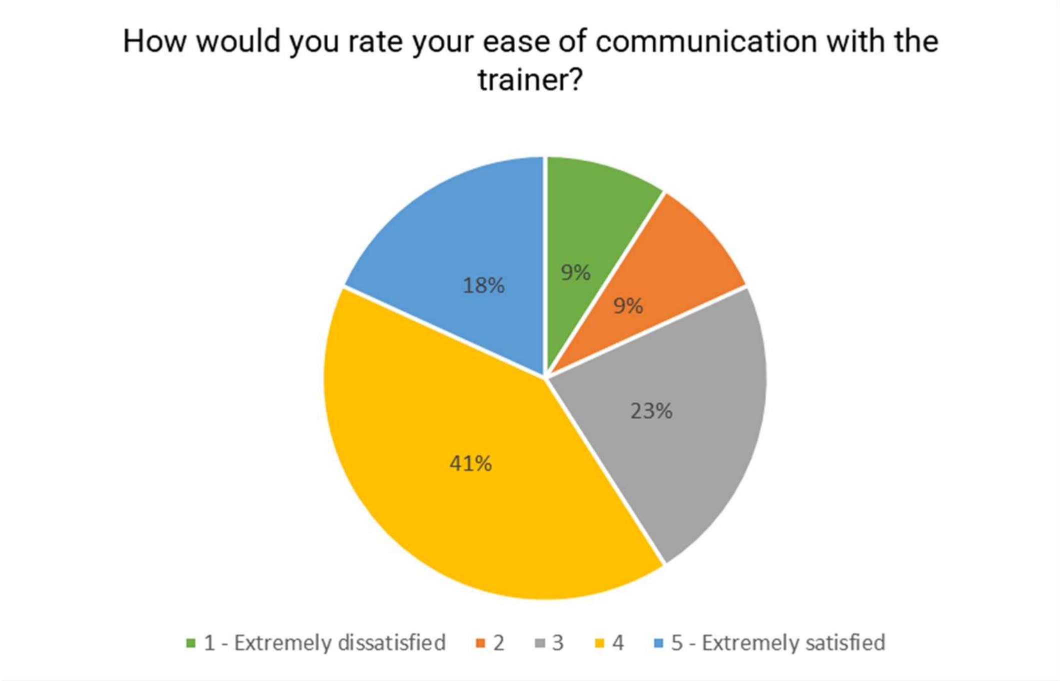


Figure B1 – Phase 2 user feedback regarding ease of communication with trainer

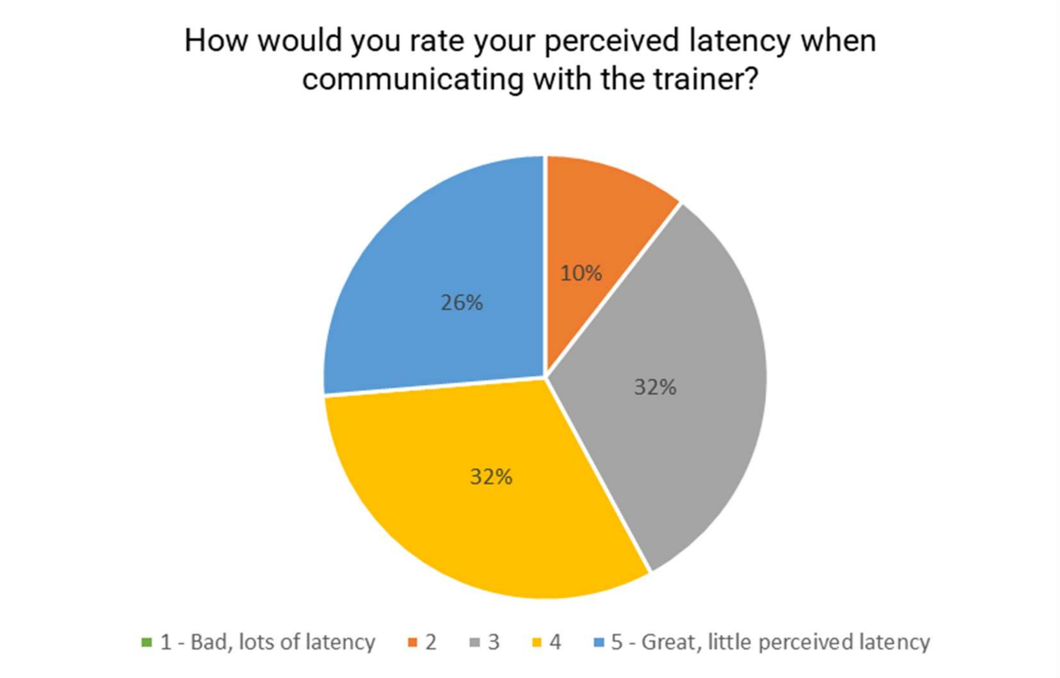


Figure B2 – Phase 2 user feedback regarding perceived latency during communication with trainer

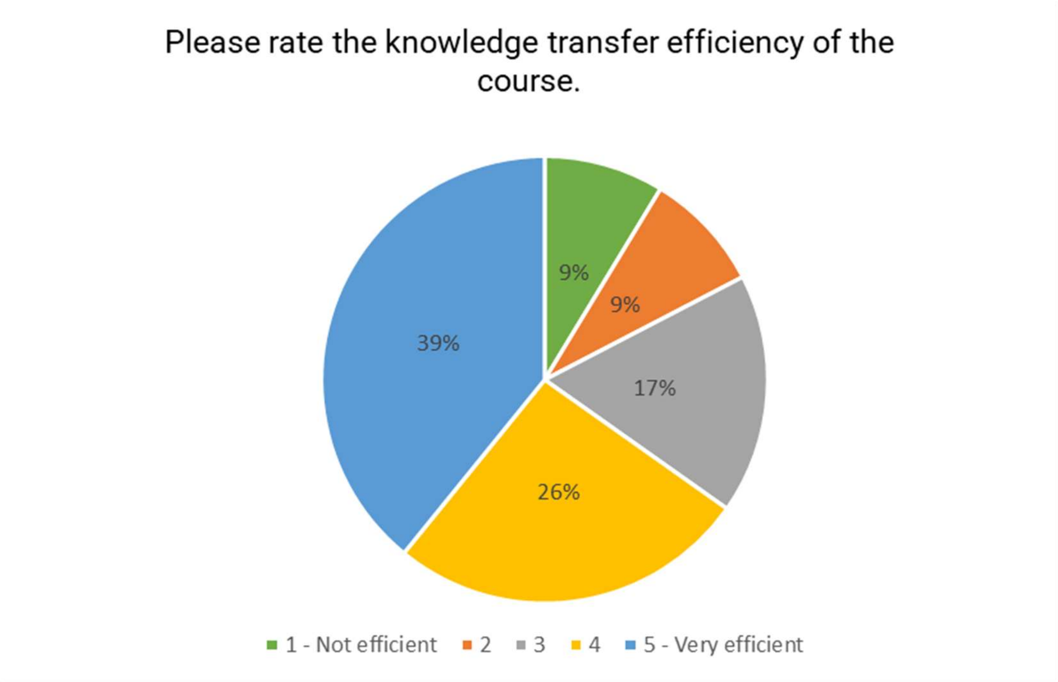


Figure B3 – Phase 2 user feedback regarding knowledge transfer efficiency

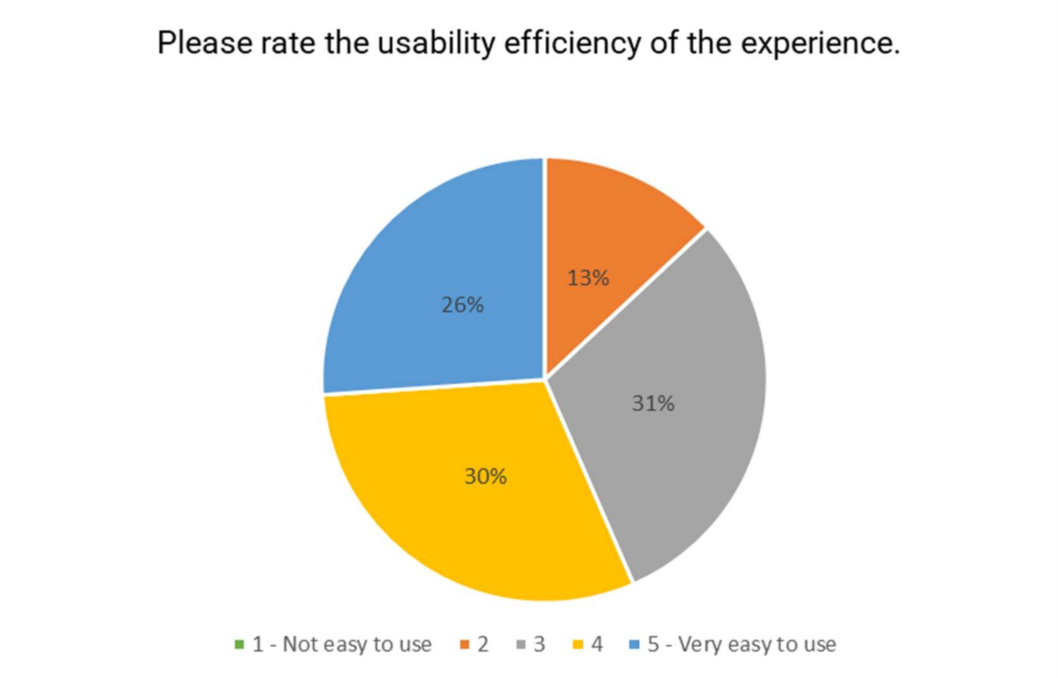


Figure B4 – Phase 2 user feedback regarding usability efficiency

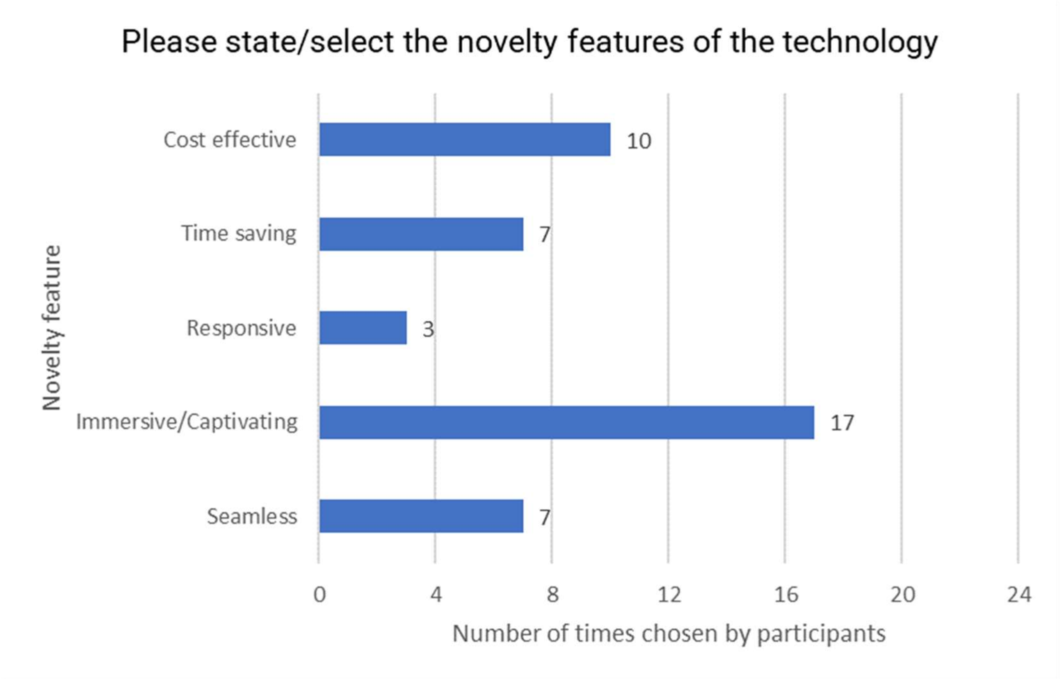


Figure B5 – Phase 2 user feedback regarding novelty features of technology

34 APPENDIX C – AR VERSUS VR USE CASES

As part of 5G-Encode, the NCC created and trialled two remote learning solutions – one presented within this report utilising AR technology and one presented in another report utilising 360° video streaming and VR technology. The main motivations for both were relatively similar but the teaching elements that these use cases covered varied. More specifically, the AR solution aimed to completely digitise conventionally on-site practical training courses in a bid to enable effective remote training. While on the other hand, the 360° video streaming VR solution aimed to enhance more traditional webinar style teaching and allow for more immersive remote learning from practical demonstrations in real-time.

As was concluded by both reports on these work packages, the latest demonstrators of the solutions were of satisfactory quality and presented promising digital products. However, it was identified that, for the NCC the AR package has more potential in the long-term based on the significant technological developments that could be made. If it is used as a teaching or training tool, it is possible to create a framework system that could be easily configurable to various topics and courses. This will enable the NCC to offer a wider variety of remote training or create a platform for other providers to utilise as well. On the other hand, the AR packages also has potential of being an effective manufacturing aid. Adding functionality that can validate the composite layup and highlight any possible issues will considerably benefit companies that want to reduce scrap rates.

Nevertheless, the 360° video streaming package in its current format is still a useful capability for the NCC to have and can be implemented in various scenarios for real-time remote teaching. But to improve its immersivity element and fully extract the VR potential, more development must be made in the course setup. For example, having multiple stations around the 360° camera, so the whole field of view is utilised productively. Alternatively, different points of view can be added to allow the users to engage more fully with the practical demonstration presented.

35 -- AUGMENTED REALITY –

36 ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK's biggest investments in using 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It is designed to validate the idea that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that the UK industry exploits the 5G technology and remains a global leader in the development of robust digital engineering capabilities when implementing complex composites manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLL/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and SMEs.

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

37 EXECUTIVE SUMMARY

Training courses with practical elements are typically carried out by trainers either within their training facilities on-site or at a suitable location at the customer site. Both scenarios have economic and environmental costs related to travel, with most being infeasible within the recent COVID-19 climate. Although there are distance learning options, and internet-based courses available, they are limited to webinar style 2D solutions. The use of 5G and more immersive technologies provides a unique opportunity to engage more effectively with the trainer and the practical elements of the training course.

The use case presented within this report evaluates the use of latest AR software, hardware, and 5G connectivity to demonstrate a fully immersive AR remote training solution. This solution is used to guide the user through the manual composite manufacturing process of one of the practical courses offered by the NCC. On-screen text instructions, overlayed 3D graphics, and tutorial videos support the trainees wearing the AR headgear. The work package also relies on 5G's reliable, safe, high bandwidth and low latency connectivity to facilitate high quality two-way communication (video and bi-directional audio feeds) between trainer and trainee.

The use case development was split into two testing phases. The first phase was conducted on 4G LTE and limited to a controlled setting at the NCC with four trainees across two sessions. None of the participants indicated that the solution was of sufficient quality to justify its use over conventional on-site training. The root cause for this was not found to be the network connectivity, but the initial development of the AR application.
The second phase was conducted using the 5G test bed deployed at the NCC. The testing was extended to an external location and opened to a wider testing group of at least 20 trainees. Even with the expanded scope, almost 79% of users were satisfied with use of the package over on-site courses. The network provided sufficient connectivity to enable the two-way communication function with good quality which was appreciated by all users. Metrics exceeding 700 megabits per second download speed and around 3 milliseconds latency were recorded.

The immersive technologies tested in this report are shown to be a good option for remote training but require high quality digitisation and integration in the process. The 5G technology was shown to be reliable and high-performance with no significant or lasting interruptions throughout the two days of demonstration sessions at Millennium Square. However, the use case was not very heavily reliant on the network because the only feature relying on it - i.e., two-way communication, was only used intermittently for relatively short periods of time.

Future developments can include features that increase the use of 5G with the development of online libraries containing interactive digital content. This development should also modularise the solution and improve its adaptability and cross application re-use.

The AR technology must reach a more mature and robust stage before being applied in real-world cases. To enable this wider-scale adoption access to operational public or private 5G networks is a prerequisite.

38 ABBREVIATIONS

2D	*Two-Dimensional*
3D	*Three-Dimensional*
3G	*Third Generation Mobile Network*
4G LTE	*Fourth Generation Long-Term Evolution Mobile Network*
5G	*Fifth Generation Mobile Network*
AP	*Access Point*
APC	*Automated Pre-Forming Cell*
AR	*Augmented Reality*
CPE	*Customer Premises Equipment*
DCMS	*Department for Digital, Culture, Media, and Sport*
DL	*Downlink*
eMBB	*Enhanced Mobile Broadband*
IoT	*Internet of Things*
IP	*Internet Protocol*
Kbps	*Kilobits Per Second*
KPIs	*Key Performance Indicators*
LRI	*Liquid Resin Infusion*
Mbps	*Megabits Per Second*
MMTC	*Massive Machine-Type Communications*
NCC	*National Composites Centre*
NCC HQ	*National Composites Centre Headquarters*
NCCi	*National Composites Centre – Filton Site*
NR	*New Radio*
NTP	*Network Timing Protocol*
P2P	*Peer-to-Peer*

PTP	*Precision Timing Protocol*
RAN	*Radio Access Network*
SA	*Standalone*
SMEs	*Small and Medium-Sized Enterprises*
UEs	*User Equipment*
UL	*Uplink*
UoB	*University of Bristol*
UPF	*User Plane Function*
URLL	*Ultra-Reliable Low Latency*
VMs	*Virtual Machines*
VR	*Virtual Reality*
WECA	*West of England Combined Authority*

39 INTRODUCTION

Effective knowledge transfer through training is a core part of people development and is essential for social sustainability. Classroom and workshop training where all attendees are co-located within the same demonstration space are a proven method to facilitate this.

Traditionally, such practical training courses provided by the NCC to customers across the UK have been carried out by trainers either within its training facilities on-site or at a suitable location at the customer site. However, both scenarios can be linked to significant economic and environmental costs due to travel, accommodation, and transportation of equipment. As such, with the continuous drive for sustainability over the past two decades the work developing alternative solutions has become more vital.

Additionally, the recent COVID-19 pandemic put extra pressure on training providers and on companies in need of practical training. This was due to the stringent restrictions put in place such as barring all non-essential travel and gatherings for a significant period.

Though there are distance learning options, and internet-based courses available, the capability to engage effectively with the trainer and deliver practical aspects of a course is difficult. More immersive solutions need to be proposed to address this industry challenge.

The augmented reality practical training demonstrator that is presented in this report will highlight the latest AR wearable technology as an example of an advanced distance learning solution. Practical training for the manual lay-up of composite materials through the ‘Introduction to Pre-preg’ manufacturing training module offered by the NCC is selected as the use case.

The solution aims to exploit the capabilities of the 5G technology available to enable extra functionality and provide trainees with a real-world experience similar to when on site with the trainer. This is realised by a two-way communication stream back to the trainer.

39.1 AR Project Objectives

The main project objective was to evaluate the effectiveness of applying the AR technology over a fully functional 5G network to improve user experience and training performance of interactive remote training and collaboration. The technology was designed to effectively emulate a physical classroom or workshop without the need for the trainers and trainees being physically in the same space.

The use case was created to fill the gap for virtual practical training courses. This is particularly pertinent in current times due to the COVID-19 pandemic and sustainability drivers as outlined above. Additionally, this demonstrator can create a work package which has wider implementations in the manufacturing industry for more immersive demonstrations remotely in a variety of scenarios.

One opportunity from a working AR demonstrator is the ability to cascade the digitalisation methodology into other similar courses within the composite manufacturing industry. However, there is also the possibly of applying this more widely within the manufacturing sector as well as outside, as there are various practical courses which could benefit. Example applications may include repairing scenarios, overhauls, and maintenance work.

The potential benefits for companies of all sizes across the UK because of this are numerous. These include:

- Drastic reduction in costs for supplementary activities such as travel, accommodation, and transport.
- Sizeable decrease in emissions as a result of training activities.
- Overall improvements in workforce ability and skill due to more effective training.

39.2 Purpose of 5G in AR Assisted Training

To create a comprehensive virtual training experience and achieve an equivalent knowledge transfer as with traditional courses, the network and any associated internet connection must have sufficient bandwidth to service network traffic created as result of running an on-line experience.

5G has the potential to realise this without the need for a wired connection as its radio performance, capacity and flexibility capabilities are significantly enhanced from its predecessor, 4G.

The use case has several specific requirements for the network connection.

- Achieve a high average data throughput speed so the video and audio quality in the two-way communication between trainer and trainee is not limited and end user service quality is good.
- Provide sufficient bandwidth to enable the two-way communication function on multiple devices.
- Ensure latency does not impact the overall quality of the two-way communication and knowledge transfer from trainer to trainee.

With average speeds theorised to be at least an order of magnitude greater than 4G LTE, 5G shows a significant improvement. Further, the use of higher frequency bands that have been less widely used thus far allows 5G to drastically increase its available bandwidth. As a result, the number of additional devices that can be connected is theoretically much larger. Finally, depending on the location, usage, and maturity of the 5G network, the latency theoretically predicted ranges from below 2ms to 10ms. This is a sizeable difference to the average results of around 20-40ms from 4G LTE, though this can go up to 200ms.

Therefore, it is possible to see that 5G offers significant improvements in all three parameters from the previous generation network and those are the biggest justifications for its use in this work package.

39.3 Use case overview and architecture

The conventional 'Introduction to Pre-preg' practical training course involves the manual lay-up of a simple part in the form of a frustum using pre-impregnated (pre-preg) composite materials and a foam core material.

Trainees have the chance to try the process for themselves following several live demonstrations by the trainer that outline the key steps and skills necessary to complete the process successfully. This provides the trainees with more manageable tasks to follow. The process, itself, includes details about working with the different materials and using specific tools, alongside theoretical explanations from the trainer which make the visual and auditory cues crucial to learning.

The suggested AR training course provides an effective individual guide program for each trainee to use and progress through the method to be executed at their own pace. This package aims to be stand-alone and have all the necessary information for the practical course within it. Delivery is in the form of on-screen three-dimensional (3D) graphics, text instructions and tutorial videos.

The additional 3D graphics are added as an overlay on top of the physical environment to enable visualisation of the respective instructional information for each step. Where needed, the tutorial videos provide further support for the trainees by enabling each trainee to replay their instance of the video to improve their knowledge of the process.
Additional functionality also allows for the collaborative training aspect through real time two-way communication, to an instructor offering extra support to trainees and an enhancement of the learning experience. This function is called 'Expert Helper' and is a live video and audio call where the trainee can show and discuss over any issues with the trainer using the camera on their connected mobile device.

Figure 1 below shows the fundamental architecture of the proposed AR solution. The 'Expert Helper' function is driven from the NCC Headquarters (HQ), while the trainees are based in a remote location with the required hardware.

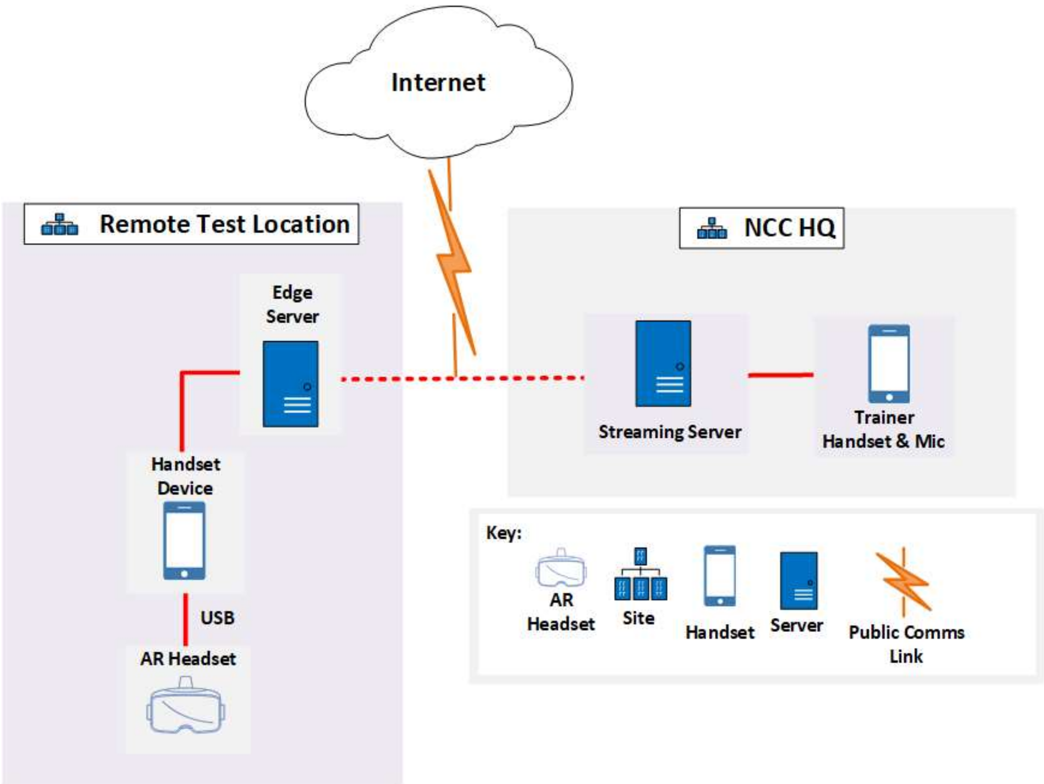


Figure 36 – Fundamental use case architecture

As outlined earlier, in Section 1.2, the 'Expert Helper' feature is heavily reliant on the 5G network, to maintain the required quality throughout the course duration.

To satisfy all the recognised requirements and overcome any digitisation challenges, MatiVision, an immersive technologies expert company were consulted for support in this use case. Based on their experience, it was possible to steadily produce different concepts that would enhance the course content. From the initial discussions, plans were made to create the necessary 3D graphics and demonstration videos alongside the supporting NCC staff. MatiVision could then begin work on the 'Expert Helper' streaming platform.

39.4 Use case and network metrics

To quantify and recognise whether the objectives have been met, two use case sub-categories have been introduced:

1. Use case monitoring
2. Network monitoring

The first sub-category covers the user experience of the AR course and is measured through user feedback. The main points are whether the user would be happy to use this style of training over conventional on-site practical training and based on a one-to-five grading, rank the experience.

The second sub-category measures the network performance using a selection of metrics collected from the radio network.

Tables 1 and 2 below define all the measurable quantities for the use case and the test bed, respectively. These are taken from the 'Benefits Realisation' document which contains all requirements defined by the project partners and sponsors during the project inception.

Table 6 – Use case monitoring measurable quantities

Use case metric	Target audience	Measurement type	Unit of measurement
Would use alternative AR course instead of on-site course	Uptake by NCC (and industrial partners)	Feedback from survey after course	Yes / No
Would use alternative AR course instead of on-site course	Uptake by academic institutions	Feedback from survey after course	Yes / No
Quality of guided instructions	All	Feedback from survey after course	1 – 5 Grading* (1 = Extremely dissatisfied, 5 = Extremely satisfied)

* Note – need to score 4 or above to class as a high score.

Table 7 – Testbed monitoring measurable quantities

Network metric	Counter	Description	Units
Server to user bandwidth	Total downlink IP throughput	Total downlink throughput (all users)	Kilobits per second
Server to user bandwidth	Total downlink IP throughput	Total downlink throughput (each user)	Kilobits per second
Latency tolerance	E-RAB level IP latency in downlink	Mean IP latency in downlink at the E-RAB level	Milliseconds
Jitter tolerance	NTP mean jitter	Mean value of the jitter estimator between AP and NTP servers averaged over granularity period	Milliseconds
Packet loss tolerance	Downlink PDCP SDU air-interface loss rate	Fraction of IP packets (PDCP SDUs) which are lost on downlink interface	Percentage
Packet drop – downlink	Downlink PDCP SDU drop rate	Fraction of IP packets which are dropped on the downlink	Percentage
Packet drop – uplink	Uplink PDCP SDU drop rate	Fraction of IP packets which are dropped on the uplink	Percentage

39.5 System Requirements Development

As described in Section 1.3, the proposed solution is aiming at providing a comprehensive practical course remotely which has thus far been a great difficulty. This has been the case because of the issues of capturing the required level of detail without having the trainers on-site presenting the course and answering any questions.

However, with the latest advancements in AR hardware and supporting software solutions, the first difficulty has been alleviated as the AR glasses can be pre-programmed with all required information and 3D graphics.

The ever-growing interest in video games, which use the same software approach, has resulted in more accessible and affordable solutions usable for training and assistance use cases in the manufacturing industry.

As the technology is still in an early growth phase there are several AR glasses available on the market in quite a wide price range. The Nreal glasses picked and used for this work package are a sensible compromise between quality, functionality, and cost. Additionally, these are one of very few other alternatives which can be directly connected to a 5G network.

This is possible because the Nreal glasses are not standalone but require an additional piece of hardware to provide power and network connectivity, and store and run the course application. This hardware is also necessary to enable the 'Expert Helper' functionality which would otherwise not work with the Nreal glasses central processing unit (CPU). As such, a mobile device could be chosen with the specific CPU and network connectivity capability integrated to enable all the functionality and 5G connection.

As there is a live stream element in the 'Expert Helper' functionality, the system relies on peer-to-peer (P2P) streaming to keep the latency down to a minimum. This means that the server is only used to relay messaging and the actual streaming takes place between the devices themselves. This keeps the hosting requirements to a minimum.

39.5.1 Project Methodology

To gauge the performance improvements of a 5G network and understand the capabilities of an already proven and tested network, the use case testing was split into two testing phases:

- Phase 1 – implement a 4G LTE network architecture to capture baseline data of the performance of the setup.
- Phase 2 – implement a 5G network architecture to test the capabilities of the newer technology and make an analysis of performance when compared with the 4G technology.

The Phase 1 results and discussions were presented in an earlier report but will be briefly summarised within this report for completeness and ease of reference.

Sections 2.4.1 and 2.4.2 describe the approach for delivering each phase of the use case.
Sections 2.5.1 and 2.5.2 detail the relevant phase results and discussion.
Sections 3.1.2 and 3.1.3 document previous 4G network testing results and outcomes.
Sections 3.1.5 and 3.1.6 present 5G network testing results and outcomes.

40 USE CASE DEVELOPMENT AND INVESTIGATION

40.1 Use Case Architecture

The system setup of the use case was split across two locations:

1. The main NCC Headquarters (HQ)
2. A remote test location

The equipment and connections within the NCC HQ side did not change through both phases 1 and 2. The equipment only included a control mobile device for the trainer running the 'Expert Helper' function on which they can view the trainee video capture and communicate accordingly. This was connected wirelessly to a 4G small cell in phase 1 and a 5G small cell in phase 2.

The video and audio capture from the trainer's mobile device was transmitted to a streaming server via a wired network connection. The streaming server managed the feed and transmitted it to a caching server which received it in a one-to-one relationship and managed the necessary connection requests. The main differences between the two testing phases related to the remote test location side of the setup and will be described in further detail in Sections 2.1.1 and 2.1.2.

40.1.1 Phase 1 – 4G LTE Architecture

Phase 1 – 4G LTE trials used two sites: NCC HQ and a remote test location at NCC, Filton called NCCi. NCCi is located around 5 miles away from NCC HQ. The specific hardware used for the trials at NCCi included two pairs of Nreal AR glasses connected to two mobile handset devices through USB and a separate master control device. A 4G small cell provided the 4G connection and transmitted video and audio data from the caching server to the mobile handset devices and a master control device. Figure 2 below combines and visually summarises the architecture described in Section 2.1 and 2.1.1.

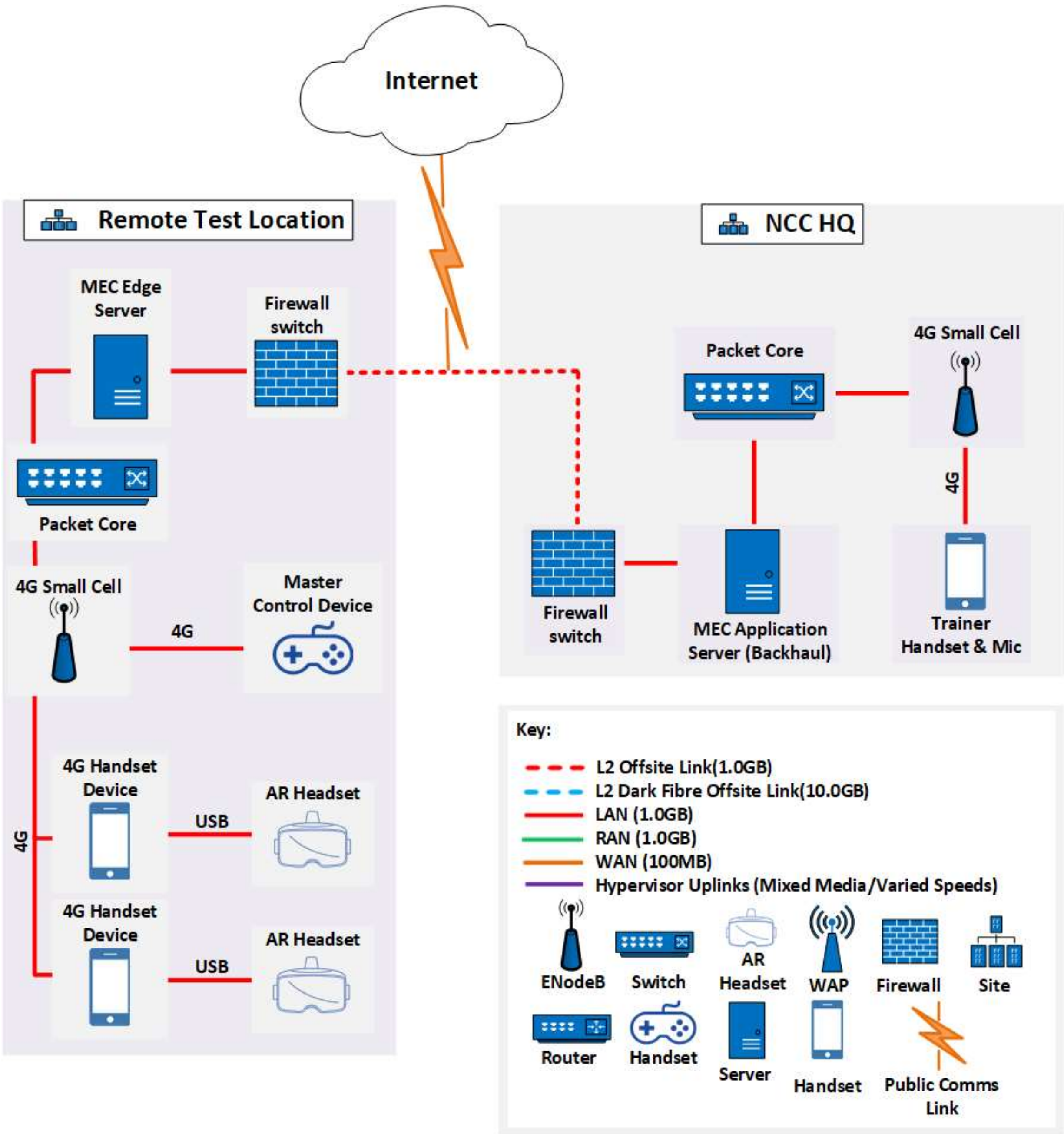


Figure 37 – Phase 1 - 4G LTE trials architecture map

40.1.2 Phase 2 – 5G Architecture

Phase 2 – 5G trials used NCC HQ and a remote location in Millennium Square, Bristol. Millennium Square is located approximately 8 miles from the NCC HQ. The hardware necessary for the trial was increased to five pairs of Nreal AR headsets connected to five mobile handset devices through USB and a separate master control device. The handsets powering the AR glasses were connected to a customer equipment device (CPE) over Wi-Fi while the CPE was linked to a 5G small cell over a Nokia 5G connection. Figure 3 below combines and visually summarises the architecture described in Sections 2.1 and 2.1.2.

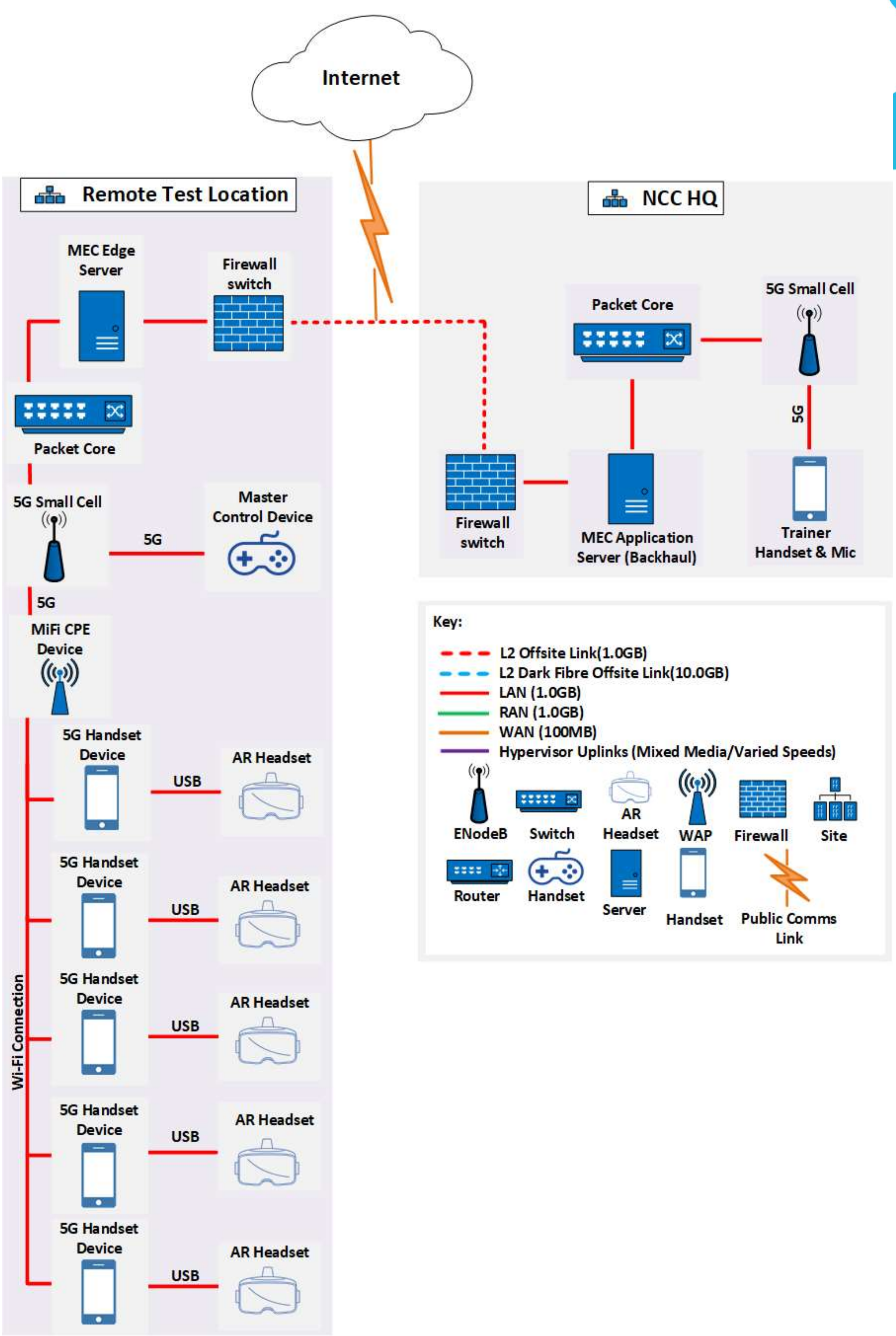


Figure 38 – Phase 2 - 5G trials architecture map

40.2 Use Case and Network Benefits

With a successful outcome from the project the use cases will prove that there are significant benefits for similarly positioned work packages using AR technology and a 5G network.

40.2.1 Use Case Benefits

Being able to effectively digitise practical training courses unlocks similar use cases spanning a variety of industry sectors not limited to manufacturing.

This will be significant in the development of remote working packages and will improve the training outreach throughout the UK. A functional AR solution will reduce the need for travel, accommodation, and transport of equipment to and from provider and customer sites. This will be crucial in decreasing the overall financial as well as environmental costs associated with these services. As a result, the products will experience long-term cost reductions that will make them more affordable to small and medium-sized enterprises (SME).

As mentioned above an effective remote working solution such as this one will contribute to the overall environmental sustainability goal of enterprises such as the NCC by using less energy in a more efficient capacity. This will lead to a sizeable carbon footprint reduction that will be a further contributing factor. In time these benefits will be able to cascade down into the wider manufacturing and advanced engineering fields and have a greater effect on the UK net zero strategy overall.

The use case can also have social sustainability benefits as well. A matured solution has the potential of improving the training experience and knowledge transfer to the trainees and thus producing a more skilful workforce.

Further, in terms of specific benefits relating to composite manufacturing, the AR solution can enable quality assurance to be included all the way through the laminating process. The technology provides the capability to verify the steps carried out by the operator against an acceptable standard and ensure quality compliance. This will also result in a reduced scrap rate and a saving in cost and energy consumption.

40.2.2 Network Benefits

Based on the predicted capabilities of a 5G network, the use case can specifically benefit from the lower latency, the higher bandwidth, and faster average speeds.

The shorter latency of 5G allows for real-time communication with the trainer which can improve the trainee experience and understanding. The lower latency can also improve the capabilities of time sensitive signals such as those in precision machine control applications. This is pertinent in the liquid resin infusion (LRI) use case within the 5G-Encode project and more details can be found regarding this in that final report.

The wider bandwidth available in 5G will enable a much larger amount of data to be transferred from one location to another at any one time by single and multiple devices. As such, larger cohorts of trainees can be accommodated in each course delivery. For other use cases this can aid substantial amounts of data acquisition and transfer from various sensors to a processing unit. This is crucial in the automated pre-forming cell (APC) end effector upgrade use case within the 5G-Encode project and more details can be found regarding this in that final report.

The speed itself will provide better video and audio quality to the 'Expert Helper' function of the AR solution. Additionally, for other use cases it can increase efficiency due to a better productivity overall. This will specifically aid the asset tracking use case within the 5G-Encode project and more details can be found regarding this in that final report.

40.3 Use Case Development

To ensure that the hardware presented throughout Section 2.2 and the ancillary software work effectively for the specific use case, developments had to be made over the project timeline. These were as follows:

- AR glasses audio capability:
  The 'Expert Helper' function as well as the extra tutorial videos in the application require audio capability. Available AR hardware with in-built audio functionality were selected. The Nreal glasses cover this requirement having dual microphones and dual speakers integrated in their frames. No additional hardware, for example, headphones were required. This both reduced costs and complexity of kit setup.

- <u>AR glasses ergonomics:</u>
  The user ergonomics as well as the operational safety while using the AR hardware was particularly important for the use case. The Nreal glasses aided both considerations based on the extra features integrated into the design. A variety of nose pads were available for each user to select based on comfort, and a cable hook allowed for the cable to secure the glasses onto the head of the user. The latter feature both ensured that the glasses would not move or fall off, but also reduced the risk of catching the cable while working on the course.

- <u>Mobile handset CPU:</u>
  The AR application that facilitates the digitised training course required a specific computational power to run properly. As a result, this led the decision on the specification of the mobile handset device that had to used. A Snapdragon 865 CPU was the minimum requirement and the OnePlus 8T device was chosen as a suitable compromise between robustness, quality, and cost.

- <u>Mobile handset 5G capabilities:</u>
  Additionally, the mobile handsets were chosen for their 5G capabilities. These enabled the phones to function over the N77 and N78 5G bands which would be used in the Phase 2 trials and thereafter.

- <u>'Expert Helper' streaming capability:</u>
  A bespoke server application was created to initiate the P2P streaming functionality. This server-side application allows two remote devices to relay messages with each other without knowing the network topology beforehand. The application can also be used to relay the expert helper stream in case the devices cannot open a P2P channel between them.

- <u>Training course program:</u>
  A custom real-time application was created to fulfil the requirements for the practical 'Introduction to Pre-preg' training course. Each step was carefully created as a real-time 3D graphics step. Each object, placement, tools to be used, all were created in 3D so the user can have an exact view of the objects and an overview on how to use them for each step.

- Ancillary equipment:

  A specific environment needs to be maintained while working with pre-preg composite materials. This ensures the workstation is clean, free of all debris or contaminants and the user can safely use all the equipment and constituents. As such, additional belts and phone cases with clips had to be procured, to allow for the phones to be used from an easy to access yet safe place.

- Additional footage and graphics:

  A key consideration of the project was to provide a comprehensive training experience which is easy to understand and follow by users from various knowledge backgrounds. Multiple types of instructions, tips and information were created within the course to provide multiple learning channels for trainees with differing skill levels. These sources included offline tutorial videos performed by the trainers and supplementary documentation and drawings in the form of on-screen graphics.

- Course trainer setup:

  For the use case proof of concept stage, it was found that a single trainer available for the 'Expert Helper' function was sufficient. This may have to be reconsidered should the trainee cohorts be larger, and the support need increased e.g., for more complicated processes in training deliveries.

40.4 Use Case Testing

In both Phase 1 and Phase 2 the testing programme was the same. Workstations were setup for the users with the necessary composite material and consumables kit, all specific tools, and the AR hardware. The number of users and their location changed from Phase 1 to Phase 2. Phase 1 users were based on the 4G network capabilities, while the Phase 2 was based on revised network capabilities and latest COVID guidelines. Further details and the results of the trials are presented in the following sections.

40.4.1 Phase 1 – 4G LTE

As described in Section 2.2.1 the Phase 1 trials were carried out within the available NCC premises between the HQ and the NCCi site at Filton. The trainee workstations for the course demonstration at NCCi are shown below in Figure 4.

Figure 39 – Phase 1 trainee workstations setup for course demonstration

During the Phase 1 tests the mobile handset devices USB tethered to the AR glasses were connected to 4G LTE using SIM cards. To be able to link the users to the 'Expert Helper' function, the trainer's mobile device was connected to the same 4G network. Figure 5 below shows the trainer workstation at the NCC HQ working on the 'Expert Helper'.

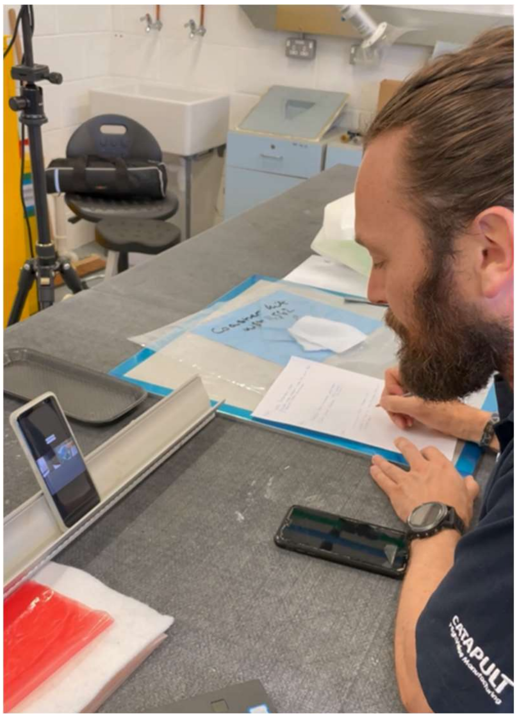


Figure 40 – Phase 1 trainer working on 'Expert Helper'

The trainer was able to observe all the video feeds streamed from the trainees and offer help accordingly. Figure 6 below shows that view, however 'NCC' text boxes have been added in places where IP needs to be protected.

Figure 41 – Phase 1 ‘Expert Helper’ screen view

The graphics viewed by the trainees within the augmented reality included ply placement indications alongside the text instructions. This aided the lay-up process and ensured the part was made correctly. A screenshot of the view with the AR glasses is presented below in Figure 7.

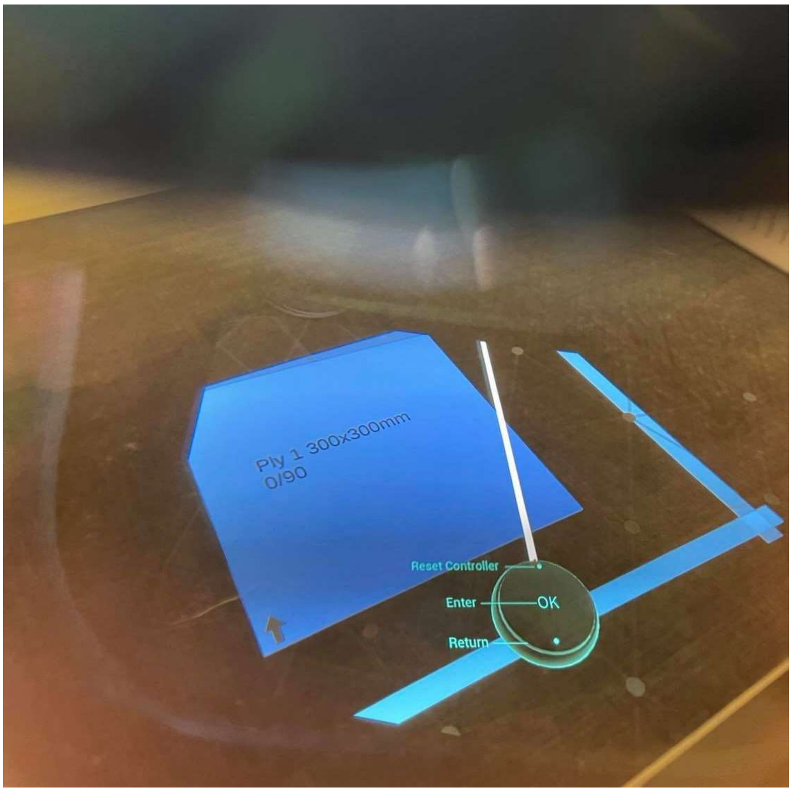


Figure 42 – Screenshot of Phase 1 AR vision system ply indication graphics

As outlined in Section 1.2, user feedback was collected to quantify the use case performance as experienced by the trainees. Figure 8 below presents the results regarding the satisfaction of the trainees with the guided instructions presented in the AR program, while Figure 9 shows how many would use AR instead of on-site training.

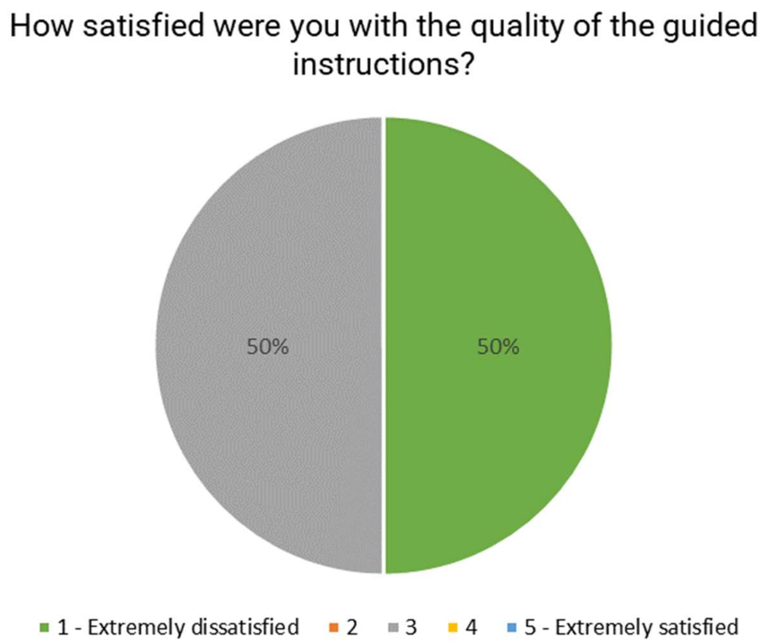


Figure 43 – Phase 1 user feedback regarding satisfaction with guided instructions

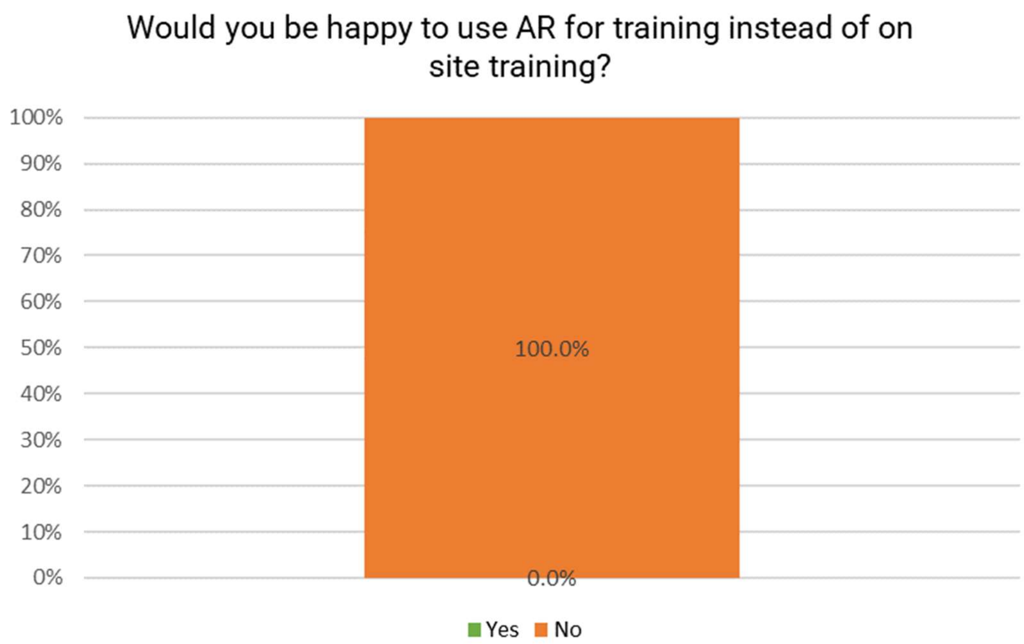


Figure 44 – Phase 1 user feedback regarding the use of AR instead of on-site training

The feedback forms included more questions to aid the understanding and development of the use case. These questions focused on the displayed graphics, 'Expert Helper' performance and knowledge transfer of the technology. The results from these have been included in Appendix A.

40.4.2 Phase 2 – 5G

The Phase 2 trials as outlined in Section 2.2.2 were carried out on Millennium Square in the Bristol City Centre as part of a two-day continuous demonstration made up of four separate user sessions. The number of workstations used simultaneously was increased to five based on bigger hardware capability and larger bandwidth available. However, the specific setup was similar to that used in Phase 1 as it was found to be working as necessary and the kits prepared were satisfactory. The overall setup is shown in Figure 10 below, while Figure 11 shows a different angle of some of the workstations in use.

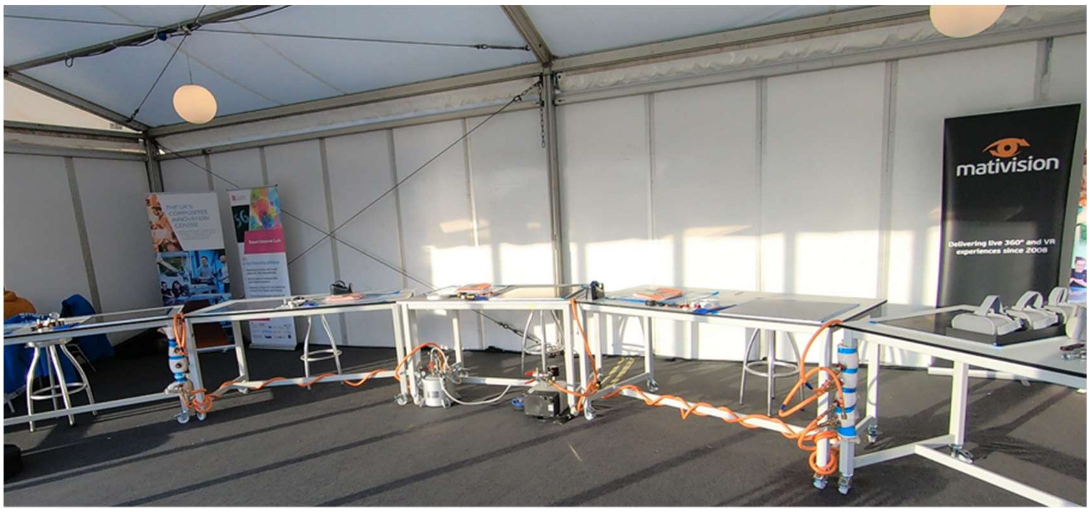


Figure 45 – Phase 2 trial setup on Millennium Square, Bristol

Figure 46 – Phase 2 trial AR workstations in use

For the Phase 2 trial the mobile handsets USB tethered to the AR glasses were connected via Wi-Fi to a CPE device as outlined in Figure 3 which in turn were connected to a small cell through 5G. This was easier to setup and was less likely to run into networking issues when used at the remote location of the tests.

The ‘Expert Helper’ capability was implemented from the NCC HQ in a similar fashion to the Phase 1 trial. The trainer was able to review the live stream of the trainee seeking assistance and give advice using the two-way communication. Figures 12 and 13 below show the ‘Expert Helper’ workstation and the view of the trainer on their mobile handset device, respectively.

Figure 47 – Phase 2 ‘Expert Helper’ workstation

Figure 48 – Phase 2 ‘Expert Helper’ view on mobile handset device

From Phase 1, additional graphics were added to the AR guide program as well as re-worked text instructions to better capture the course content. Captured photos from within the AR glasses in Phase 2 can be seen in Figure 14 below.

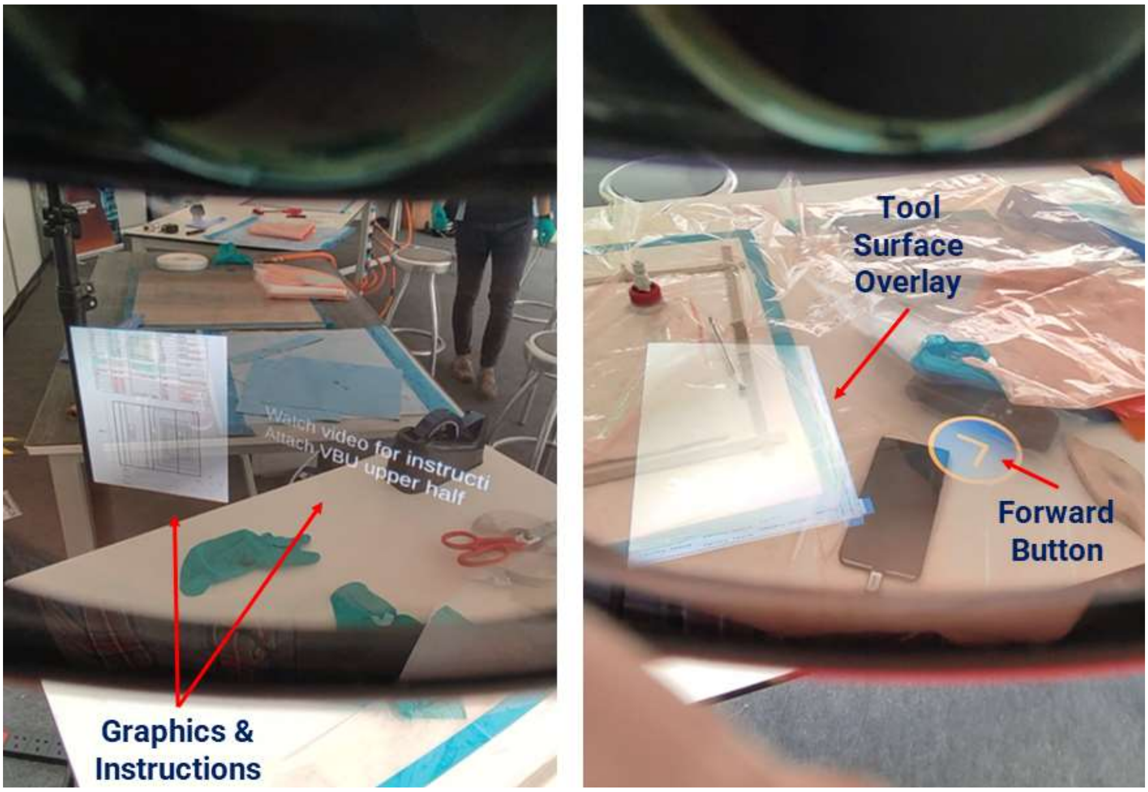


Figure 49 – Phase 2 AR glasses views: graphics and instructions (left), tool surface and navigation button (right)

Similar to Phase 1, user feedback was collected from all the AR sessions within the Phase 2 demonstrations and at least 20 sets were collected which resulted in a more comprehensive view of the experience. Figure 15 shows the latest results on the satisfaction of the users with the AR guided instructions, while Figure 16 presents the percentage of users who would use AR over on-site training.

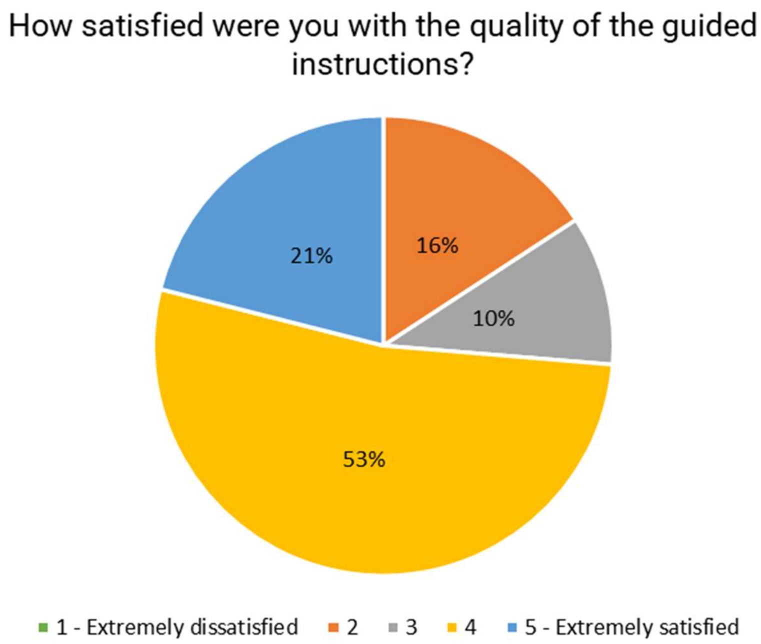


Figure 50 – Phase 2 user feedback regarding satisfaction with guided instructions

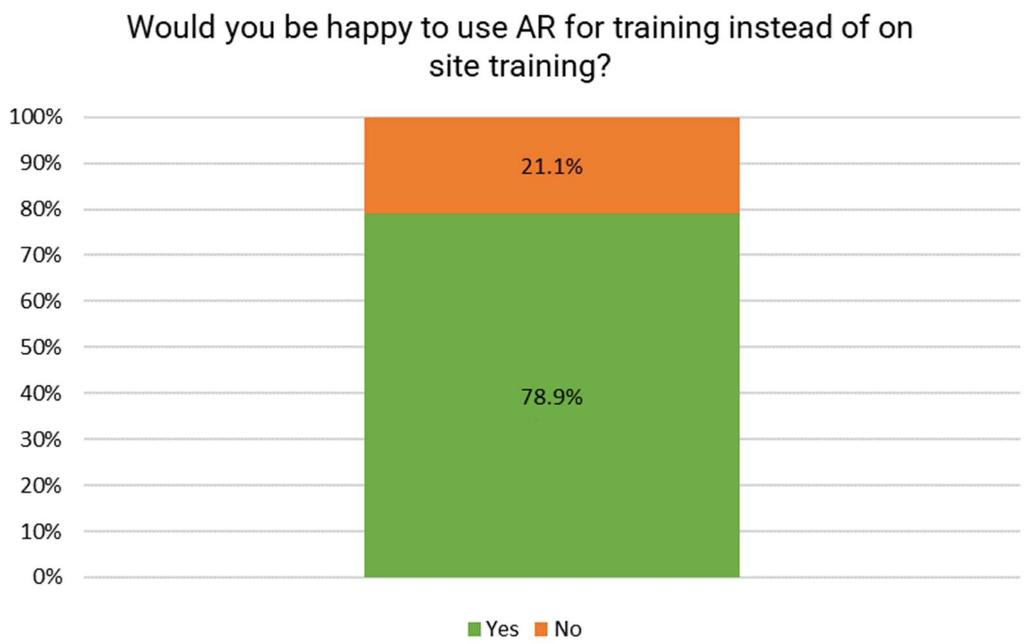


Figure 51 – Phase 2 user feedback regarding the use of AR instead of on-site training

Further user feedback from the Phase 2 VR trials has been presented in Appendix B.

40.5 Use Case Discussion

40.5.1 Phase 1 – 4G LTE

From the results of the user feedback presented in Figures 8 and 9 as well as the additional figures in Appendix A it was clear that the experience in the 4G trials was not of a satisfactory level. The data shows that the users were not convinced that the technology could be applied in a real-life scenario in its current format. However, the trial allowed for the use case to be run in its entirety to users not involved to the program development. This was crucial at that stage of the project to highlight key parts which worked well and those that needed improvement. Also, the trial allowed for the baseline 4G network metrics to be gathered which were important for the overall aims of the project.

The poor outcome of the trial could be explained by the relatively low development of specific digital content that went into the course. This showed that more effort was required in modifying the content to better suit a virtual presentation rather than simply re-using the existing conventional information. This was key to the future improvements made in the use case to enhance the user experience in the Phase 2 trial.

Phase 1 did allow for all the capability to be tested, and in particular the 'Expert Helper' functionality. This was seen to be working well with qualitative and quantitative feedback from the users showing that the communication with the trainer was good and latency was low enough for real time conversations.

40.5.2 Phase 2 – 5G

The results of the user feedback data in Figures 14 and 15 showed promising improvements in the AR experience. 74% of all users were left very satisfied with the guided instructions presented. Approximately 79% expressed interest in using the technology instead of a conventional on-site training course. As per the project objectives, data was recorded separately for this statistic depending on uptake – i.e., industrial, or academic. This total percentage was made up of 80% positive response from the industrial users and just under 78% from the users with an academic background.

From the additional feedback in Appendix B, over 75% of users were satisfied with the 'Expert Helper' function and its latency which enhanced the experience overall. Additional confirmation of this were the physical outcomes of the manual lay-up with a sizeable portion of users able to progress efficiently through the course after following the instructions and some using 'Expert Helper.' Finally, 14 of the users identified the technology as immersive and captivating which is extremely hopeful and clearly works towards reaching the main objective for the use case.

Nevertheless, even with these optimistic findings, the demonstration was extremely useful in highlighting several limitations or points for future work.

One limitation was the connecting cable between the AR glasses and mobile device. This caused discomfort when carrying out the manual lay-up steps as the users had to be careful with knocking the phone off the workstation or risk of disconnection.
Unfortunately, the Nreal glasses do not have further capability which allows for Bluetooth connections. Additionally, there were difficulties experienced by some users with operating the augmented reality glasses and software.

The technology is new and requires some time to get used to it, but this can be facilitated by having an AR tutorial section at the beginning of the course in the future. The location of the trial had high natural light exposure which degraded the AR overlays and graphics effects. This showed the limitation of the technology in very bright and reflective locations.

For the AR program there are some improvements to consider for the overall layout of the content in the field of view. Specifically:

- The navigation buttons should be re-positioned and re-worked to include a highlight when in use.
- The sizing and position of the 'Expert Helper' portion on-screen could be optimised to allow for an easier use and improve visibility from both trainer and trainee. A setup more similar to a video phone call in terms of size of the outgoing and incoming video window would suit better.
- The content of the course itself needs to be refined and further considerations made into its digitisation.

There are outstanding challenges which would benefit the application and use case in the future, these include:

- Addition of quality control features or instructions within the AR guide. There are methods that can be added to aid the user ensure the part being made is up to an acceptable standard. These need to be studied and digitised. However, at the maturity level of the technology at the time of the outlined trials it was decided the priority for this will be lower and its consideration delayed.
- Development of composite manufacturing specific content and in particular tutorial videos that aid complex process steps. This has the potential to be integrated into the server enabling the 'Expert Helper' function which will allow for videos and other media to be streamed directly to the AR hardware.
- Enable 'Expert Helper' to be able to view from the camera on the AR glasses rather than using the mobile handset.
- Introduce the 360° camera from the 360° video streaming VR use case in the trainee area to allow the trainers back in NCC HQ to view the progress of the course. This would also enable further aid to be given to struggling trainees and improve the experience.

40.6 Use Case Conclusions

The use case development outlined within this report shows progress in terms of the performance of the package and the experience achieved for the users. It is recommended that this progress be considered alongside the progress made in the Virtual Reality (VR) use case. A summary of this is included in Appendix C. As a result, the objective of producing an immersive and comprehensive practical training course in augmented reality can be considered completed at this stage. However, the set of trials carried out thus far have identified improvements that can further enhance AR and course delivery.

From the results presented in Sections 2.4.1 and 2.4.2 it is possible to draw several conclusions:

1. The use case proved viability for a sizeable group of users to competently progress through the practical training course remotely.
2. The immersive experience demonstrated the feasibility of transferring knowledge to trainees efficiently. This was supported in the user feedback regarding the use of AR courses instead of conventional ones. However, this is quite heavily based on the quality of the instructional content and the 'Expert Helper.'

3. Correlating this feedback with that of the 360° video streaming VR use case shows that there is a need for further development to be made before the same level of acceptance is reached.
4. Improvement tasks have already been identified methodically based on qualitative feedback from the users, the NCC trainers and the development teams.

The ‘Expert Helper’ feature was found to work well in both trials and did not show any improvement when the network changed from 4G to 5G. The quality of the communication was approximately similar in both trials which meant a substantial improvement from greater bandwidth or speeds could not be clearly observed.
The trials were inconclusive in terms of the number of trainees able to connect to the feature using a 4G network and whether this figure can be improved with 5G.

Lastly, there were usability difficulties with the technology which could be related to the technological background of the trainees. Differences in proficiency could also be observed based on age. However, all of these can be alleviated with additional consideration into the introduction of the AR kit and application to the trainees. As stated earlier, developments are planned in this area and usability should improve in the future.

41 5G INDUSTRIAL ASSESSMENT

41.1 4G LTE and 5G Network Testing

As described earlier, to make a reasonable comparison between 5G and existing network technologies, a trial was conducted using a 4G LTE network which acted as the experimental baseline. The use case testing was also fundamentally the same which ensured that the improvements from one trial to another could be identified.

Apart from the developments within the use case scenario itself, data was also recorded from all trials to quantify the network performance, as outlined in the following sections.

41.1.1 4G LTE Test Setup

The 4G LTE system setup was outlined in Section 2.1.1. However, one specific consideration that was necessary during the baseline testing was surrounding the other work packages within the 5G-Encode program. To gauge the AR network usage and not hinder the use case performance the trial was carried out independently from other use cases. This ensured that the available bandwidth was maximised and would enable the best possible presentation for the experience.

41.1.2 4G LTE Network Metrics

Network performance was reviewed during the AR Phase 1 trial. The AR demonstration was conducted between 14:00 and 16:00. The ip.access 4G RAN network was configured to accumulate metrics for 60 mins, sending a log to the log server at every hour. This logging characteristic is reflected in the charts presented in this section.

Figure 17 below displays the 'Total Uplink IP Throughput', and this measurement provides the total uplink throughput in kilobits per second (kbps). The uplink throughput in kbps was calculated by dividing the count of the total volume of uplink data received in kbits, by the time taken to receive the data in seconds. The maximum achieved uplink throughput and target ranges for this measurand are displayed in Table 3 below.

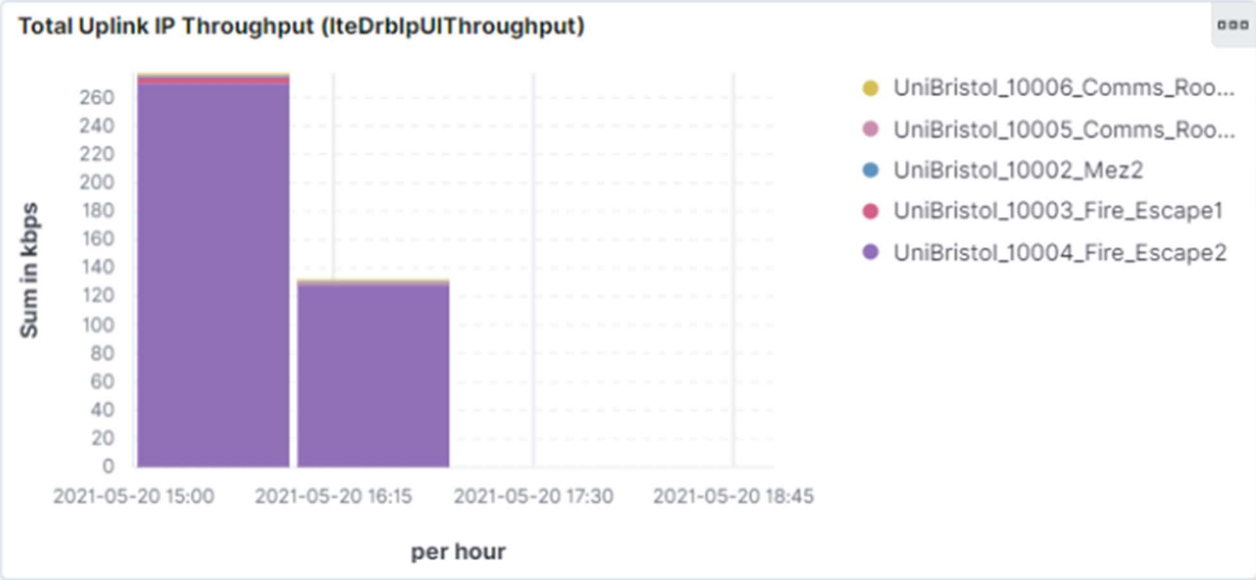


Figure 52 – Phase 1 total uplink IP throughput

Table 8 – Total uplink IP throughput targets

	Maximum Recorded (kbps)	Phase 1 Target (kbps)	Phase 2 Target (kbps)
Total Uplink IP Throughput	~260	1,000 - 10,000	10, 000 - 100,000

Figure 18 displays the 'Total Downlink IP Throughput', i.e., the total downlink throughput in kbps. The downlink throughput in kbps was calculated by dividing the count of the total volume of downlink data received in kbits, by the time taken to receive the data in seconds. The maximum achieved downlink throughput and target ranges for this measurand are displayed in Table 4 below.

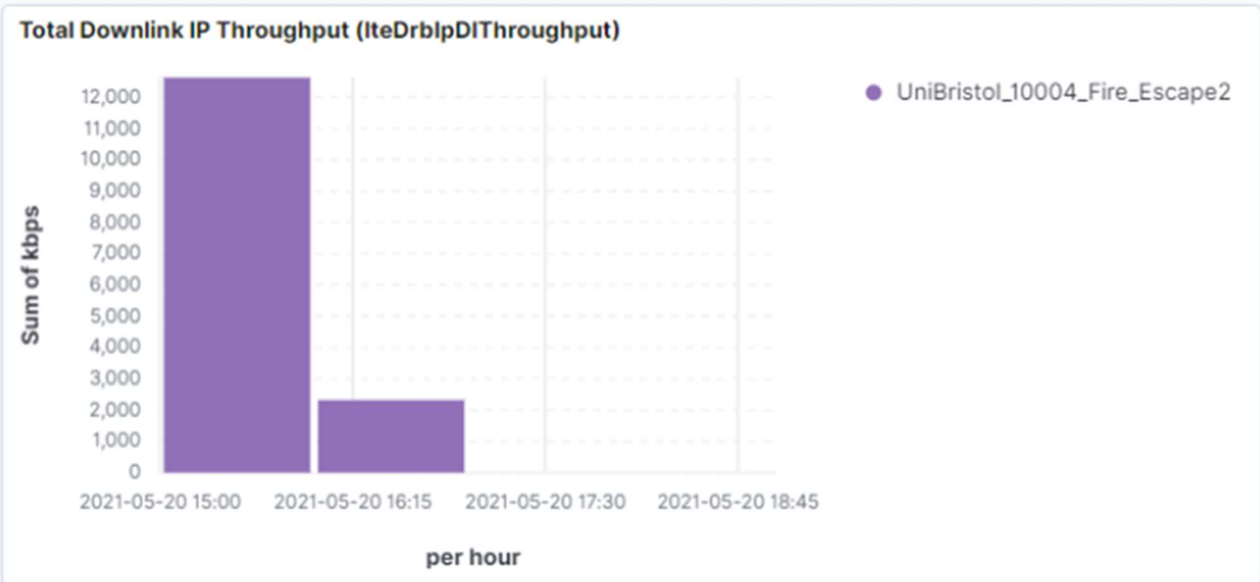


Figure 53 – Phase 1 total downlink IP throughput

Table 9 – Total downlink IP throughput targets

	Total data throughput recorded between 15:00 and 16:00 (kbps)	Phase 1 Target (kbps)	Phase 2 Target (kbps)
Total Downlink IP Throughput	~12,000	>= 4, 000	>= 20, 000

Figure 19 shows the measure of IP latency in the downlink for each radio unit passing data to support the use case. Latency between devices communicating over the network was on average 8ms. In the benefits realisation specification, the measured latency is significantly less than the stated value.

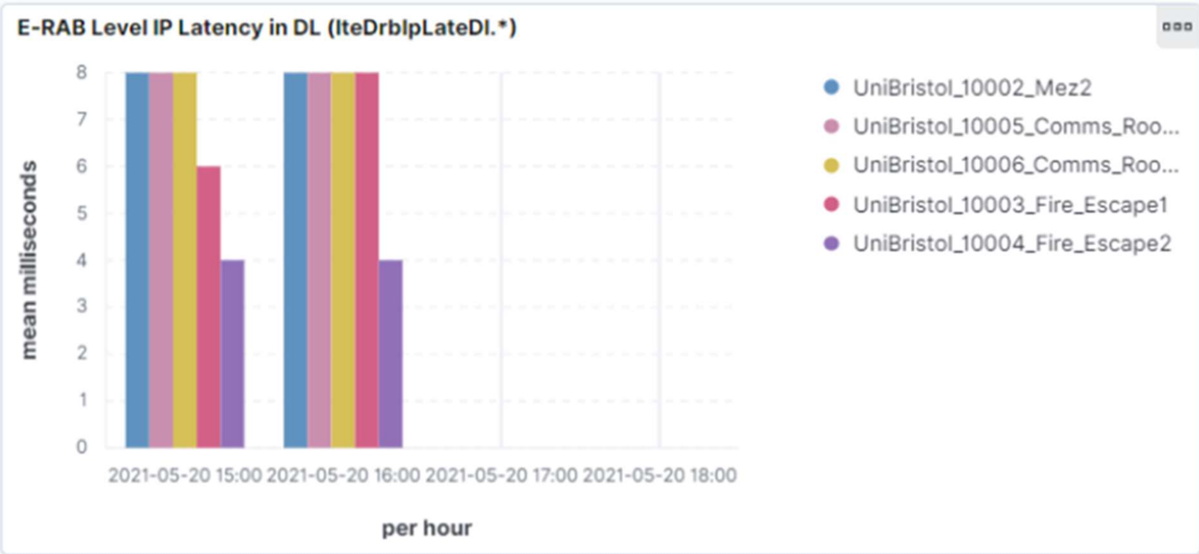


Figure 54 – Phase 1 IP latency downlink

Figure 20 shows mean packet jitter experienced during the use case Phase 1 test. In the benefits realisation specification packet jitter is specified in milliseconds, this relates to measurements possible in a wired network. Referring to Section 2.4.1 in the 4G/5G Network Performance Evaluation Guideline, packet loss and jitter are defined with the following statement:

"The main factors that cause packet loss and jitter are signal quality over the air interface, eNodeB load, and packet loss or jitter on the transport network. Poor air-interface signal quality may increase the packet error rate, which results in more packet retransmissions and segmentation. As a result, the number of lost packets and jitters increases."

Thus, the metric generated was measured in mean packet jitter not milliseconds as documented in the benefits realisation guide.

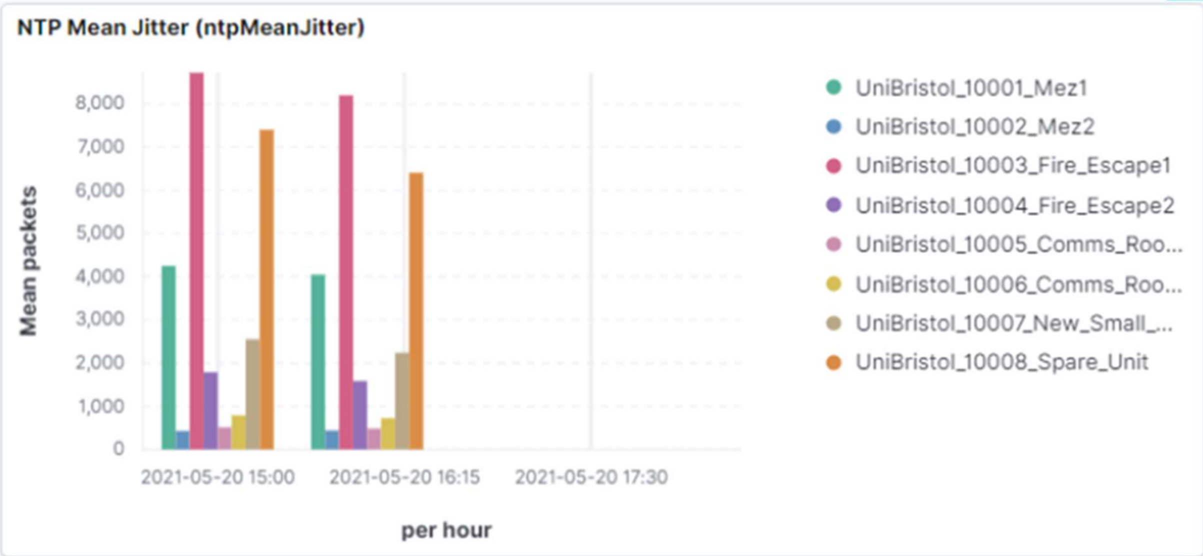


Figure 55 – Phase 1 NTP mean jitter

41.1.3 4G LTE Outcomes/Shortfalls

The maximum 'Total Uplink IP Throughput' recorded was approximately 26% of the lower bound of the target value (Actual ~ 260 kbps, Target = 1,000 to 10,000 kbps). During the AR trial, three devices uplinked video stream as part of the trial. Data suggests that more devices will be required to reach the target uplink throughput.

The maximum 'Total Downlink IP Throughput' recorded a 200% increase on the target value for the initial phase (Actual ~ 12,000 kbps, Target = 4, 000 kbps). Data suggests that three devices downloading the video stream were sufficient to evidence fulfilment of network downlink requirement.

The mean 'IP packet latency downlink' was recorded in milliseconds and was 96% lower than the target value for the initial phase (Actual ~ 8ms, Target = 200ms). This measurement was taken with no other traffic on the 4G radio network.

The mean 'NTP Mean Jitter' was recorded in packets and does not match the target value specified in milliseconds for the initial phase. This measurement was taken with no other traffic on the 4G radio network.

41.1.4 5G Test Setup

While 5G is already known to provide much higher throughput performance and lower latency compared to 4G LTE, it also provides the required network and data isolation by deploying network slicing as a standard (3GPP Rel.15/16). By doing so, the data arriving at the end-destination of the Independent (Public) networks can be effectively controlled and monitored, along with the network resources and equipment which can also be managed/orchestrated accordingly.

Based on the latency requirements of a use-case, the 5G Core and edge compute capability allow the user data plane (UPF) and application services (VMs, servers, applications, etc.) to run locally at the edge (closer to the end-users), significantly reducing the latency while minimising the backhaul requirements. The high throughput on the downlink (DL) along with the very low latency enable the provision of VR and AR services while also providing a large degree of freedom in terms of video quality and number of connected users.

When analysing network metrics consideration was required for the differing technologies, vendor implementation statistics and in the case of 5G, vendor software maturity to support statistics.

An example of a technical difference is the clocking used in 4G which is Network Timing Protocol (NTP) based and 5G which is Precision Timing Protocol (PTP) based.

For the radio technologies 4G was created using an ip.access solution and 5G created using an Airspan ORAN solution. In 5G statistics there are no measures in place to directly measure PTP, this impacts the capability to monitor, view and report on timing related latency and jitter.

The 5G-ENCODE network architecture between the Private Network (NCC), and the Satellite (NCCI) and Independent (UoB) networks for the VR/AR demonstration is shown in Figure 21 below. From a cellular network perspective, the independent network hosted by the UoB 5GUK test network, represents the public network and acts as an extension of a private network, i.e., NCC network.

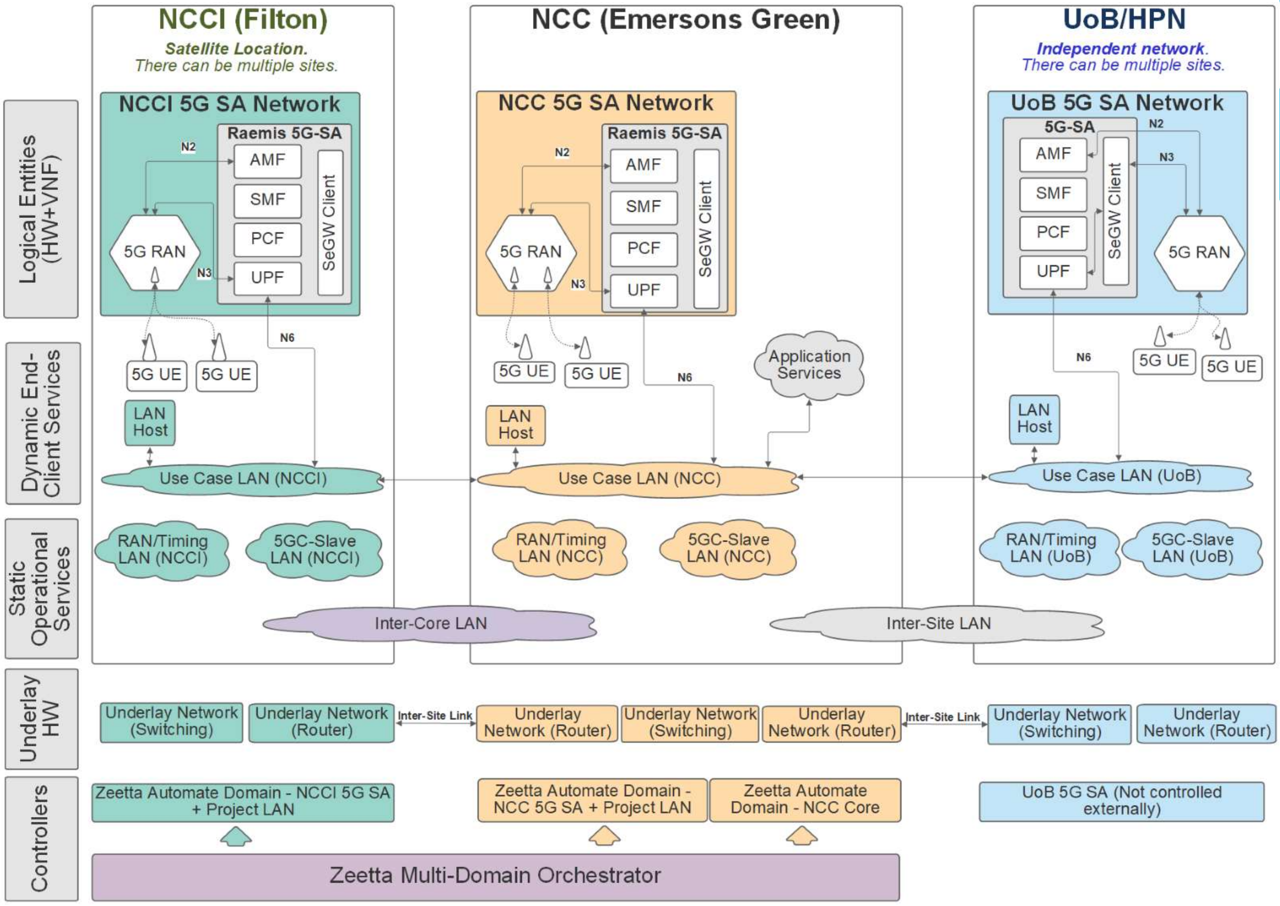


Figure 56 – 5G Encode network architecture

41.1.5 5G Network Metrics

Network performance metrics were collected during the final AR and VR demonstrations at Millennium Square and are shown in Table 5 below as KPIs (Key Performance Indexes). The network requirements for the AR demonstration were found to be quite low during the trial. This was based on the one-to-one interactions of the 'Expert Helper' function which were short and at random periods of time throughout the demonstration. As such, a brief test was devised to gather data on the usage where all five devices were connected to the 'Expert Helper' simultaneously.

Table 10 – Phase 2 5G measured network metrics

Measured KPIs	Value	Unit
Server to Users throughput (i.e., Total Cell Throughput) – Total Downlink IP Throughput.	16.1	Mb/s
Server to Users throughput (Individual User Throughput) – App-based DL Throughput on each end-user.	3.22	Mb/s
DL Latency Tolerance – Downlink IP Latency.	3.15	ms
DL Jitter Tolerance – Standard Deviation of the app-based latency.	2.05	ms
% DL Packet Loss Tolerance – Downlink PDCP SDU Air-Interface Percentage Loss Rate.	0.12	%
% DL Packet Drop Rate – Downlink PDCP SDU Percentage Drop Rate.	0.12	%
% UL Packet Drop Rate – Uplink PDCP SDU Percentage Drop Rate.	0	%

These KPIs were derived from a variety of metrics collected from the 5G network (5G Core – open5gs) and the UEs (User Equipment – Android devices/CPEs). The overall network performance was found to be satisfactory in terms of meeting all user service demands and enabling all necessary demonstrator functionality. The AR/VR service provisioning showed no problems or interruptions throughout the demonstration.

The total cell DL throughout was 16.1 Mbps on average, reaching a peak of 31Mbps, as shown in Figure 22 below. It should be noted the supported cell capacity was much greater than the one achieved during the demonstration. The wireless link between the 5G NR (New Radio) and the 5G CPE devices was tested before the demonstration, exceeding 700Mbps in DL. Consequently, the stress on the network during the AR/VR demo was well below its throughput limit. It is worth noting that there was a small packet drop in the DL due to some initial inconsistencies between the 5G CPE and the 5G NR. The number of packets dropped was negligible. No dropped packets were detected on the uplink (UL).

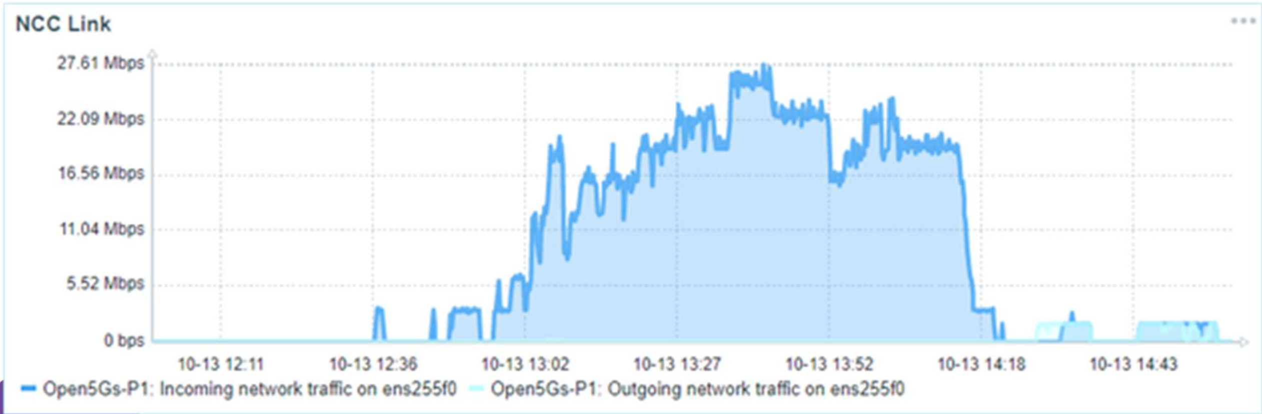


Figure 57 – Phase 2 5G downlink throughput

The average DL latency and jitter between the 5G CPE and the streaming/video server during the AR/VR service provision was measured at 3.22 ms and 2.05 ms, respectively. Hence, the latency performance of the 5GUK Test Network was also satisfactory in terms of end user experience. However, advanced optimization on the 5G network and 5G CPE devices could potentially drop these figures even further.

41.1.6 5G Outcomes/Shortfalls

Although all handsets used with the AR glasses were 5G capable, only 5G NSA operation was enabled on the devices by the manufacturers. This made the 5G SA operation of the 5GUK Test Network incompatible with the tested devices. Thus, CPEs were utilised instead and 5G network connectivity was provided to the end users through Wi-Fi.

Meanwhile, the involvement of an additional hub with a different RAT (Wi-Fi) to forward the packets introduced additional latency and limited the management of the devices which remained hidden from the 5G core behind the Wi-Fi network. Hence, the use case architecture was limited and did not allow the benefits from the 5G network to be fully realised in this demonstration.

Nevertheless, the network requirements of the AR demonstration and the 'Expert Helper' function were quite low. No significant issues were reported during the short periods of usage (typically <5 minutes) at sporadic intervals throughout the course. Furthermore, users made use of the 'Expert Helper' function at random times, avoiding high throughput peaks, thus reducing the network connectivity requirements.

The 5GUK Test network was stable throughout the demonstration and without any issues. During this demonstration one of the three inhouse developed CPEs presented instability with its network connectivity due to a malfunctioning SIM card. However, the 5GUK team was able to resolve the problem and restore the service for the duration of the demonstration.

41.2 5G Discussion

41.2.1 Benefits of 5G

Benefits recorded by the Phase 2 trials based on the 5G connectivity have been outlined throughout the report but in summary:

4. Data capacity due to available bandwidth (exceeding 700Mbps downlink):
    - Ensured good video and audio quality of 'Expert Helper' function for multiple concurrent users.
5. Average speed to each connected device:
    - Ensured good video and audio quality of stream to and from trainer.
6. Low latency (sub 10 milliseconds):
    - Improved trainee experience by decreasing delays between video and audio feeds of 'Expert Helper.'

A 5G network within the industrial setting of the NCC HQ also has the potential to facilitate different course locations. A matured and robust system would allow for the AR training course to be carried out throughout the factory as needed.

41.2.2 Limitations of 5G

Most of the 5G-capable devices currently on the market do not support 5G SA operation (disabled on software level), i.e., operating on a pure 5G cellular network without the anchoring 4G cells. 5G Networks and devices are not yet mature enough to support a fast and easy deployment of AR/VR services. Vendors have been slow to implement and support the basic 5G SA functionality, even to their most recent and flagship devices.

In order to overcome the limited support for 5G SA, the 5GUK engineering team of Smart Internet Lab has developed multiple in-house-built 5G CPE devices. By doing so, 5G SA connectivity could be established and demonstrated between the 5G CPEs and the 5G network, while enabling the provision of 5G services to the AR/VR devices through Wi-Fi 6. These devices are not planned for mass production.

The current inhouse development at Smart Internet Lab is hampered as Wi-Fi services are still pending their integration with the developed CPE devices. The chip-crisis around the world makes it exceedingly difficult and expensive to purchase Wi-Fi 6 Access Point Modules in small numbers (for creation of a Wi-Fi hotspot). Hence, external Wi-Fi 6 Access

Points (APs) were connected to the ethernet ports of the CPEs, and traffic was diverted from 5G, to ethernet, then Wi-Fi.

41.3 5G Conclusions

One main conclusion can be drawn regarding the 5G network based on the user feedback and data collected from the Phase 2 trials. The 5G network setup by the UoB team was sufficient to meet all user service demands during the trial and enable all the AR demonstrator capabilities. The 'Expert Helper' was of a consistent and sufficiently high video and audio quality. There was the scope for multiple users to utilise the two-way communication feature, though it was rare for that need to arise.

However, based on the two trials outlined and compared within this report, it is not possible to conclusively state that there were significant improvements from 5G over 4G LTE. This is because the network requirements of the use case were low and both technologies did not present many issues covering those.

To investigate the full capabilities of 5G in this application, a further trial would be necessary. In this test, devices will have to be continuously added on the 'Expert Helper' until failure of either the server application or the network limit is reached. Though, this occurrence in a real-world course of this use case is unlikely to happen in its current format. Additionally, by having the 360° camera as part of the system which feeds back to the trainers, the 5G element will be utilised further and the network performance tested.

There are further developments that can be made to the AR solution which sees a greater reliance on the mobile network. These developments involve the use of libraries of tips, graphics and tutorial videos on cloud or server storage. For this trial, the videos embedded in the AR application were kept to a minimum with consideration of the internal device storage. However, going forward these can be streamed from a library and as such the capabilities of the network will become much more decisive in the performance of the demonstrator and 5G is likely to be utilised nearer its full potential. This will lead to a more modular solution that lends itself to modification for other applications as well.

Regardless, the metrics recorded suggest that the 5G network has the capability to achieve all network targets set out for the project. The downlink exceeding 700Mbps as well as the 3ms and lower latency values were an impressive display for the technology. Based on further testing and optimisation the 5GUK team are optimistic that further improvements can be made to these.

Though as identified in Section 3.2.2, it is important to note that there are continuous difficulties in setting up a 5G SA network. This can be a considerable drawback to marketing and introducing 5G to the wider market of SMEs in the manufacturing sector and beyond. This was identified during the Phase 2 trials, as there was some instability in one of the CPEs which caused some delays in connecting the necessary hardware for the demonstration.

In summary, the benefits experienced by the use case from the 5G network were sufficient in enabling all functionality of the solution. However, this was not observed to be significantly better than that recorded in Phase 1. Nevertheless, the use case was able to reach its main objective. The experience was immersive and useful for the users and has the potential of being a viable innovative remote learning solution.

42 APPENDIX A – FURTHER PHASE 1 USER FEEDBACK

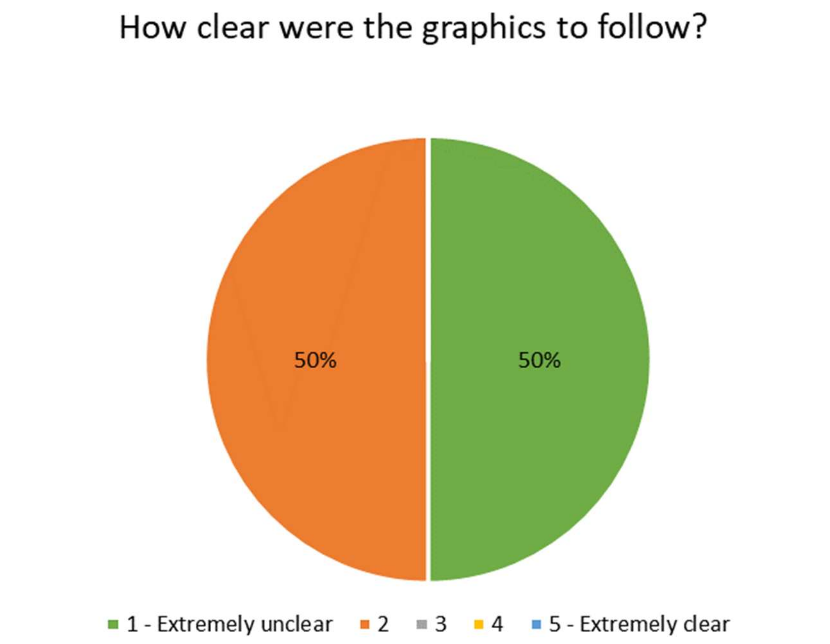


Figure A6 – Phase 1 user feedback regarding clarity of graphics to follow

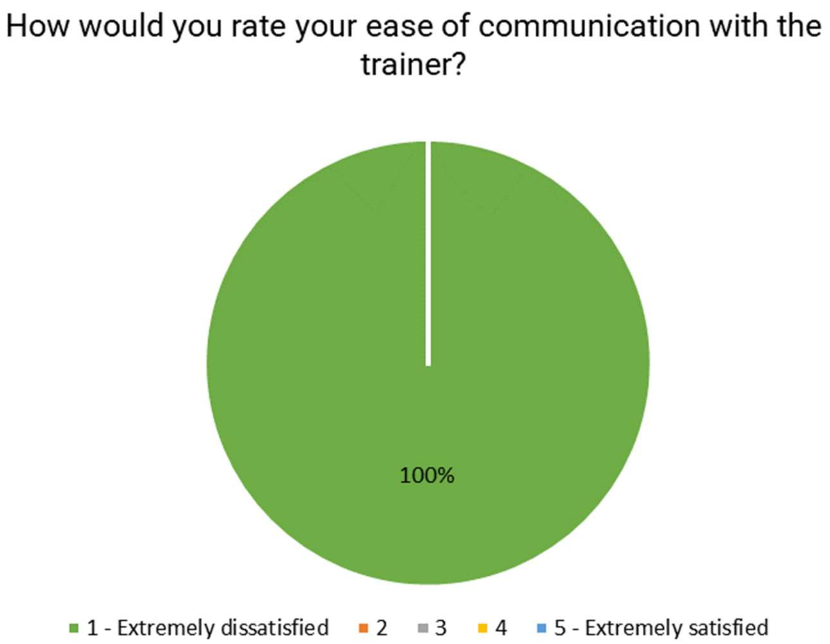


Figure A7 – Phase 1 user feedback regarding ease of communication with trainer

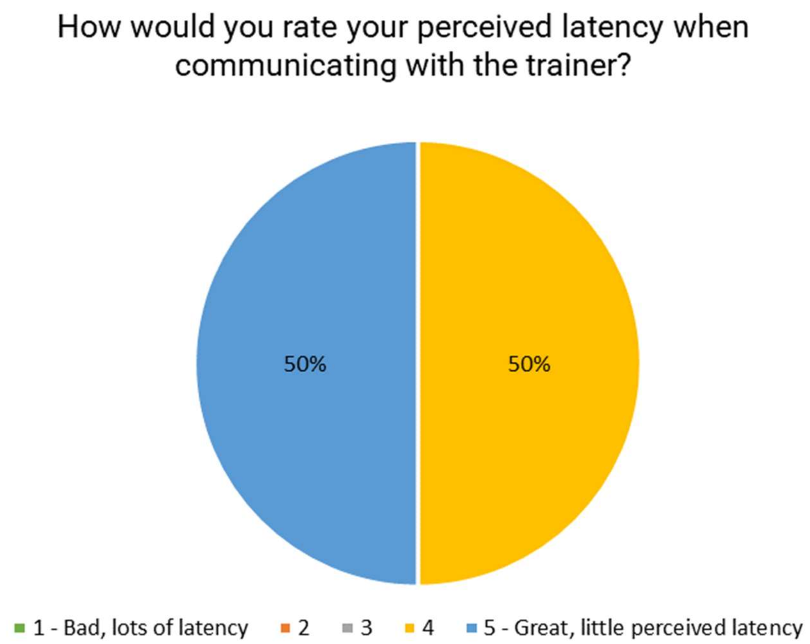


Figure A8 – Phase 1 user feedback regarding perceived latency when communicating with trainer

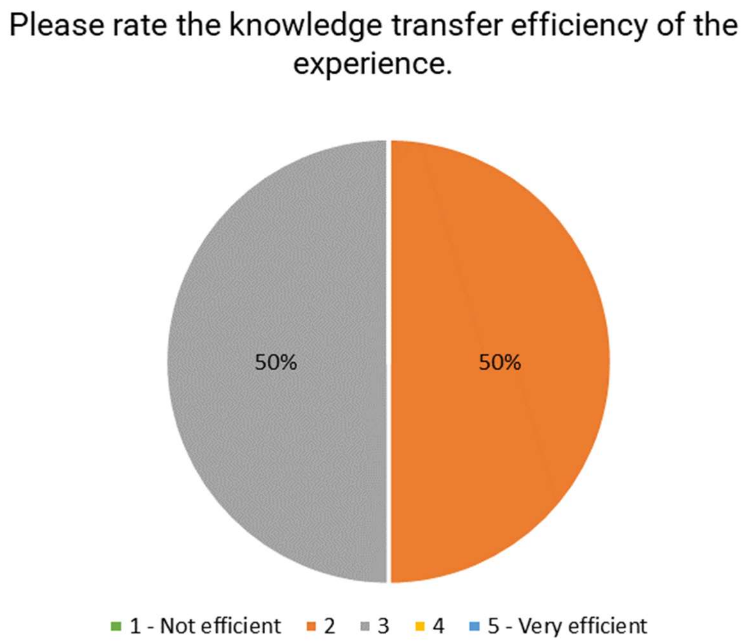


Figure A9 – Phase 1 user feedback regarding knowledge transfer efficiency

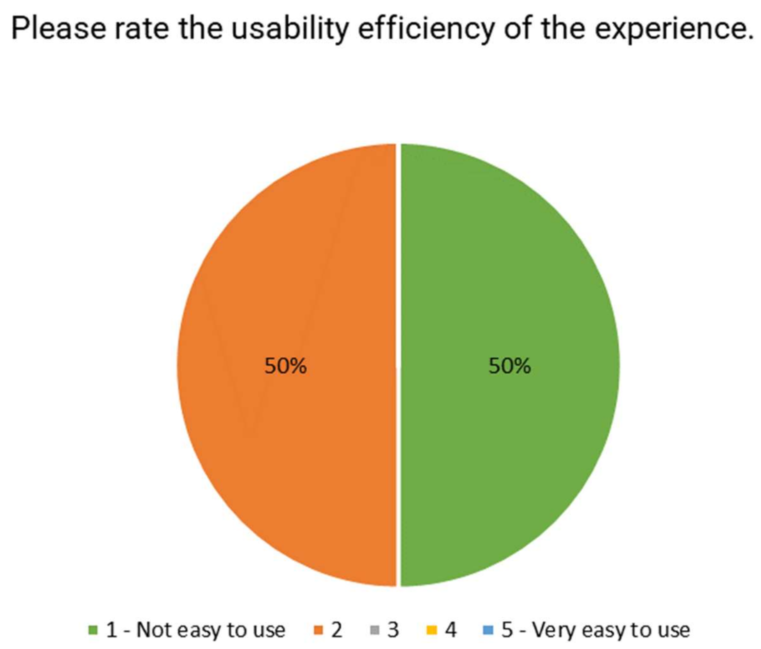


Figure A10 – Phase 1 user feedback regarding usability efficiency

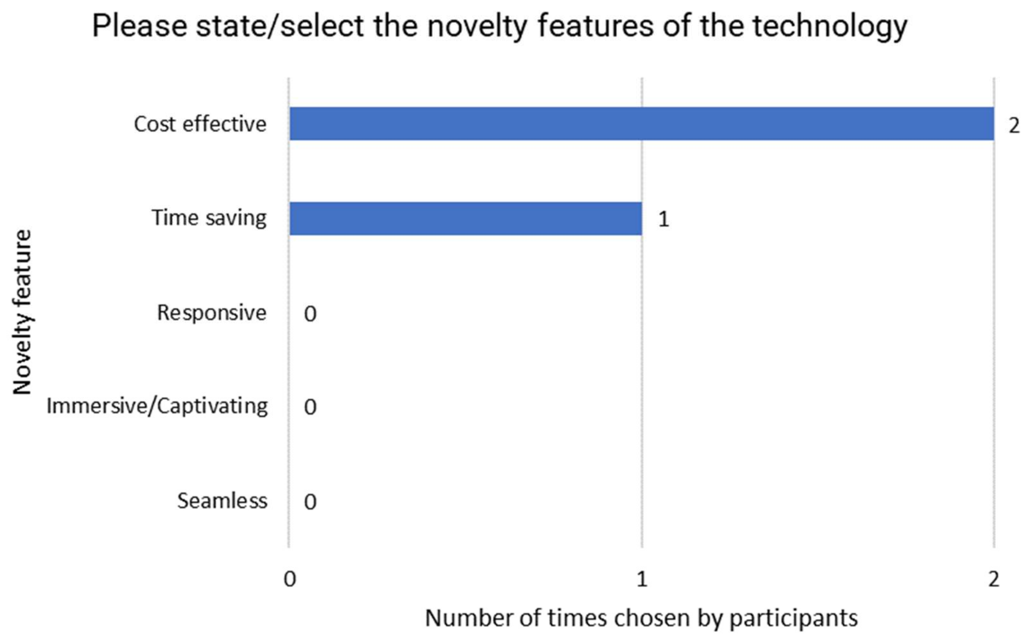


Figure A11 – Phase 1 user feedback regarding novelty features of technology

43 APPENDIX B – FURTHER PHASE 2 USER FEEDBACK

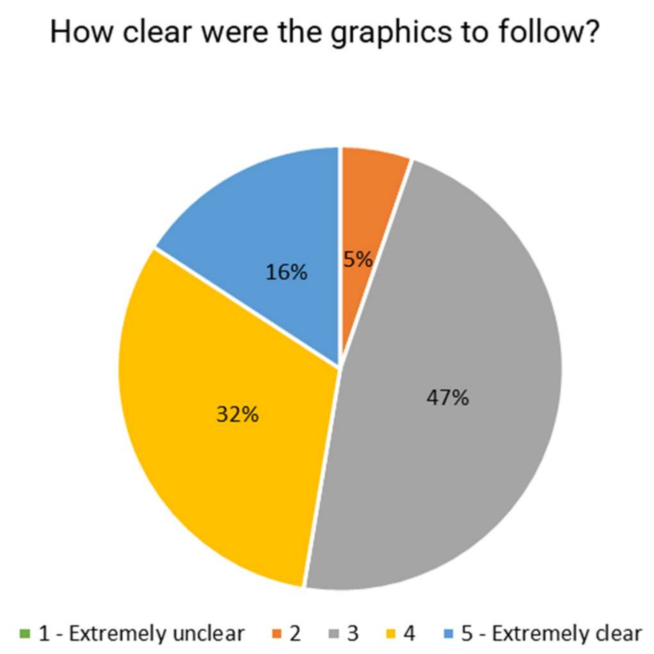


Figure B6 – Phase 2 user feedback regarding clarity of graphics to follow

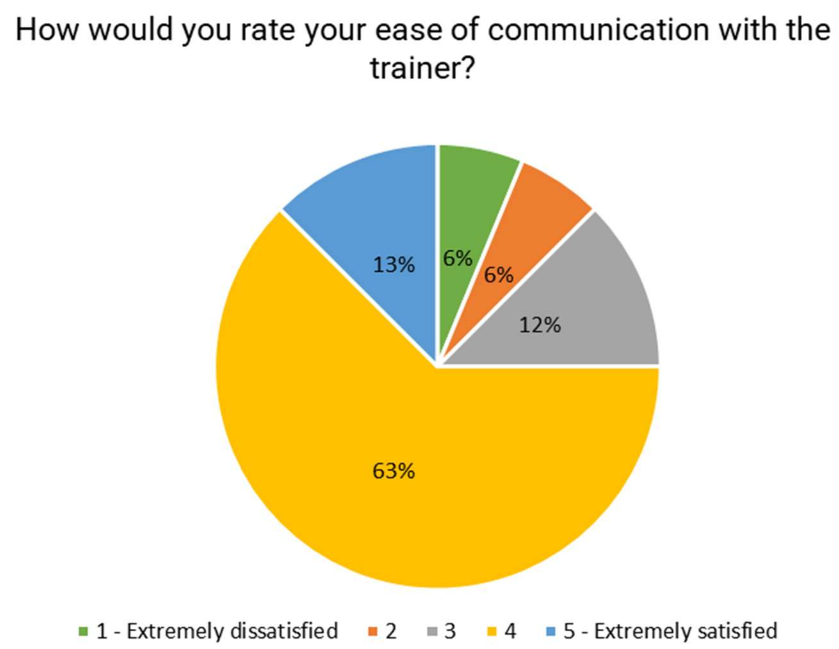


Figure B7 – Phase 2 user feedback regarding ease of communication with trainer

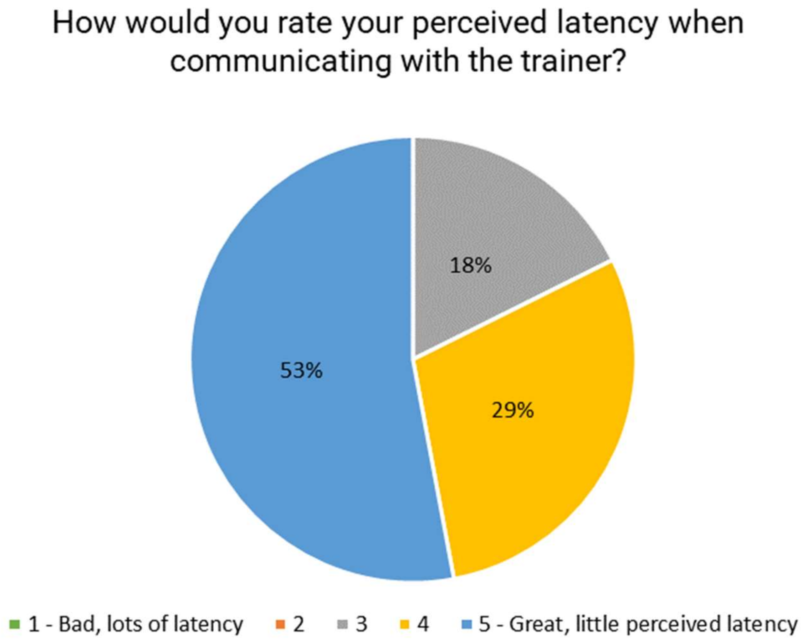


Figure B8 – Phase 2 user feedback regarding perceived latency when communicating with trainer

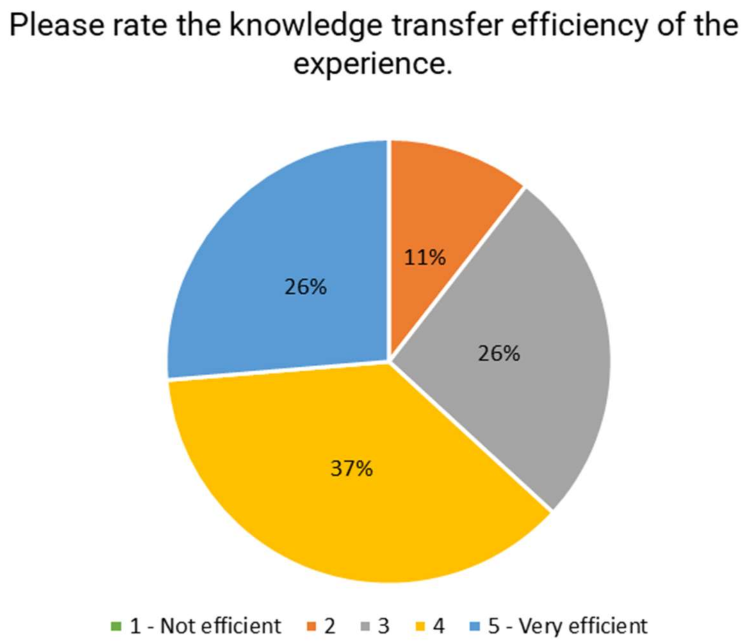


Figure B9 – Phase 2 user feedback regarding knowledge transfer efficiency

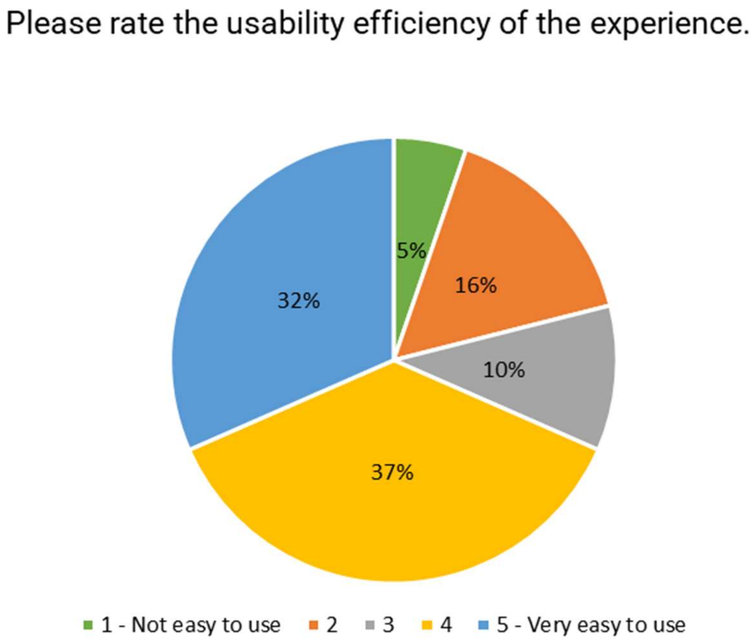


Figure B10 – Phase 2 user feedback regarding usability efficiency

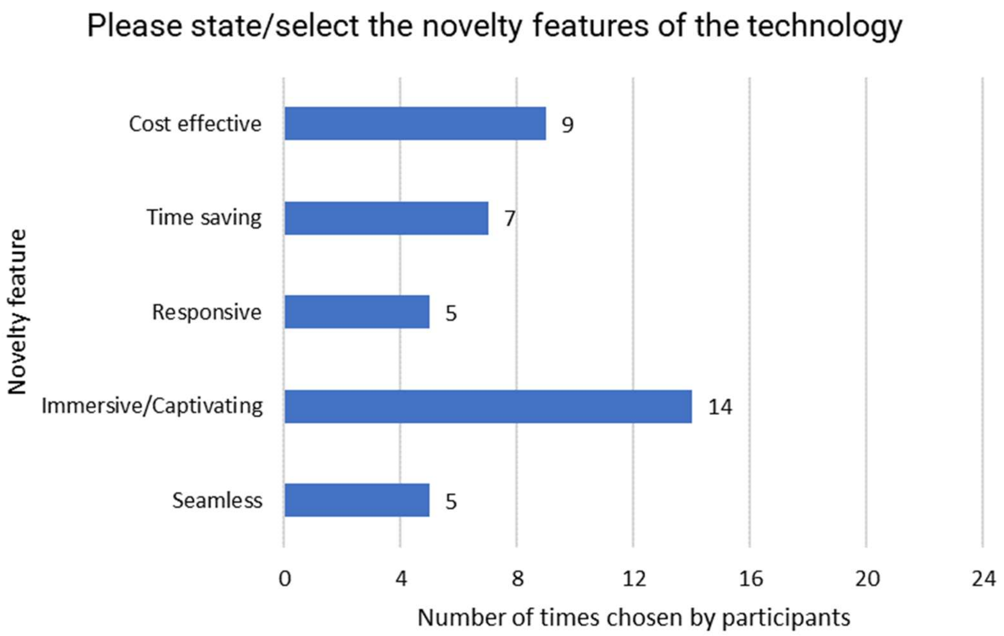


Figure B11 – Phase 2 user feedback regarding novelty features of technology

44 APPENDIX C – AR VERSUS VR USE CASES

As part of 5G-Encode, the NCC created and trialled two remote learning solutions – one presented within this report utilising AR technology and one presented in another report utilising 360° video streaming and VR technology. The main motivations for both were relatively similar but the teaching elements that these use cases covered varied. More specifically, the AR solution aimed to completely digitise conventionally on-site practical training courses in a bid to enable effective remote training. While on the other hand, the 360° video streaming VR solution aimed to enhance more traditional webinar style teaching and allow for more immersive remote learning from practical demonstrations in real-time.

As was concluded by both reports on these work packages, the latest demonstrators of the solutions were of satisfactory quality and presented promising digital products. However, it was identified that, for the NCC the AR package has more potential in the long-term based on the significant technological developments that could be made. If it is used as a teaching or training tool, it is possible to create a framework system that could be easily configurable to various topics and courses. This will enable the NCC to offer a wider variety of remote training or create a platform for other providers to utilise as well. On the other hand, the AR packages also has potential of being an effective manufacturing aid. Adding functionality that can validate the composite layup and highlight any possible issues will considerably benefit companies that want to reduce scrap rates.

Nevertheless, the 360° video streaming package in its current format is still a useful capability for the NCC to have and can be implemented in various scenarios for real-time remote teaching. But to improve its immersivity element and fully extract the VR potential, more development must be made in the course setup. For example, having multiple stations around the 360° camera, so the whole field of view is utilised productively. Alternatively, different points of view can be added to allow the users to engage more fully with the practical demonstration presented.

45 – ASSET TRACKING IN FACTORY

46 ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9 million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G on industrial use cases within the composites manufacturing industry. It will also validate the premise that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project showcases how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLL/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network is expected to enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

The state-of-the-art test beds were deployed across three sites, centred around the National Composites Centre (NCC) in the southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project.

The project consortium brings together a Tier 1 operator (Telefonica), leading industrial players (e.g. Siemens, Toshiba, Solvay), disruptive technology SMEs (Zeetta Networks, Mativision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

47 EXECUTIVE SUMMARY

An autonomous asset tracking solution, as the one proposed by this use case, offers the opportunity to effectively track mobile tools and assets such that current unproductive time spent searching for these items is minimised. When applied to time sensitive materials, such as prepreg carbon composites, this solution could also reliably monitor product out-life and a tooling maintenance schedule to minimise material wastage and ensure representative product traceability information, as well as high quality manufacturing standards of components.

The use case evaluated in this report encompasses key features, typical of an automated fibre placement process – a high value manufacturing method to produce composite parts, as well as post processing operations (e.g. curing, non-destructive testing, metrology scanning).

The proposed asset tracking solution relies on both software and hardware components, with the existing sensor gates deployed on the NCC factory floor communicating real time data to a live web application via a 4G, 5G or wired power over ethernet (POE) connection.

Based on the 4G asset tracking baseline findings, it was concluded that the performance of the test bed was directly linked to the network stability. 5G technology showed the potential to enhance the asset tracking solution by enabling connectivity to a much wider range of devices and assets simultaneously, without compromising its stability, offering improved speeds and latency.

This digital asset tracking solution showed great benefits in the form of productivity improvement, cost savings and better tooling control. By ensuring easy access to real time asset location information, it is possible to more efficiently plan a manufacturing schedule based on asset availability, minimising the unproductive time spent on searching and locating tooling or materials as production commences. It has been assessed that a 93% reduction in search time per job is possible with the present asset tracking solution, removing the likelihood of rescheduling a production run due to item unavailability.

Another major benefit of the proposed asset tracking solution is the ability to closely monitor stock life and availability, leading to an improved stock management and minimal material wastage, with implicit cost savings of at least £56,000 per year for production facilities similar in size and manufacturing rates to the NCC. Also, by closely monitoring the usage of tooling in production cycles, it is possible to reliably record and schedule maintenance, and, thus, ensure a high-quality standard of production.

The asset tracking technology detailed in the present report showed to be an effective means to wirelessly monitor both item location and material out-life in a production environment, but for a relatively small number of products. It is of interest for this use case to explore further the 5G capabilities for asset tracking and assess how a higher number of assets managed by the system would impact the performance and accuracy of the test bed. Seeking an out-of-factory tracking solution is also a scope of work the NCC would like to trial in the near future; however, access to public or private 5G networks outside production facilities is a prerequisite.

48 ABBREVIATIONS

4G LTE	Fourth Generation Long-Term Evolution
5G	Fifth Generation
AFP	Automated Fibre Placement
AI	Artificial Intelligence
AT	Asset Tracking
CPE	Customer Premises Equipment
IoT	Internet of Things
MES	Manufacturing Execution system
NCC	National Composites Centre
NDT	Non-destructive Testing
POE	Power over Ethernet
Plataine TPO	Plataine Total Production Optimisation
RF	Radio Frequency

49 INTRODUCTION

49.1 Aims and Objectives

In a manufacturing environment, there is a high likelihood that there will be time wasted when locating resources and equipment that could potentially lead to a loss in productivity or a reduction in profits. Thus, asset tracking in any form can be an invaluable tool to help businesses operate safely and effectively, while ensuring the highest standards.

Consequently, a proposition for a wireless asset tracking solution was made that included the ability to closely track assets in a production facility – from material and tooling, to finished parts and equipment – while monitoring time sensitive properties of the material from manufacturing through to use in production. Ultimately, a digital passport of the component would be generated to ensure traceability of material and tooling data.

The present use case was based on an automated fibre placement (AFP) manufacturing workflow; the process being in line with the Preform – Cure – Verify composite manufacturing cycle. An AFP process was chosen as the manufacturing process for the simple reason that it is a relevant production method to high value manufacturing (HVM) employed across a range of sectors – from Aerospace and Defence, to Automotive and Energy industries.

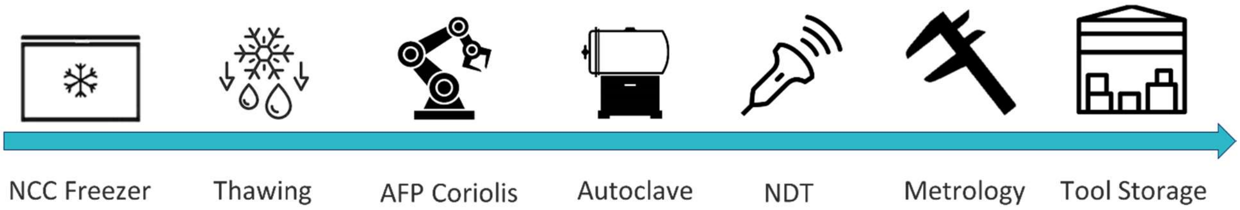


Figure 58 Factory movement flow corresponding to the respective RFID stations

However, the remaining stations in the manufacturing workflow (e.g. Freezer, Thawing, Autoclave, NDT, Metrology and Tool Storage) remain representative for any manufacturing process (i.e. automated or manual); thus, making the proposed asset tracking solution easily adaptable to other production methods or workflows.

An automated fibre placement process is an autonomous machine-driven manufacturing method that implies costly specialised equipment, tooling and material stock. Thus, it is of essence for such expensive and complex production processes that tooling and raw materials are delivered to the required standard to ensure both product and equipment quality.

Numerous composite materials have limited shelf lives, requiring special storage conditions at -18°C to preserve their high-performance characteristics. Thus, the material work life and, implicitly, its performance are highly dependent on the experienced exposure time to room temperature conditions. Typically, this information is recorded manually by technicians, operators or engineers, being rather an estimate than a representative value. It is therefore critical to ensure that the material is still in-life to guarantee certain component performance characteristics (i.e. mechanical properties).

Similarly, monitoring tool maintenance and ensuring its appropriate storage when not in use is key to guarantee the quality of tool and, implicitly, the performance of the final component. Considering the implicit costs of producing a component using an AFP process, it is of even greater importance to minimise potential causes of defects during manufacturing due to outdated material stock or defective tooling.

Consequently, the engineering challenge that this use case identified within the context of high value manufacturing was the absence of reliable in-factory asset tracking methods that could provide accurate item location, availability and out-life/maintenance information.

The principal aim was to demonstrate the ability of this solution to provide accurate live location information of the tagged assets. It was of great importance for this application for the location to be accurate enough to enable users to quickly identify the item.

Also, the main objective for this use case was to design and implement a wireless in-factory tracking system for an automated fibre placement process. The system functionalities were tested and measured against 4G and 5G test bed capabilities, to determine the ability of 4G LTE and 5G to drive the intended use case business benefits.

The proposed tracking solution is aimed to be a wireless system that employs technologies of both the 4th and 5th generations of wireless communications, offering improved flexibility, setup simplicity and high performance.

49.2 Purpose of 5G in Asset Tracking

Over the past years, the Industry 4.0 initiative escalated the rapid increase in production efficiency, promoted the creation of new business opportunities, and enabled high data rate wireless connectivity in high volume manufacturing settings. Factory automation represents a principal industrial area targeted as part of this engineering movement, with typical applications such as real time control and monitoring of assets to stimulate fast production rates and improve product or service quality.

Traditionally, factory automation is employed in discrete manufacturing, where processes consist of many discrete operations and steps. Thus, in-time messages or commands are key to minimise delays in the production flow. Consequently, network stability and fast response times (i.e. low latency) are of essence for those applications, and implicitly, for the present use case that is required to provide real time asset location.

For material out-life monitoring, it is also critical to have representative data of the product location, as if not correctly detected by the sensors, the updated material work life could potentially be incorrect (i.e. asset reported as stored in the freezer while being physically stored at room temperature, leading to unrepresentative work life information). Therefore, a 5G network would provide improved reliability and stability of the wireless connection, minimising the likelihood of missing a tagged asset.

Another network requirement for asset tracking is the ability to connect many devices to the network without compromising its connectivity or stability. The proposed asset tracking solution relies on RFID gates being deployed in stations representative of an AFP workflow that offer information on asset location. Deploying the existing infrastructure further into the NCC factory floor requires more sensors to be installed in the production environment – sensors that are connected and send data over the same network.

Furthermore, in the NCC production environment, numerous radio frequency interference sources were identified on the factory floor (i.e. high voltage power supplies, large metal structures). Those were found to act in the same frequency spectrum as the NCC private

4G network, causing large packet losses and latencies in a number of stations that in turn greatly affected the end user experience (e.g. delayed or incorrect asset location update). It was believed that a 5G connection would move the frequency bandwidth higher in the spectrum – from 1.8 GHz (where both the 4G LTE network and the recorded electromagnetic interferences were acting) to 5 GHz (5G network). Thus, the interferences would be avoided, and a robust connection would be provided to the system.

The ability to wirelessly monitor location and life of assets in a production environment, combined with increased network reliability, device connection capabilities and low latency are 5G characteristics that would enable a real time asset tracking experience for this use case. These network characteristics were also the use case requirements employed in measuring the success of the asset tracking test bed.

50 OVERVIEW

50.1 Use Case Architecture

An asset tracking solution was designed and deployed within the NCC factory floor and encompasses key features, typical of an AFP process. The system comprises both software and hardware elements and focuses on tracking time-sensitive materials, tooling and finished components, using 4G and 5G private networks, as well as RFID technologies. The engineering concept behind the proposed solution relies on a static system – several RFID gates are strategically positioned in areas representative for an AFP process.

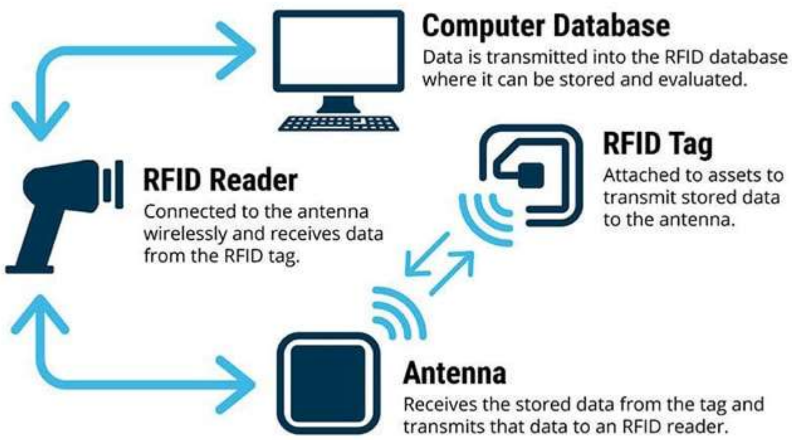


Figure 59 System architecture diagram [1]

As the tagged asset moves between workstations, passing the RFID gates, the RFID tag is detected by the antenna and the asset location is automatically updated in the live web asset tracking application offered by Plataine (i.e. Plataine TPO). A key system functionality is the end user ability to access goods information and monitor assets remotely, on edge devices by simply connecting to the web application (Figure 3).

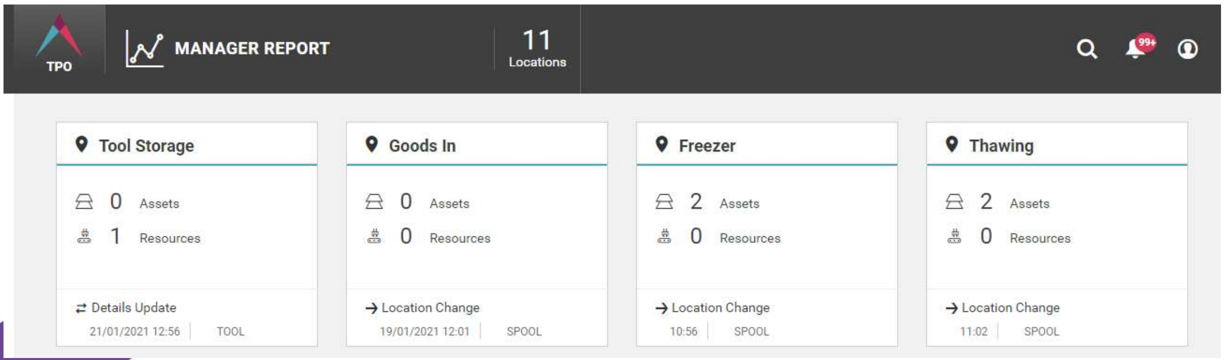


Figure 60 Plataine TPO user interface

The solution presents the ability to effectively track mobile tools and assets in real time, as well as remotely monitor time-sensitive composite material characteristics, such as composite shelf or work life. Also, the Plataine TPO environment offers users the great benefit of storing asset information and manufacturing documentation (i.e. manufacturing reports, NDT scans), providing a live database of all active assets on the shopfloor.

The asset tracking solution (i.e. Plataine TPO) is independently communicating asset information (e.g. material stock and availability, tool readiness and maintenance requirements) to the employed manufacturing execution system (MES), Siemens Opcentre. Each manufacturing activity is translated in a set of operations and steps, which are then released in Opcentre in the form of a work order.

Depending on the material availability and existing stock, spools of material are assigned to the work order and the manufacturing information is captured in the form of a report. Ultimately, a digital passport of both AFP prepreg materials and associated products is generated in TPO, containing manufacturing and post-processing information.

The RFID gateways were installed in seven distinct locations around the NCC factory (Figure 3) that would follow the manufacturing process flow (Freezer – Thawing – AFP Coriolis robot – Autoclave – NDT – Metrology – Tool storage in Figure 4). Thus, the zonal location of each asset can be closely monitored throughout the entire production process.

Each gateway consists of two RFID antennas directly connected to an RFID reader via a co-axial cable, which in turn is connected to a 4G and, respectively, 5G router, or uses a POE connection. Table 1 summarises the network connections found in each shopfloor area.

Workstation	**Network connection**
Freezer	4G (wireless)
Thawing	5G (wireless)
AFP Coriolis cell	4G (wireless)
Autoclave	Wired POE
Non-destructive testing (NDT)	4G (wireless)
Metrology	4G (wireless)
Goods In & Tool storage	Wired POE

Table 11 Available network connections

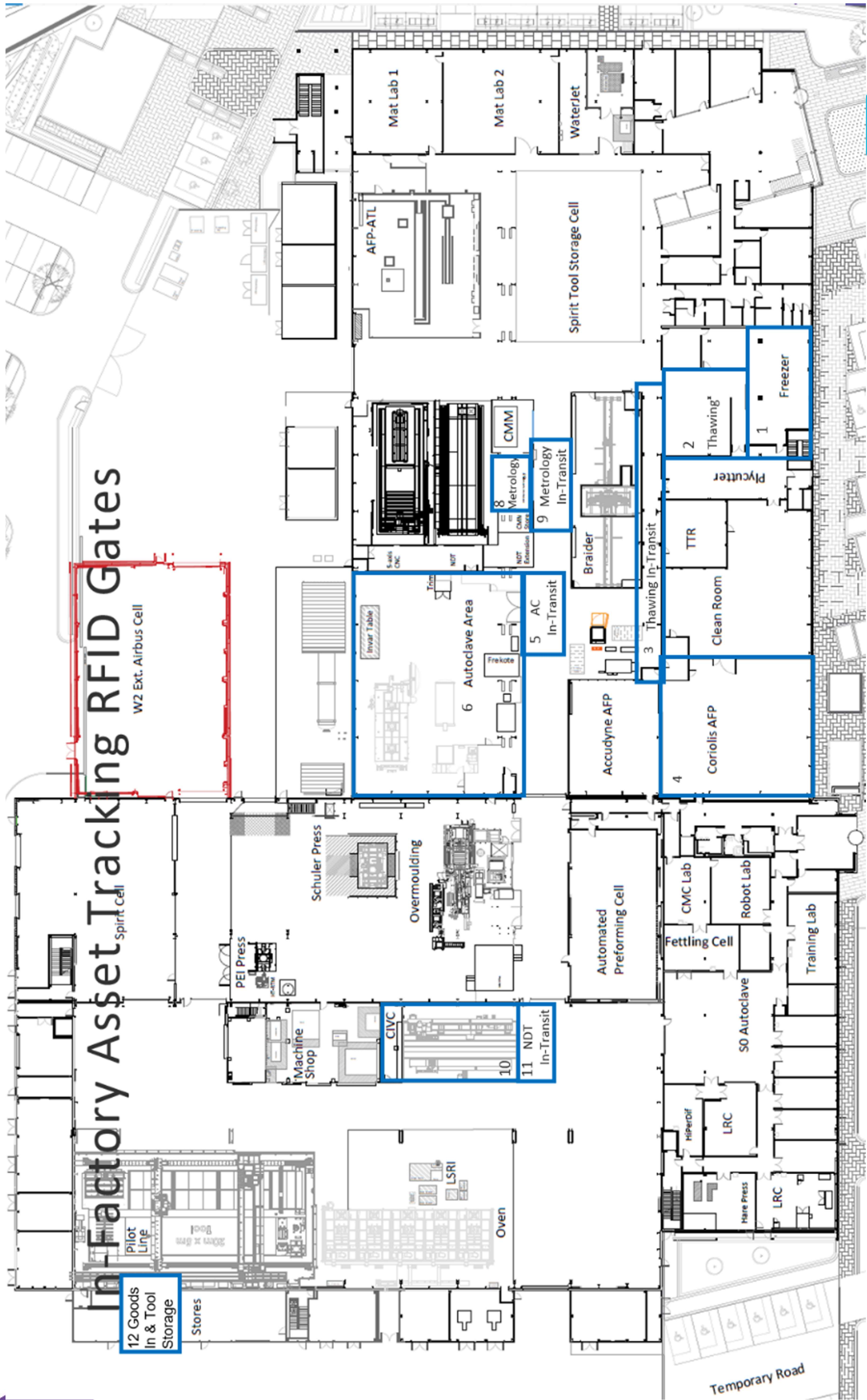


Figure 61 RFID gateways placement in workshop stations

50.2 Use Case Metrics

Network stability, latency and packet loss

The asset tracking solution relies on a static sensor system as the RFID gates indicate the zonal location of the assets on the factory floor. Thus, network stability was key for this application to ensure continuous connectivity of the system to the network and a robust data update. Considering the manufacturing environment the RFID gates are located in, there is an increased chance in electromagnetic interference (i.e. presence of high voltage supply units, large metal structures). Thus, it was of essence for this use case that these existing interferences did not alter the network signal, speeds or packet loss.

Key for this application were both latency and packet loss as those could greatly impact the real time update of asset location in the web application (e.g. the asset location update was not captured due to data being lost or it was not representative of its real location– slow response). Thus, it was desired within the use case that 0% packet loss was achieved, as well as low latency. However, these network performance metrics proved to be greatly affected by electromagnetic interferences, as experienced with a 4G connection.

5G also offered minimal latency and improved upload speeds (up to 57 Mb/s) that could facilitate the quick update of the tagged asset location in the web application. For this use case, a maximum latency of 10ms was required, easily achieved with a 5G network connection. Therefore, compared to the 4G baseline, a 5G network was believed to considerably improve the user experience when using the asset tracking test bed, offering accurate real time information on the asset location and its properties, as well as supporting future real-time optimisation studies for production planning.

Improved capacity to handle vast amounts of data wirelessly

In a production facility, the number of tools, materials and cured components (i.e. assets) could vary considerably depending on production capabilities. The larger the production facility or manufacturing rate, the larger the number of assets to monitor. 5G offered the great advantage of managing great amounts of data, while accommodating a larger number of end devices within the Internet of Things to connect, without compromising network stability, latency or speeds.

Thus, a reliable real time asset tracking system had to manage a large number of RFID gates, as well as a considerable amount of data traffic as numerous assets updated their location continuously on the factory floor. Consequently, as 5G could address this system requirement, it became of interest to assess its implicit capabilities.

50.3 Development Journey

The aim of the project was to provide the end users with a reliable real time asset tracking solution that could provide accurate and representative data on the item location and availability, as well as time sensitive information, such as product out-life or tool maintenance requirements. It was key for the use case to enable an interactive and user-friendly system interface where the asset condition and location could be remotely monitored on handled edge devices. Thus, three sub-systems were identified to enable the desired asset tracking capabilities:

- RFID hardware acting as gates between stations.
- An asset tracking web application (i.e. user interface).
- An MES solution.

The current industrial applications for asset tracking solutions rely extensively on RFID technologies. Thus, it was of interest to deploy an RFID gateway system on the factory floor that would autonomously communicate information on asset location to a live web application where the data could be accessed remotely – Plataine TPO.

Plataine, a world-leading provider of intelligent automation and optimisation software solutions for advanced manufacturing, was identified as a valuable partner for this use case based on their experience with smart asset tracking applications based on RFID technologies.

As an IoT and AI-based optimisation solution (i.e. Plataine TPO) was employed as the asset tracking web application, it was decided to also integrate an MES (Siemens Opcentre) as part of the proposed system architecture and create a fully digitalised AFP manufacturing ecosystem. Nowadays, the MES solution represents the backbone of automated manufacturing processes, as it generates and captures most essential manufacturing data.

As Plataine and Siemens had previously tested this autonomous data sharing between the two systems, it was of interest for the use case to understand how an automatic data transfer of manufacturing information from Opcentre to TPO could be integrated in a high value manufacturing production. This communication represented a mean to minimise the number of manual inputs required from the operator or engineer and capture all asset information in a centralised live environment (i.e. TPO recording asset location, material information – expiration date, out-life and stock –, tooling maintenance, manufacturing data).

Thus, the 5G-Encode AT use case aimed to integrate these three independent sub-systems in a single industrial application that provides full asset traceability information, from material and tooling data to key manufacturing details. The real time AT capabilities were then unlocked by deploying a 5G network connection on the factory floor (i.e. RFID data transferred from the shop to the TPO server via a 5G network).

51 USE CASE DEVELOPMENT AND INVESTIGATION

51.1 Use Case Development

The use case team developed an asset tracking solution comprising of both software and hardware components. Their functionality and testing completed are detailed in the following sections.

51.2 In-factory Asset Tracking Testbed

A system network architecture was designed and implemented in the NCC factory floor, following an AFP process flow and utilising wired and both 4G and 5G network connections, as well as RFID technologies (Figure 5).

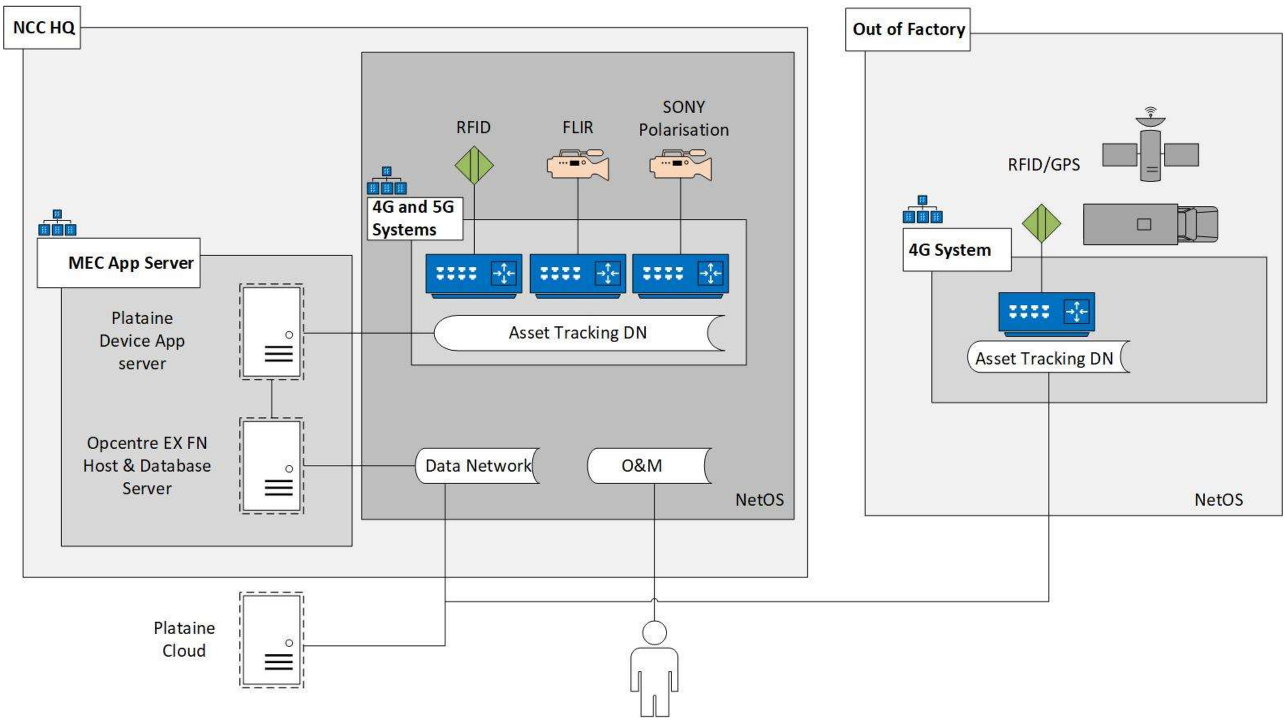


Figure 62 Asset tracking network architecture

An initial 4G solution was developed within the NCC shopfloor to act as a baseline. Originally, six 4G small cells operating on a 5 MHz bandwidth were placed in the NCC factory to provide coverage to the use cases within the 5G-ENCODE project. RFID gateways were installed in seven distinct locations representative of an AFP process flow, so that the zonal location of each asset could be remotely monitored using the asset tracking user interface provided by Plataine.

The RFID sensors make an IP connection to the Plataine device-app server deployed on the project network, updating the asset location as it passes by each gateway. An example of an RFID gate and implicit hardware components can be pictured in Figure 6.

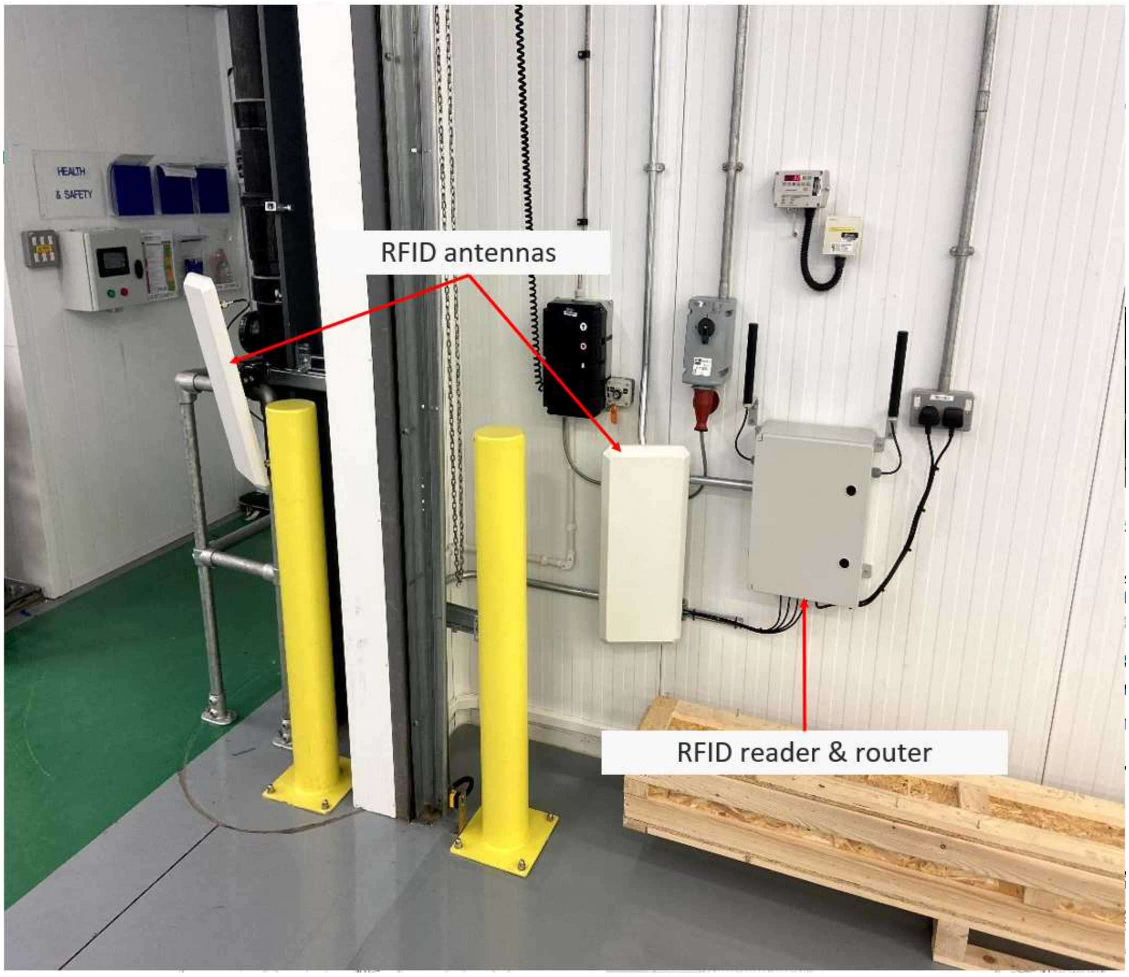


Figure 63 RFID gate in the AFP Coriolis cell

An RFID gate consists of two main components as identified in Figure 6:

- An electronics box consisting in a Zebra FX7500 RFID reader, a Siemens Scalance M876-4 4G router and two Siemens SINAUT ANT-794-4MR antennas to pick up the 4G signal.
- One or two Laird wide band circular polarity RFID antennas.

The RFID antennas are connected directly to the RFID reader via a co-axial cable, which is connected to the 4G router via an RJ45 (i.e. ethernet) cable. The 4G router sends and receives data over the NCC private 4G network and communicates directly with the use case server. This solution allows for the data sent over the 4G network to be viewed and managed on edge devices remotely.

Five of the stations were originally connected to the 4G network, while the remaining two (i.e. Autoclave, Tool storage), utilise a wired POE connection. This was due to the existing concerns over the 4G signal strength in those areas.

For the 5G test bed, the same system architecture was employed as for the 4G baseline, mimicking the exact same process flow. The main difference consists in having a 5G network connection in one of the cells (i.e. 'Thawing' station), with the rest of the RFID gates being connected to 4G. A Robustel 5G router (Figure 7) was installed in the respective cell, with the RFID reader connected to the Robustel unit via an ethernet cable.

Figure 64 Robustel router setup in the 'Thawing' station

No other stations were upgraded to a 5G connection due to unavailability of resources (e.g. reduced number of available NCC IT engineers and 5G routers, short installation window prior to the deployment of the upgraded test bed).

Furthermore, each individual cell is modelled in Plataine TPO as shown in Figures 8 and 9, offering information on the material, tooling and preforms existing in each respective area. For instance, for a spool of material, by accessing the asset entry, it is possible to view information on the material utilisation and out-life.

This information is automatically shared with the MES solution (i.e. Siemens Opcentre) once a production run is scheduled. The manufacturing data, along with an update of the available material stock are then autonomously shared by Opcentre with TPO at the end of manufacturing. Thus, the number of manual operations executed by the operators in capturing this type of data is reduced. Further information on the autonomous systems communication between Opcentre and TPO is provided in Appendix B.

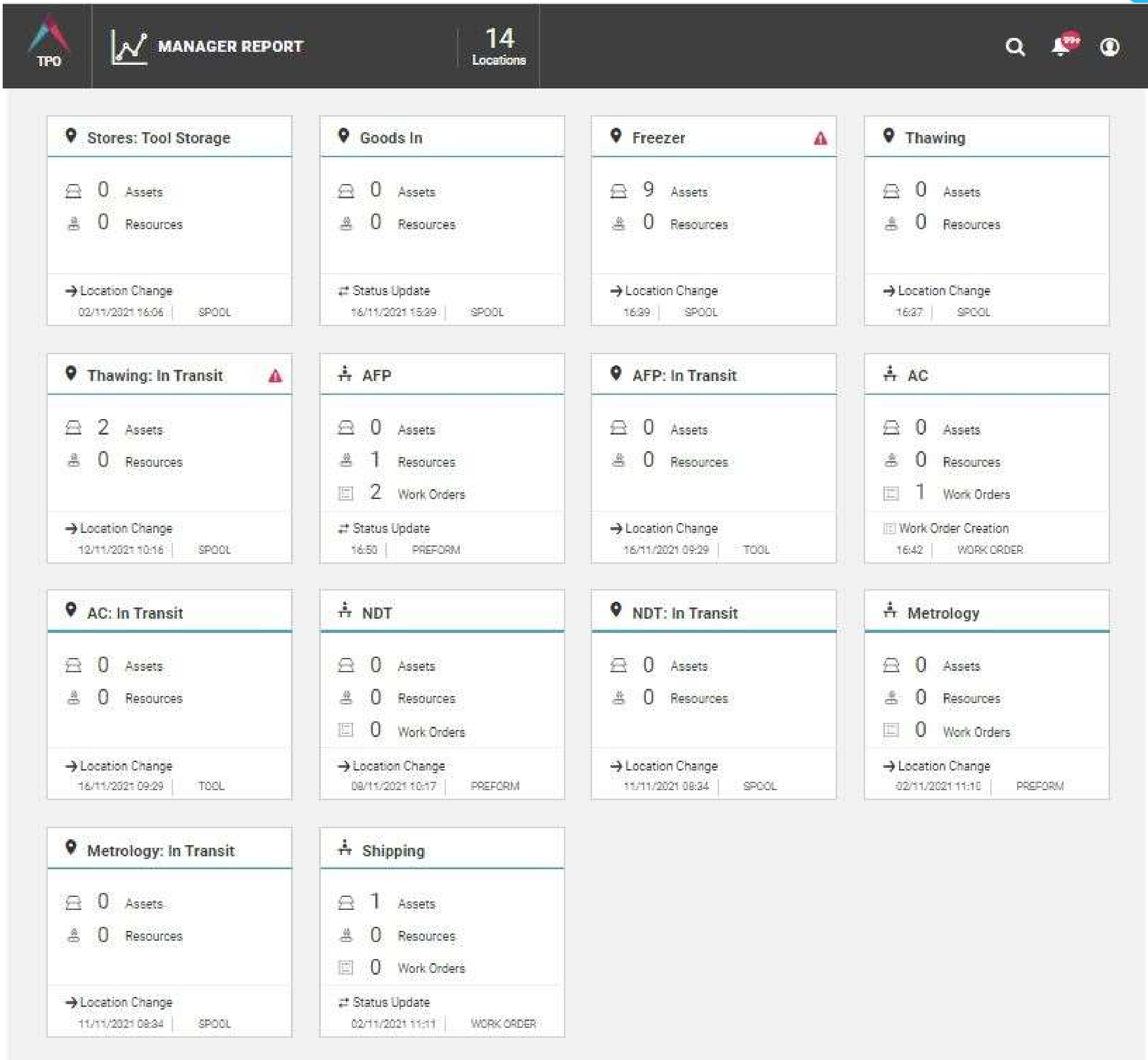


Figure 65 Plataine TPO – Visualisation of AFP stations

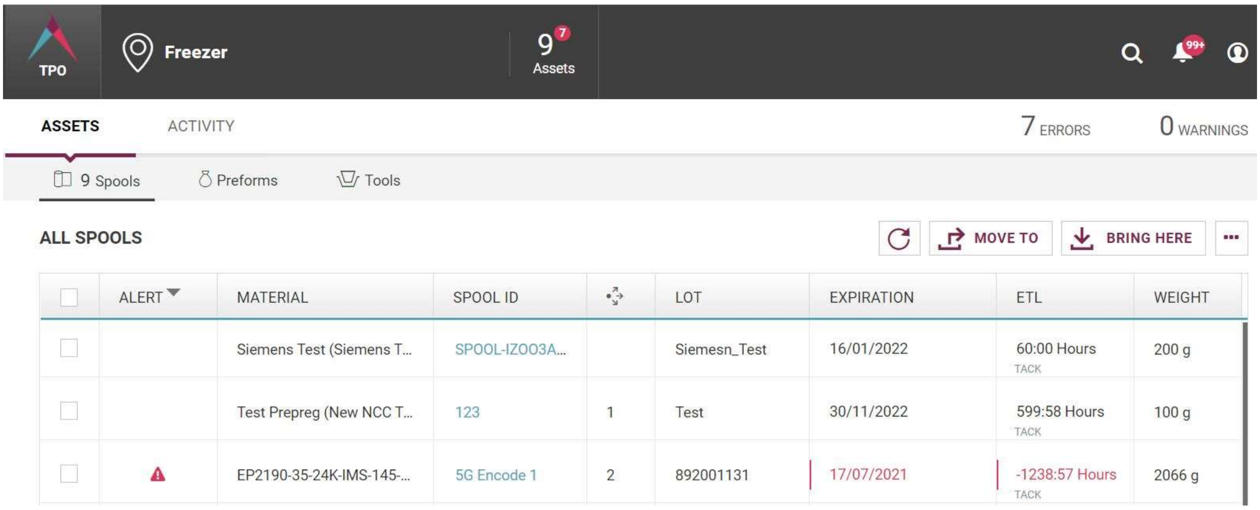


Figure 66 Plataine TPO – Defined asset entries

In order for the assets to be tracked on the factory floor, each item is tagged with a unique RFID label. The tags are printed using a Zebra (ZD500R) passive RFID printer that is connected via a CAT6a port to the same network as the asset tracking system, to enable full system functionality. An example of the RFID tags used in the use case is shown in Figure 10. For tooling, the assets are tagged using high-temperature resistant RFID labels as those experience numerous curing cycles at elevated temperatures.

Figure 67 Example of asset RFID tag

51.2.1 Out-of-factory Asset Tracking

One of the requirements for this use case was to enable out-of-factory tracking of temperature sensitive materials. An automatic solution for in-transit data sharing between Solvay (i.e. the supplier) and the NCC (i.e. the customer) was sought to closely monitor material out-life during delivery between the two sites (Solvay facilities in Wrexham to NCC headquarters in Bristol Emersons Green).

Figure 12 shows the different operations the spools of material undergo from delivery to producing a final cured component.

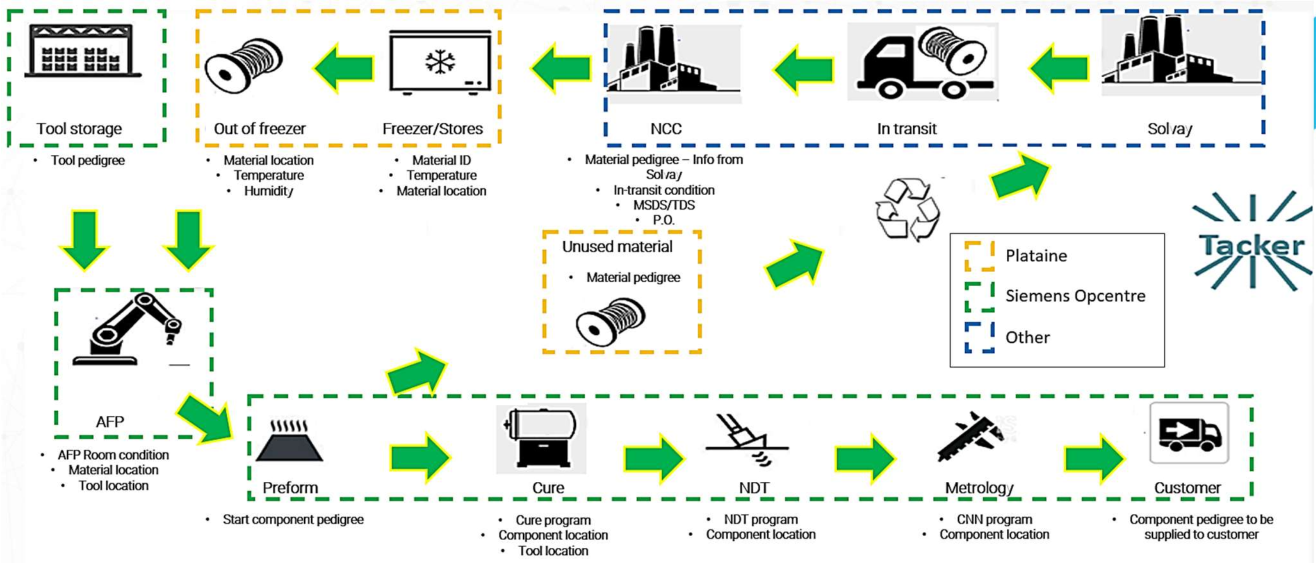


Figure 68 End-to-end material monitoring – from supplier to production

Originally, a 5G solution was desired; however, due to limited coverage of the public 5G network, a 4G out-of-factory solution was trialled. Two options have been considered:

- Utilise Solvay's in-transit sensor technology (Sensitech) as an LTE solution to track asset location via 4G and GPS while monitoring environmental conditions.
- Tether an RFID sensor to a dual sim 4G / 5G device and track the asset into the transit, user GPS data to track the device while in-transit and transition to the NCC private network when in range.

Solvay's decision was to monitor the product out-life when in-transit using Sensitech sensor technology as the required solution infrastructure was readily available and easy to integrate as part of a handover process with the NCC.

The information was to be captured automatically in Plataine TPO once the material arrived on site, with the asset having already been created in the web-application. However, due to the increased cost of the proposed solution, an alternative process was implemented. This alternative solution consists in the material manufacturing information to be supplied by Solvay to the NCC once the material is released for delivery. This information is captured in an EXCEL CSV template that can then be easily imported into Plataine TPO and generate the asset entries.

In-transit data (i.e. temperature readings and GPS location) are continuously recorded during transportation by Solvay using their Sensitech sensors. To preserve material properties and out-life, the products are stored directly in the freezer while processing the delivery at the NCC. If any material out-life is lost in transit, this information will be provided by Solvay and captured in Plataine TPO.

51.3 Use Case Testing

When assessing the use case test bed performance, two types of tests were considered:

- Application tests (evaluating the performance of the asset tracking system from the user's perspective and identifying areas of improvement for the proposed solution).
- Network tests (relating the performance issues derived from the application test to representative network performance metrics and evaluating those against the network requirements).

When enabling the independent system communication between Opcentre and TPO, further testing was required. These tests were completed in the form of dry runs by creating and scheduling a number of work orders and assessing the means by which data is exchanged between the two systems. In this section, the application tests and implicit findings are detailed.

51.3.1 Application Testing

The application tests consisted in following the process flow and record any system performance issues that were negatively impacting the user experience. The main aim during an application test was to validate that the RFID hardware (i.e. reader and respective antennas) was enabled at each one of the seven stations and that the tagged asset location was updated in Plataine TPO as the asset moved between stations.

Once the material entries were generated in Plataine by importing the Excel CSV spool template, the respective RFID tags were printed and attached to the product packaging. As the work order was scheduled and the material was moved to the 'Pick list' in TPO, the spools were withdrawn from the freezer and placed on the acclimatisation rack. For the material to be assigned to a work order in Opcentre, the spools of prepreg tape had to be located in the 'Freezer' station. The RFID gate would detect the tagged material and the

'Defrost' timer would start. In the meantime, the time the material spent outside the freezer was recorded and subtracted from the material work life.

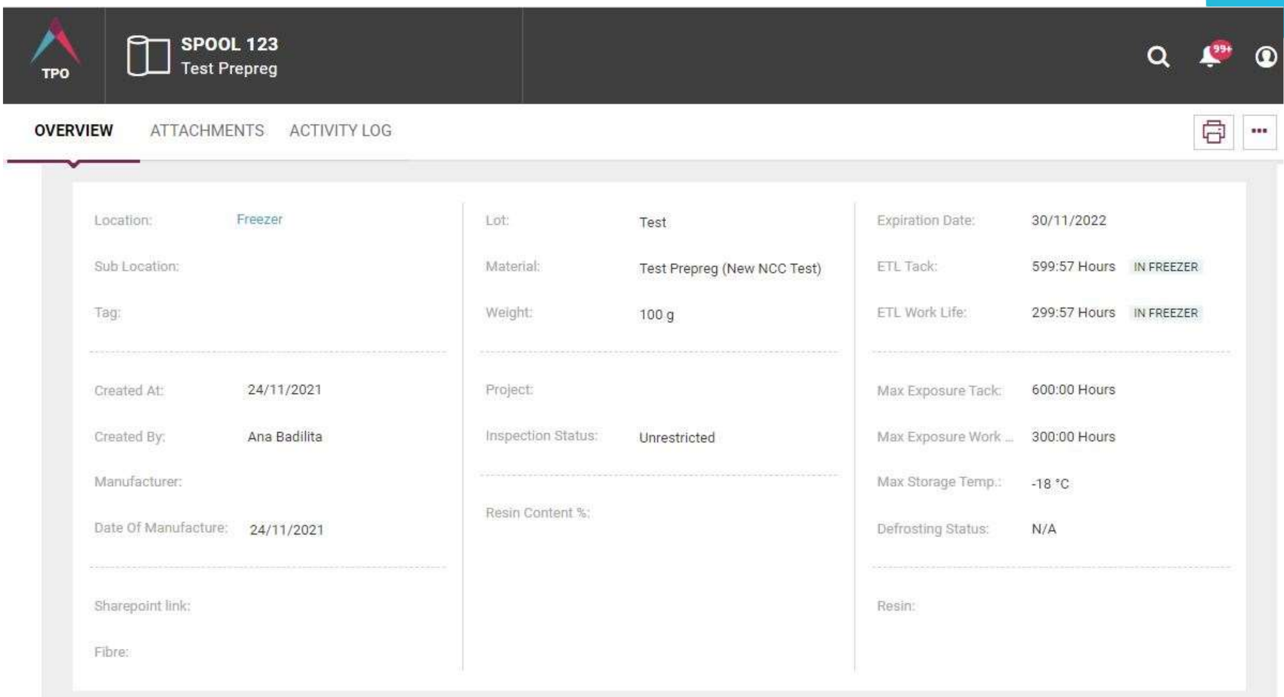


Figure 69 Material shelf and work lives captured in TPO

When the material was fully defrosted, the work order was executed on the AFP Coriolis robot and a new preform entry was created in Plataine. Curing and post-processing reports were attached to the newly created asset entry once each operation was completed. For each created preform, information on the material batches, tooling and manufacturing were captured in Plataine. At the end of the manufacturing operations (i.e. production of the uncured preform), the spools of material were weighed, and the available stock quantities were updated in Plataine TPO as the composite material was returned to the freezer. For simplicity, right corner preforms were created on the AFP robot and closely monitored during the manufacturing stage.

Each asset was tracked around the shopfloor while the location update was monitored in the Plataine web application. For the goods to be easily detected by the RFID stations, the tags had to be partially visible to the antennas. Thus, placing the tags on the outer product packaging and ensuring a direct line of sight with the RFID gate was agreed as the best practice to facilitate asset detection.

For the 4G baseline, in certain areas, such as the 'Thawing' station and the AFP Coriolis cell, the material detection was delayed; thus, it was necessary for the spools to be carefully manipulated in the proximity of the gate for the antennas to detect the RFID tags. After further calibration work was completed on the antennas, it has been decided that the delay in updating the material location in TPO was a network issue rather than a hardware one. Consequently, it was of interest to assess the network performance with a series of network tests. These are detailed in section '4.1.1 4G LTE Testing and Outcomes'.

Overall, the test bed showed great potential for a robust real time asset tracking solution, but further work was required to understand how the network performance influences the user experience and, implicitly, the test bed performance.

51.4 Use Case Discussion

51.4.1 Limitations of Use Case

The proposed asset tracking solution has proved to be an effective mean to monitor both the location of tagged assets, but also the material work and shelf lives. However, the existing system was configured for a single linear production flow and was tested using a relatively small number of assets.

When considering a high-volume manufacturing environment, the number of assets that are to be tracked is considerably larger compared to the one used to develop and evaluate the proposed asset tracking test bed. A future requirement created as a result of this project is to assess how large amounts of data are managed and updated in the web application using the current system architecture.

A 5G connection would facilitate a larger number of end devices (i.e. RFID gates) to be connected to the network and also easily cope with larger amount of data being uploaded to the server relatively quickly; thus, offering a real time asset tracking experience for a representative production environment. Also, this would allow a large number of RFID gates (i.e. stations) to be connecting to the network and, therefore, facilitate a better coverage in big warehouse spaces or manufacturing settings. These 5G capabilities are of interest to assess in future trials and tests.

Another limitation of the proposed use case is that the RFID gates only indicate zonal location of the asset. The system architecture was deployed within the NCC factory floor, targeting a number of cells that are representative of an AFP process. Those cells are relatively small and facilitate identifying the correct asset quickly and efficiently if the zonal location of the good or material is already known. If we are to consider larger manufacturing areas or production lines, either at the NCC or other similar production environments, the proposed system might not be as efficient in aiding users to easily identify the exact location of the asset.

For an automatic mean to closely monitor tools or materials, it is of great importance to minimise the manual input required from the end user. This is why an alternative mean to communicate part or material information was considered. However, this type of autonomous system communication was only enabled between the MES solution and TPO.

For future work on the asset tracking solution, it would be of great importance to integrate automatic means of data sharing with the TPO web application, similarly as for Siemens Opcentre. For instance, it would be beneficial to enable TPO to independently communicate with other pieces of software or systems used at the NCC (e.g. Polyworks software tools used by the metrology team). The current procedure solely relies on communicating the metrology reports via email and manually attaching it to the preform entry in TPO, causing potential delays in releasing the information online or accidently skipping this final step.

51.4.2 Siemens Opcentre and Plataine TPO Communication

The Siemens Opcentre and Plataine TPO communication was meant to enable an automatic and independent material and manufacturing data exchange between the two systems. Once the work order is created, scheduled and started in Siemens Opcentre, certain commands would be enabled to closely monitor the available material stock. These commands include a stock update with the new available quantity on the spool after manufacturing is completed or a request for additional material if necessary.

With the NCC factory floor being the first manufacturing environment this communication was enabled in; a number of issues were encountered. However, the communication was enabled successfully, and it is now possible to extract material information from Plataine TPO when scheduling a work order in Siemens Opcentre.

A number of issues had to be addressed prior to testing this communication; some of those blockers included:

- A Siemens software update to configure the composite material class in Opcentre that delayed configuring this system feature.
- Differences in date and units of measurement formats between the two systems that prevented a correct information exchange (Figure 14).
- Incorrect links created between Opcentre and TPO to access the material information and update its stock.

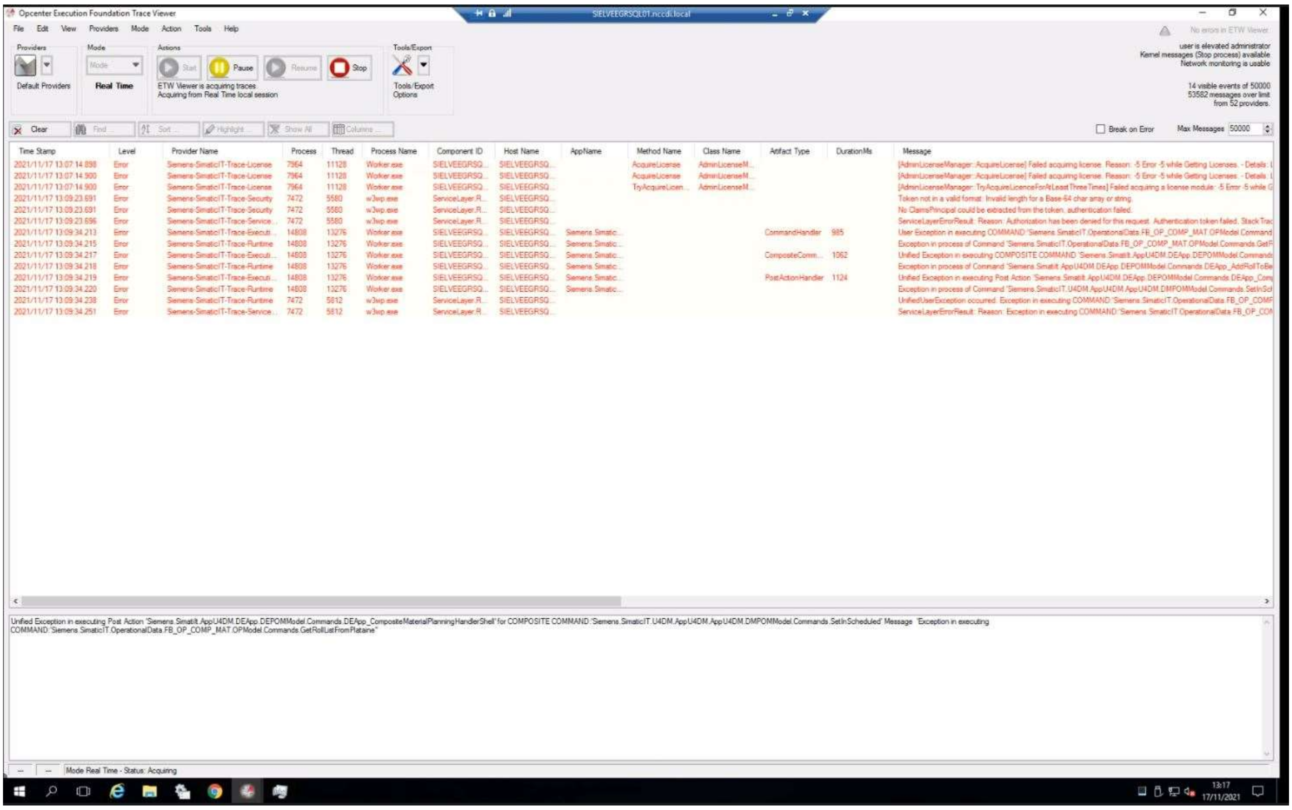


Figure 70 Errors caused by time and date format issues in Siemens Execution Foundation Trace Viewer

While those have been addressed successfully, a number of tasks are still pending:

- Enabling more than one material entry to be linked to a work order in Opcentre.
- Configuring additional commands
    - To update existing stock information in TPO based on the material quantities consumed during manufacturing.
    - To request and assign additional stock from TPO during an operation in Opcentre.

- To attach a part manufacturing report from Opcentre to the respective preform entry in TPO.

These features will be tested prior to project closure.

51.4.3 Lessons Learnt

Flexibility of asset tracking solution

For this particular use case, the asset tracking solution was demoed for one specific manufacturing process – an automated fibre placement process. The existing system was configured for a linear production flow, using a relatively small number of assets and covering only seven work cells in the NCC factory: Freezer – Thawing – AFP Coriolis cell – Autoclave – NDT – Metrology – Tool storage. However, the technologies and web solution employed by the use case proved to be easily adapted and customised for any manufacturing environment or process.

RFID gate calibration

When deploying the RFID gates in the NCC factory floor, the calibration of the antennas was a critical operation to ensure the functionality of the asset tracking solution. Based on the performance of the RFID gates over the past year, it is believed that periodic recalibration of the hardware is required. It would also be of interest to explore remote means to calibrate the RFID antennas, as the current procedure is mostly manual and highly tedious. This involves an operator to define the coverage area of the antennas around each gate manually using an RFID tag, being a time-consuming trial-and-error process.

Collaboration and cross-team knowledge sharing

For this use case, the engagement of zone owners, technical authorities and technicians was of great importance to integrate an asset tracking test bed in the factory floor workstations. This enabled the use case team to identify potential industrial challenges that could have been resolved by the proposed asset tracking solution. For instance, by enabling the manufacturing execution system to update material stock and automatically provide part manufacturing data to Plataine TPO, the number of manual steps that are usually completed by the technical authorities or project managers were drastically reduced. It also improved time efficiency as tasks were not delayed and they were completed instantaneously as the work order was completed in Opcentre.

Re-use by other organisations in the Enterprise

There is a strong business interest in deploying the asset tracking solution in the rest of the NCC factory. The findings of this use case showed great potential and benefits for composite manufacturing, attracting the interest of several teams and business units.

Automation of data transfer

As one of the use case requirements was to enable out-of-factory tracking of composite materials, an automatic solution for in-transit data sharing between Solvay and the NCC was sought. The existing solution relies on the manual transfer of material information between the two parties, which is then imported in Plataine TPO. However, Plataine is currently exploring solutions to address this use case limitation by implementing a new feature in their web solution that could potentially facilitate automatic data sharing between Solvay and the NCC.

Expanded use to organisations outside the Enterprise

As the NCC is a research and development centre for composite materials, it would be valuable to expand this solution to other suppliers, as well as customers. This way, the existing infrastructure for out-of-factory asset tracking will continue to develop and facilitate easy access of small to medium size businesses to this technology.

51.5 Use Case Benefits

51.5.1 Business Value Propositions

The key performance indicators value drivers for asset tracking were identified and summarised below:

- Productivity improvement – time resources saved on unproductive tool location searches.
- Sustainability – improved material stock management solution (i.e. minimal material wastage).
- Cost savings – reduction of costs associated with outdated material disposal.

- Cost savings – reduction of costs associated with damaged tooling requiring attention or rework (i.e. improved monitoring of tool maintenance requirements).
- Tool and equipment control – close monitoring of tool utilisation and its maintenance schedule (i.e. number of production cycles a tool has seen).

These performance indicators were used to assess and quantify the benefits of the proposed asset tracking solution in a production environment.

51.5.2 Use Case Benefits

Provide accurate and real time location of assets

Lack of tool storage or inconsistent work practices in a production environment can lead to tools becoming more susceptible to loss or damage, especially if stored inadequately. In turn, this will cause difficulties to future users to easily locate the assets when required. Consequently, a significant amount of time resources is wasted searching for and locating tools, which can lead to further losses of time and cost to the business.

The key benefit of this asset tracking use case is to efficiently track mobile assets in real time to minimise the current unproductive time spent searching for those items.

Based off the experience of the NCC, a productivity improvement of up to 5% in time is seen per standard 7h manufacturing jobs when the asset tracking system is employed; this is measured by booked hours against predicted hours for specific tasks. Consequently, time savings in the production environment directly minimises the business costs of manufacturing as productivity is increased and the resources – operator / machine time – are efficiently used in the shopfloor.

Monitor key assets and provide better selection of material for the application based on material work / shelf life

Composite materials have a limited shelf and work life, requiring special storage conditions (e.g. -18 °C) to preserve their high-performance characteristics. Once the material reaches its expiry date the, the remaining stock is typically disposed as its mechanical properties degrade, resulting in waste.

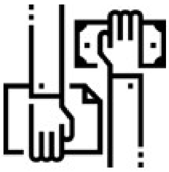
Plataine TPO allows users to search for existing material stock (i.e. consume first available stock prior to placing a new material order) and facilitates a better approximation of future orders based on similar production runs (i.e. minimising risk of overspent either due to overestimating quantities or a need for additional spools of prepreg). The asset tracking solutions enable project managers to better forecast project spending based on similar productions and offers better control over stock with estimated savings between £56,000 and £200,000 in raw material every year.

Monitor key assets and allow for better selection of tooling

Monitoring tooling maintenance and ensuring its appropriate storage is key for guaranteeing the quality of tools and, implicitly, the performance of the final cured component. In addition, if tool utilisation and maintenance are not accurately recorded, costly quality issues to the final product may be caused.

Plataine TPO captures key tool information along with its current location. Thus, it is possible to monitor its use, predict future maintenance work and ensure its appropriate storage. Based off the experiences at the NCC, an annual savings of up to £200,000 were estimated, accounting for cost savings of tooling repurchase or rework due to either loss or damage.

Reduce bureaucracy



Excessive bureaucracy elimination

The existing solution at the NCC relies extensively on tracing information on paper or storing it in multiple locations to ensure its traceability. Time-sensitive information and stock quantities are captured manually, while materials are assigned to work orders and production runs via an internal request form that is also manually filled and processed.

The proposed asset tracking solution independently communicates with the MES solution offered by Siemens, enabling an automatic data sharing process between the two systems. The material is linked automatically and uniquely to a work order and, once the product is removed from the freezer, its remaining out-life is closely monitored.

Based off the experiences of using the asset tracking system at the NCC, a time saving of 47 min per work order was recorded, which, implicitly, resulted in a £46 saving per job. Considering the average number of jobs that are scheduled in the NCC per year, the total cost saving is of £63,000, while requiring only 13% of the original time (i.e. manually recording material out-life, requesting materials).

51.6 Use Case Conclusions

An asset tracking and monitoring solution such as the one proposed by the present use case could potentially have an outstanding impact on the cost and quality of production for any manufacturing facility, using, or intending to use large numbers of assets. A key benefit of the proposed solution is also the ability to automatically monitor product work life for assets that possess time sensitive properties, leading to savings up to £200,000 a year in stock.

Also, another key benefit is the system's capability of recording asset availability, either in the form of stock quantities for consumables or maintenance requirements for tooling. The Plataine TPO system allows to keep a record of the material stock based on its weight and it can be automatically updated via the Siemens Opcentre and TPO communication channel. This can lead to a better understanding of a facility's stock management practices, while tooling usage and maintenance monitoring can lead to an improvement in quality by driving down the number of non-conformances resulting from improperly maintained tools (e.g. savings of up to £200,000 pounds per year for tooling reconditioning).

Also, the number of manual steps required from the end user is small, taking only 13% of the original time to request material stock, update its weight post-manufacturing and record part manufacturing data. This considerably improves the efficiency of the process and minimises human error (e.g. manually recording material out-life).

The proposed test bed shows to be an adequate mean to communicate RFID data around a production shopfloor; and, while there are a number of tasks to be completed to improve the robustness of the existing system, the proposed solution appears to have great potential for a reliable real time asset tracking solution. In the short term, there are a number of pending activities to be completed to improve system reliability. These include testing a 5G connection in the 'AFP' station to reduce the likelihood of the reader to disconnect from the system and enabling the communication between the MES solution and TPO.

52 5G INDUSTRIAL ASSESSMENT

52.1 4G LTE and 5G Network Testing

A number of tests were carried out within the NCC factory to ensure that each RFID station was connected to the Encode network either via 4G, 5G or POE. At the time of writing, the ‘Tool Storage’ station was not online as an additional switch was required to connect the gate to the Encode network. Thus, the gate was not included in any of the testing below.

For both 4G and 5G, the network performance was evaluated by simply executing a ping test in the ‘Command Prompt’ window to determine the latency and packet loss experienced at that port. Also, during the application tests, the network is monitored to assess its performance during the entire manufacturing process.

Two major testing periods were delivered:

- January 2021 – evaluating the performance of the 4G testbed (formally referred to as 4G testing).
- November 2021 – assessing the network performance of the testbed with the 5G router installed in the ‘Thawing’ station and the upgraded 4G network (often described as 5G testing).

These consisted of running an application test in parallel with a network diagnostic and link the test bed performance to the respective network metrics.

52.1.1 4G LTE Testing and Outcomes

For the 4G baseline, each station was pinged 50 times and the packet loss and latency were measured. The results are shown in Table 1.

Station	Packet Loss (%)	Min Ping (ms)	Max Ping (ms)	Average Ping (ms)	4G Signal (dBm)
Freezer	0	22	470	81	-62
Thawing	6	21	105	79	-70
AFP Coriolis	8	22	541	84	-59
Autoclave	0	0	0	0	N/A
NDT	0	25	113	66	-62

Metrology	0	22	217	73	-49

Table 12 4G RFID Stations – Ping test data

The average ping measurements were found to be less than 100 ms for every station, which for this application, it was considered of adequate value. However, the maximum ping values were alarmingly large in some of the areas, including the 'Freezer' station and the AFP Coriolis cell. These were deemed as outliers from the average; however, the asset tracking solution at the time still performed relatively poorly in the 'Freezer', 'Thawing' and 'AFP' stations from the end user's perspective. These issues were detailed in section 4.1.2 '4G Test Bed Limitations'.

Further investigations were conducted at the time in those cells. The signal strength was monitored for 100 seconds to investigate both the consistency and the magnitude of the signal in each station. The recorded values in decibel-milliwatts (dBm) are also summarised in Table 1. As a general rule, a value greater than -73 dBm indicated a satisfactory signal strength. As all seven stations recorded values above the lower limit, it was concluded that the 4G Siemens routers were an adequate mean of communicating data between the asset detection hardware and the server.

Looking into the packet loss measurements from January 2021, it was thought that those could be a result of potentially poor signal strength or electromagnetic interferences. For the 'AFP' station, the signal strength was one of the highest observed among the seven different cells and it was concluded that interference was a more likely cause for the poor network performance in the area (e.g. high voltage supply unit powering the AFP robot, a roller door isolator switch located in the proximity of the RFID gate). As previously mentioned, the packet loss appeared to affect the Plataine asset management system, leading to the RFID gate becoming not operational.

Similarly for the 'Freezer' and 'Thawing' stations, there were a number of interference sources in these areas, including high voltage power lines, an IT server room and numerous large metallic structures located next to the stations. In all three areas, the interference was occurring in the lower frequency spectrum (1.8 – 2 GHz), affecting the 4G network.

It was thought that by changing the bandwidth frequency (i.e. upgrading to a 5G connection that acts in the higher frequency spectrum) the network performance could be improved.

Another hypothesis was that the stations were subject to shadowing effects caused by the presence of obstacles that were obstructing the signal from the 4G cell to the RFID gate.

A network upgrade was successfully completed and an improvement in the packet loss and response times was observed (4% – maximum packet loss in the 'AFP' station and 2% - maximum packet loss in the 'Thawing' area). The minimal packet loss that was still seen in the AFP cell did not appear to greatly impact the tracking as the asset location was updated in real time and all tags were correctly detected by the gates. However, as the testbed performance in the 'Acclimatisation' station was still highly unsatisfactory.

Further network performance metrics on the upgraded 4G LTE network were provided as part of an application test conducted in July 2021. The network performance was monitored for the entire test period, between 09:00 AM and 11:30 AM on the day. The recorded metrics are provided in the graphs below.

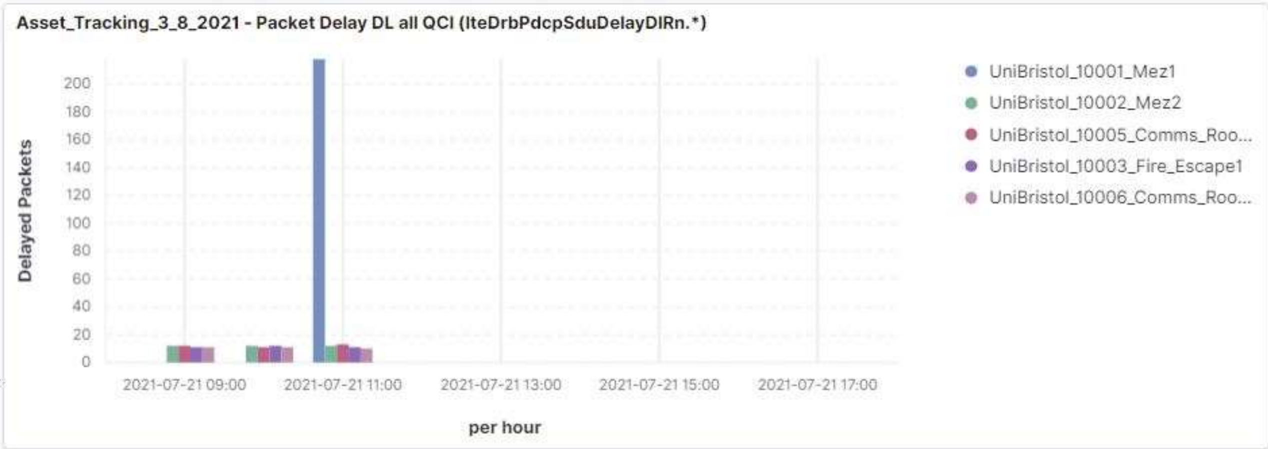


Figure 71 Packet Delay (Latency)

Regarding the latency results (Figure 15), the measurements indicate consistent average values of 10 to 13 ms across all cells, with the exception of one, where values of up to 210 ms were recorded. The extreme values seen in this cell ('Thawing' station – UniBristol_10001_Mez1 in the plot legend)) were believed to be caused either by poor coverage from the network cell or interference in the 4G bandwidth. For the rest of the cells, the recorded latency values were deemed as satisfactory.

Comparing these values with the network metrics previously recorded during the January tests, an improvement in latency could be seen in most areas, exception being the 'Thawing' station. This consolidated the team's decision to deploy a 5G network connection in this particular station on the factory floor.

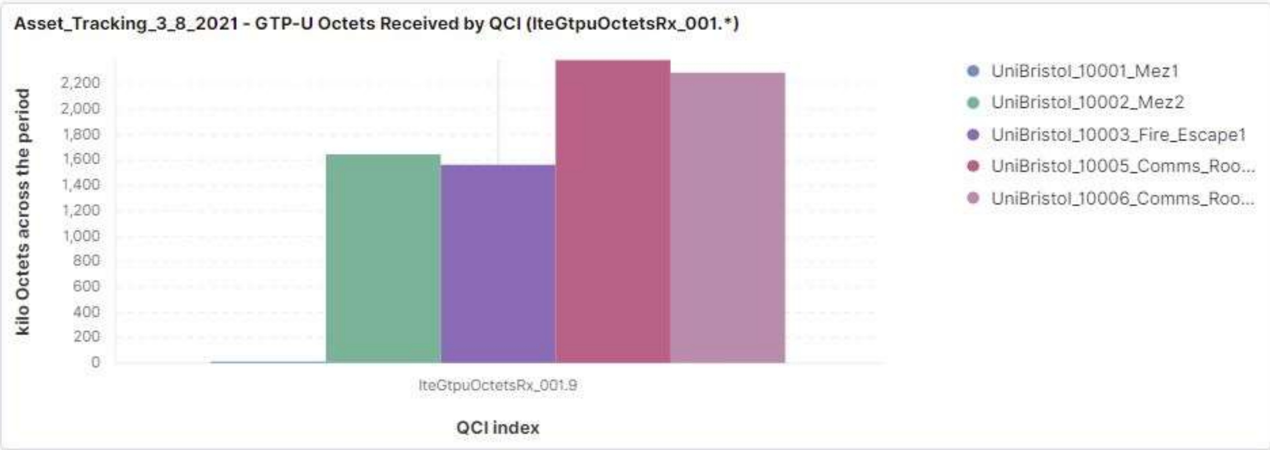


Figure 72 Downlink Throughput

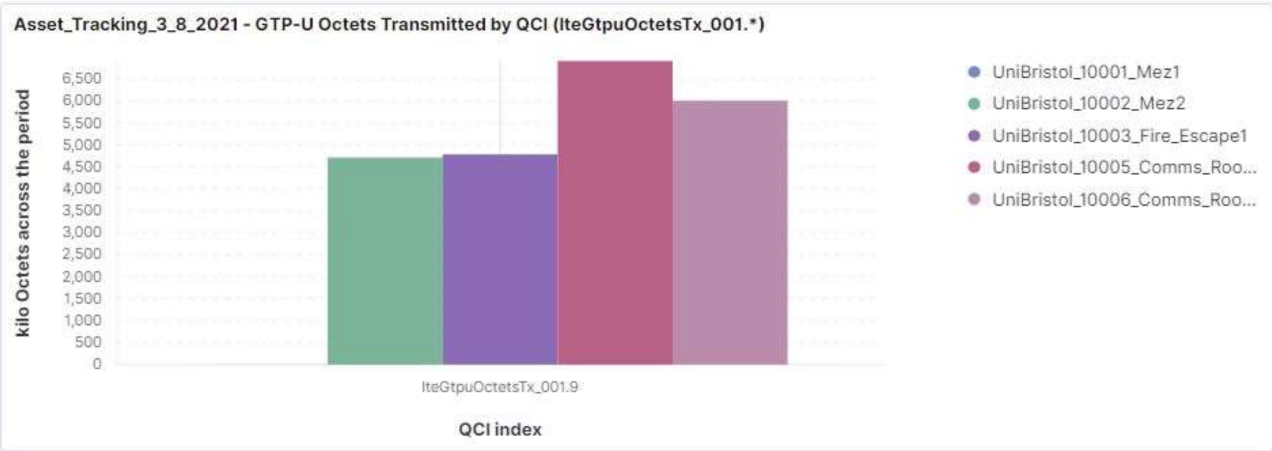


Figure 73 Uplink Throughput

The traffic generated by the RFID tags was also monitored for both uplink and downlink. The recorded values in the shopfloor areas are shown in Figures 16 and 17. Peak traffic values of 380Kb (downlink) and 80Kb (uplink) or above were considered as satisfactory. Thus, based on the recorded data, the results were deemed as acceptable.

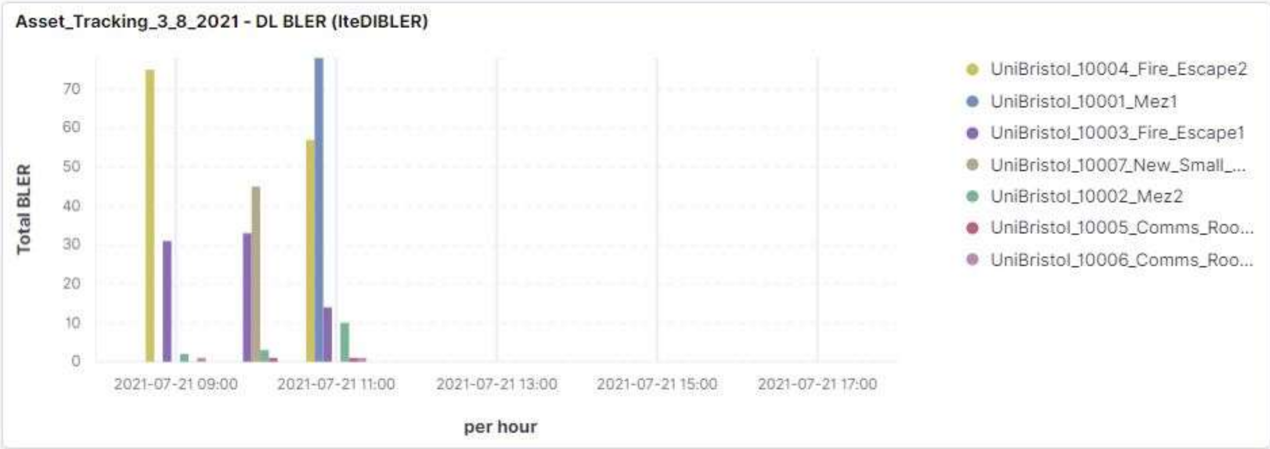


Figure 74 Block Error Rate – Downlink

Figure 75 Block Error Rate – Uplink

The block error rate – BLER – (Figures 18 and 19) was also recorded as part of the 4G network test. The metric is defined as the ratio between the number of received erroneous packets of data to the total number of transmitted packets, reflecting on the RF channel condition as well as on the level of interference experienced by the system.

Values between 2 to 5% are considered satisfactory for a 4G wireless connection; thus, for some of the cells, the high BLER results represented a concern. The causes of the poor block error rate performance seen in some of the areas were still unclear at the time, but it was believed these were related to either poor network coverage in some of the cells or the presence of interference.

No packet loss was seen throughout the test period.

Due to the poor network performance recorded in the 'Thawing' area, also proved by the additional network metrics measurements, it was decided for the cell to be upgraded to a

5G connection. It is important to understand that with a 4G cellular connection the likelihood of encountering a certain level of packet loss is higher than for a wired POE connection. However, as the recorded values in the 'AFP' station were meeting the requirements for a wireless connection, these packet loss values were deemed acceptable.

52.1.2 4G Test Bed Limitations

The 4G test bed presented a number of performance issues that were directly linked to 4G network limitations. Increased packet loss and latency represented a concern in two main areas, 'Thawing' and the AFP Coriolis cell. A detailed description of the tests carried, and their respective results are captured in section '4. 5G Industrial Assessment'.

The poor network performance directly affected the test bed performance. One of the main challenges was capturing all instances of the asset moving between stations due to packet loss. In the case of time sensitive assets, for instance uncured composite materials, missing the instance the material moved in or out of the freezer could have meant that the recorded time the product spent at room temperature was not accurately captured.

Another issue was the delayed location update in the web application as the asset moved passed an RFID gate. In this case, the location of the asset was not representative of its physical location, making the system less reliable and accurate.

Also, the recorded packet loss did appear to affect the Plataine asset management system, as well as the connection consistency of the reader to the 4G network. The web application is configured to notify the user if any packet loss is recorded by sending a notification in the user interface. Then, the reader is rebooted, and the network connection is established again. However, it was often required to reboot the reader manually by switching it off and on, as the RFID gate would not be operational.

The cause for the unsatisfactory network performance was down to be the presence of electromagnetic interferences in these two areas. The main sources of interference were identified as the high voltage supply unit that provided power to the AFP robot in the Coriolis cell, as well as large structure cells and the NCC's uninterrupted power supply for the IT server room located in the 'Thawing' and 'Freezer' areas.

A network upgrade was completed and enabled a more stable 4G connection, and also an improved user experience when using the test bed. This upgrade consisted in increasing the 4G frequency bandwidth from 5 MHz to 20 MHz. Some minimal packet loss could still be observed in the AFP Coriolis cell; however, as these values were within the tolerance requirement for a wireless network, it was not a concern for this use case.

The signal strength and implicitly the slow response times recorded in the 'Thawing' area still paused some issues (i.e. slow location update of the assets in Plataine TPO resulting in a less representative real time asset tracking solution). Thus, as the use case had only one available 5G router, it has been decided to upgrade the network connection in the 'Thawing' area to a 5G one.

52.1.3 5G Testing and Outcomes

Similarly to the 4G tests, the 'Thawing' station was pinged 50 times and the packet loss and latency were measured. The 4G network connection in the rest of the cells was also monitored. These network metrics tests were performed regularly over a period of three weeks and the average values were summarised in Table 2.

Station	Packet Loss (%)	Min Ping (ms)	Max Ping (ms)	Average Ping (ms)
Freezer	0	26	113	69
Thawing*	0	11	41	26
AFP Coriolis	2	25	114	70
Autoclave	0	0	0	0
NDT	0	25	114	66
Metrology	0	23	115	72

Table 13 Upgraded 4G and 5G RFID Stations – Ping test data

* Thawing area was upgraded to a 5G network. All other areas remained connected to a 4G network (i.e. wireless or POE connections).

The end user experience in the 'Thawing' station was drastically improved after the upgrade to a 5G network connection. No packet loss was experienced over the 3-week monitoring period. The response times were also considerably improved with values as low as 11 ms. These metrics corresponded to a better asset tracking experience consisting in faster updates in the web application and high system reliability in monitoring tagged assets. It appears the 5G connection in this station addressed all performance issues that were causing great inconveniences for the end user when engaging with the test bed.

A correct asset location update was considered crucial for this use case. If any RFID gates had not successfully detected a moving asset between stations, its location would not have been correctly updated in the user interface. This would have led to delays in identifying the correct location of the item and, for time sensitive products, if not correctly detected by the antennas, their remaining out-life would have not been captured accurately.
Thus, the improvements brought to the network improved the test bed performance.

52.1.4 5G Pre-requisites for Use Case Application

The 5G network capabilities at the NCC are summarised in Table 3.

Network Metric	Metric Value
Latency	< 10 ms
Uplink speed	Approx. 57 Mb/s
Packet loss	0 %

Table 14 U5G Use Case Requirements

Looking at the network metrics values recorded as part of the 5G testing, the average latency was 26 ms, with a minimal value recorded of 11 ms. The uplink speed was also recorded as varying between 5 to 24Mb/s, with 0% packet loss recorded throughout the 3-week monitoring period. Even though, these values are below the expected 5G network performance capabilities, from an end user experience, the data transfer is fast and representative of the live location of the asset. 0 % packet loss also minimises the likelihood of missing a tagged asset as it passes an RFID gate. Thus, the reliability of the system in detecting the asset and updating its location is improved.

It can be concluded that, with the current 5G network, all interference and performance issues recorded on the 4G test bed have been addressed and the recorded network metrics values were satisfactory to meet use case requirements. It would be of interest to assess the impact of a 5G connection on the test bed performance in the 'AFP' station.

52.2 5G Discussion

52.2.1 Benefits of 5G

5G wireless systems are expected to be enablers for factories of the future, addressing the existing limitations of the 4G LTE technologies. Higher speeds, lower latencies and the capability of connecting many end devices without affecting network connectivity and stability are just a few of the improvements proposed by the fifth-generation mobile network. Those are also key network requirements for our use case.

Compared to a 4G connection, 5G offers reduced latency and higher upload speeds (up to 57 Mb/s in the uplink) that facilitates the quick update of the asset location once detected by the RFID gate. For this use case, a maximum latency of up to 10 ms is required, easily achieved with a 5G network connection. Therefore, compared to the 4G baseline, the 5G network considerably improved the user experience when using the asset tracking test bed, offering accurate real time information on the asset location (i.e. 11 ms latency).

As highlighted in a previous section ('5G Testing and Outcomes'), the user experience in the area upgraded to a 5G connection was drastically improved after the network upgrade. No packet loss was recorded over the 3-week monitoring period, improving network reliability in the area.

Another major benefit of 5G is its capability to allow many end devices to connect simultaneously to the network. In a production facility where multiple RFID gates might be required to cover large manufacturing units, 5G can provide a reliable connection to a high number of smart devices, without compromising its performance (i.e. speeds, latency, connectivity). Also, larger data transfers can be managed on a 5G connection, allowing to easily track a large number of assets.

As proved by this use case, 5G also removed the main sources of interference, otherwise specific to a production environment, by moving the bandwidth frequency higher in the spectrum. Based on the original assumptions, the poor network behaviour was related to the existing signal to noise interference in the cell.

52.2.2 Limitations of 5G

Capacity

The 5G connection at the NCC proved to be reliable and address all performance issues identified on a 4G connection. However, the use case employed a minimal number of assets to be tracked and only one RFID gate connected to 5G. It would be of interest to assess the capabilities of 5G by deploying the connection in other stations on the factory floor, while tracking a larger number of assets.

Device availability

5G is still a relatively new technology, with a limited number of devices available on the market (i.e. 5G CPE routers or 5G enabled sensors), which made testing of business cases particularly challenging. As the 5G standalone technology evolves, it is expected that the range of smart devices compatible with a 5G connection will expand as well.

IT skills and knowledge

Having a strong knowledge and understanding of networks proved crucial as well to ensure that both the 4G and 5G network deployed within the NCC were robust and functional. Also, enterprise IT departments are usually not accustomed to dealing with cellular technology and the implicit requirements; thus, promoting a continuous information exchange across the industry would enable a faster development of infrastructure and technology, while minimising the implicit costs of deploying 5G.

5G network performance

For a 5G network, the download speeds are considerably higher compared to the upload speeds (e.g. 400 Mb/s downlink speed, 57 Mb/s in the uplink – NCC capabilities). However, the upload speeds achieved within this use case appeared satisfactory for a real time asset tracking solution. But as the number of connected end devices scales up, there could be capacity limitations that need to be accounted for.

52.3 5G Conclusions

An asset tracking solution as proposed by this use case could potentially bring great financial and quality assurance benefits to any manufacturing setting, such as a reduction of approx. 93% in asset search time, boosting productivity and minimising time waste, while closely monitoring material out-life, which ensures the final component performance.

The 5G network connection did prove to considerably improve the test bed performance and bring a better and more representative real time asset tracking experience to the end user compared to the 4G baseline.

As the 5G network is less sensitive to RF interferences, a more robust and stable connection was provided to the 5G asset tracking test bed, enabling real time updates of item locations in the user interface and minimising packet loss (i.e. robustness in correctly detecting the assets and recording their location). 5G proved to be a reliable solution in the 3.6 GHz to 3.8 GHz frequency range; moving away from the various interferences seen at specific locations as described above.

In production environments where the number of RFID gates and tracked assets is considerably high, the data upload can be easily completed via a 5G connection without compromising the network performance (i.e. connectivity, speeds, latency). Based on the recorded network metrics, a 5G connection provides fast response times (down to 11 ms), 0 packet loss and upload speeds of up to 24 Mb/s that drastically improved the overall performance of the test bed. However, those were recorded while handling a relatively small number of mobile assets. It would be of great interest to assess if, for a larger number of assets, the same network metrics are recorded.

The proposed solution is not perfect and further work is required to assess the potential of 5G in asset tracking. However, compared to the 4G baseline, 5G proved to be an efficient mean to communicate RFID data around a production environment, placing the foundations of a potentially ground-breaking cellular technology asset tracking solution.

53 REFERENCES

[1] *Smartt Tag Ltd Rfid Solutions*. SmarTT Tag Ltd RFID solutions. (n.d.). Retrieved December 9, 2021, from http://smartt-tags.com/.

54 APPENDIX A – DATA CAPTURED AS PART OF THE MANUFACTURING PASSPORT

- Material Passport: Information related to the material – In-Transit data:
    - In transit shipment date
    - Material code/lot/type references
    - Quantity
    - Weight
    - Date of manufacture
    - Storage condition
    - Shelf/out of life

- Material Passport: Information related to the material – In-Factory data:
    - Arrival date from supplier
    - Storage location
    - Storage condition
    - Material movements
    - Maximum exposure work time
    - Maximum exposure tack time

- Preform Passport: Information related to the cured composite part – Manufacturing and inspection data:
    - Manufacturing information
    - Date of manufacture.
    - Manufacturing method
    - Process key parameters.
    - Equipment and tooling
    - Curing information
    - Date of curing.
    - Cure data sheet
    - Process key parameters.
    - Equipment and tooling

- Inspection information
    - NDT and metrology requirements.
    - NDT and metrology report
    - Key Process parameters.
    - Equipment and tooling

55 APPENDIX B – SIEMENS OC AND PLATAINE TPO INTERACTION

The asset tracking solution proposed by this use case consists of two systems: a manufacturing execution system (MES) – Siemens Opcentre – and an asset tracking web application – Plataine TPO. To minimise the number of steps that technicians, engineers or other technical authorities are required to complete and the manual input of data (e.g. recording material out-life, requesting material stock), it was desired for the two systems to independently exchange asset information.

The first step is to generate a sequence of operations representative for the process flow that is to be followed, for instance the AFP process. These operations have to be linked to work areas or units, as well as to a sequence of steps describing each action to be completed in the operation. Figure 19 shows a number of operations and their implicit relations for an AFP process.

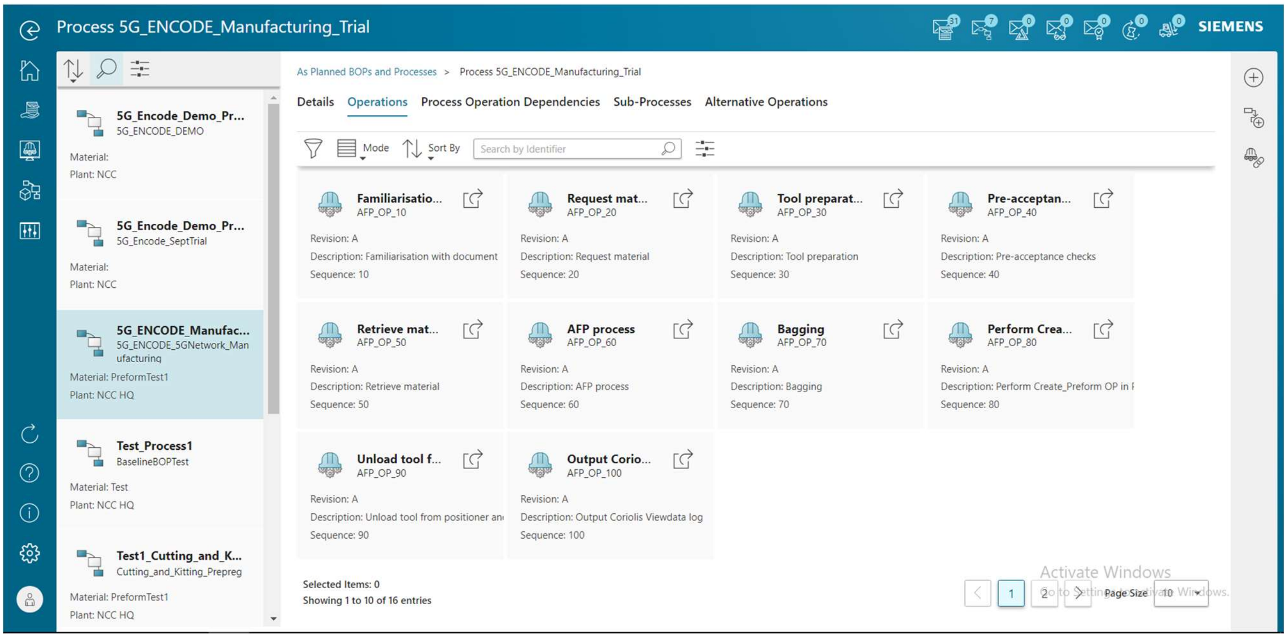


Figure 76 Operations sequence created in Siemens Opcentre for an AFP process

At the step level, it is of great importance to specify the material that is to be consumed and its quantity, for instance the number of plies of prepreg, in order to link the material managed by TPO to the work order created in Opcentre, as presented in Figure 20.

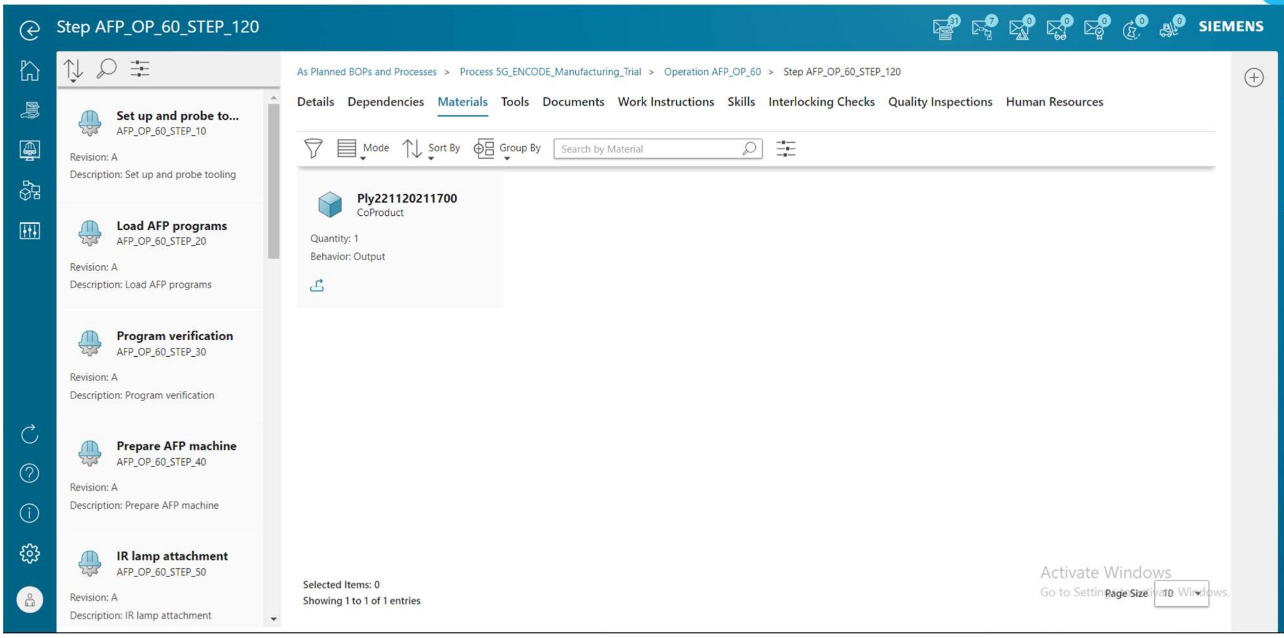


Figure 77 Step and material relation in Siemens Opcentre

The material product is to be stored in the Opcentre materials catalogue as a composite and be attributed a ‘CompositeMaterialINId’; an example of a material entry in Opcentre is offered in Figure 21. This ‘CompositeMaterialINId’ is the material name associated to the spools of AFP tape, for instance, in Plataine TPO.

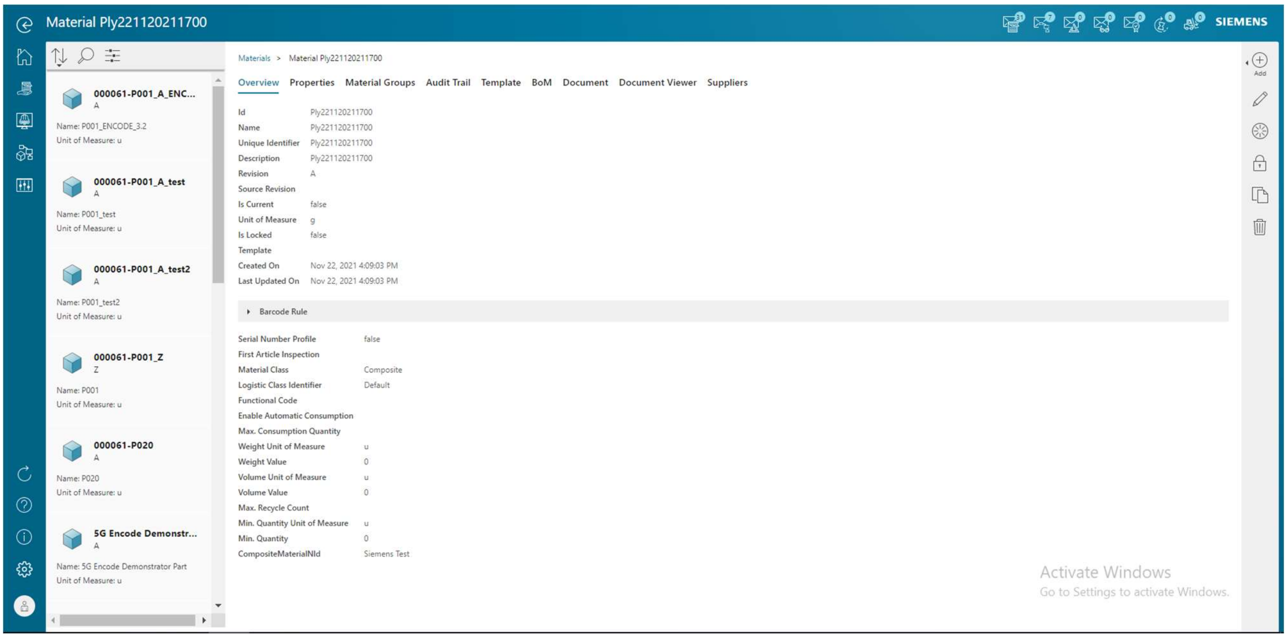


Figure 78 Material entry in the Opcentre ‘Materials’ catalogue

Once the process is released and a new work order is generated from this process, the sequence of operations can now be scheduled in APS (Siemens software for scheduling Opcentre work orders). The user interface of the scheduling tool is captured in Figure 22.

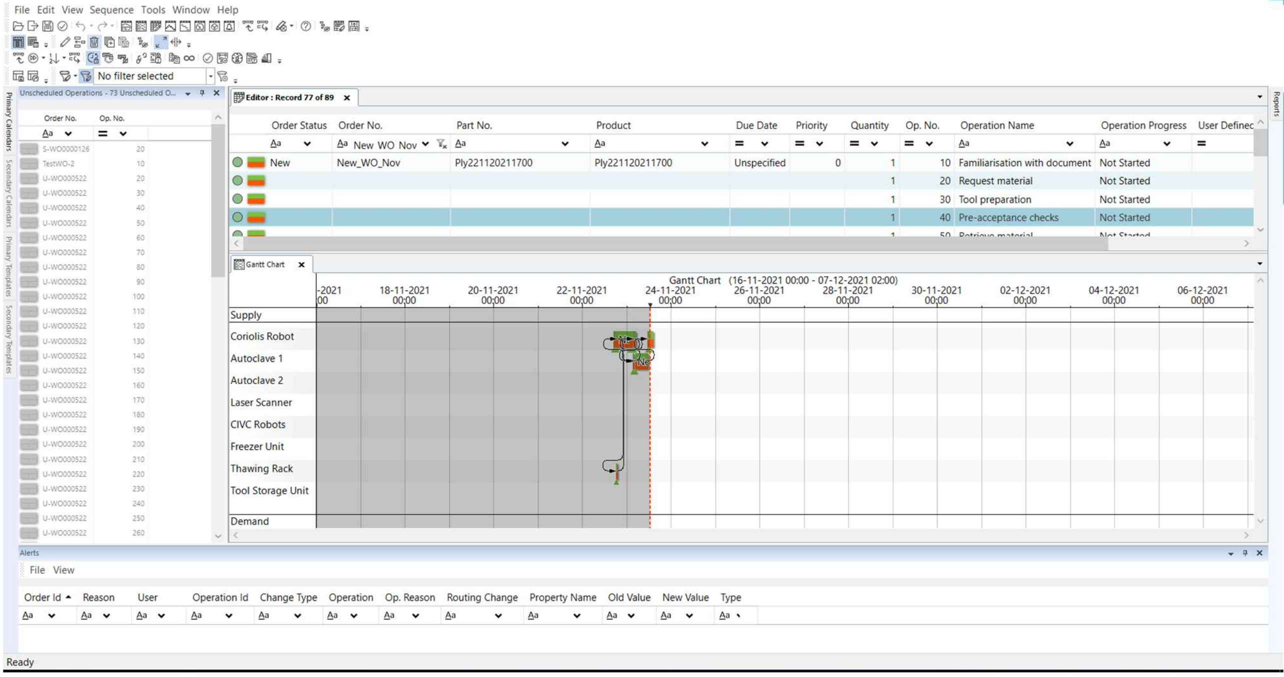


Figure 79 Siemens APS user interface

At this stage, the spools of material in Plataine, depending on the available stock, are associated to the respective step in Siemens Opcentre. Once the material is linked to a process, the spools of prepreg are moved to a 'Pick list' environment in TPO (Figure 23) to prevent the material from being assigned to multiple work orders simultaneously.

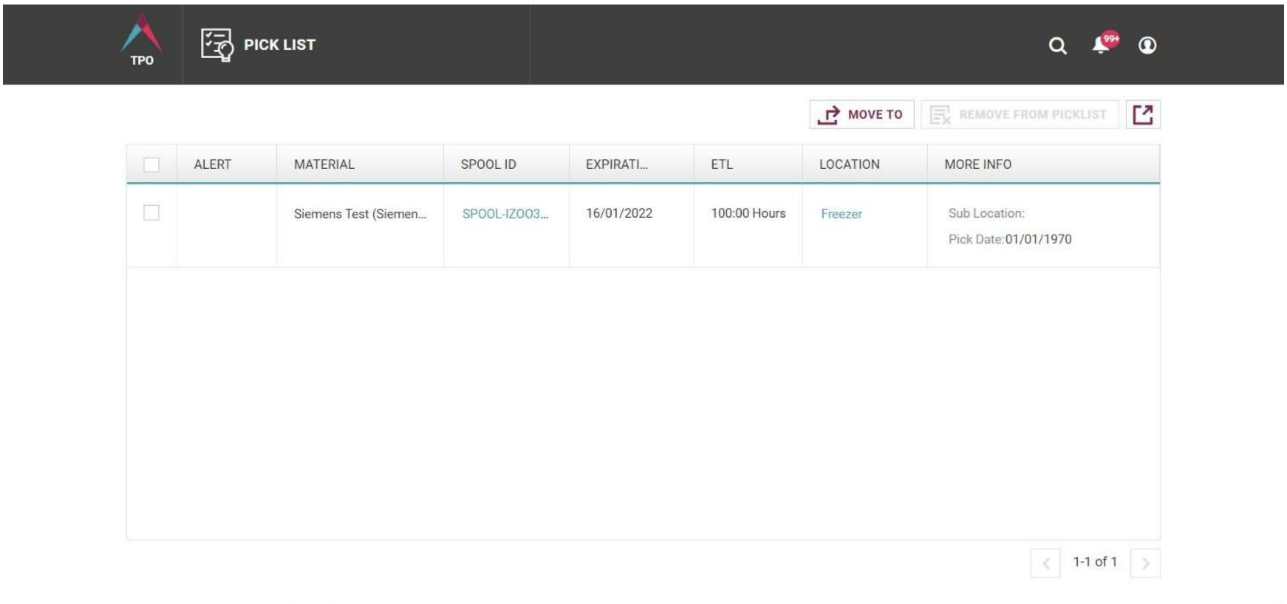


Figure 80 Plataine TPO 'Pick List'

In the 'Operator Landing' environment, where operations are signed off by the technicians or other technical authorities, it is possible to review the material information captured in TPO, including batch ID, available stock, as well as shelf-life or data. The operator user interface in Opcentre is captured in Figure 24.

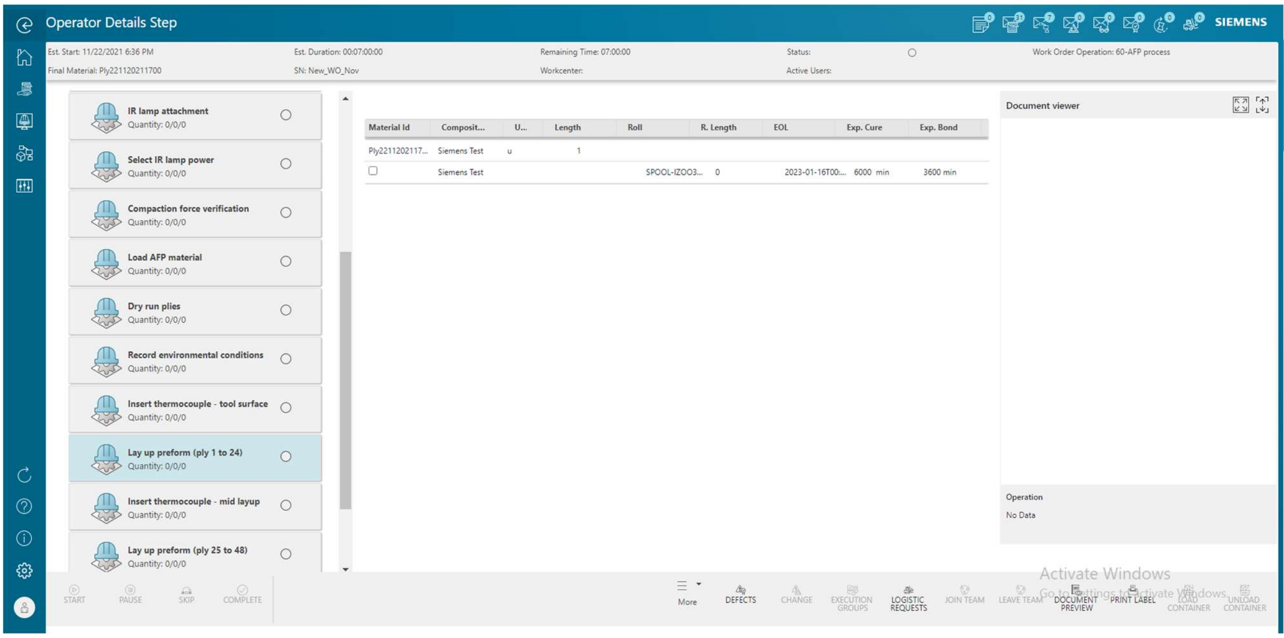


Figure 81 Material information retrieved in the Opcentre 'Operator landing'

Within this window, it is possible to update, in Plataine, the available material quantity that has been consumed during manufacturing (i.e. the remaining material stock) or request additional material spools if required. Thus, the data can be easily captured and updated as the operation is completed in Opcentre.

Once the work order steps and operations are signed off in Opcentre and the process is completed in APS, the material will be released back in the 'Material Smart Selection' environment. This window is a live catalogue of the available materials that can be used in any future work order.

56 – ASSET TRACKING OUT-OF-FACTORY –

5G-encode

57 ABBREVIATIONS

DCMS	Department for Digital, Culture, Media, and Sport
NCC	National Composites Centre
MAT	Material Asset Tracking
OEE	Overall Equipment Efficiency
BOM	Bill of Materials
IT	Information Technology
OT	Operational Technology
RFID	Radio-frequency identification
ATEX	Explosive Atmosphere *(from French "Atmosphères Explosives")*
PoE+	Power over Ethernet Plus
PoC	Proof of Concept
FLT	Forklift Truck
MES	Manufacturing Execution System
CAPEX	Capital Expenditures
OPEX	Operating Expenses
NIST	National Institute of Standards and Technology
ERP	Enterprise Resource Planning
LIMS	Laboratory Information Management System
TPO	Total Production Optimization
GPIO	General Purpose I/O
SaaS	Software as a Service
GUI	Graphic User Interface
MAT	Material & Assets Tracker
EIRP	Effective Isotropic Radiated Power

58 EXECUTIVE SUMMARY

5G-Encode is a £9 million collaborative project partially funded by the Department for Digital, Culture, Media, and Sport (DCMS) with the aim of developing clear business cases for 5G applications in the composites manufacturing industry. Solvay was a partner in the industrial use case evaluating asset tracking of time sensitive materials.

The asset tracking evaluation work package was delivered in collaboration with Plataine Ltd which provided the TPO application and the NCC, Bristol which provided the test bed for the private 5G technology evaluation. The NCC test bed was delivered together with Zeetta Networks, Toshiba, Mativision, Plataine, Siemens, Telefonica, Accedian and the High-Performance Networks Group from the University of Bristol as partners.

As a leading supplier of composite materials, Solvay evaluated the potential of the automated asset tracking technology from a material manufacturer perspective. Solvay, based at a site in Wrexham, supplied to the NCC the composite materials required for the evaluation of the automated asset tracking use case from a material manufacturer site to a customer site perspective.

The project highlighted the potential benefits of automated asset tracking in terms of waste reduction and OEE improvement from a composite materials manufacturer perspective. Potential for full automation of currently manual or semi-automatic quality tasks or ERP transactions was also highlighted. Solvay has decided to pursue further the evaluation of automated asset tracking technologies following this project.

At this stage the benefits of, in factory, 5G cellular technology to support an automated asset tracking system deployment at the Solvay, Wrexham site compared to a conventional PoE+ approach remains unclear. Further evaluation would be required before any full deployment of automated asset tracking across the Solvay's multiple Wrexham sites.

59 INTRODUCTION

Solvay Materials, part of the Solvay Group, is a global supplier of adhesives and composite materials with a strong manufacturing footprint in the UK (Cytec Engineered Materials Ltd). Solvay Materials is currently progressing its digital transformation journey with a strong focus on automation. The Wrexham site, located in North Wales, was selected to explore the potential of automated asset tracking.

The Solvay Wrexham site manufactures prepregs (fibres combined with resin) on multiple reinforcements as well as resin systems for infusion, resin transfer moulding systems, adhesives and potting compounds for the composites Industry. Solvay products manufactured at the Wrexham site are supplied to many industries globally including aerospace, motorsports and high-performance automotive.

Solvay Wrexham site was established in 1982 and has been growing ever since with the addition of the European R&I centre for composites in 2005 and the most recent site expansion with the completion of the European Adhesive manufacturing plant completed in 2015. The Solvay Wrexham site now employs approximately 250 people in production, R&I, technical service, finance, human resources, logistics and procurement.

Solvay was a project partner in the asset tracking work package. Solvay main contribution to this work package was as a material supplier of composites materials, from the factory located in Wrexham, for the case study deployed at the NCC, Bristol. The first Solvay objective was the evaluation of, in factory, automated asset tracking and its potential at the Wrexham manufacturing site. Another objective was the monitoring of the 5G cellular technology being trialled at the NCC to better understand its potential for a full roll out of automated asset tracking across its multiple manufacturing sites. A third objective for Solvay was the evaluation of the potential of automated asset tracking as an enabler for increased vertical integration between composite materials suppliers and composite materials part manufacturers, including potential for in-transit asset tracking.

59.1 Project Objectives

- Automated asset tracking within factory

The manufacturing process of composites materials involves the production of multiple intermediates required for the manufacture of the final goods which can bring some scheduling challenges (see Figure 82). Most of the intermediates as well as most of the final goods are also time and temperature sensitive. This means that they have a maximum time allowed at room temperature to maintain their critical quality attributes. This maximum allowed time is commonly referred to as out-time. When not in use, intermediates must be stored in cold storage, typically in freezer below -18°C. This is to preserve their valuable out-time. However, intermediates must also be fully deforested before being used in secondary operations. This brings extra complexity to the operation planners and production supervisors. The real time and automated tracking of material assets throughout the manufacturing shop floor and freezers is believed to have the potential to optimize production scheduling, preserve valuable material out-time, reduce wastes and maximize overall equipment efficiency (OEE) of production assets.

The first objective of Solvay will be to evaluate RFID technology for automated asset tracking of a selected number of intermediates and final goods to understand the reliability of the technology and how much of the aforementioned benefits can be harvested.

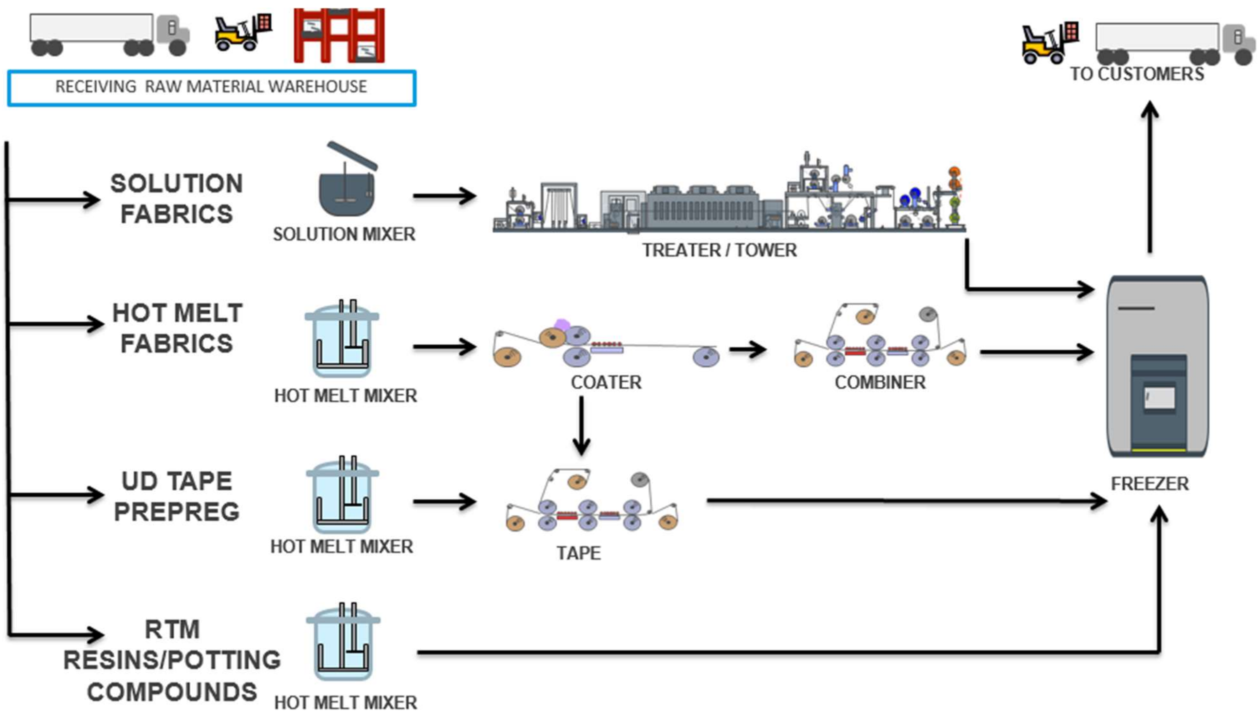


Figure 82: Schematic of manufacturing process.

- Automated out-time tracking within factory

Composite materials and their intermediates are extremely high value products. Any such products which have to be scrapped due to an excessive out-time consumption is extremely costly. By associating the defined locations of the shop floor with their respective physical temperature, the automated tracking of materials can be used to monitor real time their out-time consumption. For example, when a material asset is detected in the freezer, it is given a temperature of -18°C, or a frozen status. When it is on the production shop floor, it is given a status of defrosted, or room temperature. This automated tracking of out-time can be used to send automatic email warnings to production supervisors in case of unexpected consumption of out-time due to a delay in manufacturing for example. This would allow reduction or elimination of costly waste.

- Paperless and automation of operator tasks

The stringent quality requirements associated with the aerospace industry require operators to perform multiple tasks which are manual or semi-automatic. The automation of the asset tracking and out-time tracking could enable the full automation of BOM consumption, sub-lot pedigree, and out-time recording currently performed by operators.

- Digital material passport and in-transit tracking

The remaining out-time of a material is of great value to the manufacturing department of composites part manufacturer. Within this PoC, both Solvay and the NCC explored the automation of out-time tracking within their factory. Understanding the practical feasibility of automating the out-time tracking not only within a factory but throughout the entirety of the supply chain was also explored.

59.2 5G Potential

The installation of 5G cellular technology at Solvay Wrexham site was not part of Solvay's commitment to the work package. The main reasons are as follow:

- Cellular technology is not currently an acquired competency at site level.
- Due to its size and its unique technologies, the Solvay Group could be an attractive target for cyber-attacks. As a result, the Solvay Group has an extremely strict cybersecurity policy on IT and OT networks configuration and management. The deployment of a cellular technology as an OT network at its Wrexham site was not authorized at this stage.
- The Solvay Wrexham site has multiple ATEX-rated (explosive atmosphere) zones where conventional cellular technologies are not allowed unless ATEX compliant. The deployment of an ATEX-rated cellular technology would be prohibitively costly.

However, Solvay is interested in understanding further the potential fit of the 5G cellular technology compared with the PoE+ hardwire network technology selected for this automated asset tracking PoC.

60 OVERVIEW

60.1 System Requirements Development

The requirements for the automated asset tracking system were identified as follow:

- Must be fully transparent to current manufacturing process and not require any additional tasks from operators. (Of course, once the reliability of the system is proven, it must also reduce the complexity of the operators' tasks).
- Must be passive and not require the use of any battery-operated devices.
- Must not require the use of additional tracking device or labels to be added to the product packaging by operators.
- Must survive a high-rate industrial manufacturing environment where FLT's and pedestrian-pallet trucks are used for moving goods around the plant and onto trucks.
- Must survive the full distribution chain cycle from manufacturing, cold storage down to as low as -40°C and transportation by either road, sea or air.
- Low installation costs (CAPEX) and operation/maintenance costs (OPEX).
- Must be compatible with an industrial environment where ATEX-zones are present.
- Must not require a specialized skill set not currently supported within the Solvay Group. Must be easily maintainable.
- Must provide a high reliability and have the capability of self-diagnosis with automated alerts in case of system malfunctions.
- Must have the capability to be incorporated into the MES system once PoC is validated would Solvay decides to do so at a later stage.

Another critical requirement for this PoC was to meet Solvay cybersecurity and NIST 800-171 requirements as well as all export control regulations. For these reasons, a dedicated physical hardwire network was deployed for this PoC. We will refer to this network as the "asset tracking PoC network". This asset tracking PoC network was fully independent and physically separated from other Solvay IT and OT networks. There was no communication between the asset tracking PoC system and Solvay MES, LIMS or any other systems. This PoC was isolated and run in parallel and independently from Solvay operations. The deployment of this system based on hardwire network formed the basis for the evaluation of the relevance and potential of automated asset tracking.

60.2 Use Case Architecture

For this automated asset and out-time tracking PoC two roll-to-roll processes typical of a hot melt prepreg manufacturing process were selected as well as the productions freezers used to store the intermediates and final goods. The material assets were tracked all the way to their loading onto the reefer truck ready for dispatch, see Figure 83.

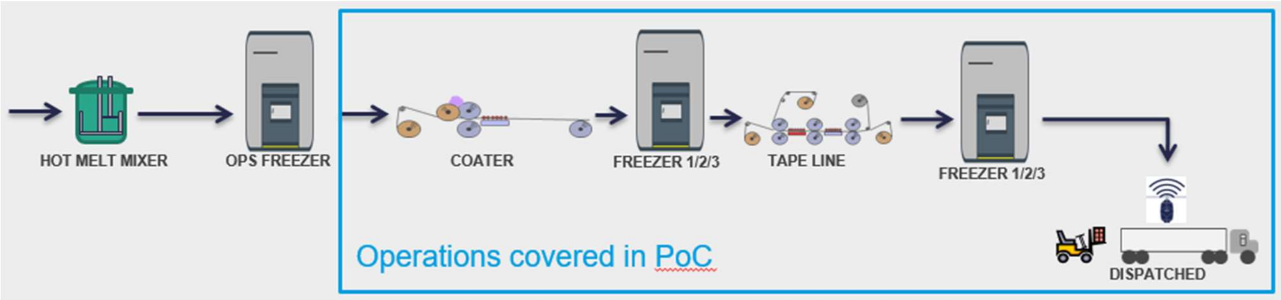


Figure 83: typical hot melt prepreg manufacturing process.

The two selected manufacturing processes and their associated workstation as configured in the Plataine TPO system for the automated asset tracking are:

- Hot melt resin coating, referred to as MSKR workstation in the Plataine TPO. See physical location in Figure 86;
- Hot melt prepreg process, referred to as MST4 workstation in the Plataine TPO. See physical location in Figure 86. An example of nine prepreg rolls boxed up and palletized for dispatched is shown below.

Figure 84: example of 9 boxed up prepreg rolls palletized and loaded by pedestrian-pallet truck for dispatch.

Passive RFID tags from Impinj were selected and laminated into our standard production labels media (see Figure 85). This approach ensured transparency to current production operations and no extra operator tasks, or labels were required.

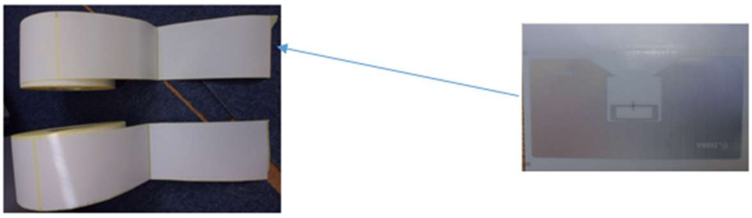


Figure 85: (top) production labels with RFID tag; (bottom) standard production labels without RFID tags.

To detect automatically the movement of the tagged material assets across the shop floor and freezers as well as their loading onto the reefer truck for dispatch, the shop floor was divided in zoned areas. Each zoned area was allocated a fixed temperature status (frozen, being defrosted or defrosted status) in order to allow the use automated location tracking data to compile automated out-time data. Between each of these zoned areas, an RFID gate was installed to detect the movement from one zoned are to another. See Figure 86.

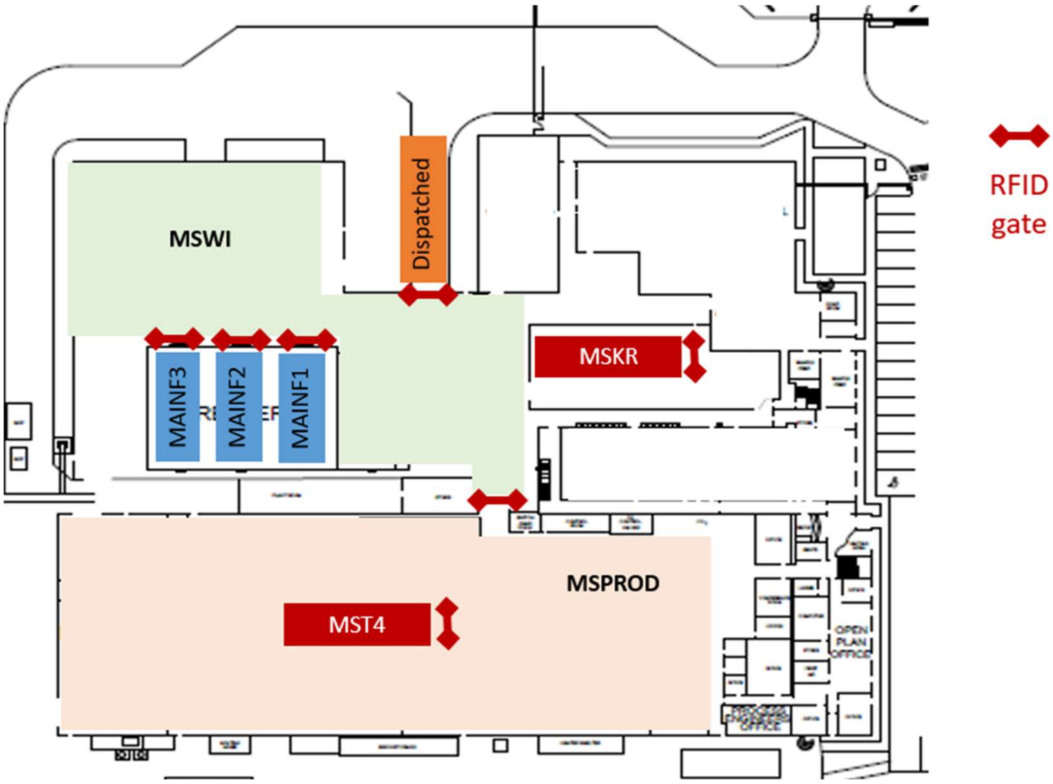


Figure 86: definitions of zoned areas and location of RFID gates for asset tracking PoC.

Each RFID gate is composed of the following elements:

- RFID antennae from Zebra
- Co-axial cables to connect the antennae to the reader
- FX7500 reader from Zebra
- Ethernet data cable
- Power supply (not required in this PoC due to the use of PoE+)

Note that the power supply requirement for the selected FX7500 readers from Zebra is a standard 24VDC but they are also compatible with PoE and PoE+.

The software solution selected to manage the automated material asset and out-time tracking is the Plataine TPO system (see Figure 87). Only the RFID connectivity was used within this PoC as well as the Material & Assets Tracker (MAT) module. Plataine TPO system is a cloud-based system with a SaaS GUI which present the advantage of a very easy deployment. It is already used successfully by multiple composite part manufacturers. Solvay was interested in evaluating this TPO platform for its material manufacturing operations. The configuration of the locations and workstations in Plataine MAT application is presented in Figure 88.

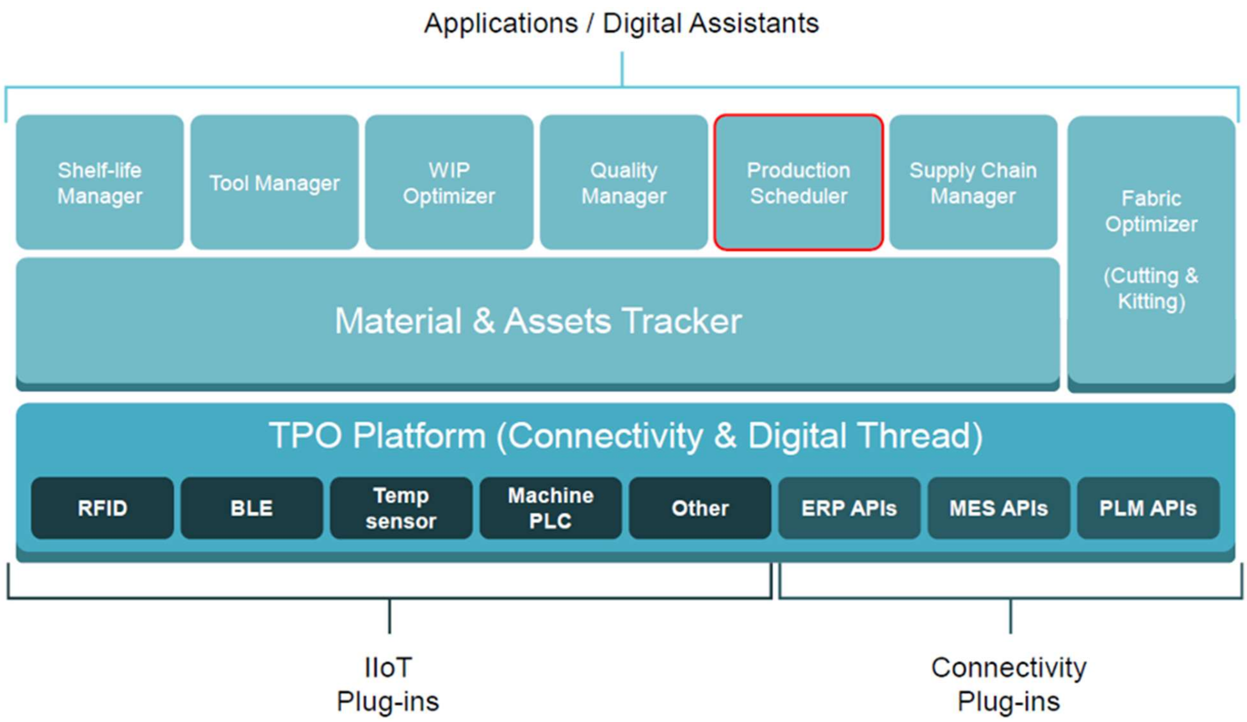


Figure 87: Plataine's TPO suite of applications.

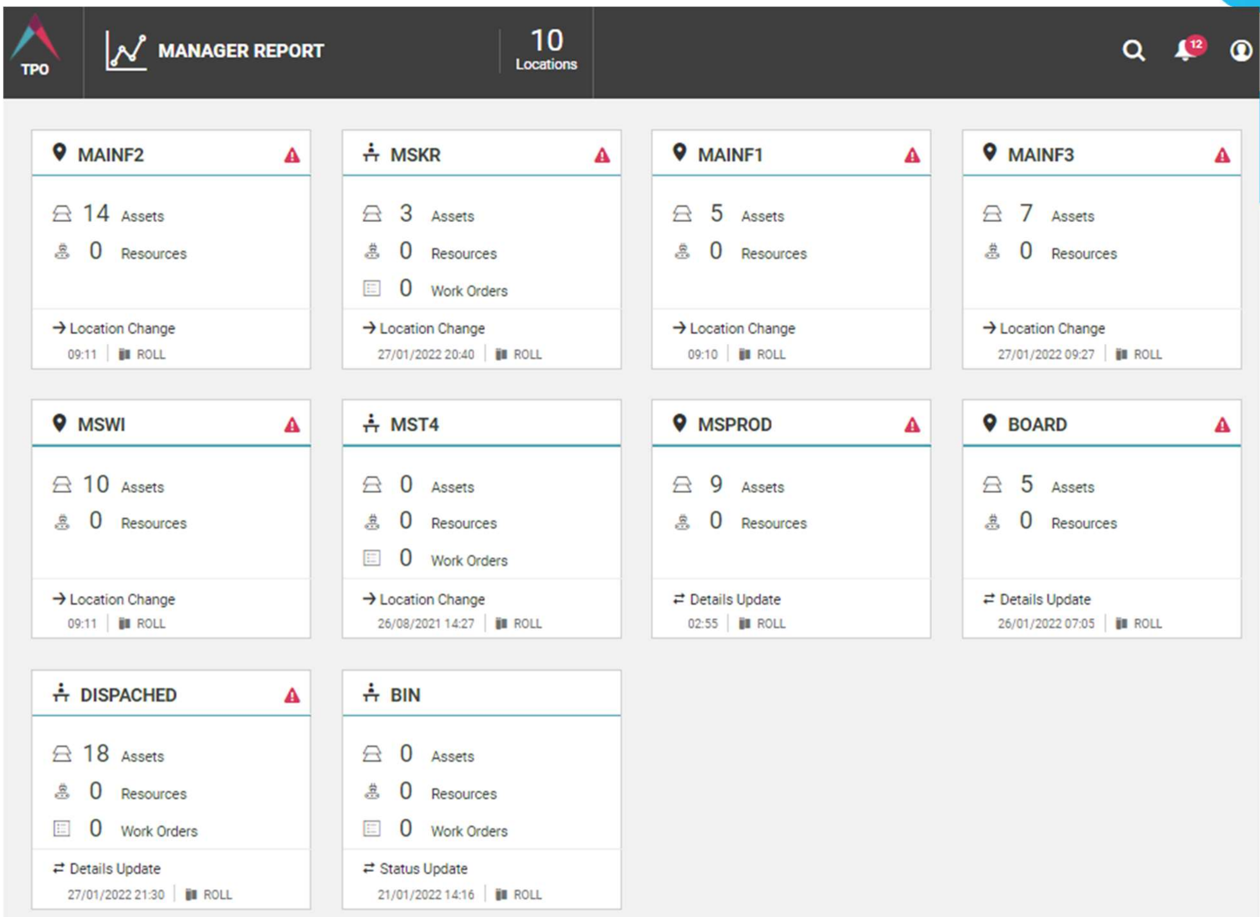


Figure 88: Locations and workstations configured in Plataine TPO for the PoC.

60.3 Use Case and Network Benefits

As discussed in the *5G Potential* section above, the deployment of 5G cellular technology at the Solvay Wrexham site was out of scope for Solvay. A more conventional approach has been taken to establish a performance baseline and then evaluate what potential benefits a 5G cellular solution could bring in any future roll out based on NCC, Bristol trials.

In terms of installation cost and safe permit to work in an industrial environment, it is cheaper and easier to install a PoE+ network than power supply lines and associated cellular hardware, etc. Since the Zebra readers were compatible with PoE+ only as power supply while still maintaining adequate GPIO capabilities, it was decided to install a dedicated PoE+ switch board at the centre of the factory. This allowed each of the RFID gates to be reached at a distance less than 90 meters. No additional power supply installation was necessary for the operation of the RFID gates. The centralized PoE+ switch board was linked to the on-premises Plataine edge server following Solvay industrial cybersecurity protocols. The communication between the on-premises and the dedicated cloud-based Plataine server was established following the standard Solvay cybersecurity protocols.

No readily available 5G compatible device able to withstand our cold storage environment could be identified. Furthermore, the 5G public network had limited coverage at the time of the PoC. One of the alternative solutions investigated was the use of a geo-fenced temperature recorder with GPS & 4G capability. Solvay is familiar with this technology which had recently been widely used to track the shipments of high value goods from the UK to the EU during the Brexit disruptions. However, the automation of the whole process would have exceeded the PoC budget so had to be abandoned.

As a compromise, it was agreed with the NCC that the material information required for this PoC will be supplied by Solvay to the NCC after material production. This information was captured in an EXCEL CSV template that was easily imported into the NCC Plataine TPO database to create the material assets to be delivered.

61 USE CASE DEVELOPMENT AND INVESTIGATION

61.1 Use Case Testing

The set-up of the RFID gates is illustrated in the figures below. RFID antennae were placed at fixed height in order to prevent pedestrian obstruction, avoid head collision, and avoid antennae damage from impact with FLT and ped-pallet trucks. After about six months following the installation, still no damages or issues with the antennae have been reported. This demonstrates a good survivability.

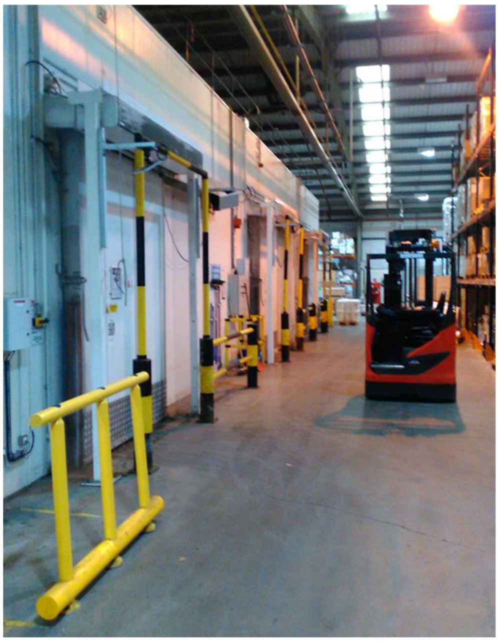
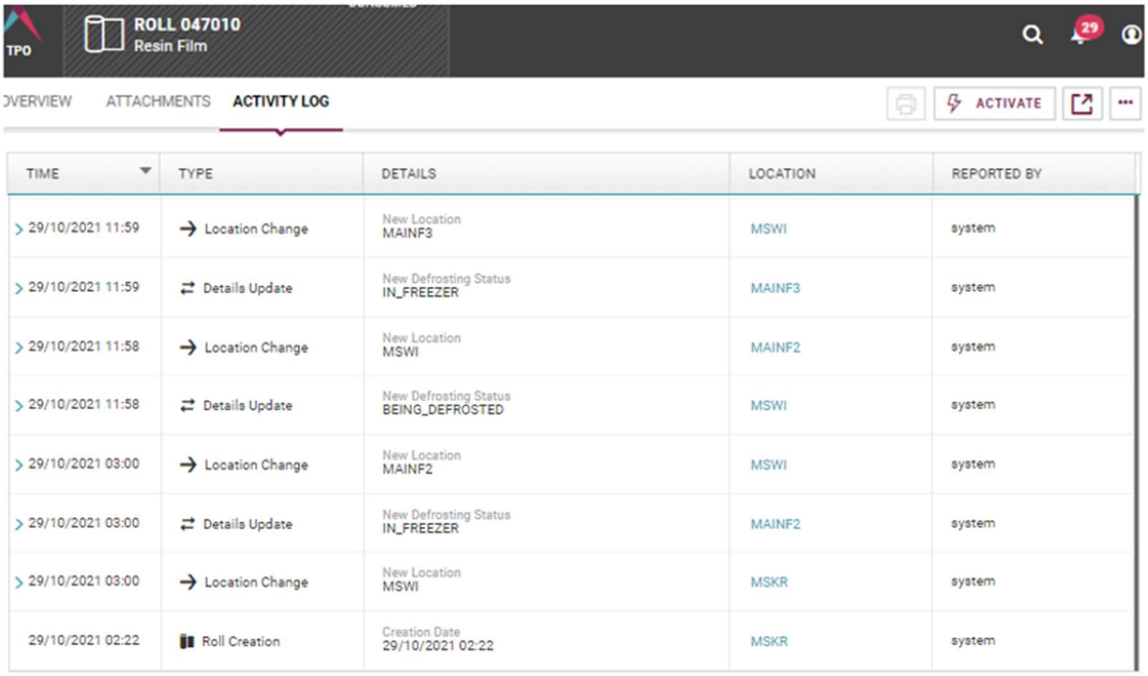


Figure 89: RFID gates at locations of freezers 1 to 3.

Figure 90: RFID gate at the truck loading bay.

Below is an example of a material asset created automatically by the system in Plataine TPO at the time of the asset creation followed by its movement across the shop floor a moment later when taken to the freezer. In this instance, the resin film roll “047010” was created automatically by the RFID system into Plataine TPO at the time of the asset manufacture during a night shift without any manual input from any production operator, see Figure 91. About forty minutes later, the operator took the pallet with the film roll to the freezer number 2. The RFID system detected automatically and in real time the asset movement and updated its status as “IN_FREEZER”, stopping the clock for the out-time consumption. During the next morning shift, the roll was moved from the freezer number 2 to the freezer number 3 to consolidate in the same locations all intermediates for next production order on the tape line. This movement was automatically detected without any loss of out-time.



TIME	TYPE	DETAILS	LOCATION	REPORTED BY
29/10/2021 11:59	Location Change	New Location MAINF3	MSWI	system
29/10/2021 11:59	Details Update	New Defrosting Status IN_FREEZER	MAINF3	system
29/10/2021 11:58	Location Change	New Location MSWI	MAINF2	system
29/10/2021 11:58	Details Update	New Defrosting Status BEING_DEFROSTED	MSWI	system
29/10/2021 03:00	Location Change	New Location MAINF2	MSWI	system
29/10/2021 03:00	Details Update	New Defrosting Status IN_FREEZER	MAINF2	system
29/10/2021 03:00	Location Change	New Location MSWI	MSKR	system
29/10/2021 02:22	Roll Creation	Creation Date 29/10/2021 02:22	MSKR	system

Figure 91: automatic asset creation in Plataine TPO system.

ER

The figure below illustrates the next manufacturing step. Two days later, the film roll was taken out of the freezer 3 with an FLT driver to defrost the film roll before its consumption on the tape line. This is illustrated in Figure 92. This figure shows that the system is capable of detecting automatically the release of the film roll from the freezer 3 and start the 12-hour defrosting countdown. Once the 12-hour defrosting time was elapsed, the system updated automatically the film roll status from “BEING_DEFROSTED” to “DEFROSTED”. The roll was then consumed within the next five hours. The label was disposed in a bin to deactivate the RFDI tag and the asset was automatically recorded as consumed.

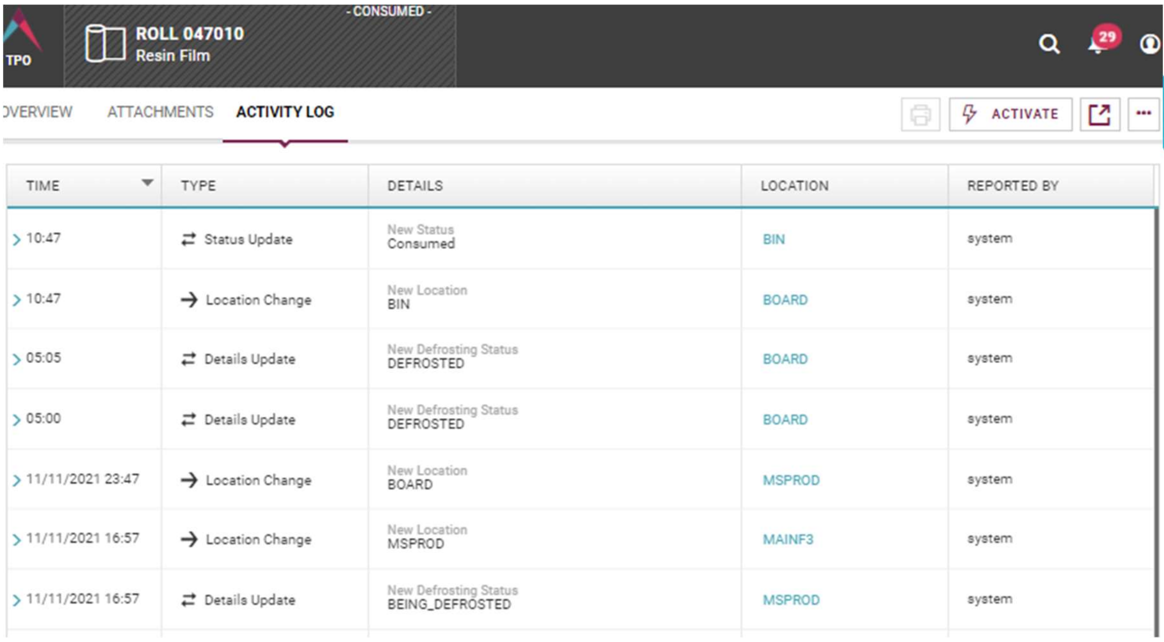


Figure 92: automated asset tracking and defrosting time recording.

61.2 Use Case Discussion

Preliminary results from the 2021Q4 trials confirm that the following automated-asset tracking system requirements have been met:

- ✓ Must be fully transparent to current manufacturing process and not require any additional tasks from operators.
- ✓ Must be passive and not require the use of any battery-operated devices.
- ✓ Must not require the use of additional tracker or labels.
- ✓ Must survive a high-rate industrial manufacturing environment with FLT's.
- ✓ Must survive the full distribution chain cycle.
- ✓ Must be compatible with an industrial environment where ATEX-zones are present.

Regarding the last point, none of the gates were positioned within any of the ATEX-rated zones present on site. Furthermore, the EIRP for the RFID installation used in this PoC was calculated as 33dBm maximum, i.e. about 2W. Guidance from the PD CLC/TR 50427:2004 BSI standard regarding the safe distance around a UHF RF transmitter in the 862MHz to 960MHz frequency range from ATEX-rated zones confirmed that there was no ATEX risk associated with the selected RFID installation as deployed.

More detailed considerations will be given in the next paragraph, but it can generally be concluded that the next two requirements below have also been met:

- ✓ Low installation costs and operation/maintenance costs.
- ✓ Must not require the acquisition of a specialized skill set not currently supported within the Solvay Group and be easily maintainable.

The relative breakdown of cost of the deployment of the automated asset and out-time tracking system is given below, excluding Solvay employees labour and overhead costs:

- Software development, deployment, license and support: 59%
- Printers and industrial RFID labelling configuration: 15%
- Network installation including optical fibre, PoE+ switch board and enclosure, fire wall, PoE+ data cables and installation testing: 12%
- RFID hardware (antennae, readers, etc…): 9%
- RFID gates installation: 3%
- RFID labels for 6 months of production on selected assets: 2%

Overall, RFID technology is a reasonably affordable technology to deploy for the automation of asset tracking. A PoE+ network installation is also seen as a reasonably cost-effective approach. If a wireless technology had been deployed, the installation of power supply cables would still have been required. Bearing in mind that 70% of the cost of the network installation is contractor labour, it is expected that the cost of routing power supply cables would have been of a similar order of magnitude.

Deploying a conventional hardwire network meant that no extra IT/OT skills were required. The network and firewall configuration and the Plataine TPO deployment were easily performed with the support of the Solvay Industrial cybersecurity team ensuring all Solvay Industrial cybersecurity protocols and NIST 800-171 requirements were met. The system will also be easily maintained by the Solvay IT/OT teams.

It was found that the weakest point in the physical installation is actually the co-axial cables installation, especially for the antennae mounted in our freezers. These RFID gates can be exposed to rough environment with risk of exposure to blast chiller (see Figure 93). It was found that ensuring a minimum db loss and good signal quality between the RFID antennae and readers required a specific skill set specific to co-axial cable installation and connection.

Figure 93: example of installation survivability testing after exposure to a blast chiller following a maintenance.

Regarding the requirement on high reliability and capability of self-diagnosis, the conclusions are as follow:

- ✓ Plataine TPO has the self-diagnosis capability. Automatic alerts will be raised in the following cases and the duration of the issues will be tracked until resolved:
  - i. As soon as a connection between an antenna and a reader is lost (e.g. due to a damaged co-axial cable or an antenna hit by an FLT). In this case the fixed IP address of the reader as well as the antenna number will be specified.
  - ii. As soon as a reader is disconnected from the on-premises edge server (e.g. a PoE+ data cable is disconnected). In this case the fixed IP address of the reader will be specified.
  - iii. If the connection between the on-premises edge server and the cloud-based server is lost.

- ✗ The required high reliability of the full system for automated asset and out-time tracking was not demonstrated. Over 750 material assets have been created and tracked so far with an estimated reliability of 60% to 80%. This lack of reliability is attributed to the complexity of the industrial environment in which we are operating with large amount of carbon fibre-based materials moving around in palletized boxes by ped-pallet trucks and FLT's. With fine tuning of the RFID antennae to optimize the detection of the RFID labels at the gates, the optimization of some material flow processes to facilitate automatic consumption and best practices in terms pallets transportation via ped-pallet trucks, it is believed that the detection reliability could be significantly improved. As a result, following the conclusion of this funded project in 2022Q1, Solvay has decided to extend the selected technology to two extra production cells as well as to extend the software license to pursue the evaluation of automated asset tracking throughout 2022 on its own budget.

62 5G INDUSTRIAL ASSESSMENT

62.1 5G Discussion

Solvay joined the asset tracking work package as a material supplier of composite materials with the aim to evaluate the potential of automated asset and out-time tracking both within the factory and ideally in-transit for its manufacturing and logistics operations. A second aim was to understand the relevance and potential of the 5G cellular technology within the context of a full deployment of automated asset and out-time tracking system within a factory and potentially throughout the supply chain.

62.2 5G Conclusions

In case of deployment, the automation of asset tracking would likely form part of the OT network which is subject to the strict Solvay industrial cybersecurity policy as well as industrial safety. Currently, cellular technologies are not allowed for process controls and process safety sensors. Since 5G mobile private network in an industrial setting remains a novel technology, it is still unclear at this stage about its potential within an industrial OT network. Further investigation is required to ensure cellular networks can be deployed securely and include local zones to minimise OT network risk. The emerging network slices included in the 5G standards but needs a deeper understanding.

In the particular case of this RFID deployment for automated asset and out-time tracking of time and temperature sensitive materials, a wireless cellular technology would probably compare unfavourably to PoE+ since cellular technology IT skills are not commonly available to deploy the cellular solution efficiently. The complexity of a cellular network deployment needs to reduce such that skills needed for deployment are easier to develop.

63 REFERENCES

PD CLC/TR 50427:2004: Assessment of inadvertent ignition of flammable atmospheres by radio-frequency radiation. Guide

64 – AUTOMATED PREFORMING CONTROL –

ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK's biggest investments in using 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It is designed to validate the idea that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that the UK industry exploits the 5G technology and remains a global leader in the development of robust digital engineering capabilities when implementing complex composites manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLL/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and SMEs.

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

EXECUTIVE SUMMARY

This report details an industrial use case relating to in-process verification of composite materials using a vision-based system. The main barrier to these types of verification systems being more widely accepted across industry is the significant infrastructure requirements for them to operate effectively. These requirements are driven from the need to process the massive amounts of data generated and the need for low latency feedback, which leads to them needing to be installed in fixed locations with large set up, and integration costs.

This use case aims to demonstrate how a decrease in infrastructure requirements and increased in flexibility offered by exploiting 5G capabilities, can make this technology more accessible for industry.

5G has ultra-fast, high bandwidth, low latency capability enabling large amounts of data to be sent and received wirelessly in near real time. The Gigabit uplink and downlink speeds present an opportunity for this use case as vast amounts of data are generated during each scan. The high throughput ability of 5G combined with the ultra-low latency theoretically lend themselves perfectly to this application as large volumes of data can be communicated in near real time.

To assess feasibility and understand solution architecture prior to 5G network availability, a baseline test was conducted using 4G LTE on a similar vision system. This test proved that vision systems of this nature can communicate data using cellular technology, however low 4G communication speeds led to the scan time being significantly increased while the quality of the gathered data was reduced.

Upgrading the industrial vision system at the NCC to 5G was successful and allowed data to be communicated to a virtual server in near real time, achieving latency values in the region of 14ms. The uplink throughput was still not sufficient to run a scan at the same parameters as the original wired set up but vastly improved compared to 4G. A maximum uplink throughput achieved using 5G was 18Mbps (2.25MBps), far from the 900Mbps seen when using CAT7 cable. The lack of comparative communication speed led to data fragmentation and network instabilities when attempting to pass large volumes of data across the network, often leading to a cease in data flow. The root cause of this has not been fully identified, however, a reduction in uplink data volume, through reduction of MTU size and scan speed, vastly improved the stability of the connection and the quality of the output.

The 5G connection did allow the processing PC to be removed from the system, significantly reducing the weight and footprint of the end effector from 45kg to 3.5kg. This allowed the use of a smaller collaborative robot to accurately position the system reducing robot system cost (~88% reduction) and, in turn vastly reducing the integration cost required to set up when compared to the original deployment (~98% reduction).

The use of industrial 5G for an application such as this is possible but there are trade-offs that must be considered. There is a significant reduction in both robot system cost and integration cost, leading to a much more flexible and easily deployable system. However, until an increase in 5G uplink throughput is possible, the time to scan will be greatly increased to achieve the same quality of output.

ABBREVIATIONS

APC	Automated Preforming Cell
FOD	Foreign Object Debris
NCC	National Composites Centre
CPE	Customer Premises Equipment
GV	GigE Vision
GVCP	GigE Vision Control Protocol
SME	Small to Medium Enterprise
MTU	Maximum Transfer Unit
RAN	Radio Access Network
IP	Internet Protocol
MAC	Media Access Control

65 INTRODUCTION

65.1 Industrial Challenge

Automation technologies are becoming increasingly more available and affordable, and as this technology is adopted more widely across a range of industries, more and more opportunities for innovation present themselves.

Composite production has always been synonymous with a high level of quality control as the quality of a component directly impacts its performance. One method of achieving high quality control is using in-process verification sensors at each stage of the manufacturing cycle, to give accurate and useful data about the material. As a direct benefit, the addition of an automated defect detection system allows the user to immediately identify when and where any discrepancies in the material or process occur, in turn reducing the need for re-work and scrapped components. Indirectly, these systems also allow the increased adoption of dry fibre into high value manufacturing to become a more feasible option, driving operation costs and energy utilisation down as the need for an autoclave is removed.

These systems however, come with a series of limitations; they can be expensive to install and integrate with existing technologies, there is a significant infrastructure requirement for them to operate at full capacity and often can be inflexible and difficult to redeploy. These limitations can often lead to this technology not being as widely adopted into industry and even less so in SME's. Consequently, composite component can go through an entire manufacturing cycle before receiving an NDT inspection, at which point, should there be any discrepancies the component must either be scrapped or sent for expensive re-work.

Within the NCC there is a cell called the Automated Preforming Cell (APC), shown in Figure 94, used for researching and streamlining automated preforming processes and technologies. Within the cell there are two Kuka robots that are used to position various NCC built and bespoke end effectors used for preforming, inspection and cutting of composite dry fibre.

Figure 94 Automated Preforming Cell at NCC showing both Kuka Robots

One such end effector is the "Verification Rig" as it's commonly known (Figure 95). This is a bespoke system that combines two of Profactor's inspection sensors, namely the F-Scan vision system and the L-Scan laser line scanner. The current deployment of this technology within the NCC requires significant infrastructure to operate and makes use of the larger Kuka KR 500 robot (shown in white in Figure 1), as the end effector assembly weighs ~45Kg.

Figure 95 Profactor F-Scan & L-Scan Verification Rig

The assembly is so large as there is a processing PC hosting the Profactor application contained within the end effector assembly, as the vast amounts of data produced must be captured, communicated, and processed in near real time. Furthermore, the APC is a highly flexible cell and mounting the PC elsewhere would mean sacrificing the ability to have complete modularity, while adding latency into the system. The ultra-high-resolution data generated during this application coupled with large robots to position the sensor, mean that the level of infrastructure required for this task is significant. This combined with a classically wired set up, used to achieve the required ultra-fast communication speeds, lead to these systems being not only expensive to set up and run, but also inflexible, complex to configure and difficult to quickly redeploy.

65.2 Project Objectives

65.2.1 Overarching Objective of Use Case

This use case aims to investigate and demonstrate how automated defect detection systems can be made more commercially accessible using innovative digital technologies and 5G.

The objectives of this use case can be summarised by three main points:

1. **Demonstrate a reduction in infrastructure costs** when compared with an existing deployment.
2. **Demonstrate an increase in capability** when compared with an existing deployment.
3. **Demonstrate an increase in flexibility/ability to deploy** when compared with an existing deployment.

65.2.2 5G in Relation to This Use Case (5G Opportunity)

5G as a technology can communicate massive amounts of data in near real time, all without the need for expensive and extensive hardwired data connections. Vision based systems used for automated defect detection require high speed, low latency, ultra-reliable communication between the sensor and the processor. The reason being that these sensors are most commonly used in conjunction with a robot/gantry to position the sensor. The positional data is communicated every 10-12ms, meaning high speed connection is critical in synchronising the sensor images with the positional data.

This use case will test the uplink throughput and low latency capability of 5G, as large volumes of data are generated at the sensor and must be communicated in near real time to the processing location. Substituting the wired connection with ultra-reliable, high-speed 5G removes the need for a bulky processing PC at the sensor location while maintaining flexibility, thus significantly reducing the footprint of the system. A smaller system can be used with a smaller robot, thus reducing the required infrastructure for this application, driving costs down and making this technology more accessible to industry.

65.3 Overview of Use Case

This use case will focus on the Profactor “Verification Rig” assembly within the NCC to investigate how this technology can be made more flexible and easily deployable. The F-Scan sensor will be removed from the assembly, upgraded to 5G and compared with the previous deployment of this technology using a wired connection, to assess its performance.

65.3.1 Top Level Architecture

The architecture of a system like this can be broken down into a number of fundamental elements, namely a sensor, a positioner, a means of transferring the data and a means of processing the data as shown in Figure 96.

Figure 96 Top Level Architecture

The sensor is used to generate valuable fibre orientation data about the surface that is being scanned, in this case a dry fibre composite preform will be investigated as this has the most relevance to industry. The sensor is held in place by a robot arm which is critical for both achieving high quality scans and getting accurate positional data of exactly where the sensor is in space. The data generated by the sensor, combined with the joint angles of the robot, must be sent via some means (most commonly CAT7 data cable), to whatever machine is hosting the software used to process it.

Breaking the system down into its fundamental elements allows for innovation within each. There is potential for sensor and positioner to be reduced in size and weight, the data transfer can be made wireless, and the processor can be made virtual. All of which combine to give a much more flexible and potentially cheaper system.

65.3.2 Use Case Metrics

To assess the level of success within this project, several use case specific metrics will be gathered. These use case metrics relate to the physical system and the benefits seen from a reduction in footprint, namely a reduction in integration cost and increase in flexibility.

65.3.2.1 Machine Integration Costs: Reduced Infrastructure Costs

How it is measured: Original integration costs versus new integration costs.

Unit: £

Detail: The use of 5G can remove the need for long extensive hardwired data lines that are costly and time consuming to install. A smaller robot will very likely attract less integration and installation cost than a larger robot. Combine this with the smaller robot housing a built-in safety circuit and the overall system costs will be significantly less than the original deployment.

65.3.2.2 Machine Integration Costs: Robot System Costs

How it is Measured: Original Robot Costs versus New Robot Costs

Unit: £££

Detail: The use of edge compute can remove the need for a high-powered processing PC on or beside the end effector. Centralising this compute power in the comms room means that the end effector can be significantly smaller and thus a much smaller robot can be used with the system. A smaller robot will very likely cost significantly less than a larger high payload robot, and standard comms room hardware used for processing will make the industrial deployment cheaper.

65.3.2.3 Increase in Flexibility: Increased Access to Tight Spaces (Capability Increase)

How it is Measured: Spatial Analysis/Reduction in End Effector Size

Unit: Measurement

Detail: By removing the processing PC from the end effector the sensor is significantly smaller and less bulky. This allows the sensor to be manipulated much more easily and the likelihood of a crash when inspecting a tight radius is significantly reduced, meaning an increased ability to scan more complex geometry at reduced cost and risk.

65.3.2.4 Increase in Flexibility: More Readily Deployable

How it is Measured: Redeployment Demonstration and Use Case Costs

Unit: £££

Detail: Using 5G and edge compute will allow the end effector to be significantly smaller and lighter, meaning a smaller robot with built in safety can be used to manipulate and position it. The overall deployment cost of the new system including all elements of the use case (excluding sensor cost as this is common across both) will be significantly less than the original.

65.3.3 Network Metrics

In order to assess the level of suitability of 5G for this application, a number of network specific metrics will be gathered during testing. Unlike the use case metrics, these relate specifically to the 5G performance and how it enables the data transfer.

65.3.3.1 Latency

How it is Measured: Pings

Unit: Milliseconds

Detail: Latency is a measure of how quickly packets are sent across the network. A common latency value for near real time applications such as this is <10ms, as is consistently seen when testing on a wired connection. 5G is theoretically capable of <10ms latency and will therefore be investigated to observe how well the data is synchronised with the robot position.

65.3.3.2 Uplink Throughput

How it is Measured: Radio Metrics

Unit: Kbps

Detail: Throughput is a measure of the rate at which data flows across the network. An application such as this will require a significant uplink throughput as large volumes of data are generated at the sensor location and transferred across the 5G to the processing location.

65.4 Development Journey

This use case was developed as a result of discussions with members of staff within the NCC as well as conversations with representatives from industry. One common takeaway was that there is a lack of in-process defect detection in use both within the NCC and further afield. Being able to deploy a verification system on a shop floor in collaboration with the individuals producing components would mean not only in-process verification but the ability to rapidly correct any defects before the manufacturing process continues.

As mentioned previously the blockers to this technology being more widely adopted include large and expensive robots often dedicated to performing one specific task, leading to inflexibility and making redeployment elsewhere in the workshop difficult. The Profactor verification rig was selected for this use case as it is industrially relevant and a prime example of where a reduction in infrastructure requirement could unlock capability.

By removing the F-Scan sensor from the assembly the overall weight is reduced from 45kg to just 3.5kg, therefore it was immediately clear that collaborative robots could be used, allowing for the system to be deployed alongside humans without the need for guarding. With ease of deployment, collaborative functionality, and increased flexibility in mind; Profactor, along with internal staff from the NCC including automation and metrology engineers, were engaged to develop a set of requirements that this demonstrator must satisfy. Requirements were broken down into functional and non-functional and are outlined in Sections 65.4.1 & 65.4.2.

65.4.1 Functional Requirements

Functional requirements relate to the physical 5G enabled verification system and the function it must perform. Ideally the system would perform exactly as it did before the 5G enablement, therefore the functional requirements are relatively straightforward.

The system must use the same interface.
The system must exhibit identical characteristics as the original system.
The system must interface with a robot to get positional readout.
The system must be capable of collecting the same information as the original deployment.
The system must use the existing application for analysis of data.
The system must exhibit the same level of robustness as the original system.

65.4.2 Non-Functional Requirements

Non-functional requirements relate to the operation of the 5G enabled verification system and how it performs its task. The system must be able to use the 5G network in the same manner as the wired network, therefore these requirements set out how the network must behave to achieve that.

The 5G Network must allow the sensor to be able to move freely within the APC cell.

The 5G network should allow the sensor to be able to move freely between cells in the NCC.

The 5G network must have an upload latency such that frames are not lost from the camera buffer.

The 5G network must have a download latency low enough so that sensor control signals are not lost.

The network density must be such that the sensor can be positioned anywhere in the cell.

The 5G network must be able to support a Gigabit connection so that the sensor can operate normally.

The 5G network must be such that it can support jumbo frames (MTU size 9016K).

66 USE CASE INVESTIGATION

66.1 Use Case Architecture (System design)

A detailed network design was conducted in order to satisfy the requirements set out in Section 65.4. One network challenge that was quickly identified was the presence of the GigE Vision (GV) industrial protocol, outlined in Section 66.1.1.

66.1.1 GigE Vision Industrial Protocol

GigE Vision (GV) is an industry standard communication protocol for vision applications typically used in instances where high data rates are required. While the name GigE refers specifically to Gigabit Ethernet connection, GV can be used with any speed ethernet connection. Figure 97 shows a basic outline of how the protocol works.

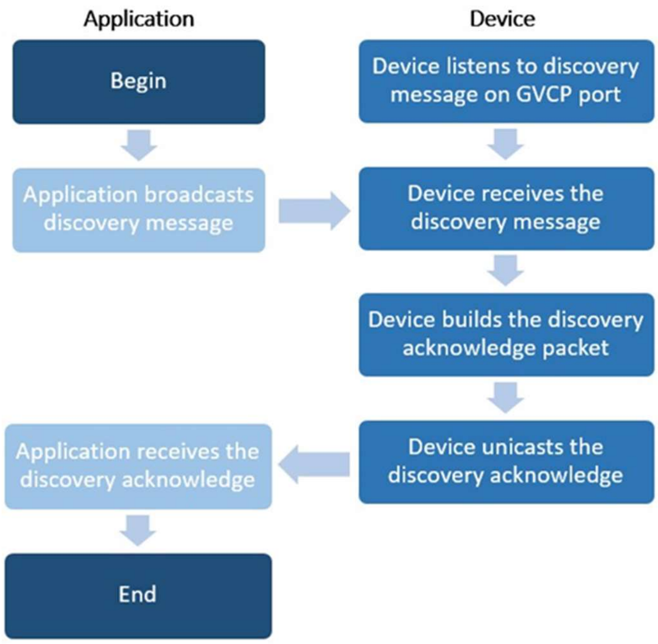


Figure 97 GigE Vision Protocol (GVCP: GigE Vision Control Protocol)

GV is inherently a layer 2 communication mechanism, meaning it is designed to be used with devices connected on the same local network as MAC address' are used to communicate. In upgrading each system to cellular communications there is a crossing of networks as the data moves across the 4G or 5G networks, meaning the auto-discovery feature of GigE Vision could not be used. This prevents the host application from seeing the device to establish a connection, and therefore another solution must be implemented to combat this.

66.1.2 Network Address Translation (NAT)

Following the advice of both Profactor and the NCC Network Lead, network address translation (NAT) was chosen as the most appropriate method for enabling communication across networks. NAT is a process that involves using a unique public IP address to represent multiple devices on a private network.

The specific form of NAT used in this project is known as NAT overload, or Port Address Translation (PAT). This allows the user to go one level deeper than standard NAT and specify not only the IP address to translate but the specific ports as well. Meaning that the same IP can be used for multiple devices connected to the one router with one or multiple ports being linked to each device to allow for data flow. Figure 98 shows an example of using PAT to translate data arriving at the router IP with a specific port, to each individual device with a unique private IP associated with that port.

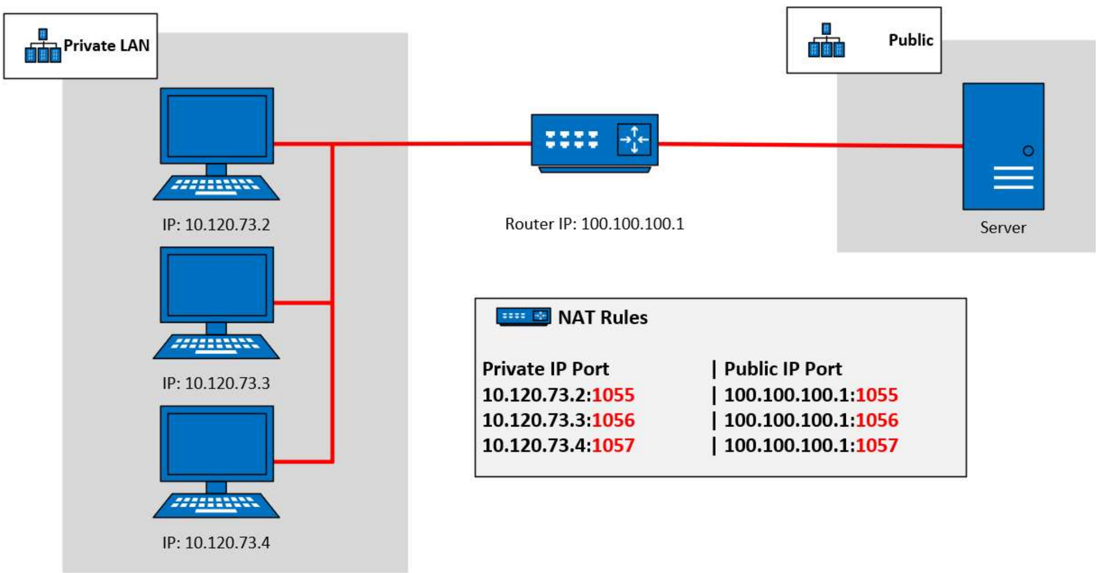


Figure 98 Port Address Translation

66.1.3 5G Demonstrator Network Architecture

Figure 99 shows the network architecture of the 5G element of this use case involving the Profactor F-Scan sensor. The sensor has two separate network interface cards (NIC); one for control and one for data, each with a separate IP address. Therefore, the sensor must be treated as two interfaces requiring specific NAT/PAT rules for each segment.

This element of the use case includes a robot that is used to position the sensor. The robot must be connected to the VM to allow for control as well as transfer of positional data to the FScan application. This is essential in ensuring the scan data has a reference of where it exists in physical space relative to the robot base.

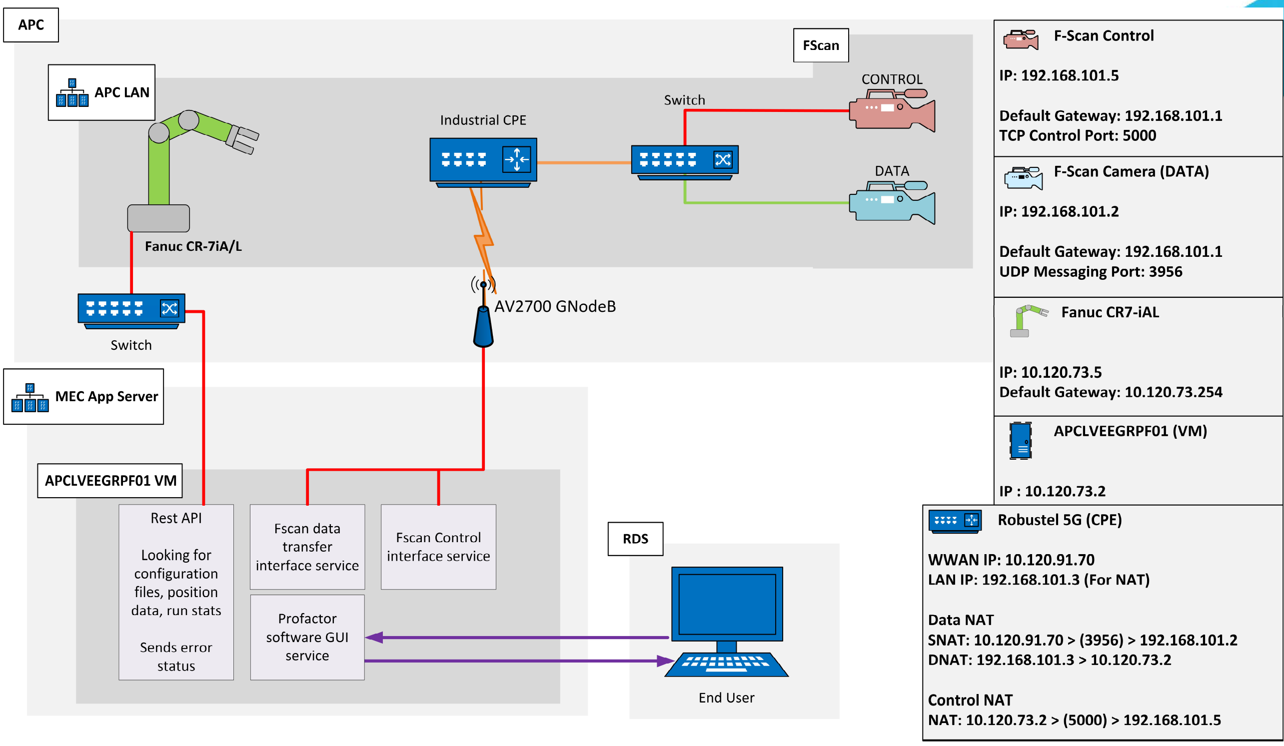


Figure 99 5G Network Architecture

As can be seen in Figure 99 both the data and control interface are directly connected to a switch, which links directly to the 5G router (CPE). This then communicates with the gNodeB radio (5G radio) to send the data back to the VM hosting the Profactor application. As the application receives the data from the sensor it processes it in near real time to give a visual output of the scanned surface that can be assessed for defects.

As previously mentioned, to achieve data flow between the VM and the sensor, port address translation is required. Figure 100 shows the communication information for the network in Figure 99 with specific IP address and ports used.

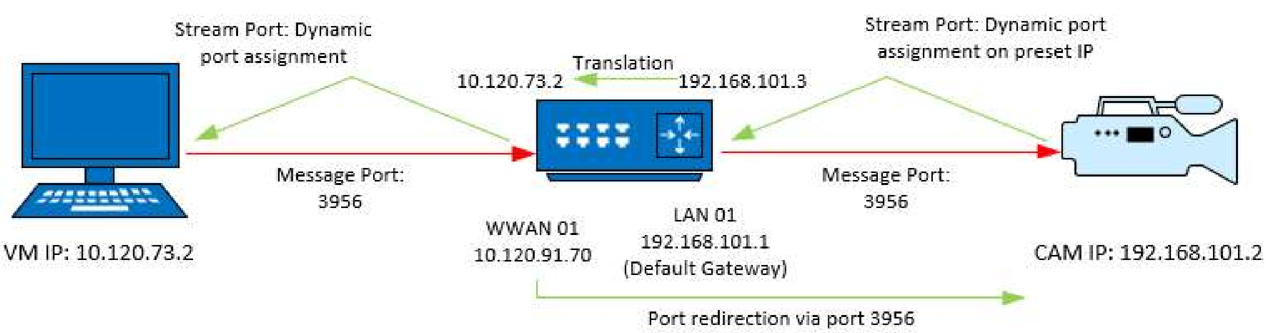


Figure 100 Port Translation for 5G Demonstrator

The application sends a discovery packet to the router on port 3956, which knows to forward that onto the camera on port 3956 using the PAT rules that are predefined. The camera receives this message and builds a data packet to return to the application which has a destination IP of 192.168.101.3 as set in the configuration file. This IP isn't associated with anything physical, however, an ARP cache entry on the router assigned this IP the same physical address (MAC) as the router (default gateway). As the GigE Vision protocol is layer 2 the data packet is sent to the physical address associated with the destination IP, which is the same as the router. The router has a NAT rule in place to translate the destination IP to that of the VM and so the application receives the data. Figure 101 shows a flow diagram explaining how the data is communicated at each step.

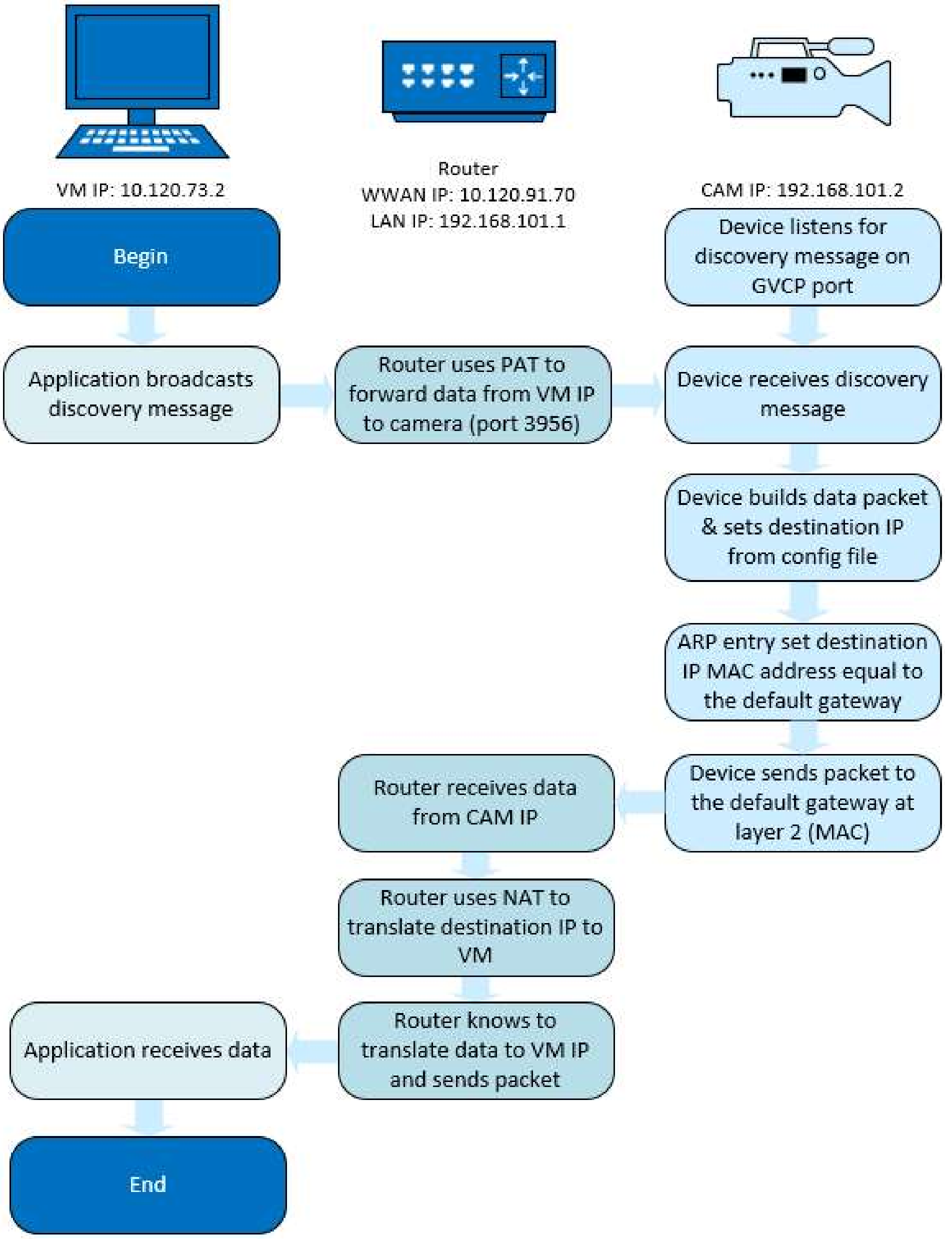


Figure 101 Data Flow Diagram

67 USE CASE DEVELOPMENT AND INVESTIGATION

67.1 Use Case Build

The original Profactor end effector provided power and data to the camera that linked directly into a high-powered PC situated on the end effector itself. Removing the Fscan sensor from the end effector means removing it from the processing PC and power supply which will therefore need to be replaced with a bespoke set up. Combined with this, the new system is designed for use with a different, much smaller robot for positioning which bring another set of challenges.

67.1.1 Fanuc CR7-iAL Cobot

The robot chosen for this task is a small Fanuc CR7-iAL collaborative robot designed for pick and place activities in parallel with a human workforce. This means that built into the robot's base is a force torque sensor that will activate the brakes whenever a peak load over a set threshold is observed. Essentially if the robot touches something it shouldn't while moving it will stop. The robot can be seen in Figure 102 and has 6 axes of motion and a maximum payload of 7Kg.

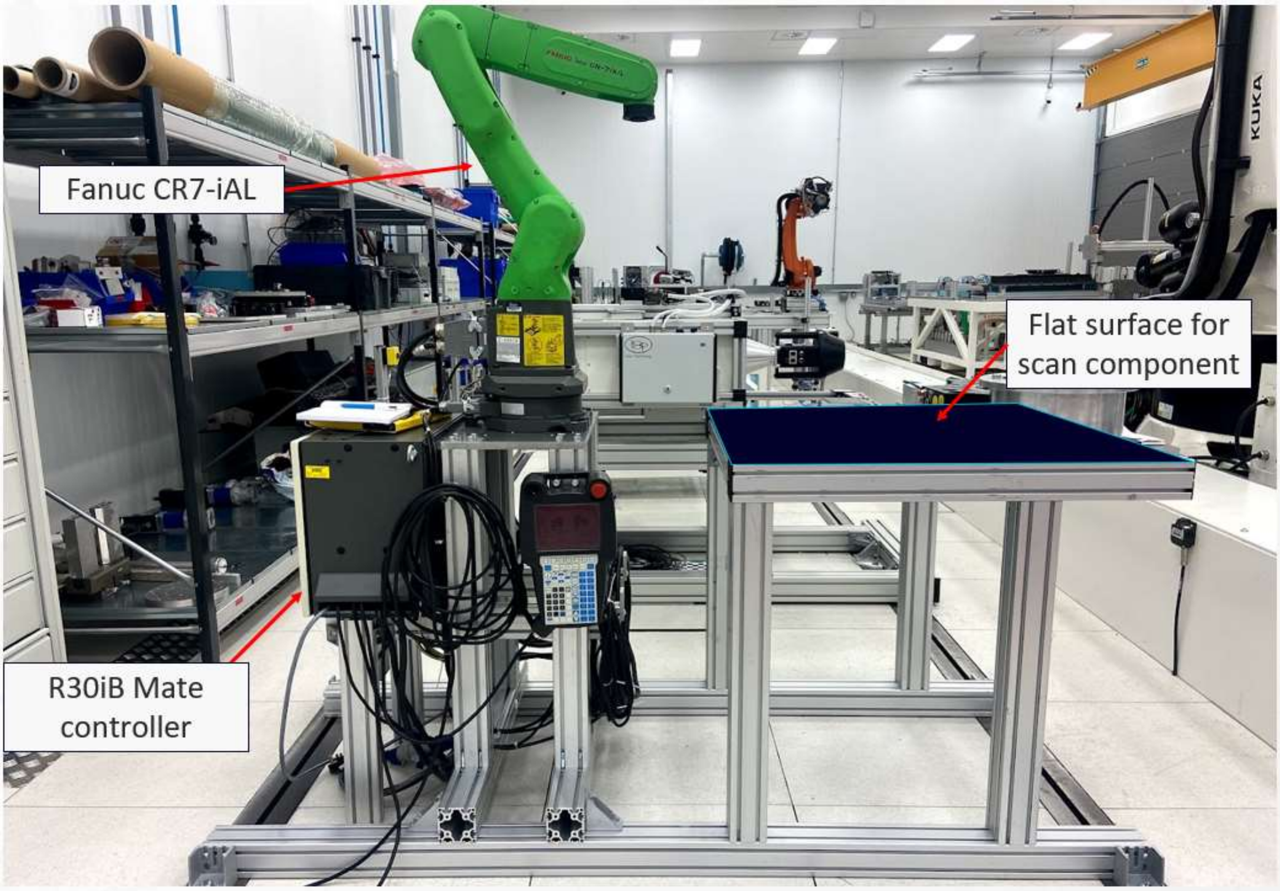


Figure 102 Fanuc CR7-iAL Cobot Set Up

This robot had not been used at the NCC up to this point and therefore required a full set up and integration into the cell before it could be used. A frame was built to position the robot off the floor and provide a structure that things can be mounted to should there be a requirement. The frame contained a mount for the Fanuc R30ib Mate robot controller and a large flat area to place the component to be scanned that can also be seen in Figure 102.

The robot controller is essential for the robot to be able to move and must be connected directly to the Profactor application to allow for both control and positional readout of the robot. The Profactor application allows the user to interact with the robot and start the scan program provided the safety circuit is complete. The decision was made to separate the robot control from the 5G network segment, to ensure the system can be safely stopped if the connection drops and control signals cannot be communicated.

To communicate between the robot and the application, User Socket Messaging was implemented on the controller which required additional input from Fanuc to install the R648 USM plug in.

Fscan_master and Fscan_server, two Fanuc specific scripts produced by Profactor were loaded onto the controller. The reason being that the original Profactor installation was designed for use with a large Kuka robot that uses a different language to communicate with the cell PLC. When Fscan_master is started on the controller by the system operator a connection is made to the application, then once the operator connects to the sensor in the application, Fscan_master starts both the scan program and Fscan_server. The scan program is what is used to position the sensor and Fscan_server is the script communicating the positional data back to the application. Figure 103 shows a simple diagram of the scripts and their linking inside the controller.

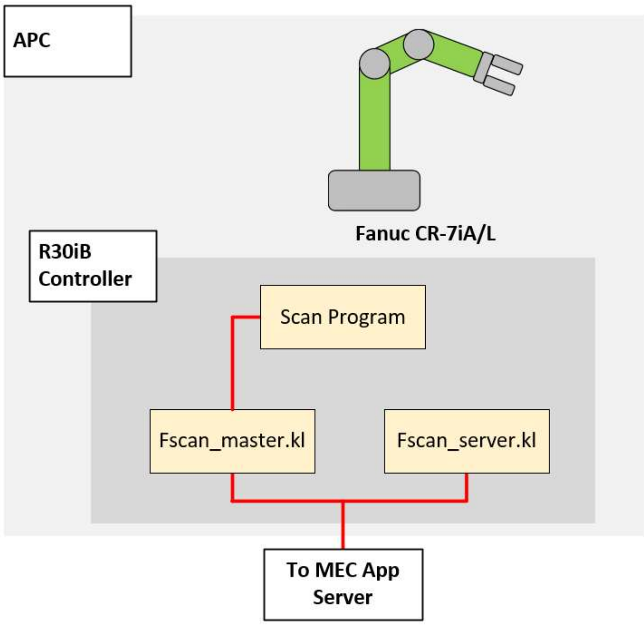
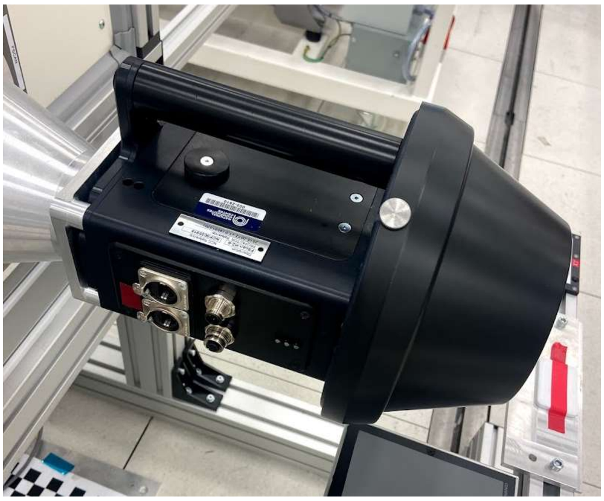


Figure 103 R30ib Mate Controller Configuration

67.1.2 Sensor-Robot Interface

Mounting the sensor onto the robot was relatively straightforward as the existing interface plate from the original end effector could be modified to fit the Fanuc. The plate consisted of 4 countersunk holes that line up with the 4 corners of the sensor, within which blots are placed that tap directly into the body of the sensor. The robot wrist has 4 x M6 tapped holes used for mounting, therefore it was a simple case of drilling 4 holes to match on the interface plate. Figure 104(a) shows the sensor in its original location attached to the interface plate, Figure 104(b) shows the interface plate mounted onto the robot.

(a) (b)



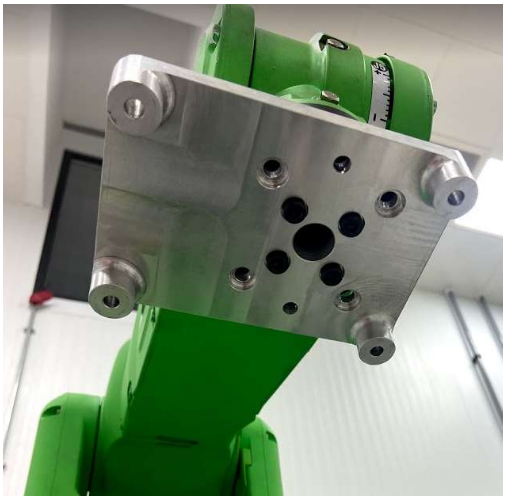


Figure 104 (a) FScan on original end effector, (b) Interface plate on CR7-iAL

67.1.3 Electrical Enclosure

As the robot has a maximum payload of 7kg there is a significant limitation on what can be held and positioned to scan components. As a result, the only thing that the robot will actually position is the sensor which weighs approximately 3.5kg, the interface plate and the cables providing power and data to the sensor itself. All other required elements of this system will be mounted to the frame in Figure 102. An electrical enclosure was produced to house the power supplies and switch required to make the system operational. Figure 105 shows a basic layout of the enclosure with each connection overlayed.

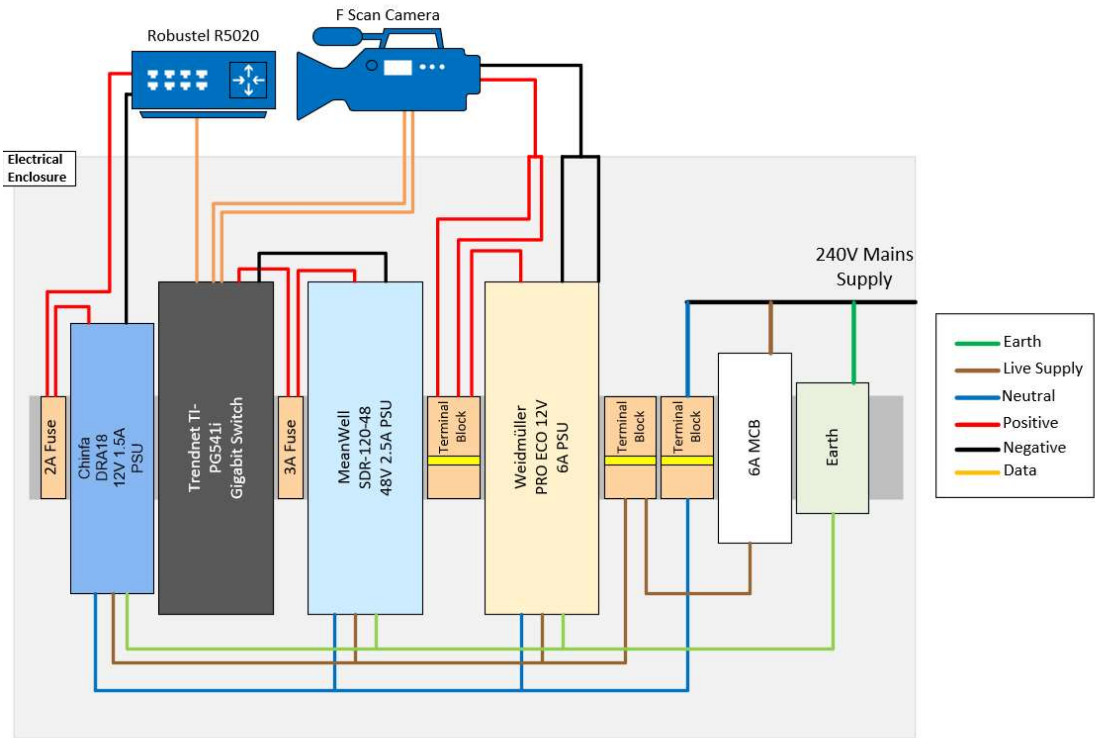
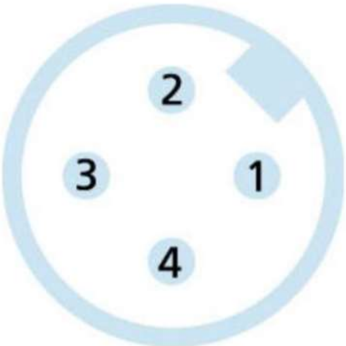


Figure 105 Electrical Enclosure

The FScan sensor has a power requirement of 12V and a peak current draw of 6A meaning this must be the provided power. To achieve this the sensor uses a 4 pin M12 power connector to act as a coupled supply as each pin has a maximum current rating of 4A. The Weidmüller 12V 6A supply in Figure 105 has two V- ports and a single V+ port meaning the output must run through a terminal block before being split off into two V+ cables to feed the sensor. Figure 106 shows the pinout diagram with the function of each pin also indicated.



Pin	Function
1	+12V
2	GND
3	GND
4	+12V

Figure 106 Power Connector Pinout

Data cables are run from the sensor into a Gigabit switch which then passes the data onto the Robustel R5020 5G router and on to the VM for processing and visualisation. The cables for both power and data were run along the length of the robot arm and into the enclosure as can be seen in Figure 107.

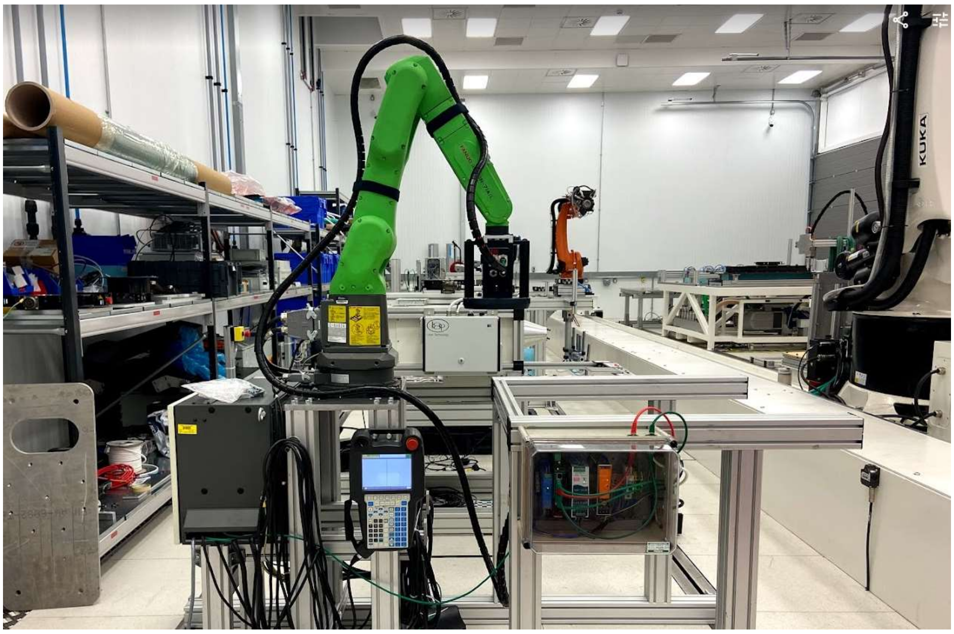


Figure 107 Sensor & enclosure mounted to robot arm

67.1.4 Virtual Graphics Processing

There is a built-in feature of the Profactor application that renders the output from the sensor in 3D, allowing the user to have a visual representation of the scanned surface. This specific feature uses OpenGL to perform the 3D rendering which requires a dedicated graphics processing unit (GPU). The server hosting the application includes two NVIDIA Tesla T4 GPUs provisioned across multiple VMs with relevant license upgrades to process and visualise the incoming data for the user. Figure 108 shows an example of a 3D rendering of a piece of woven carbon fibre than can be manipulated into any orientation to suit the user. There is an option to use the application without this feature that can be set in the json config file.

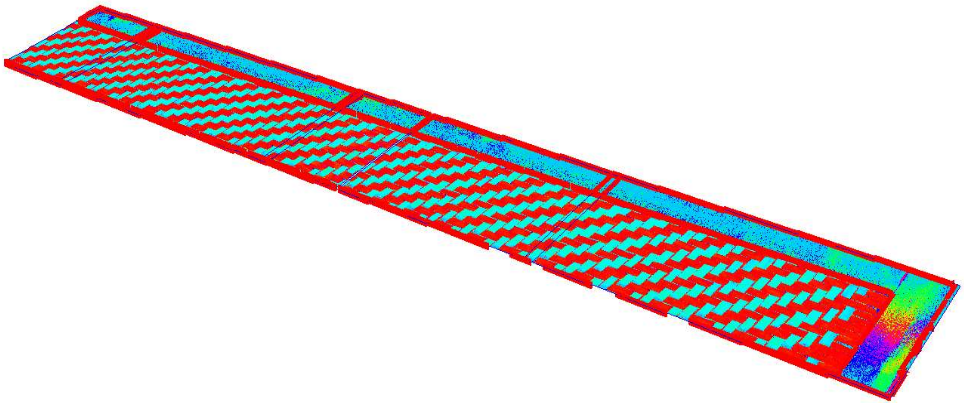


Figure 108 3D Visualisation of Scanned Surface

Should the user want to use the application without the OpenGL rendering then “hand” mode must be used. This mode only allows the user to take spot images of the surface and has no context of where it is in physical space, however, will still allow for full analysis of defects.

67.1.5 5G Integration

To make the system communicate over 5G there were a series of specific networking rules implemented on the Robustel R5020 5G router as outlined in Section 66.1.3. These are to allow traffic to flow between the VM and the camera with the presence of a GigE Vision layer 2 communication protocol. The router was mounted high up on a piece of aluminium extrusion to clear any structures that may interfere with the radio signal as shown in Figure 109.

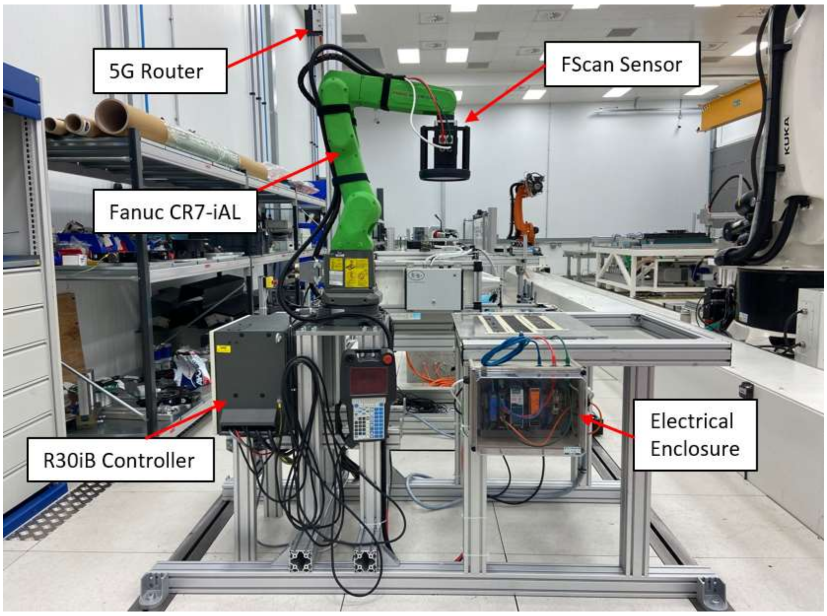


Figure 109 Completed System

67.2 Use Case Testing

In order to confirm that the system operates as expected, several tests were carried out on each aspect of the system as shown in Table 15.

Table 15 Use Case Testing Outline

Work Package	Task
Wired System Integration	Test all elements of the system individually to ensure integration is complete.
Camera testing	Test that data from the camera is communicated correctly with the Profactor application.
Robotic system testing	Test that the positional location of the robot is communicated correctly with Profactor application.
Wired Test	Perform a wired test to confirm data is transferred and processed correctly.
Application Testing	Testing graphics rendering (vGPU).
5G System Integration	Test all elements of the system to confirm everything works prior to full demonstration.

Wired system integration was carried out to ensure that all individual elements of the system were operational. This involved checking everything had the correct power being supplied, the sensor had the correct data connection, the system was patched through to the VM correctly and that everything that needed to communicate with each other could do so.

Camera testing involved ensuring that the data was reaching the correct location, and that when it did it was in the correct format. The camera inside the FScan is configured on start-up using a third-party application called eBus Player that sets the packet size and image size. This application requires a license key to remove a watermark that is linked to the physical address of the machine, which meant ensuring that the physical address of the VM was always consistent it we ever had to migrate servers.

Robotic system testing was broken down into two sections; testing the kinematic model of the robot was correct in the application, and testing communication between the application and the robot controller. The application receives the positional information from the robot in joint angles, which is then converted into cartesian coordinates based off the dimensions and rotational locations of the robot. The joint angles were confirmed to be correct within an acceptable tolerance of around 0.3 degrees, however the cartesian coordinates were incorrect. It was discovered that the robot origin uses the centre point of joint 1 rather than the centre of the base as was initially thought. To resolve this issue, rather than altering the algorithms, a simple user frame was added to the robot program that shifted the origin to the base of the robot by applying an offset in Z.

Wired system testing was carried out after all elements were confirmed to be working. Tests were carried out at varying scan speeds to investigate how the system performed as a baseline to compare the 5G system against. A strip of carbon fibre was used as the control that measured 480mm x 50mm with the sensor completing one pass across the surface. The maximum speed reached without fragmentation of the data was 300mm/s linear scan speed of the sensor with the result show in Figure 110.

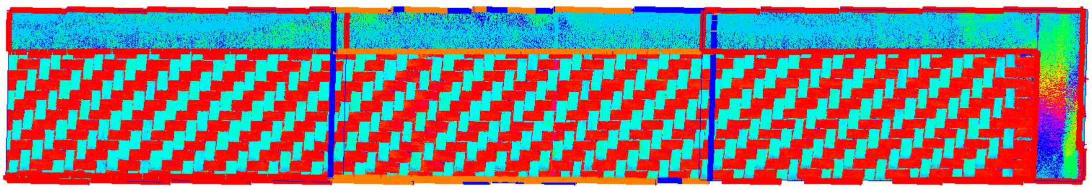


Figure 110 Scan result on wired set up

The final testing carried out involved integrating 5G into the system and confirming communication between the various elements. This was a lot more involved than initially expected as the layer 2 (physical address, MAC) framework of the GigE Vision protocol proved difficult to manipulate across a layer 3 (IP address) network. The address translation rules from Section 66.1.3 were implemented on the Robustel 5G router and the IP addresses of the sensor were altered to match.

There were several parameters that had to be altered to accommodate the 5G connection speeds that were slower than the wired set up. The linear scan speed was reduced, and the frame rate of the camera was reduced (increased frame time) to spread the volume of data being communicated over a larger time period. The frame time of the system was increased from 2200μs to 100,000μs with the linear scan speed reducing from 300mm/s to 1.5mm/s before no fragmentation was observed.

67.3 Use Case Discussion

By referring to the project requirements set out in Sections 65.4.1 & 1.4.2 an understanding of use case success can begin to be developed.

Comparing against functional requirements:

- The function of the sensor system remains unchanged when comparing to the original deployment. Both systems use the same application to process and visualise the data with no loss of functionality, capable of collecting the same information regardless of host location.

- The updated system interfaces fully with the Fanuc CR7-iAL collaborative robot, positioning the sensor over the desired component and providing accurate positional readout to the application for spatial reference. The collaborative robots' ability to work alongside a human workforce safely without the need for additional safety allows for integration into existing manual processes, however, the robot has a reduced reach when compared to the original deployment.

- The robustness of the system is difficult to quantify, however, one could argue that a simplified system designed for a specific application is less likely to fail as there are fewer elements to go wrong. A simplified robot system performing a dedicated function with a dedicated connection and power source is not only easier to troubleshoot but easier to maintain. The virtual server can be easily reconfigured from a previous disc image should anything go wrong, whereas with the original deployment a physical PC must be manually maintained or replaced.

Comparing against the non-functional requirements:

- The 5G radio installed within the APC cell had sufficient power and coverage so that the sensor system could be positioned anywhere in the cell and achieve the same network characteristics. The sensor system was positioned as far from the radio as possible (~20m) to demonstrate this, however, this was the maximum range tested within this use case as, once the assembly was built it was not removed from the cell.
- The coverage within the rest of the factory was sufficient to run other use case applications with similar observed network performance, and therefore an assumption is made that where there is signal, this use case would be operational.

- The latency observed in both uplink and downlink was capable of near real time processing and allowed the sensor control signals to perform as expected. The 5G network was however not capable of providing a connection comparable to that of the original wired deployment, and the use of jumbo frames again was not possible.

Specific 5G element of this use case are evaluated in more detail in Sections 68 & 69.

67.4 Use Case Conclusions

The use case outlined in this report shows significant progress against the objectives set out in section 65.2.1. Comparing the finished system against the project objectives it is clear to see that this use case has been successful in demonstrating the benefits of designing with digital capability in mind.

By using edge compute to centralise the processing power of the system, the end effector could be significantly reduced in size and weight as the PC is no longer present, leading to a weight reduction of 40kg.

Virtual graphics processing removes the need for compute power on the device being used for visualisation, meaning any device capable of remote desktop connection can interrogate scan results in 3D.

Reduction in end effector footprint has allowed a significantly smaller robot to be used, reducing the robot system cost by 88% & integration cost by 98%.

Reduction in end effector footprint has increased the capability of the system by allowing tighter geometries to be scanned (~1.2m x 1.2m x 0.3m versus ~0.2m x 0.2m x 0.3m)

5G enablement means the system can be deployed anywhere that has power and signal, increasing the flexibility of the system.

68 5G INDUSTRIAL ASSESSMENT

68.1 4G and 5G Network Testing

This section will focus on the specifics of the cellular networks used in this use case and the testing involved to assess their performance.

68.1.1 4G Feasibility Study

This project used a private 4G network installed at the NCC to assess the feasibility of this use case and create a cellular performance baseline. A simple NCC built data capturing system was upgraded to cellular communication using 4G LTE to investigate if GigE Vision could be made to work over a layer 3 network. 4G LTE has a maximum theoretical uplink/downlink of 50Mbps & 150Mbps respectively while 5G has a theoretical uplink/downlink of 1Gbps & 10Gbps+ respectively. Therefore, it is not expected that the 4G element will work perfectly, but highlight the benefits of 5G over 4G LTE for a similar application, and to gain early lessons on migrating from wired to cellular wireless technology.

The system chosen was the Composite Quality Capture System (CQCS), a simple data capturing tool shown in Figure 111, that uses a MicroEpsilon laser line scanner to determine out of plane defects such as missing plies and gaps, combined with a FLIR vision camera used to capture high quality images of the surface. The system was developed purely as a data collection tool and does not possess any form of verification algorithm, with data captured and stored against a digital passport of the material/component.

Figure 111 CQCS - MicroEpsilon Laser Line Scanner (Left) FLIR Vision Camera (Right)

Figure 112 shows the network architecture that was employed for the 4G element of this use case on the CQCS. Each sensor was connected directly into an industrial CPE (4G router) with specific NAT rules applied for each device to allow communication across networks. Each CPE communicates with the 4G radio (eNodeB) that is patched directly back to the Evolved Packet Core (EPC). The EPC integrates the incoming 4G LTE data into the IP network behind it and onto the specific virtual machine hosting the software elements of each sensor, thus allowing for data flow between the server and the sensors in the workshop.

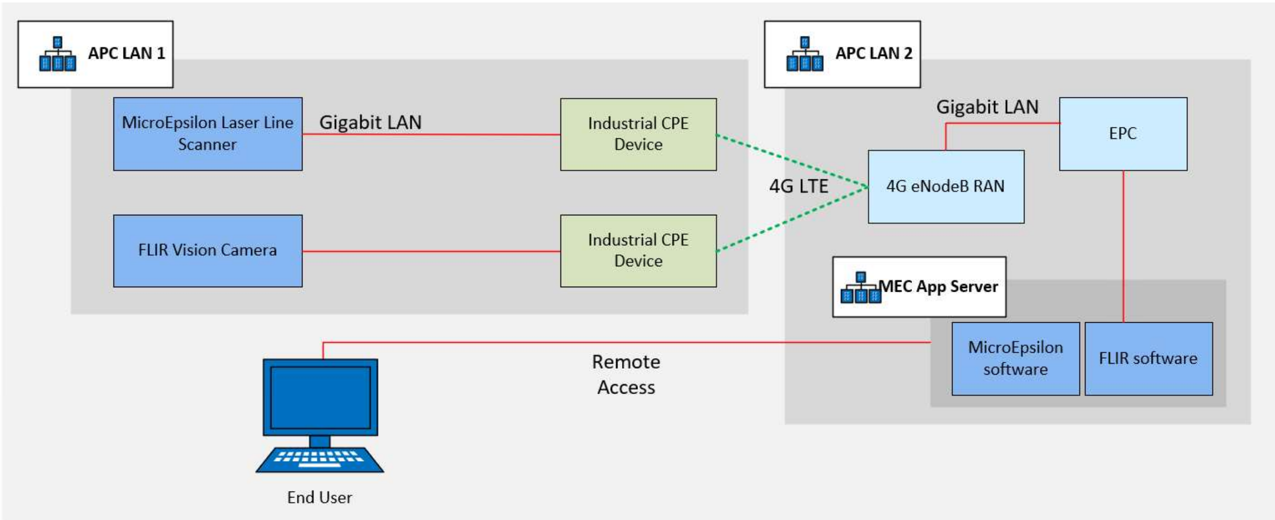


Figure 112 4G Network Architecture

The system had been designed to be used with the hardwired data network within the APC, therefore modifications were made to enable 4G communication. An additional enclosure was added that housed two 4G routers, each connected to one of the sensors in the array.

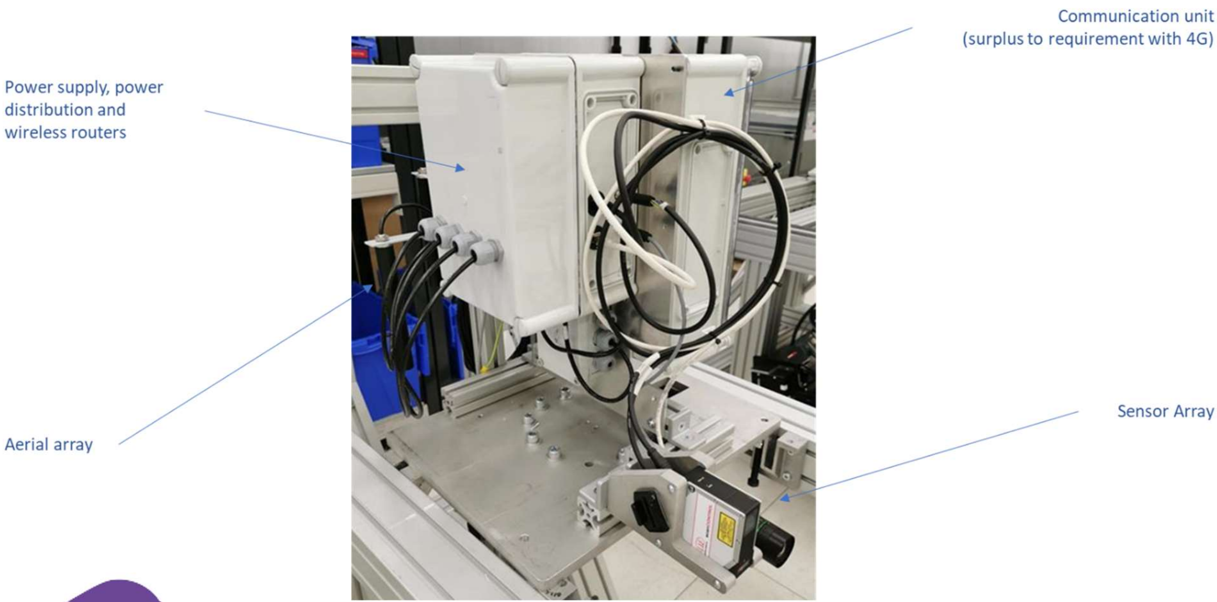


Figure 113 4G Enabled CQCS End Effector

Figure 113 shows the finished system. Each 5G router had a requirement for two omnidirectional antennas to be mounted on the rear as can be seen by the 4 grommets protruding from the side of the box marked “Ariel Array”.

As this system was not designed with any image processing capability there is no need to remove a bulky PC from the assembly, however, edge compute power was still required to host the relevant software for each sensor.

To make use of NAT to cross the different local networks, each sensor was given a fixed IP address. Of the two sensors in question, only the laser line scanner allowed the user to specify an IP address for the device, therefore, to receive data from the FLIR vision camera a third-party application was required, in this case RoboRealm.

68.1.2 4G Outcomes/shortfalls

Both devices contained within the CQCS; the Micro Epsilon laser line scanner and the FLIR vision camera, were connected successfully over the 4G network and data was successfully communicated between them and the virtual machine hosting the software applications.

The private 4G network installed at the NCC could reach speeds at the time of testing of up to 30Mbps (3.75MB/s) on downlink and 10Mbps (1.25MB/s) on uplink. Before the work was carried out it was clear that the 4G speeds were not sufficient for the system to run at its full potential, however the latency also required validation. Ping tests were conducted to get a measure of latency from the VM to the FLIR camera on the CQCS, and over 19 pings an average latency of 155ms was recorded with a maximum of 1372ms and a minimum of 40ms. This latency may be acceptable for applications that do not require real time processing, but for an application using a robot to position a sensor that updates every 10-12ms this is not sufficient.

While 4G LTE may not have been fast enough to run this process at its full potential, it does prove that this architecture is feasible, as well as providing some useful data to compare future technologies against. Validating this architecture using 4G shows that GigE Vision as a protocol can be manipulated to traverse networks and paved the way for the 5G demonstrator. There may be more scope to investigate the full potential of 4G LTE for this application in the future, however, after proving the connection is possible the focus was shifted to the 5G set up.

68.1.3 5G Test Setup

The 5G network architecture for the Profactor system was built on a similar network framework to the 4G set up, and while the speeds were not the maximum that 5G can offer they were significantly faster than the 4G. The private 5G network installed at the NCC was capable at the time of testing of reaching up to 400Mbps (50MB/s) on downlink and 57Mbps (7.125MB/s) on uplink. Regardless, this value of uplink data rate is far from the 900-1000Mbps required for the sensor to operate at full capacity.

Initially tests were conducted at the same parameters as the wired baseline outlined in Section 67.2, however, the results were poor with little to no useful data being seen on the VM. The throttled uplink speed meant that the network couldn't handle the volume of data that was being pushed up to the server, and some reconfiguration of the sensor was required. The MTU size was reduced from 9016K down to 1444K to relieve the pressure on the connection as the application was reporting a large number of skipped frames. The initial scans using the jumbo frames caused a large amount of data fragmentation with only parts of the scan being visible in the application as shown in Figure 114. This fragmentation of data seemed to cause some issues with network stability and would regularly require a reboot following a bad scan.

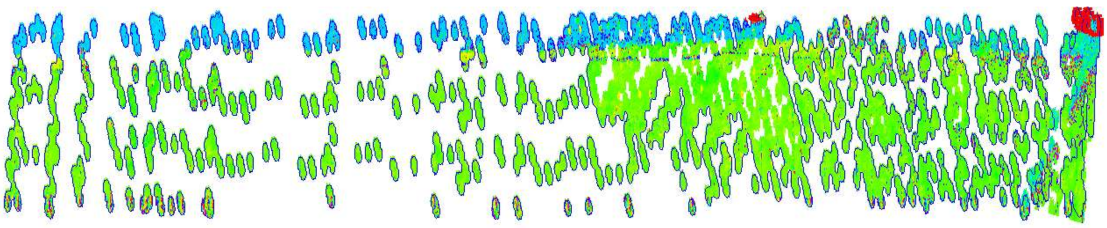


Figure 114 Data fragmentation over 5G

By reducing the MTU size, slowing down the linear scan speed of the robot and reducing the framerate of the sensor, the volume of data being sent to the server was spread over a greater time and the number of skipped frames significantly reduced. The result was a complete scan as shown in Figure 115.

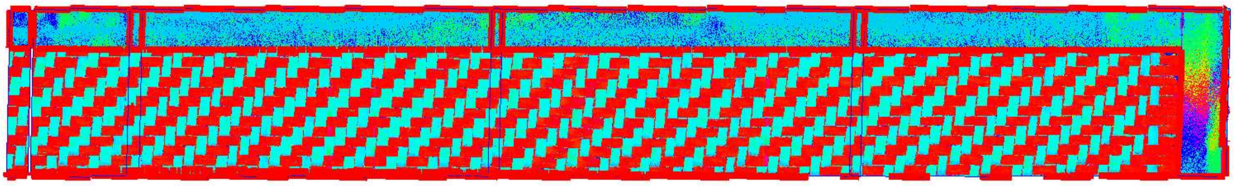


Figure 115 Complete Scan over 5G

68.1.4 5G Metrics

During testing of the 5G system, network metrics were gathered to give an indication of how the network behaved. The metrics themselves were gathered from the Airspan radio software (5G provider), over periods of 15 minutes. Each scan over 5G took approximately 5.5 minutes and therefore the values are not completely representative but give a good indication of network behaviour. The metrics of most interest to this use case are the latency and throughput performance, on uplink rather than downlink due to the nature of data generation. As outlined in Section 65.3.3, latency is a measure of how long it takes packets to be sent and received and throughput is a measure of data rate.

Figure 116 is a graph showing the uplink throughput of the distributed unit that serves the specific radio this use case is connected to. A total of 8 spikes can be seen that coincide with the 8 tests that were carried out (includes successful and unsuccessful).

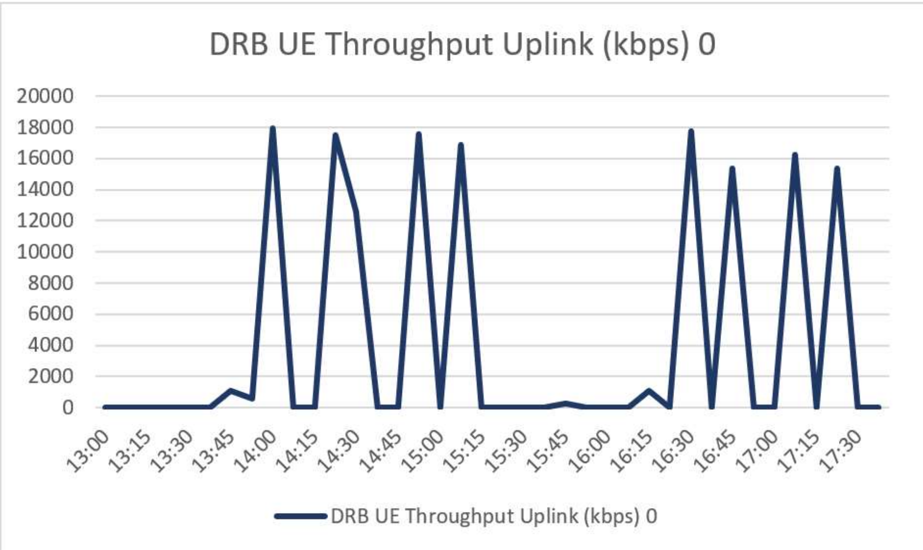


Figure 116 5G uplink throughput

A throughput of ~18Mbps (18000Kbps), can be seen from the graph which would indicate a data rate of 2.25MBps (18000/15 = 2.25). The real-world throughput may have been higher than this however, as these values are averaged over the total 15-minute period and include periods of no data transfer.

A metric that can be used in conjunction with the observed throughput is the Physical Radio Block (PRB) usage percentage. PRB usage is the amount of available radio resource. Comparing the PRB usage % on both uplink and downlink and we can begin to see the network consumption of this application.

Figure 117 shows the PRB usage % on uplink during the testing period. Comparing this to Figure 118 which shows the downlink PRB usage % and it is clear to see the difference. The use case consumes ~70% of available uplink while only consuming ~5% of available downlink.

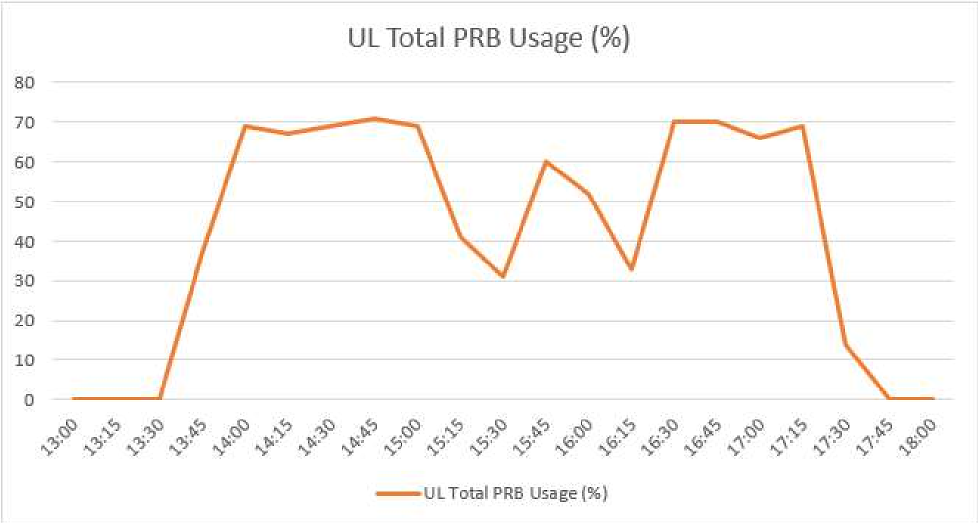


Figure 117 5G PRB usage on uplink

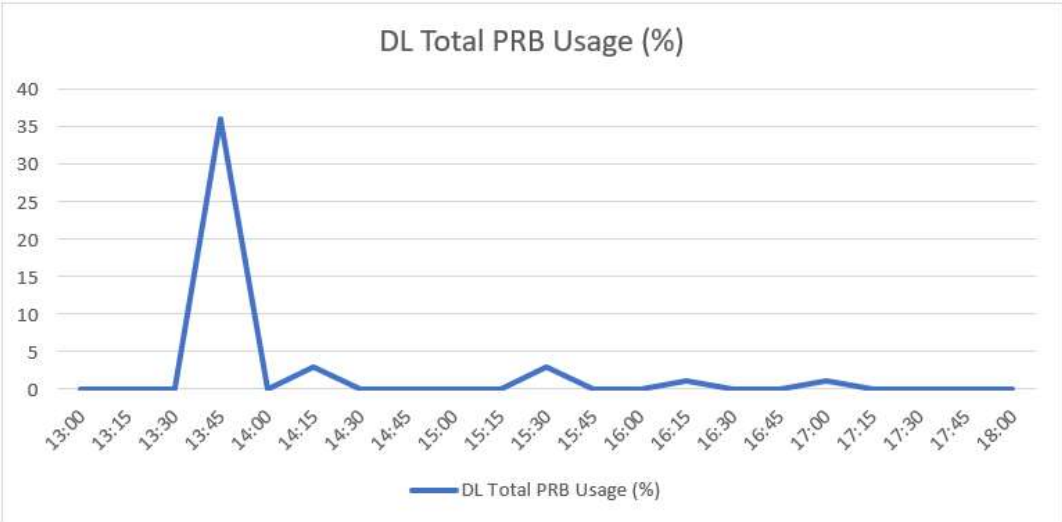


Figure 118 5G PRB usage on downlink

The PRB usage % comparison confirms the need for significant uplink throughput for this application and would indicate the need for more appropriate network balancing. In its current form this 5G network can only support one sensor system per radio; any additional systems and it would cause the network to overload.

Latency testing was carried out in a similar manner to the 4G testing. A total of 100 pings were sent between the VM and the sensor with an average of 14ms, a maximum of 164ms and a minimum of 11ms being recorded. These values are a significant improvement on the observed values from the 4G testing and are not far outside an ideal region (10ms) for this application.

Network stability was also of interest as during some scans the connection would drop completely and would require a reboot of the CPE before it re-attached. Figure 119 shows the unplanned release requests that occurred during the testing period with 4 observed between 13:45-14:00 and a further 2 observed between 14:00 – 14:15. The cause of these is not known, only that it was unplanned. This, however, does prove the presence of some network instability in either the radio or the CPE around the time of testing with high data fragmentation. The unplanned releases can be seen to cease as the scan speed was reduced and MTU size adjusted for the reduced connection speeds.

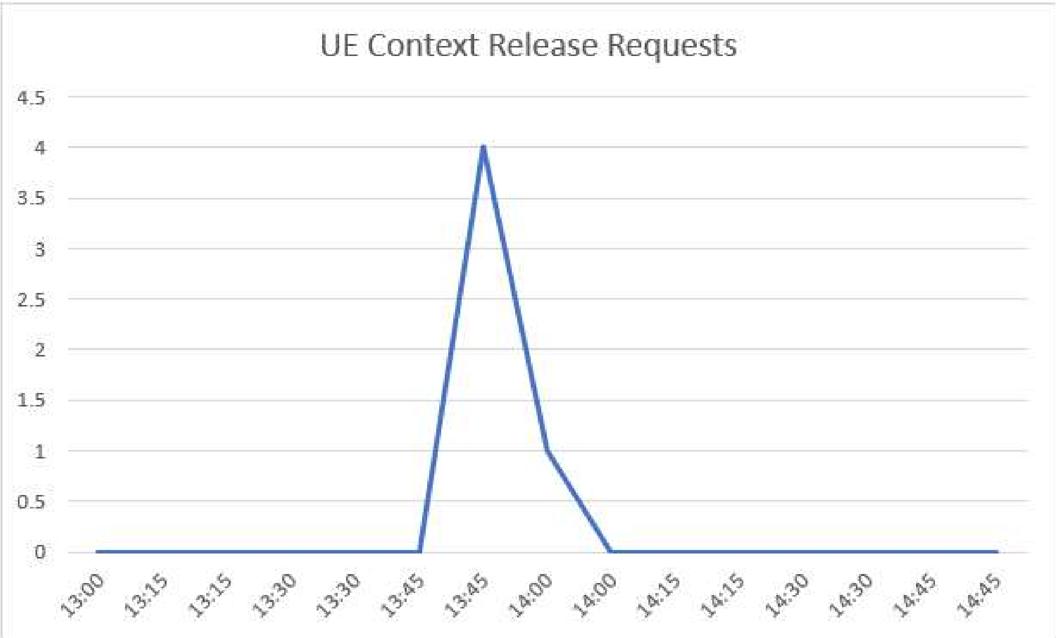


Figure 119 Unplanned session releases

69 5G DISCUSSION

69.1 Benefits of 5G

The benefits that 5G as a technology can bring to smart manufacturing have been partially demonstrated in this use case but regardless, as the technology matures there is no doubt of the potential improvements 5G can bring.

The flexibility of deployment that 5G can add to a factory, coupled with the vast number of interconnected devices that can simultaneously link back to the same core means that 5G as a technology will surely aid in accelerating toward Industry 4.0. Having infrastructure in a factory interconnected, but not restricted with hardwired data connections mean the level of flexibility increases dramatically. Being able to alter the layout of a factory without the need to alter the infrastructure behind it means both the cost and time associated with setting up a new or novel process are dramatically reduced.

In upgrading the sensor system to 5G this concept of data transfer has been proven. While the speeds may not have been what was expected, the communication of large volumes of data across a private 5G network have been demonstrated. In turn allowing for a powerful system to become more accessible and deployable.

69.2 Limitations of 5G

Some limitations of this technology have been clearly highlighted by this application. The lack of uplink speed meant that the scan was 200 times slower than the baseline. Also, intermittently, during periods of high data transfer (>70% of available uplink bandwidth), the CPE device would indicate a connected state although data transfer had ceased and rendered the device unusable. Testing concluded that data transfer issues were prevalent on the specific device attached to the radio and not the radio itself. Further investigation indicated that when the device data transfer ceased, irregular core flows were observed within the RAN software specific to the radio in question, therefore proving the CPE device was not operating as expected. Root cause for this issue has still not been fully identified but this behaviour has been observed across multiple CPE devices from multiple manufacturers (all CPE devices leveraged the same 5G microchip). Remediation of this issue involved a soft reboot of the CPE device, which led to a successful reattach to the 5G packet core and data transfer resumed.

Another major challenge in upgrading this system to 5G was the presence of the GigE Vision industrial protocol. This protocol is widely used for applications that produce large amounts of data but has always been limited to devices on the same local network. Enabling communication of a layer 2 GigE Vision device across a layer 3 network required a deep understanding of the process in which data is transferred. Without the presence of a highly skilled network engineer is it unlikely this process would have been possible and could therefore be a blocker to this being more widely adopted into industry.

69.3 5G Conclusions

5G testing showed the difference in requirement between uplink throughput and downlink throughput for this application, and the PRB usage % indicated the need for increased uplink throughput and improved network balancing. As a result of the observed network performance, scan parameters had to be adjusted to ensure the output was of use. The framerate of the sensor, the MTU size, and the linear scan speed of the robot were all significantly reduced to prevent any fragmentation of data.

The knock-on effect of this was that the scan speed over 5G was approximately 200x slower than when compared to the wired baseline. Therefore, it is fair to say, in its current state the installed 5G network at the NCC, while functional, is not sufficient to make this a superior method of transferring data when compared to a wired set up. 5G, however, is a very infant technology and as with all things, greater understanding leads to greater performance. As the software behind the 5G deployment matures, the capability of the technology will improve, and with an upgrade planned for January 2022 that promises to increase the observed connection speeds, this improvement may come sooner than expected.

To conclude, this use case has been an overall success. The project objectives of demonstrating how digitisation and 5G can lessen the barriers to more widespread acceptance into industry have been met. Reductions in robot system costs, integration costs and deployment costs have all been observed and an architecture has been designed to connect layer 2 (MAC) devices over a layer 3 (IP) network. It should be noted that until a 5G specific industrial standard for high throughput applications is developed, GigE Vision will continue to add complexity to upgrades of this nature.

70 APPENDICES

70.1 APPENDIX A – Reduced Integration Cost Detail

It must be noted that the original deployment of the Profactor verification rig within the APC was an addition to an existing cell. The costs shown are that of the elements of the cell that are required for the original system to operate. The use case costs are independent of this as they do not make use of this existing hardware.

Item: Original Deployment	Cost (£)
Fixture Kits	37,818
Cell Control system (safety, monitoring, control software)	68,570
Cell Control System – Electrical Cabinets	69,303
Installation	96,068
Total	**271,759**

Item: Use Case Deployment	Cost (£)
Electrical Cabinet	1,516
Extrusion (£16/m)	160
Installation & Commissioning (50h x 75£/h)	3,750
Total	**5,426**

% Of Original Cost	1.99

70.2 APPENDIX B - Reduced Robot Cost Detail

Item: Original Deployment	Cost (£)
Kuka KRC510	70,967
ATI Omega Force Torque Sensor	23,900
Track system	66,528
Tool Changer	19,185
Total	**180,580**

Item (Updated)	Cost (£)
Fanuc CR7-iAL	22,091

% Of Original Cost	12.23

70.3 APPENDIX C - Reduced Deployment Cost Detail

Original APC Breakdown	Cost (£)
Integration	271,759
Robot system	180,580
Total	**452,339**

Total UC Cost Breakdown	Cost (£)
Integration	5,426
Robot system	22,091
NCC Support (200h x 75£/h)	15,000
Profactor Support	11,150
Total	**53,667**

% Of Original Cost	11.86

71 – LIQUID RESIN INFUSION –

72 ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK Government's biggest investments in 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It also is designed to validate the premise that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that UK industry makes the most of the 5G technology and ultimately remains a global leader in the development of robust engineering capabilities when implementing complex composites structures manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLLC/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the Southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and small and medium enterprises (SMEs).

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

73 EXECUTIVE SUMMARY

This report outlines the development of the 5G Closed Loop Liquid Resin Infusion (LRI) use case. LRI is a process used by the aerospace, automotive, marine and several other industries to create composite components. It has many benefits over prepreg, such as cheaper material costs and faster manufacturing times – however is highly dependent on the skill of the operator, is very manual, and often produces many scrap components when developing new parts. There is a need to automate LRI to make parts right-every-time, reduce the environmental impact by generating less scrap, and lower cost and manufacturing time.

The Closed Loop LRI system utilised 5G and digital technologies to improve the process. The system used a sensor array to monitor key LRI process variables and sent this data to a control model. The model decided how the process should be altered in real time and sent commands to a feedback system that implemented the decisions. A visualisation system used dashboards to display process data in real-time and generated a traceability report for each part. All sensor data and control commands were sent over 5G.

To enable a modern closed loop system to work effectively there are numerous requirements to consider. A high speed, low latency, highly reliable network is needed to transfer process data across. Next, because the amount of data needed to properly model a manufacturing process could be vast, the network needs to be able to handle large numbers of sensors connecting to it. In practice the sensors need to connect to the system wirelessly as attempting to connect a huge number of wired sensors is impractical. Finally, a high-performance computing capability – located on the edge – is needed to run complex models (for instance AI) that will control the manufacturing process. 5G has the potential to meet these requirements through characteristics including **Ultra-reliable low latency communication, edge computing**, and **massive Machine Type Communication** (allowing thousands of devices to connect to the network at once).

The system was initially tested on a 4G network to establish a baseline, and then tested on a bespoke 5G network to assess if there was a discernible increase in real world performance of the use case. Additionally, the system was tested on a low cost off-the-shelf/open source 5G network; its performance was assessed to understand if this cheaper system could allow smaller companies to leverage the benefits of 5G.

The Closed Loop LRI system realised numerous benefits. It led to reduced manufacturing labour costs of around 25% while the live dashboards gave engineers a clear view of the process and allowed them to reduce cure cycle time by around 50%. Using wireless 5G communication enabled the system to be flexibly deployed anywhere in the factory. Finally, the automatic generation of the part traceability report saved over 8 hour of engineering time and associated costs.

Overall, the use case was able to operate well over 5G, however network dropouts due to poor reliability caused some data loss – more work is required to enhance device stability on the 5G Standalone Open RAN network (5G SA ORAN).

Reliability issues were also seen with the off-the-shelf/open source 5G network.

There was not a discernible performance increase seen over the 4G baseline. The use case however was a small-scale demonstrator – it is likely that if the system was expanded to a more representative scale (such as an aircraft wing manufacturing process) the advantages of 5G would become visible.

74 ABBREVIATIONS

3GPP	3rd Generation Partnership Project
AI	Artificial Intelligence
COTS	Commercial off the shelf
DoC	Degree of Cure
eNB	evolved Node B
gNB	next Generation Node B
GPS	Global Positioning System
HSS	Home Subscriber Service
IoT	Internet of Things
IP	Internet Protocol
JSON	JavaScript Object Notation
LRI	Liquid Resin Infusion
LTE	Long Term Evolution (AKA 4G)
MEC	Multi-access Edge Computing
MME	Mobile Management Entity
mMTC	Massive Machine Type Communication
MQTT	Messaging Queue Telemetry Transport
NCC	National Composites Centre
NSA	Non-Standalone (in relation to 5G)
NUC	Next unit of Computing (a bare bones miniature PC)
OAI	Open Air Interface
O-RAN	Open-RAN
ORS	Online Resin Monitoring Software (Synthesites Ltd)
OSA	OpenAirInterface Software Alliance
PDN	Public Data Network

PDU	Protocol Data Unit
PLC	Programmable Logical Controller
PLMN	Public Land Mobile Network
PPS	Pulse Per Second
RAN	Radio Access Network
RF	Radio Frequency
SA	Standalone (in relation to 5G)
SDR	Software Defined Radio
SE	Systems Engineering
SME	Small to medium enterprise
SPGW	Serving & PDN Gateway
SQL	Structured Query Language (relational database)
Tg	Glass transition temperature
UE	User Equipment
URLLC	Ultra-Reliable Low Latency Communication
USB	Universal Serial Bus
USRP	Universal Software Radio Peripheral

75 INTRODUCTION

75.1 Industrial Challenge

Liquid resin infusion (LRI) is a process used by the aerospace, automotive, marine and many other industries to create composite components. These can range from boat hulls to full aircraft wings, such as on the Airbus A220. It offers higher rate and lower cost production compared to other methods used to make composites (such as prepreg moulding, which has higher material costs, and longer processing times). The technique however is highly dependent on the skill of the operator, is very manual, and often produces many scrap components when developing new parts.

As industry grows its use of LRI, there is a need to improve the process to enable parts to be made 'right first time' and 'right every time' - lowering the cost and time of developing new components and reducing the environmental impact of composite production by generating less scrap.

These improvements to LRI composite manufacturing can be achieved through data analysis and automation of the LRI process by the application of digital and 5G technologies.

75.2 Project Objectives

The first stage towards enabling 'right first time'/'right every time' manufacturing is automation. Prior to this project the LRI process was almost entirely manual. **The purpose of this use case was to develop a system that could automate elements of LRI process** by using closed loop manufacturing.

Achieving this objective would enable:

1. Reduction in labour costs
2. Reduction in manufacturing time (and thereby cost)
3. Improvement in part quality

75.3 Purpose of 5G

75.3.1 Why 5G?

Due to the time sensitive nature of the LRI process, closed loop manufacturing systems require process data to be captured, sent, and processed in real time. This data can then be acted upon to alter process parameters, such as temperatures and pressures, thus steering the process to a successful outcome.

To enable a modern closed loop manufacturing system to work effectively there are numerous requirements to consider:

- A **high speed, low latency, highly reliable network** is needed to transfer process data across.
- Because the amount of data and sensors needed to properly model a manufacturing process could be vast, the **network also needs to be able to handle large numbers of sensors** connecting to it. Capturing data in this way is also critical in developing digital twins.
- In practice the sensors need to **connect to the system wirelessly** as attempting to connect a huge number of wired sensors into a network is impractical.
- A high-performance **computing capability – located on the edge** – is needed to run complex models (for instance AI) that will control the manufacturing process.

5G has the potential to meet these requirements through characteristics such as mMTC, URLLC, and edge computing.

The Closed Loop LRI system used an **IoT sensor array** to capture data on the manufacturing process, and this data was sent to a **control model** over a 5G network. Control decisions from the model were also sent over 5G to the **real-world feedback system.**

This use case was performed on a small scale to prove the concept of using 5G in closed loop manufacturing in an industrial setting, meaning the capabilities of 5G were not fully utilised in practice – however as this system is developed further (for example on a 17-meter aircraft wing manufacture) these 5G benefits would likely be required.

75.3.2 Assessment Methodology

To assess 5G properly, the Closed Loop LRI system was first tested on a **local 4G network**. After, this the system was tested in the same way on a **local 5G network**. The performance of system was assessed and compared on 4G and 5G respectively to establish what – if any – real world performance increase could be seen when switching to 5G.

The 5G network used by this use case was a bespoke system design and developed for the 5G ENCODE programme and was deployed at the NCC HQ in Bristol, UK. The network was a **5G SA system**. Full details of the network can be read in report 5G Encode Platform Commissioning Report[1].

In addition to the 4G baseline and bespoke 5G SA network, the use case was also tested on a **5G NSA network developed by Toshiba**. Purchase and installation of full scale 5G networks in an industrial environment is expensive, costing hundreds of thousands of pounds at a minimum. These costs are prohibitive for SMEs to adopt 5G and realise its benefits. To address this Toshiba developed a 5G network using COTS hardware and open-source software. This network was an order of magnitude cheaper to purchase and install than a standard full scale 5G network.

The viability of using a COTS/open-source low cost 5G network in an industrial environment was assessed by testing the performance of the Closed Loop LRI system on Toshiba's 5G NSA network.

The performance of the use case on the 4G and 5G SA networks can be found in the section 5G Industrial Assessment, while performance on the Toshiba network is found in the section Toshiba 5G NSA.

[1] https://www.5g-encode.com/media-and-publications (see 5G Encode Platform Commissioning Report)

76 OVERVIEW

76.1 The Liquid Resin Infusion Process

76.1.1 Process Overview

A composite is a form of material that takes two different material types and combines them together to create a single material structure with performance greater than that of the individual constituent materials. A common example of a composite is a carbon fibre reinforced plastic – the carbon fibres form the base strength of the material structure while the plastic holds the fibres together. Composites typically have higher strength-to-weight ratios than metallics, making them attractive to aerospace and many other industries.

The LRI process is one of the two primary techniques used to create composites parts (the other being prepreg moulding). It involves placing dry fibres in a mould tool cavity and then infusing liquid resin (plastic) into the fibres under vacuum pressure. The stages of the LRI process are shown in Figure 120.

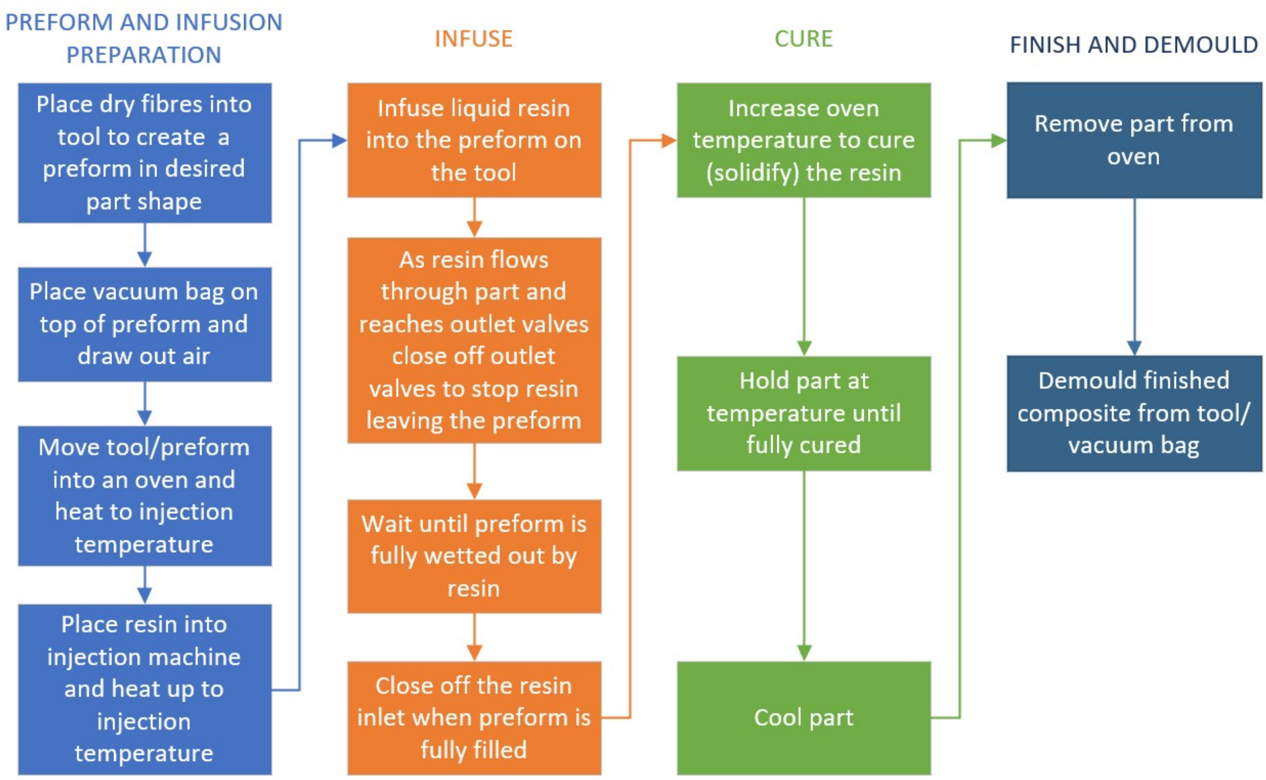


Figure 120 - The stages of the LRI process

76.1.2 LRI Manufacturing Equipment

The manufacturing system used to make composites by LRI typically has 3 main elements:

1. **Tool and vacuum bag**
    a. *The tool is where dry fibres are placed to form the part shape (known as a preform).*
    b. *The vacuum bag is placed onto the preform to form a mould cavity.*
2. **Oven**
    a. *This used to heat the tool/preform to the required injection temperature.*
    b. *After the infusion phase the oven temperature is increased to cure (solidify) the resin.*
3. **Resin injection machine**
    a. *This is used to hold the liquid resin and heat it to the required injection temperature.*
    b. *The resin needs to be heated to reduce its viscosity and make it easier to infuse into the dry fibre preform.*
    c. *The machine infuses the liquid resin into the fibre preform via a pipe.*

Images of the three elements can be seen in Figure 121, Figure 122, and Figure 123. For this use case a silicone vacuum bag was used.

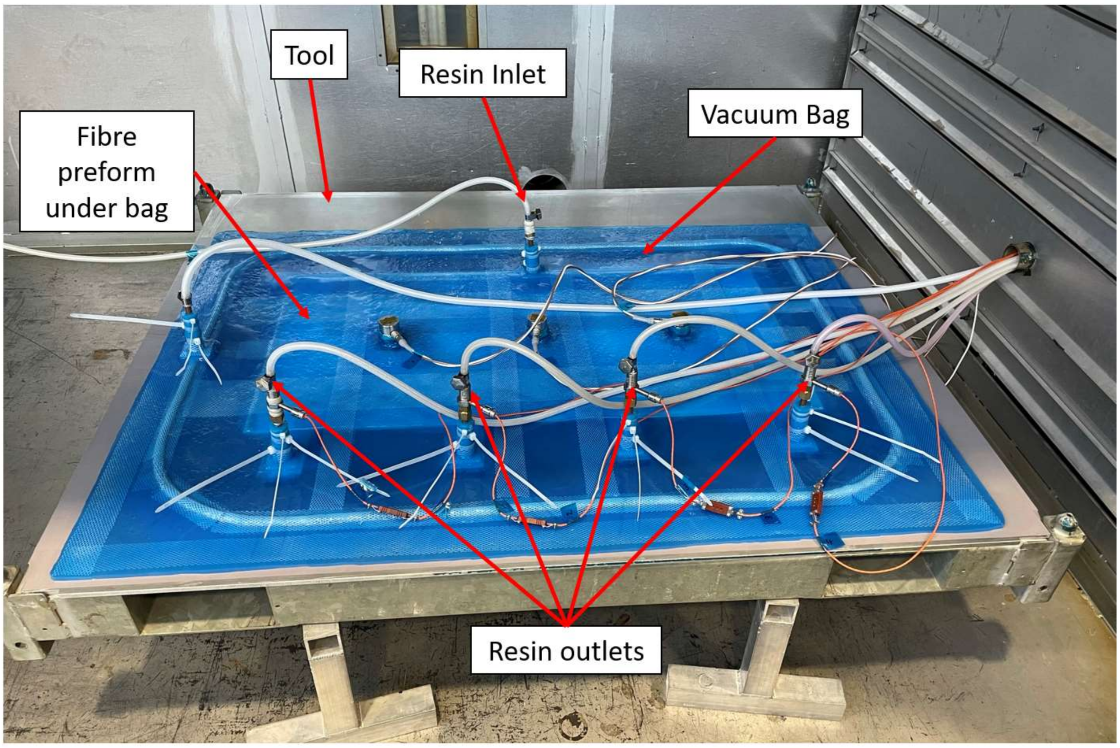


Figure 121 - Flat panel aluminium tool with a silicone vacuum bag

Figure 122 - Industrial oven

Figure 123 - Resin injection machine

76.2 Top Level Use Case Architecture

The Closed Loop LRI system comprised of two parallel systems. First was the system that would automatically control elements of the LRI process, named the Closed Loop Control System. Second was the system that would visualise the process data to engineers, this was called the Data Visualisation System. High-level architectures of both systems are shown in Figure 124 and Figure 125.

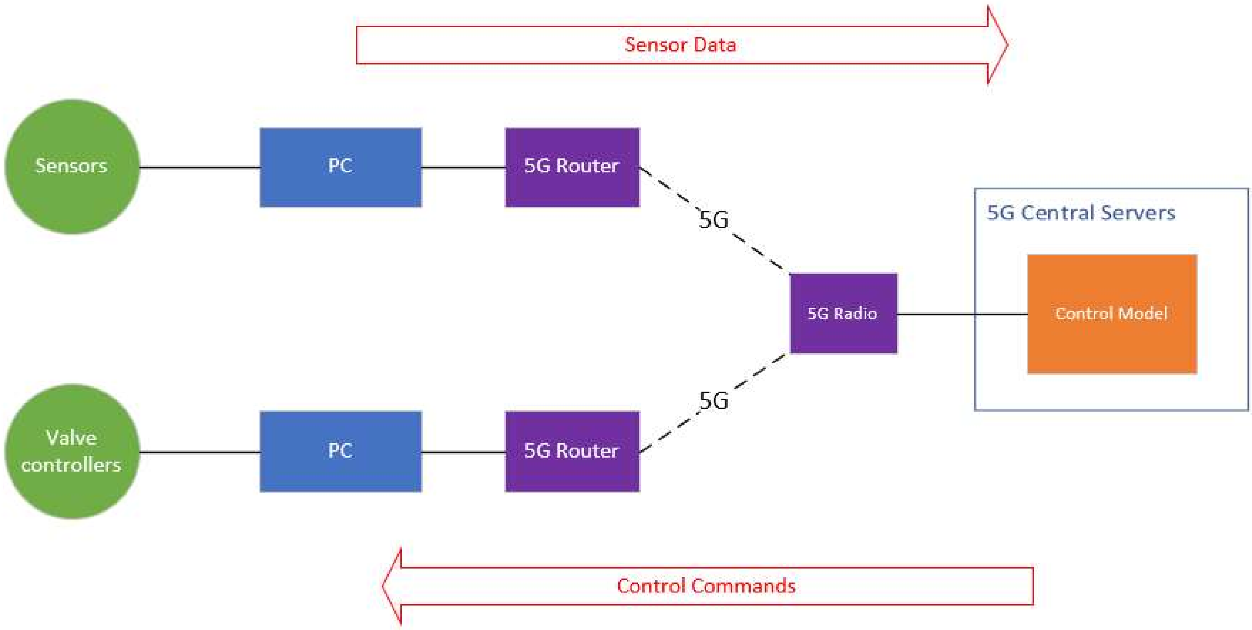


Figure 124 - Top level Closed Loop Control System architecture

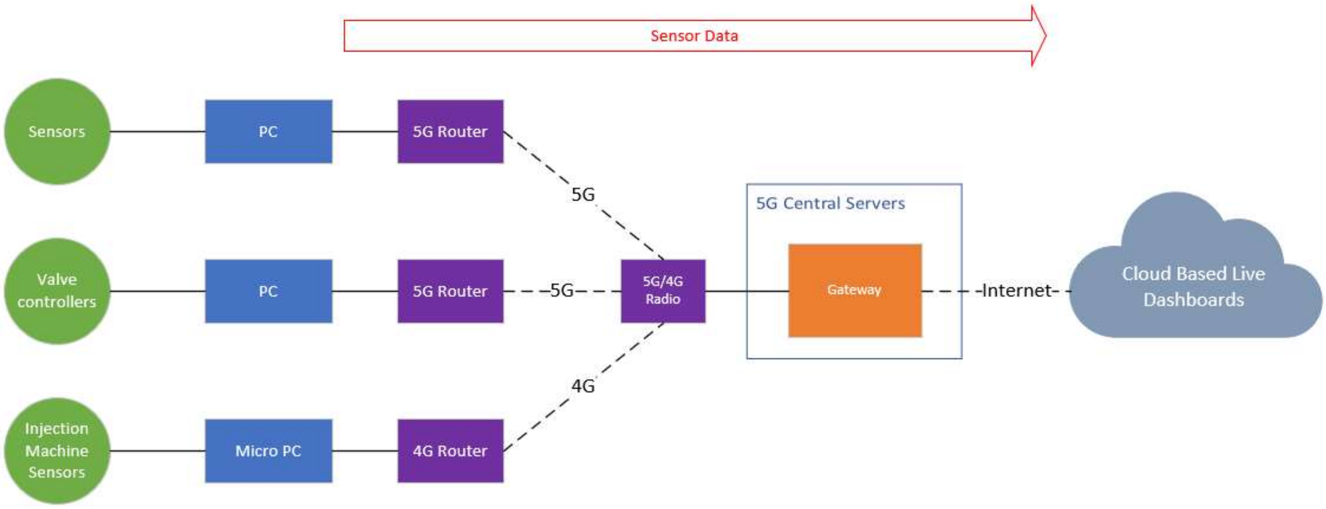


Figure 125 - Top level Data Visualisation System architecture

Closed Loop Control System – The system used a **sensor array to capture LRI process data**. The resin flow location was the key piece of information needed for control. This data was sent wirelessly over the 5G network to a control model (hosted on the 5G edge compute servers). The **control model used the data to make decisions** on what should happen in the process, and then sent these commands (over the 5G wireless network) to the feedback system to be implemented in the real world. The **feedback system had numerous valve actuators that could control resin outlet lines** and actuated these based on the control models commands.

Data Visualisation System – The system collected process data from three sources: the **sensor array** (resin characteristics, temperatures), **feedback system** (valve open/close status), and the **injection machine** (machine parameters). To enable the injection machine to stream data an IoT micro-PC and a router were integrated into it. All data was sent over the wireless 5G network[2] to a cloud gateway, which then forwarded the data onto a Microsoft Azure cloud platform. The data was stored in a data warehouse, and this was then **visualised on three separate dashboards**. The two live dashboards displayed the **process variables in real-time** (resin monitoring, and injection machine). The third dashboard displayed a **part traceability report** which gave a full data history of the manufacture.

Detailed architectures and descriptions of each system can be found in Use Case Development and Investigation.

[2] The injection machine used 4G to send data as suitable DIN-rail mountable industrialised 5G routers were not available at the time of the project.

76.3 Measures of Success

This section details the factors that will be measured to determine the success of the system.

76.3.1 Use Case Metrics

The following metrics have been used to measure the success of the use case:

Reduction in manufacturing labour time

How is it measured: Labour time saved or avoided

Unit: % reduction

Detail: Automating elements of the LRI process reduces the need for labour. Highly skilled operators are often doing low-value tasks in LRI, the Closed Loop LRI system will automate these low value activities, reducing the time (and cost) for part manufacture. This also frees up operators to perform higher value activities elsewhere in the factory.

Reduction in time to generate part traceability report

How is it measured: Engineer time

Unit: % reduction

Detail: Collating together manufacturing data from various sources (such as data loggers and machines) into a spreadsheet, time-syncing them, and creating graphs is a time-consuming exercise. Nevertheless, this is a critical activity for understanding what happened during manufacture for traceability and part insight. This system sought to perform the task automatically by collection and visualisation of data on dashboards.

Enhanced process insight

How is it measured: Variables monitored during manufacture are displayed on a single platform

Unit: Number of variables

Detail: Presently, little process monitoring is performed either mid or post-manufacture in LRI. If it is performed engineers must often look at multiple platforms/systems to view the data. Increasing the number of variables monitored during the process and displaying these on a single, easy to understand platform allows engineers to make data driven decisions to improve the process and part quality.

System Flexibility

How is it measured: Level of difficulty in redeploying system to other LRI processes

Unit: N/A

Detail: The combination of an IoT data capture architecture and use of wireless 5G allows the system to be deployed to any LRI process, anywhere in the factory. This means the benefits enabled by the Closed Loop LRI system are not locked to a single process/area.

76.3.2 Network Metrics

The following metrics have been used to measure the success of 5G on the use case:

Latency

How is it measured: Time taken for data to go from the Sensor Array to the Control Model (or from the Control Model to the Feedback System)

Unit: milliseconds

Detail: Low latency is critical for control-based systems; if latency is high, the commands may be slow to execute and cause quality or safety issues.

Reliability

How is it measured: Percentage of the time the 5G network was 'up' during a manufacturing cycle (network up time ÷ total manufacturing time)

Unit: %

Detail: Reliability is even more critical than latency, as if a network drop out occurred, data or commands may fail to send/be received and again cause quality or safety issues.

Packet loss

How is it measured: % of data lost in transit over the network

Unit: %

Detail: If data or commands are lost over the network they will not be properly received or executed.

Wireless performance

How is it measured: Wireless signal strength and consistency in industrial setting

Unit: N/A

Detail: Factories are typically challenging environments for wireless networks; large metallic building framework, heavy machinery, and electrical interference can cause signal issues. The 5G network must be able to provide strong consistent signal despite these factors.

76.4 Closed Loop LRI System Requirements

The requirements for any closed loop manufacturing system are threefold: monitor the key variables, use this data to decide how the process should be altered, and then implement the decisions. To meet these core requirements, the Closed Loop LRI system developed three sub-systems: Sensor Array, Control Model, and Feedback System. These are shown visually in Figure 126.

A data visualisation platform is not strictly necessary for a closed loop control system to work, however the ability to view process data in real time (or assess the data after the process) provides significant benefits, as outlined above in Use Case Metrics. Because of this, a fourth sub-system – the Data Visualisation System – was also developed.

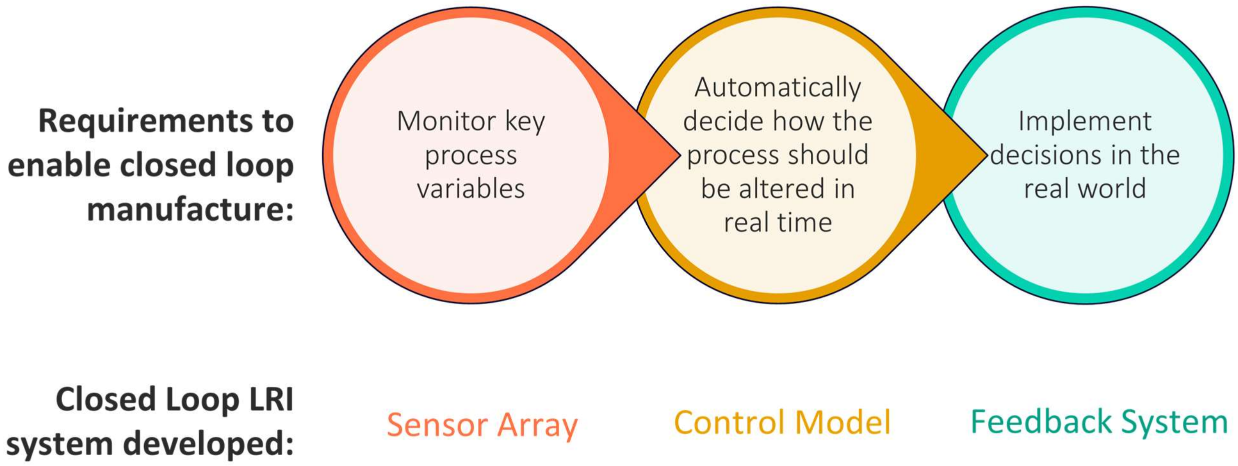


Figure 126 - Key main requirements for developing a closed loop manufacturing system

Overarching system requirements:

1. Monitor key LRI process variables
2. Decide how the LRI process should be altered in real time
3. Implement control decisions in the real world LRI process
4. Visualise real time data to the process operators
5. All elements of the system must communicate over 5G
6. The system must be easy to deploy anywhere in a factory with minimal rework (i.e. flexible)
7. The system must be able to manage an increase in the number of sensors or controllers easily (i.e. scalable)
8. The system must operate safety

Sub-system requirements:

1. **Sensor Array**
   1.1. Monitor LRI process variables in real-time, including:
      1.1.1. Resin flow (resin arrival status)
      1.1.2. Resin degree of cure
      1.1.3. Resin Tg
      1.1.4. Resin viscosity
      1.1.5. Part temperature
   1.2. Collect real-time resin injection machine process data
   1.3. Send all process data to the Control Model and Data Visualisation systems via 5G
2. **Control Model**
   2.1. Receive process data from Sensor Array and decide optimal time to closes resin outlet valves
   2.2. Send control commands to Feedback System
   2.3. Communicate with Sensor Array and Feedback System via 5G
3. **Feedback System**
   3.1. Receive control commands over 5G
   3.2. Control the resin outlet valves of the LRI process
   3.3. Manual override functionality in case of control model or network failure
4. **Data Visualisation System**
   4.1. Show real-time view of LRI process data in a single view
   4.2. Generate post-manufacture part traceability report automatically
   4.3. Store process data and make it accessible

77 USE CASE DEVELOPMENT AND INVESTIGATION

77.1 Use Case Architecture

As mentioned in the Introduction, two separate architectures were designed for the Closed Loop LRI system:

1. Closed Loop Control System Architecture
2. Data Visualisation System Architecture

These architectures reflect the different needs of the two systems. An on-premises design was used for the Closed Loop Control System as it required low-latency and high reliability for data flows. Running the system on-premises meant all data stayed within the building and data flows could be assured.

In parallel to this, the Data Visualisation System utilised a cloud-based architecture. As this system was not being used for control, and real-time latency was not as critical, using the cloud was preferred.

A top-level view of when to use cloud or on-premises solutions for digital manufacturing applications (such as closed loop manufacture) is shown in Table 16.

Table 16 - Benefits, limitations, and ideal use situations for on-premises or cloud solutions

	On-Premises	Cloud
Benefits	• Simpler to guarantee latencies • Easier to ensure robust data flows • Data security (data does not leave the building)	• Comes out cheaper overall • Many readymade tools for data capture and analysis • Easier to create a solution quickly • Highly scalable
Limitations	• More difficult to scale if systems expand • Hardware needs to be managed internally or through a service contract	• Still requires some level of on-premises solution to send the data to the cloud • Data transfer reliability, latency, and speed only as good as your internet connection (which may not be in your control)
Ideal use	• Situations where data flow speeds, latencies, and robustness are critical (e.g. closed loop control) • Safety critical situations (e.g. automation)	• Situations where you are using data for anything other than real-time control and feedback (e.g. data reporting for finished parts)

77.1.1 Closed Loop Control System Architecture

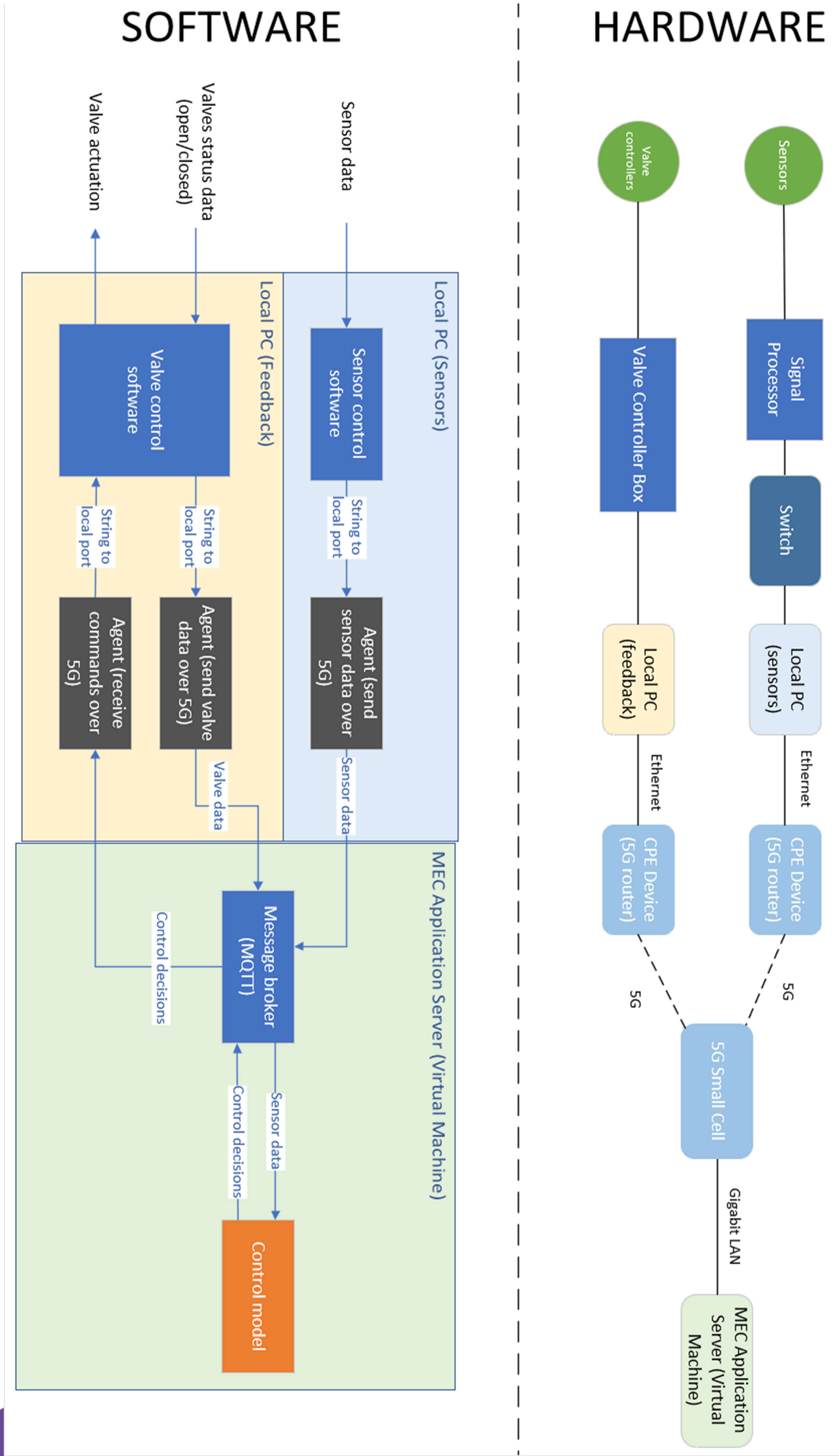


Figure 127 - Closed Loop Control System Architecture diagram

77.1.2 Closed Loop Control System Description

The control element of the Closed Loop LRI system was designed with three primary sub-systems: **Sensor Array**, **Control Model**, and **Feedback System.** The sub-systems and their interaction with one another are shown in Figure 128, whilst the full architecture of the system can be seen in Figure 127. The upper part of Figure 127 shows the hardware elements of the system and the lower part shows the software that is running on the hardware elements (Local PC (Sensors), Local PC (Feedback), and MEC Application Server (Virtual Machine)). The flow of sensor data, valve data, and control decisions can also be seen in Figure 127.

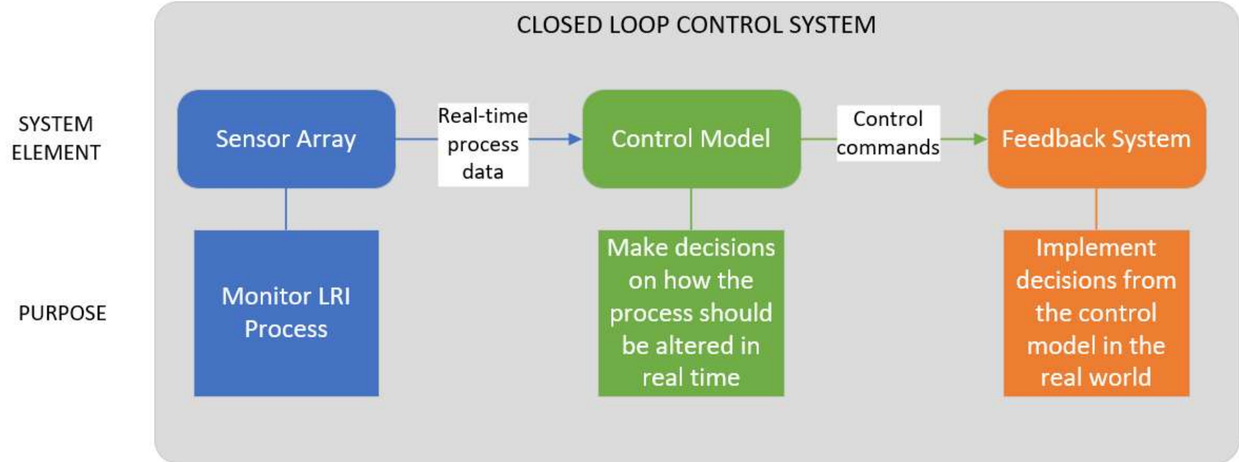


Figure 128 - Control system elements and flow of data within system

Sensor Array – The Sensor Array was developed to monitor numerous critical variables in the LRI process, however for the purpose of the control system only one parameter was of interest – resin arrival status. The location of the resin as it flowed through the part was monitored using resin arrival sensors (these 'trigger' when resin is in contact with them). The sensors were used to detect resin flow as it reached the outlet pipes, and this data was passed onto the Control Model.

Feedback System – The Feedback System was designed to automatically open or close the outlet lines of the infusion set up. This was performed using bespoke valves actuators that could be controlled remotely by the control model. The Feedback System had no intelligence (i.e. it did not know when valves should be open/closed) – it relied on the Control Model for commands.

Control Model – The Control Model received the resin arrival status data from the sensor array and then made decisions as to when the outlet lines of the infusion should be opened or closed. The Control Model sent its commands to the feedback system for implementation.

5G - The Control Model was run on a virtual machine on the MEC Application Server. This server is the 'edge compute' element of the 5G network and allows computational models to be run at a location in the network that is close to the data acquisition and feedback elements of a system. This ensures a low latency communication between the Sensor Array/Feedback System and the Control Model, which is critical for closed loop control. The Sensor Array and the Feedback System were connected to the 5G network using 5G routers (also known as CPE devices). All sensor data and control decisions were sent over the 5G network.

Full details of the Infusion Setup, Sensor Array, Control Model, and Feedback System can be found in their respective sections in Use Case Development.

Data Visualisation System Architecture

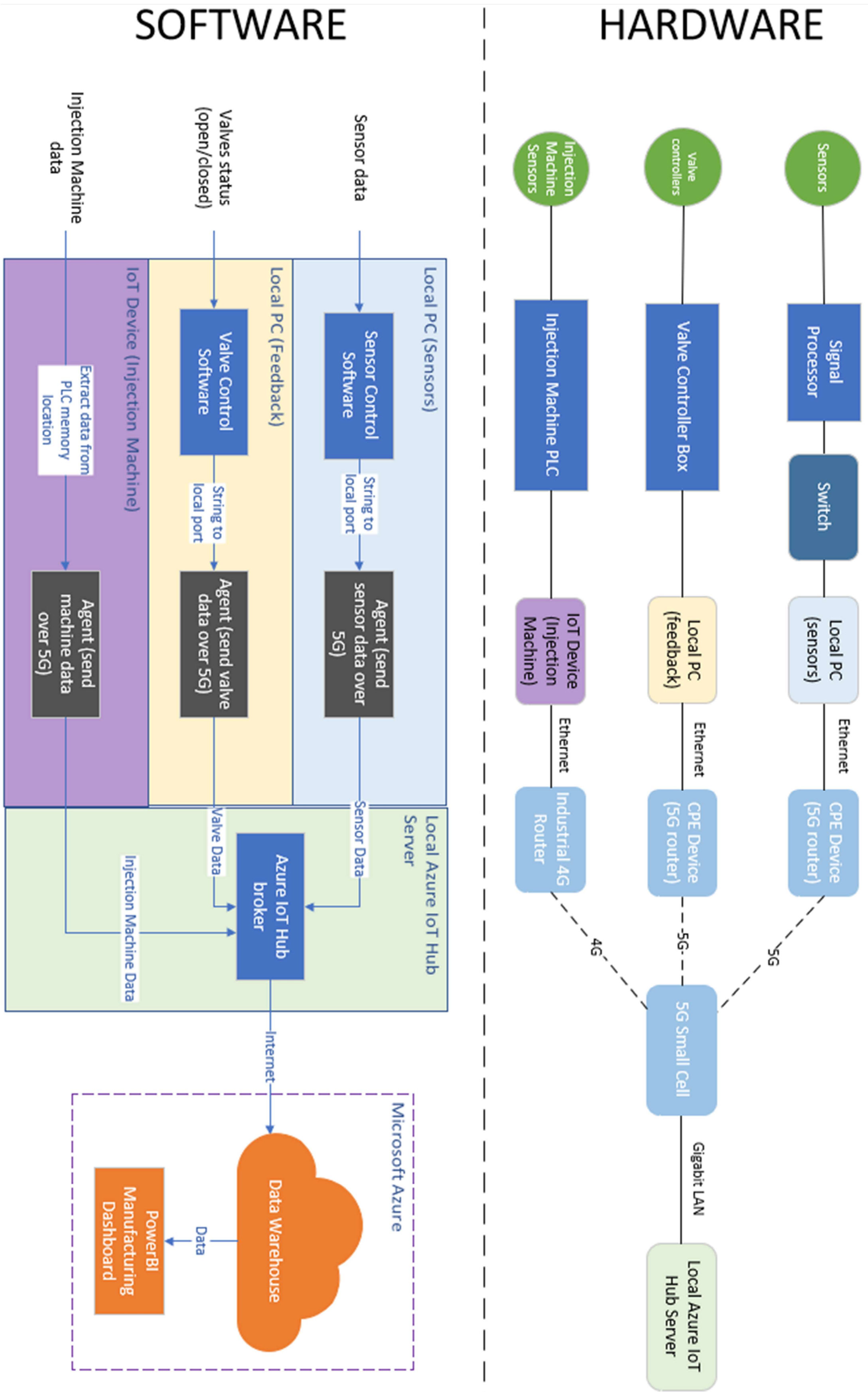


Figure 129 – Data Visualisation System Architecture diagram

77.1.3 Data Visualisation System Description

The Data Visualisation System took the data collected during the manufacturing process and displayed it in real-time on live dashboards. There were three main sources of data collected during manufacturing:

- **Sensor Array** – this collected data on the state of the part including resin characteristics (resin arrival status, degree of cure, Tg, viscosity) and temperatures.
- **Feedback System** – this collected data on the status (either opened or closed) of the automated valves in the feedback system.
- **Injection Machine** – this collected all key data from the resin injection machine, such as temperatures, pressures, and weights.

This data was sent to the systems Microsoft Azure cloud platform, where it was processed into the data warehouse. The data from the warehouse was then visualised on three different dashboards:

1. **Resin Monitoring (Live)** – this real-time dashboard displayed all the information on the state of the part, including resin characteristics and the valve open/close status.
2. **Injection Machine (Live)** – this real-time dashboard displayed all the key information from the resin injection machine.
3. **Part Report** – this report dashboard gave an overview of all the data collected during the manufacturing process. When the manufacture was complete, the data was instantly collated into a single easy to read report that could be interrogated and used to make data driven decisions to further improve the manufacturing process.

All three dashboards were **viewable from anywhere in the world** thanks to the use of the cloud platform.

Visualisation System Purpose

The purpose of the dashboards was to give LRI engineers greater insight into what was happening in the process in both real-time and post-manufacture. Gathering and displaying data pertinent to the process allows operators to make informed decisions about how the process should be changed in real-time to improve the part quality. Further, the ability to interrogate process data after manufacture helps engineers understand if the part has been made to the required quality and lets them assess how the process might be improved (e.g. by reducing cost, manufacture time, or improve part quality).

Additionally, the real-time data collection of key processing variables allows other elements of the LRI process to be controlled automatically in the future. Though only outlet valves are being controlled by the Closed Loop LRI system at present, items such as oven temperature control through degree of cure monitoring could be integrated in the future with relative ease as degree of cure is already being collected in real-time by the Data Visualisation System.

Finally, acquiring data on each part manufactured creates real-world data sets. These data sets can be used to train AI models in the future which will be able to control even more of the LRI process automatically.

Full details of this system can be found in the Data Visualisation System section under Use Case Development.

77.2 Use Case Development

77.2.1 Infusion Setup

The infusion setup consisted of three main elements: vacuum bag & tool, injection machine, and oven. The purpose of each element has been outlined in the LRI Manufacturing Equipment section, and the equipment used is the same as those shown in Figure 121, Figure 122, and Figure 123.

A silicone vacuum bag was used as it is reusable and more environmentally friendly than standard bagging material. Additionally, it is possible to embed sensors into a silicone bag (unlike a conventional bag), which ensures the sensors are in the same location on the part for every manufacture.

Figure 130 shows a diagram of the infusion set up. There was a single resin inlet and four isolated resin outlets. The resin enters the bag cavity at the inlet, fills the fibres, and flows through to one of the four outlets. The outlets continually draw vacuum on the part to keep the resin flow moving.

The details of part are shown in Table 17.

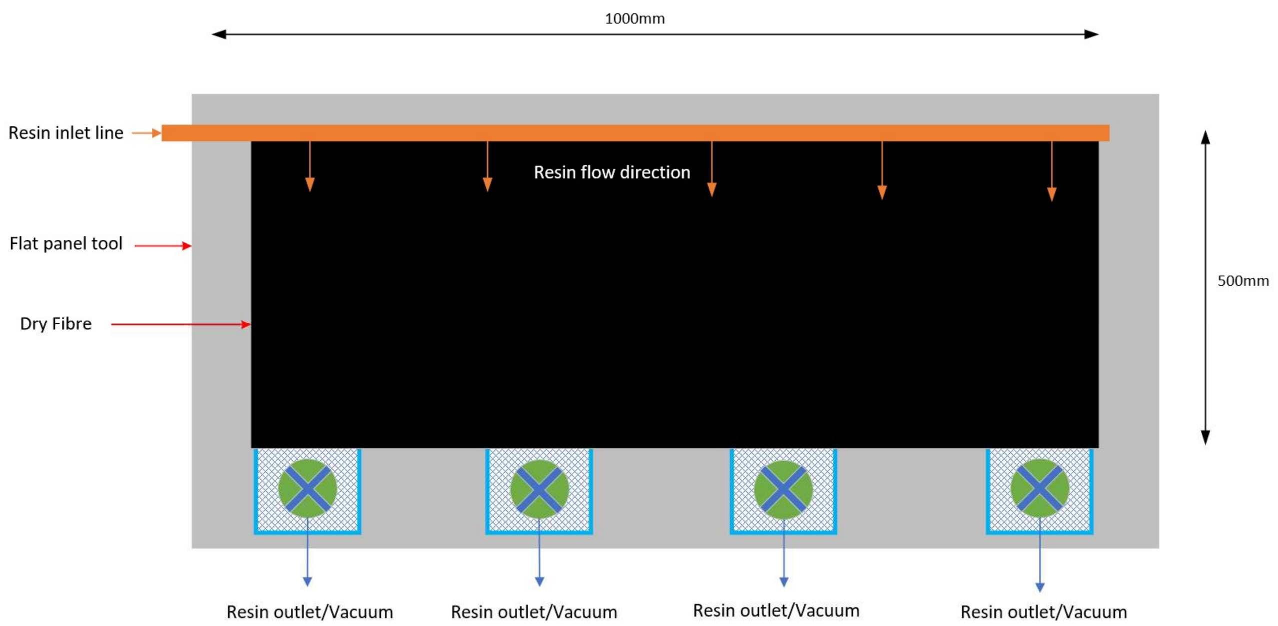


Figure 130 - Infusion set up diagram

Table 17 - Composite part details

Composite Type	Fibre	Fibre architecture	Resin	Size	Shape
Glass fibre reinforced polymer (GFRP)	Glass fibre	Plain weave	Hexcel RTM-6 epoxy (one part)	1 x 0.5 m	Flat panel

77.2.2 Sensor Array

The Sensor Array consisted of seven sensors in total:

- 4x In-line resin arrival sensors
- 3x In-bag resin cure monitoring sensors

All sensors were supplied by Synthesites Ltd[3], Greece.

In-line resin arrival sensors – These sensors are hollow tubes that are designed to fit within the pipework of an infusion set up, or 'in-line'. They are piezoresistive sensors, meaning they detect changes in resistance and use this to determine if resin is in contact with the sensor. The sensors are initialised as 'off' or 'resin not arrived', and when resin reaches the sensor they would switch to 'on' or 'resin arrived' (i.e. they are Boolean sensors). The Sensor Array had one resin arrival sensor at each of the four resin outlets – this enabled the Array to detect when resin reached each outlet separately. Images of the sensors are shown in Figure 131 below.

[3] https://www.synthesites.com

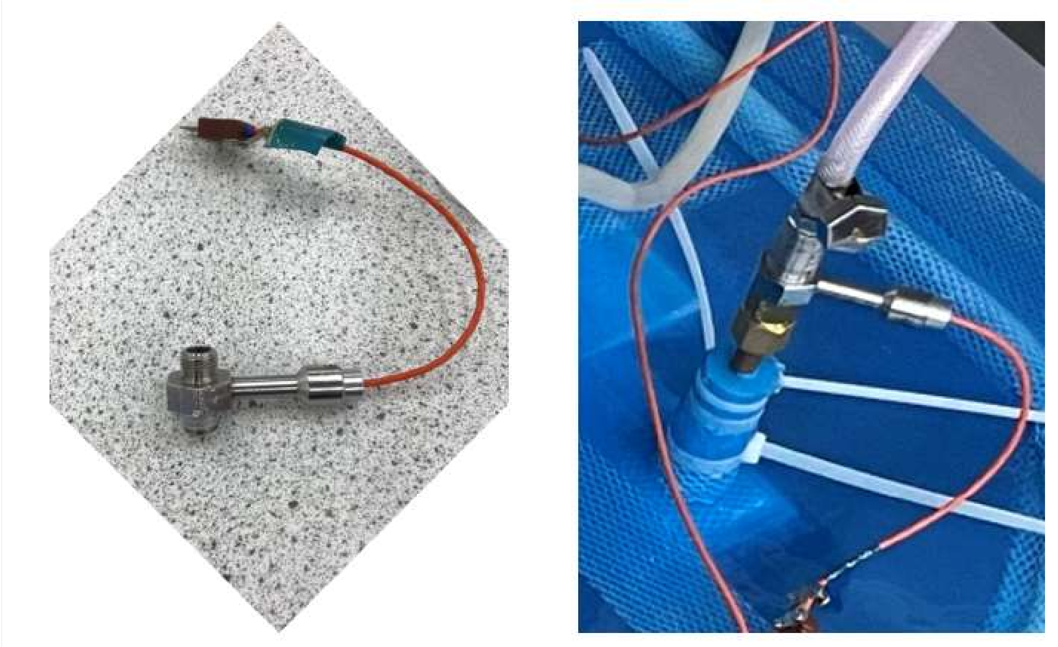


Figure 131 - In-line resin arrival sensor (left), sensor in place within infusion set up (right)

In-bag resin cure monitoring sensors – These sensors were disk-shaped and designed to be in contact with the part during the LRI process. They too were piezoresistive sensors, and they could monitor a wide array of resin characteristics in real-time:

- Resin arrival status
- Degree of cure (DoC)
- Glass transition temperature (Tg)
- Viscosity
- Temperature

The sensors 'activated' when resin contacted them. The sensors themselves monitored only resistance and temperature directly, however the Synthesites Sensor Control software converted these measurements into resin arrival status, DoC, Tg, and resin viscosity in real-time. The sensors were integrated into the silicone bag to enable them to be in direct contact with the part during manufacture. The sensors and bag integration are shown below in Figure 132.

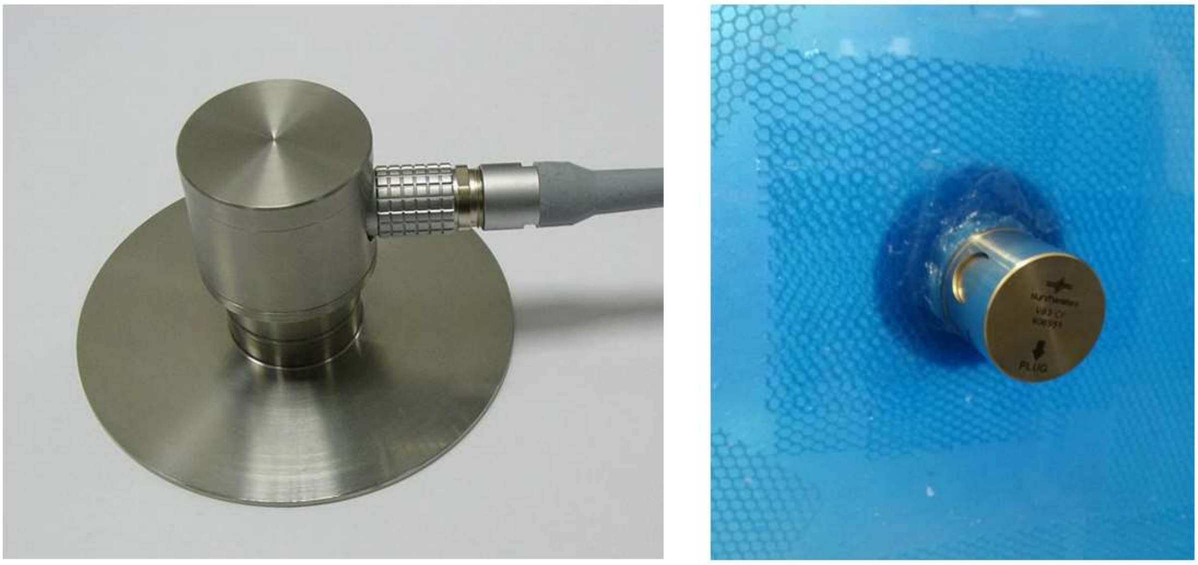


Figure 132 – In-bag resin cure monitoring sensor (left), and sensor integrated into a silicone bag (right)

The arrangement of the sensors in the Sensor Array within the LRI set up is shown in Figure 133 and Figure 134.

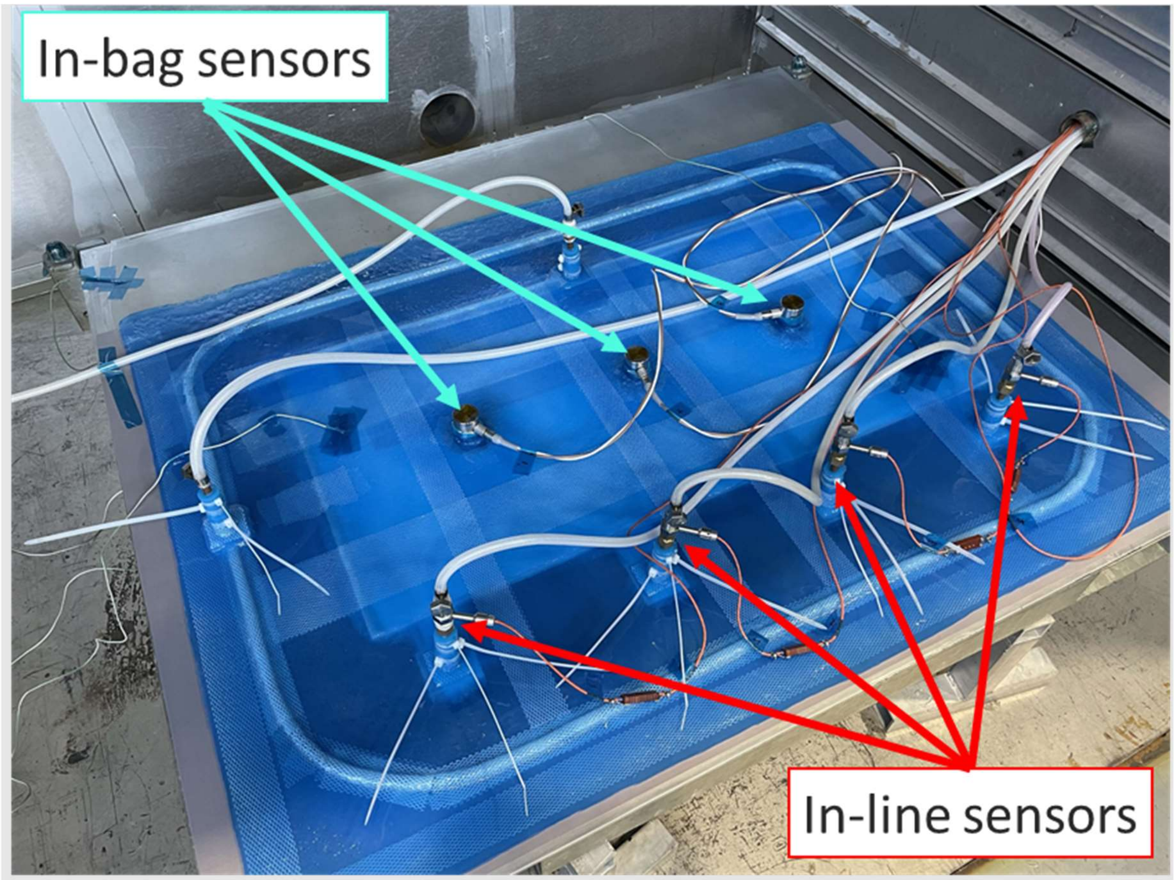


Figure 133 - Image of Sensor Array in the LRI manufacture setup

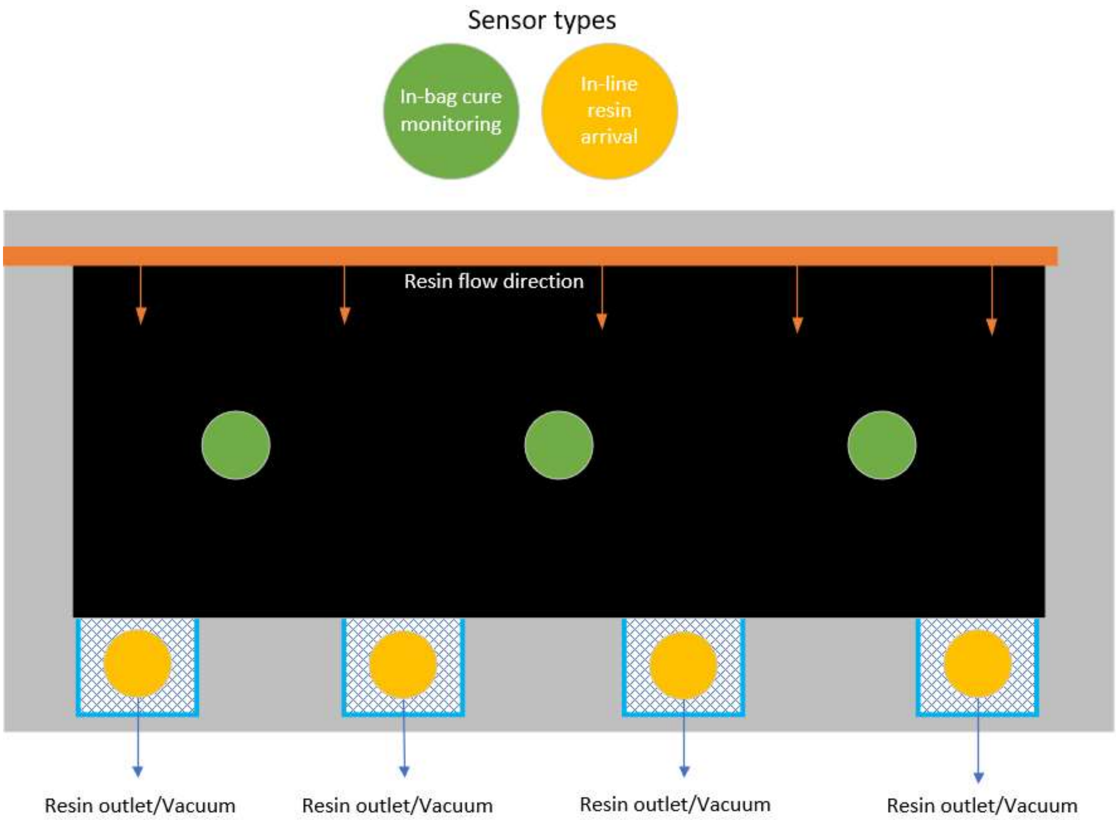


Figure 134 - Diagram of sensors in the Sensor Array

Additional elements of the Sensor Array (highlighted in the architectures in Figure 127 and Figure 129) are as follows:

- **Local PC (Sensors)** – Hosted the Sensor Control Software and Sensor Agent
- **Sensor Control Software** – This was a combination of two software products from Synthesites Ltd: OptiVIEW, and ORS. The software managed the sensors and made the sensor data available to 3rd party applications (i.e. Sensor Agent) via local ports.
- **Sensor Agent** – A custom build Python script that collected the sensor data from the Sensor Control Software, converted it into an MQTT message format, and sent it to the Control Model and the Azure IoT Hub Broker.
- **CPE Device (5G Router)** – this connected the Sensor PC (and thereby Sensor Array) to the NCCs 5G network, allowing the Sensor Agent to send the data over the network. The router used was an AirSpot 5G CPE from Airspan – this is shown in Figure 135.

Figure 135 – AirSpot 5G CPE

77.2.3 Injection Machine Connectivity

The injection machine used for the LRI manufacture was a CIJECT 6 Resin injection machine from Composite Integration, UK[4]. The machine already had sensors recording numerous variables important to the LRI manufacturing process, however the data was kept locally within the machine. To be able to extract the machines manufacturing data in real-time and send it to the Data Visualisation System, a custom system was developed and integrated into the machine's electrical cabinet. There were two primary elements: an IoT device, and a router. The architecture of these devices can be seen in Figure 129.

IoT Device – The device used was a Hilscher netIOT Edge Gateway (NIOT-E-TPI51-EN-RE), essentially a small, industrialised computer similar to a Raspberry Pi. The device was connected (via ethernet) to the injection machines' PLC. A custom developed node-red script running on the IoT device extracted the real-time machine data from the PLC, converted it into an MQTT message format and sent it to the Azure IoT Hub Broker. The data being live streamed from the injection machine included:

- Resin temperature
- Resin weight
- Resin pot pressure
- Various pot temperatures including:

[4] https://composite-integration.co.uk

    - Resin pot air temperature
    - Resin pot heater plate temperature
    - Resin pot heater belt temperature
- Injection hose temperature

Router – The IoT device had to be connected to the manufacturing network for it to be able to send the machine data (in MQTT message format) to the Broker. To facilitate this connection an industrial 4G router (Siemens SCALANCE E M876-4) was used. The router was placed into the machine cabinet and connected via ethernet to the IoT device. High gain 4G antennas were fixed to the machine to provide network signal to the router. A 5G router was not used in this instance as no DIN-rail mountable industrial 5G routers capable of working on a 5G SA network were available on the market.

The machine itself can be seen in Figure 123, while Figure 136 shows the IoT Device and the Router integrated into the machine cabinet.

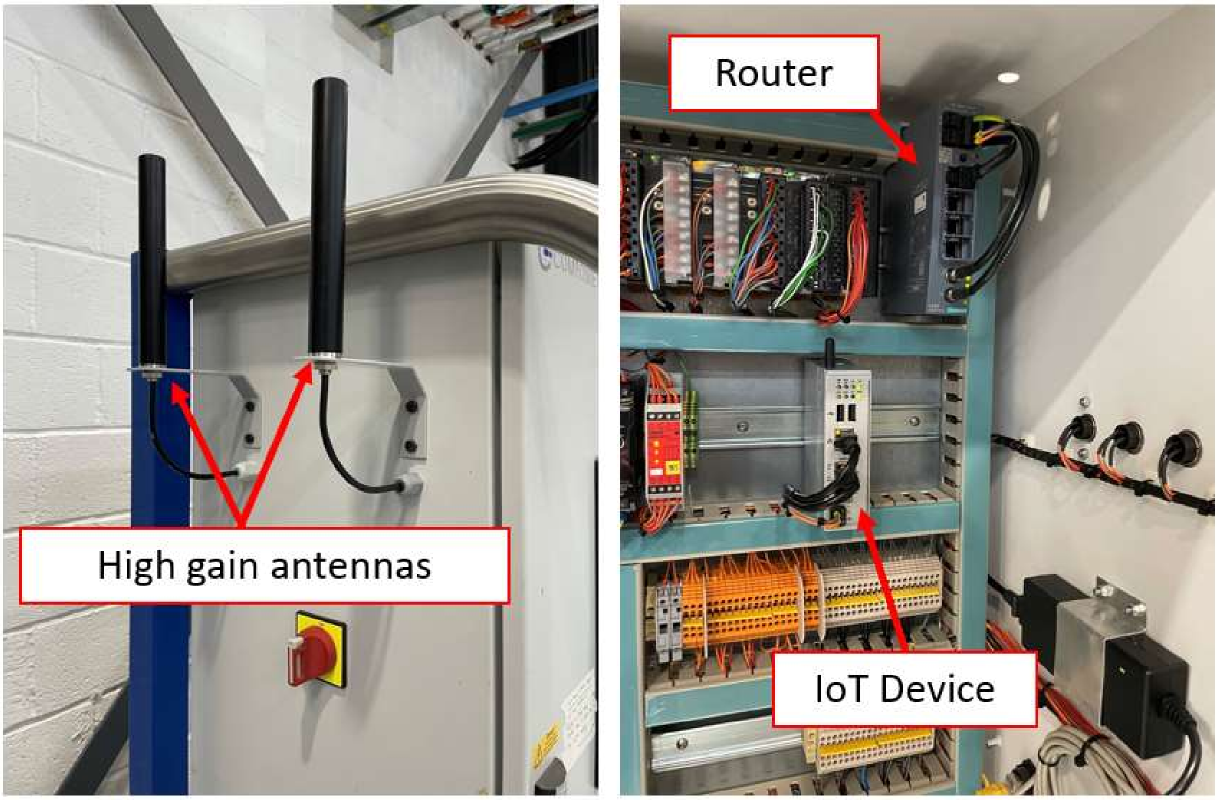


Figure 136 - IoT Device and 4G Router integrated into injection machine

77.2.4 Control Model

The Control Model was hosted on a Windows 10 virtual machine running on the MEC Application Server, this can be seen in the architecture in Figure 127. The server was located on-premises in the NCC server room (as opposed to in the Cloud). The model was a custom developed Python script. It packaged its commands into an MQTT message format that could be read by the Agents in the Feedback System.

To be able to receive and send MQTT messages from and to the Sensor Array and Feedback System, an MQTT message broker was used; it was hosted on the same virtual machine as the Control Model. The broker used was the open source Mosquitto MQTT Broker[5] from the Eclipse Foundation. All sensor data/control commands sent between the Sensor Array, Feedback System, and Control Model were via the MQTT broker.

The Control Model operated as follows:

1. Start Control Model – command all valves to set to the 'open' position (default position).
2. Wait for resin arrival signal from the Sensor Array's In-line sensors located at each of the four resin outlets
3. When resin is detected at an outlet, the Control Model receives the message from the Sensor Array – the model begins a 60 second timer.
4. Once the 60 seconds is complete, a control command is sent to the Feedback System to close the valve on the pipe that resin was detected at.
5. The model repeats this process for each valve (as resin is detected) until all four valves are closed.
6. Stop Control Model.

As the part geometry was not complex, the model developed was relatively simple; it replicated technician logic. It was sufficient to control the infusion for this particular part however the model could be upgraded for more complex parts that require greater levels of intelligence to control their process towards a successful manufacture. This could involve advanced AI models that use real process data to continuously learn and optimise the infusion strategy based off the results of previous infusions. The architecture of the

[5] https://mosquitto.org/

Closed Loop LRI system is designed to enable any future control model to be 'plugged in' with relative ease.

77.2.5 Feedback System

The Feedback System automatically controlled the opening and closing of the four resin outlets based off the commands it received from the Control Model. The top-level architecture can be seen in Figure 127 while the detailed architecture of the system is shown in Figure 137.

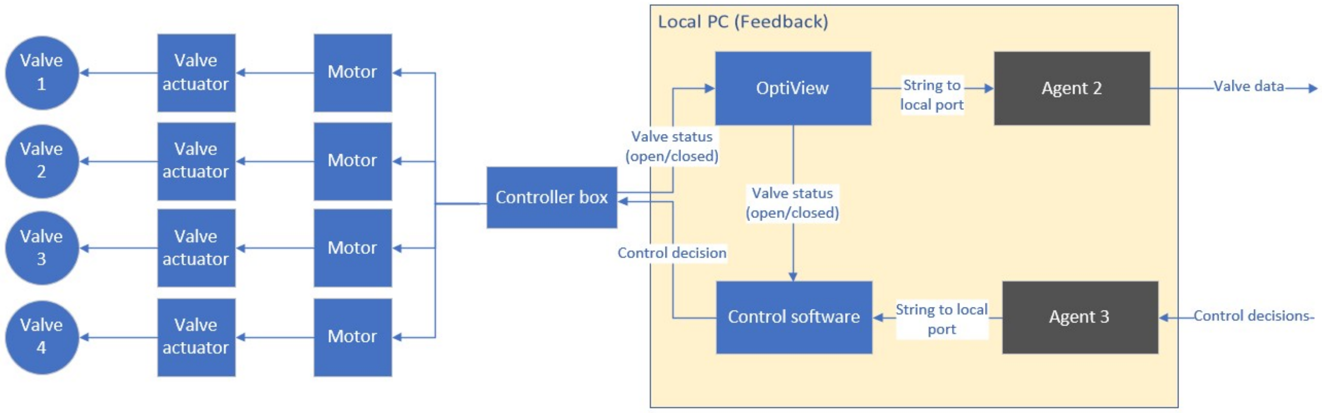


Figure 137 – Feedback System detailed architecture

The system consisted of several separate elements. These elements and their purpose are listed below:

77.2.5.1 Hardware

Figure 138 – Synthesites Controller box

Controller box – Synthesites product which the valve motors and valve relays plug into. The Controller box provides power to the motors to engage the Valve actuators and cause valve closure/opening. Upon completion of an opening or closure operation a valve status message is relayed back to the Controller box from the Valve actuator. The front of the box has 3 LED lights for each valve. 2 of the LEDs are used to indicate whether the connected valve is in the open or closed state. The other LED indicates when the motor is in operation. Each valve has 2 buttons on the front of the Controller box which enable manual opening (green button) and closure (red button). The Controller box was designed for safe operation with multiple fail safes. The emergency E-stop button kills all power to and from the box, whereas the PC deactivation button only kills communication between the box and the Feedback PC.

Figure 139 – Feedback PC (NUC)

Feedback PC (NUC) – An industrial minicomputer that facilitates hosting Feedback Agents 2 and 3, the Synthesites Control software and Synthesites OptiView software. The Feedback PC facilitates the interfaces between multiple pieces of software. The interface between Feedback Agent 3 and the Control software, the interface between the Control software and OptiView, and the interface between OptiView and Feedback Agent 2 are all facilitated by the Feedback PC. The Feedback PC is physically connected to the Controller box and AirSpot 5G CPE device via ethernet.

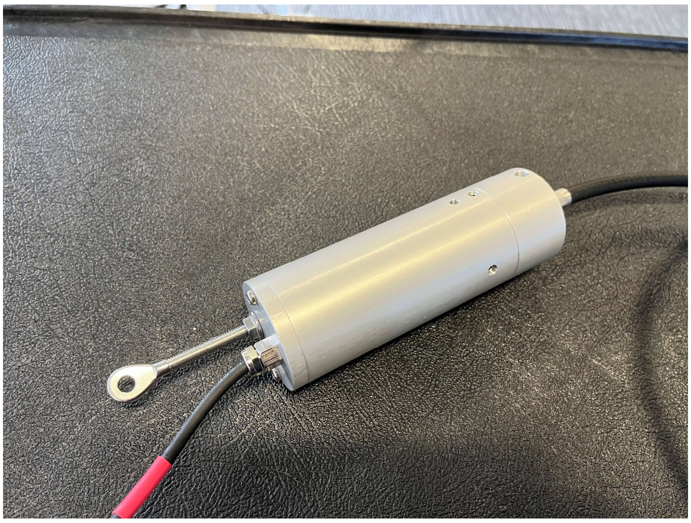


Figure 140 – Valve motor

Valve motors – Electric motors that provide the physical force required to open and close valves. The motors have power supplied by the Controller box and are each connected to a Valve actuator.

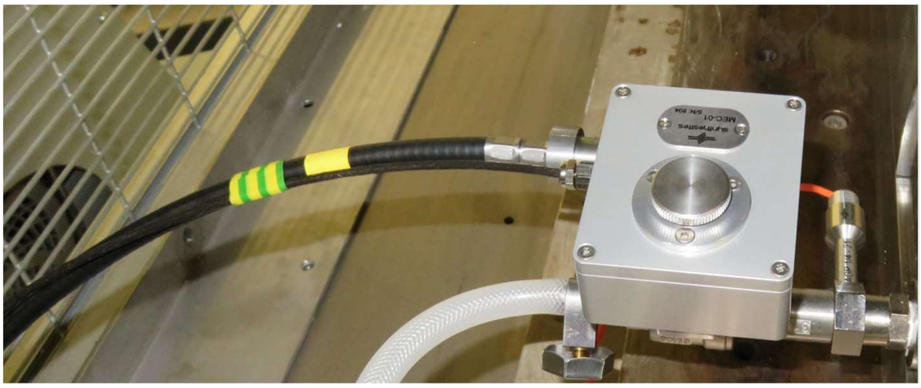


Figure 141 – Valve actuator

Valve actuators – The physical element that sits on top of the ball valve to physically implement opening and closing of vent valves. The connection between actuators and their designated motor is achieved with 2 metallic cables housed within a single thick black cable housing. When power is supplied to a motor, force is applied to one of these metallic cables, rotating the ball valve and resulting in opening or closure.

AirSpot 5G CPE – Wireless 5G router used to connect the Feedback PC (and thereby the Feedback System) to the NCCs 5G network. This router was the same type as that used in the Sensor Array and is shown in Figure 135.

77.2.5.2 Software

There are 4 main software elements to the feedback system. Some software was developed by Synthesites (Control software and OptiView) and some by the NCC (Feedback Agent 2 and Agent 3).

Control software – Synthesites software set up to receive open/close signals from Agent 3 via local ports. The Control software then transmits these signals to be implemented by the Controller box. The Control software also receives the current physical state of the valves (open/closed) from the OptiView software running locally on the Feedback PC.

OptiView software – Synthesites software that relays valve status messages to Agent 2 and the Control software.

Feedback Agent 2 – JavaScript developed within Node-RED. Agent 2 effectively initialises the valve statuses, then relays any updates to the valve statuses onwards to the Azure IoT Hub broker (see Figure 129 for system architecture details). The following operations are executed in sequence:

- The state of each valve is initialised and set to "open" – this message is sent to the Azure IoT Hub broker for the Data Visualisation System.
- Agent 2 connects to OptiView and receives any change in valve status from it.
- When a valve status changes Agent 2 sends the change in a message to the Azure IoT Hub broker for visualisation.

Feedback Agent 3 – JavaScript developed with Node-RED. Agent 3 effectively receives control messages from the Control Model (via the on-premises MQTT broker), then parses them to the Control software. The following operations are executed in sequence:

- Subscribes to on-premises MQTT broker (to listen for commands from the Control Model)
- Waits for a change-state command for any valve (e.g., Open → Close) then sends the message through to the Control software.
- If the last message sent through to the Control software hasn't been implemented, then Agent 3 creates a queue of messages ready to be sent one at a time once the previous message has been implemented by the feedback system.

77.2.6 Data Visualisation System

The Data Visualisation System was built using Microsoft Azure; the architecture can be seen in Figure 129. The three key elements to this were: **Azure IoT Hub**, **Data Warehouse**, and **Power BI Dashboards**.

Azure IoT Hub – The IoT Hub served as the gateway to the Cloud based Azure platform. It was hosted on premises on the NCCs servers. All data collected during manufacturing was sent to the IoT Hub over the 5G network, and the Hub then forwarded the data to the Azure data warehouse in the cloud (via the internet).

Data Warehouse – The warehouse was hosted in the cloud and served as the database for all manufacturing data. The database type used was SQL.

Power BI Dashboards – The Power BI application was also hosted in the Azure cloud and interfaced with the data warehouse to extract and display data in real-time on live dashboards, and on a post-manufacture report dashboard.

The two live real-time dashboards developed using Power BI were: **Resin Monitoring**, and **Injection Machine.** The resin monitoring dashboard displayed all the data collected by the Sensor Array, and the valve open/close status collected by the Feedback System. The injection machine dashboard displayed all the data collected by the Injection Machine Connectivity system. Real data displayed on each dashboard can be seen in Figure 145 and Figure 146.

The final dashboard developed was **Part Report** – this showed a one-page summary of the part manufacture. It contained all the data collected from the Sensor Array, Feedback System, and injection machine, displaying it in a simple and easy to digest report. Additionally, the manufacturing data was tagged with important metadata such as time of manufacture, part number, ambient conditions, names of individuals involved, and many others. It did this by tagging the metadata of the part to the incoming data from the manufacture. To do this a Microsoft Power App called 'LRI job control' was developed and is viewable in Figure 142.

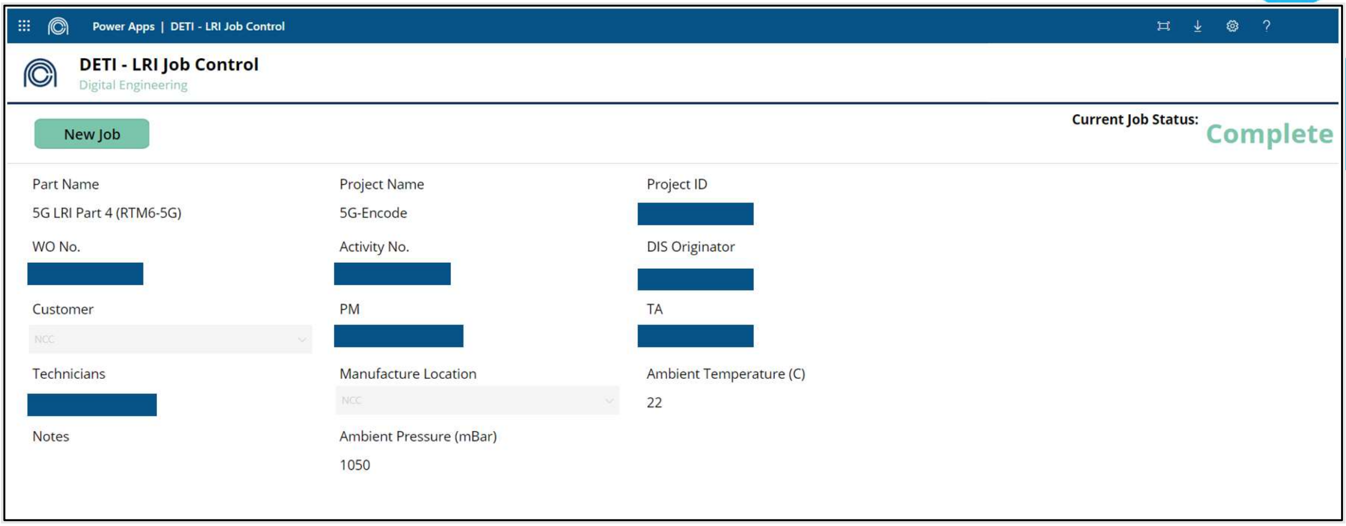


Figure 142 – LRI Job control application

The app had several fields that were filled in by the operator prior to part manufacture. The operator then used the app to ‘start’ and ‘stop’ the job – all live data collected between the ‘start’ and ‘stop’ was tagged with the metadata. The Part Report dashboard had a drop-down selector that could be used to easily switch between the reports of all the parts made using the Closed Loop LRI system.

This collection formed a comprehensive dataset on each part, giving engineers the ability to make informed data-driven decisions during and after manufacture. A Part Report generated during use case testing can be seen in Figure 147 under Data Visualisation System Results.

77.3 Use Case Testing

77.3.1 System Setup and Tests

The Closed Loop LRI system was deployed into the NCC factory – the set up can be seen in Figure 143 and Figure 144.

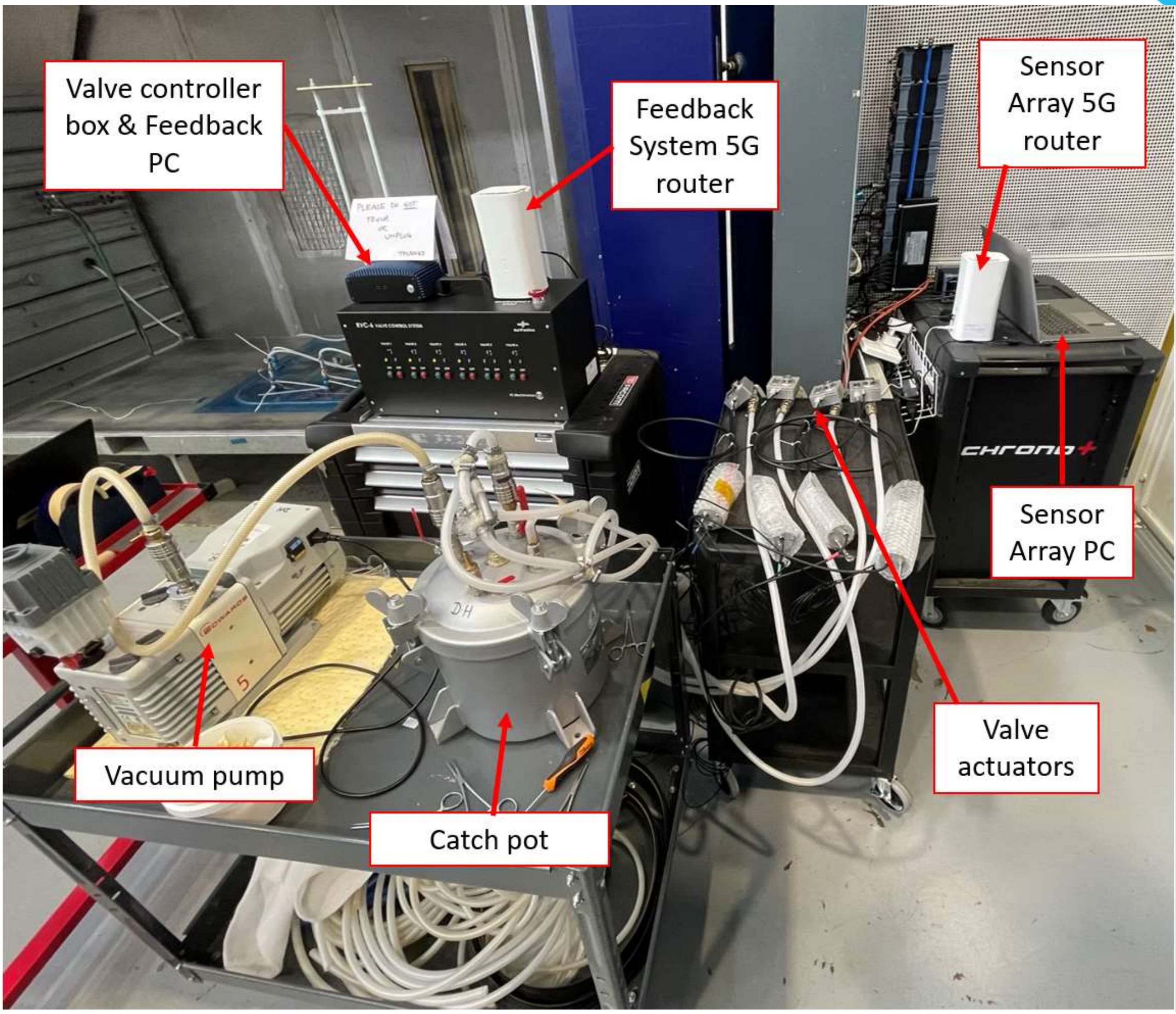


Figure 143 - Closed Loop LRI set up (outside the oven view). Catch pot and vacuum are used to pull vacuum on bag/part

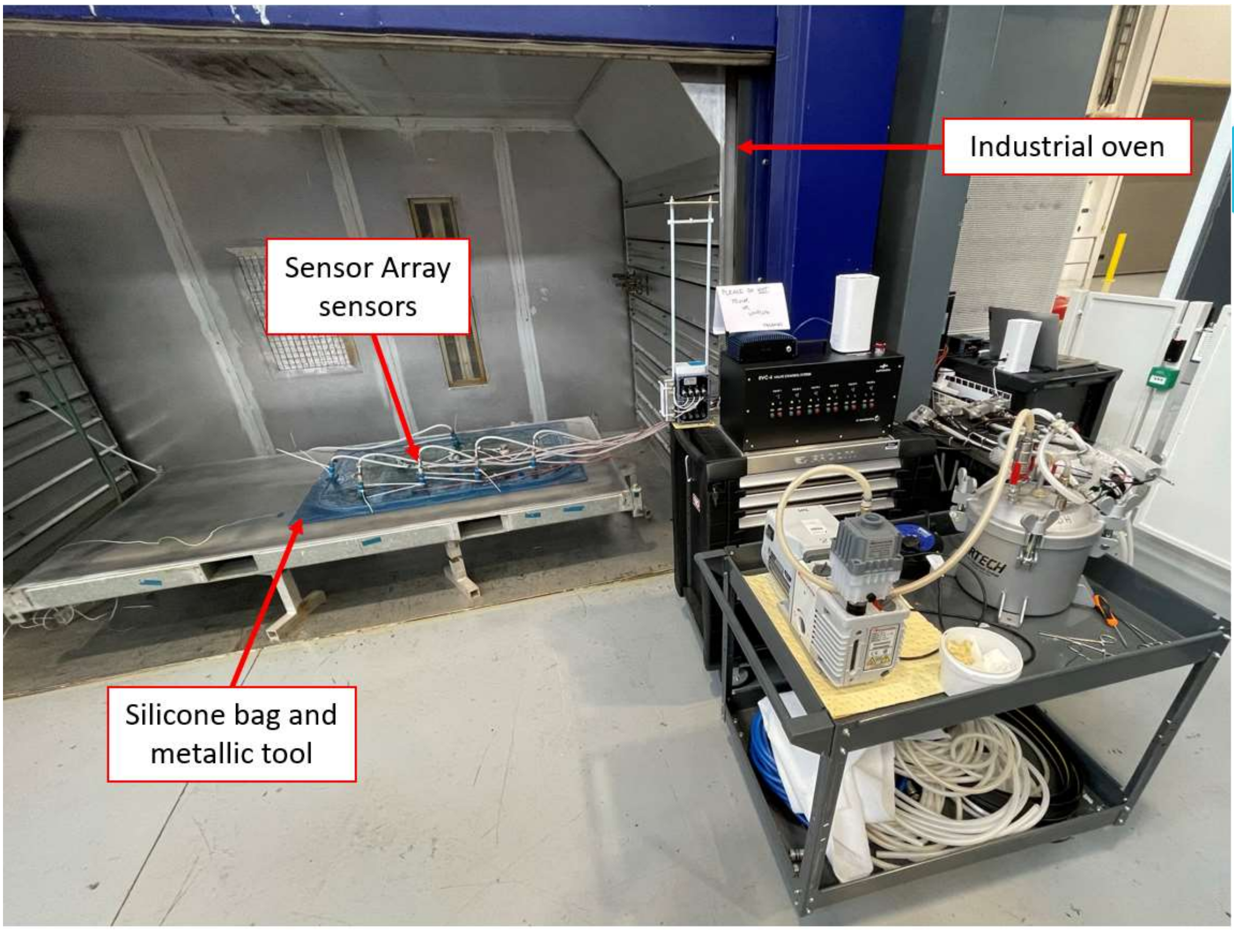


Figure 144 - Closed Loop LRI set up (inside oven view)

Three full manufacturing trials were performed with the Closed Loop LRI system, and their details are shown in Table 18. The trials were identical except for the network used to run them.

Table 18 - Table of manufacturing trials

Part No.	1	2	3
Network Used	4G	5G SA	Toshiba 5G NSA

77.3.2 Use Case Results

77.3.2.1 Closed Loop Control System Results

For all three trials the **Closed Loop Control system worked effectively**. The Sensor Array, Feedback System, and Control Model worked together as planned. As resin was detected by the In-line resin arrival sensors this information was sent over the network to the Control Model, and the control models' commands to close vents were successfully sent (over the network) and implemented by the Feedback System.

Some issues were experienced with the sensors in the Sensor Array, namely the In-line resin arrival sensors. For each trial performed one of the four sensors failed to trigger even when resin was in contact with the sensor. This meant that the Control Model did not close the sensors corresponding resin outlet valve correctly. These issues were likely due to faulty sensors.

Overall, this was a minor issue, and the system was considered a success.

77.3.2.2 Data Visualisation System Results

All elements of the **Data Visualisation System worked as planned and provided excellent insight into the manufacturing process**. The data collected by the Sensor Array, Feedback System, and injection machine was successfully streamed in real-time to the Azure cloud. Snapshots of the live dashboards can be seen in Figure 145 and Figure 146.

Figure 145 - Resin monitoring dashboard showing live manufacturing data

Figure 146 - Injection machine dashboard showing live data from the injection machine

The Part Report dashboard also worked as planned – the live data collected during manufacturing was successfully tagged with the part metadata, and all this information was displayed on the part report card. Figure 147 shows the data report from part number 1 (performed on 4G).

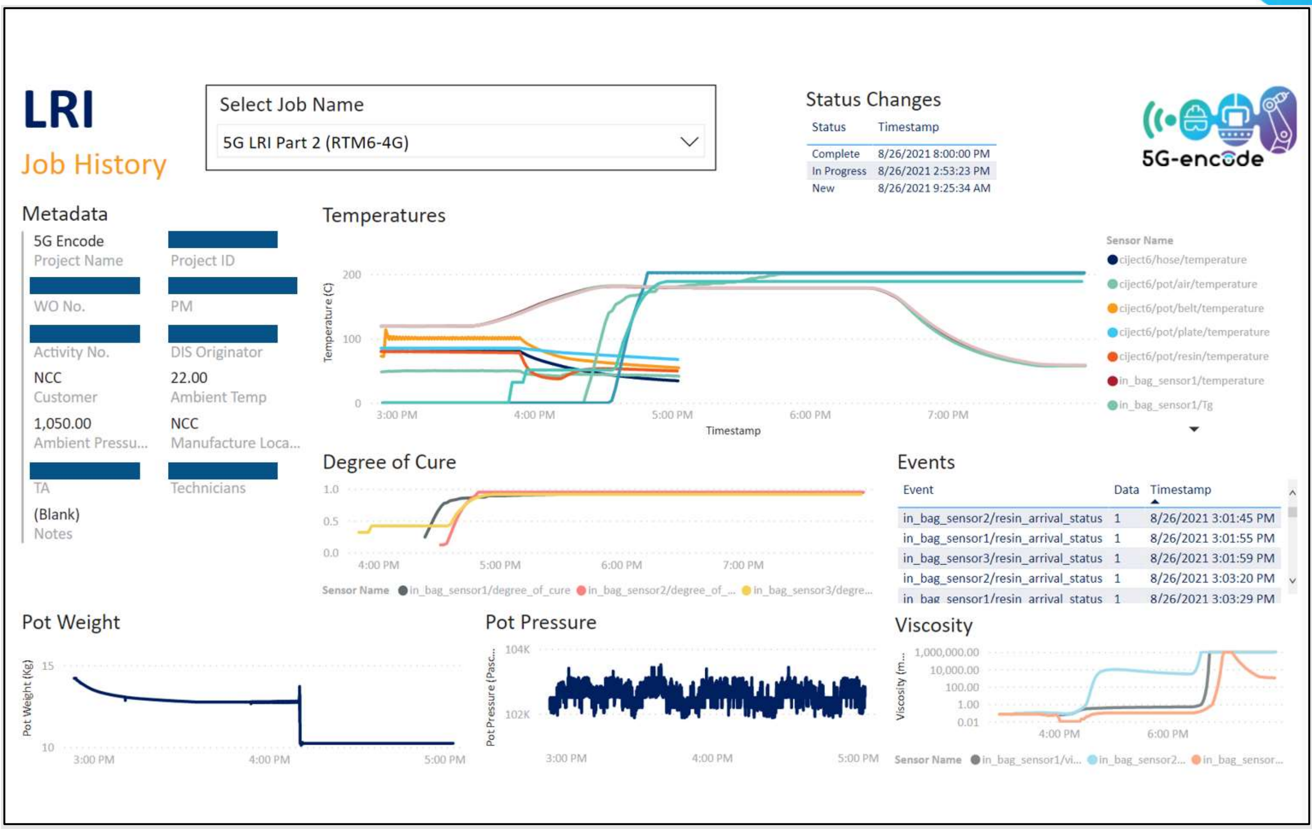


Figure 147 - Part Report dashboard showing the data for part number 1

During the trials it was noticed that the three In-bag cure monitoring sensors often gave differing readings during the initial part of the manufacture (infusion), however the sensor readings began to correlate in the cure phase. Use of an incorrect release agent for the sensors was the suspected cause of this issue.

Some stability issues with the Toshiba 5G NSA and NCC 5G SA network were experienced on parts 2 and 3 respectively. Network drop off resulted in a loss of data capture for the Data Visualisation System – this is explored in more detail in
5G Industrial Assessment.

77.4 Use Case Discussion

77.4.1 Use Case Benefits

The benefits realised by the Closed Loop LRI system are as follows:

Enhanced process insight – A far greater understanding of what is happening during the LRI process is possible with this system. To the authors knowledge, nothing currently exists in LRI manufacturing that can collate the data across the entire process (part, oven, injection machine) and feed this back in real-time to engineers on a single platform. At present, data is either not collected or stored locally on machines. At best equipment has vendor specific platforms that must be switched between to get a view of what is happening. The Closed Loop LRI system provides a single platform to view all process data cleanly, allowing data driven decisions to be made mid or post-manufacture to improve part quality or optimise the process. The total number of process variables monitored and displayed on the system is thirteen[6].

For the part made in this project, the data showed that the cure time could be halved and still give the same part quality. This optimised process is **cheaper**, allows for **higher oven utilisation**, and has **reduced the environmental impact** of the part manufacture.

Data capture flexibility – The system has been designed for flexibility, meaning it can be deployed onto any LRI manufacturing system in the NCC with relative ease (as data capture and control is all performed wirelessly over 5G). Additionally, the system is scalable, allowing new sensors or controllers to be added easily.

Manufacturing labour cost savings – The infusion element of the LRI process typically requires 2 operators, one to control the outlet valves and one to monitor the injection machine. The Closed Loop LRI system controls the valves automatically, meaning only one operator is required – this allows the other operator to work on more high-value activities.

[6] Resin parameters: temperature, Tg, degree of cure, resin arrival, viscosity, valve open/close status – Machine parameters: injection hose temperature, heater belt temperature, heater plate temperature, pot air temperature, pot resin temperature, pot weight, pot pressure.

Report generation cost savings – Creating a part data report often takes many hours or even days of work. Data from various sources like machines or dataloggers must be extracted, then collated into a spreadsheet. They then need time-syncing, and finally graphs can be generated. They are critical however in understand how the part was made. This activity is now done automatically and is available in near real time after part manufacture is finished.

An overview of these benefits and their value is shown in Table 19.

Table 19 - Table of benefits

Benefit	State prior to Closed Loop LRI system	State with Closed Loop LRI system	Value
Enhanced process insight	Minimal understanding of process (mid or post manufacture)	Detailed data, clearly displayed, allowing for data driven decision making	Part cure time has been halved due to enhanced process understanding (optimised process)
Data capture flexibility	Minimal flexibility in existing data capture systems	Highly flexible system – deployable on different LRI processes	All other benefits are not tied to a single LRI process, but achievable anywhere
Manufacturing labour cost savings	Two operators required for manufacture	Only one operator required	25% labour cost (1-hour time) saving per part [increases with increasing system complexity]
Report generation cost savings	One full engineers' day to generate report	Report generated automatically	100% cost (8-hour time) reduction per part

Specific monetary values for labour cost savings are dependent on labour rates – these vary between industry sectors. As an example, an industry with an engineers' charge rate of £80/hour would realise a cost saving of £640 per part by utilising the automatic report generation.

77.4.2 Use Case Limitations, Lessons Learnt, and Recommendations for Future Work

77.4.2.1 Limitations of the Use Case

Though significant advancements have been made through this use case in automating and giving greater insight into the LRI process, it is only the beginning. The opening and closing of outlets valves is a small part of the full LRI process - much of it remains manual.

The part made using this system was a flat panel, however there is a need to show the system working on a more realistic geometry, such as a plane wing. Additionally, the data collected on the part was not validated (e.g. degree of cure, Tg), meaning further analysis is required before the sensor data can be relied upon.

Significant further benefits could be realised if more process elements were controlled by the Closed Loop LRI system. Key next steps include:

- Automating the oven cure cycle using the degree of cure reading from the Sensor Array
- Automating the full injection process though control of the injection machine and inlet valves

Furthermore, the control model used was basic, employing only technician logic. This model was chosen as infusing a flat panel is relatively simple and did not require complex control; however, if the system is deployed to a complex part infusion, or if more process elements are to be controlled by the model, **a more intelligent (likely AI based) model would be needed**. A model of this kind could also facilitate continuous process optimisation by learning from the results of previous infusions. A Machine Learning approach to resin infusion has already been studied by the NCC and the Centre for Modelling and Simulation (CFMS), Bristol[7] and this type of model could be deployed into the Closed Loop LRI system.

[7] https://cfms.org.uk/news-events-opinions/news/2018/february/cfms-and-ncc-to-produce-digital-demonstration-of-machine-learning-in-composites-manufacturing/

If successful, these developments (among others) would lead to:

- Reduced part manufacture cost and time
- Automatic quality assurance (no need to conduct non-destructive testing or material analysis)
- Reduced environmental impact though:
    - Reduced equipment/energy use to make the same parts
    - Less scrap as parts made right every time

77.4.2.2 Lessons Learnt

Some of the key challenges overcome during the project included:

- Modifying a composite sensor system to work on a cellular network – the data from the sensors is typically used locally and had not been sent over a wireless 4G or 5G network before
- Streaming live data from a machine over a cellular network – the injection machine is a legacy piece of equipment and was not designed for this purpose
- Development of an architecture that can be used to enable any kind of closed loop manufacture (flexible and scalable)
- Enabling a valve control system to receive and execute commands remotely over a cellular network

Though successful there are some challenges still outstanding, these include:

- Sensor system and valve system still have a significant number of cables, this needs to be reduced to make the system more viable for use in industry
- The data streaming from the injection machine is not robust enough and needs further investigation to ensure it works every time

77.5 Use Case Conclusions

The aim of the Closed Loop LRI use case was to begin the process of automating the LRI manufacturing technique through use of 5G and other digital technologies. Additionally, it sought to bring greater insight into the process through data capture and visualisation. These aims have been achieved and have resulted in the development of an industry leading digital LRI system. The benefits realised including reduced manufacturing costs &

times, along with greater insight into part quality, are in line with the benefits expected from a system of this kind (described in Project Objectives).

Future work is required to scale up the system, control more elements of the process, and apply the use case to more real-world part geometries; doing so will reap benefits far beyond the scope of this project. The system however has been designed for scalability and flexibility, meaning it is ready for future expansion.

78 5G INDUSTRIAL ASSESSMENT

All manufacturing trials performed were identical except for the network used to run the trials on. This section assesses the performance of the use case on the 4G, 5G SA, and Toshiba 5G NSA networks. The methodology for this is outlined in Introduction: Assessment Methodology.

78.1 4G Discussion

78.1.1 4G Test Setup

For the 4G trial the router of choice was the Siemens SCALANCE E M876-4 (pictured in Figure 148). This connected the Sensor Array and Feedback system to the Control Model and can be seen in use in Figure 149.

Figure 148 - Siemens SCALANCE E M876-4 4G router[8]

[8] https://support.industry.siemens.com/cs/document/109480265/delivery-release-of-scalance-m876-4-mobile-wireless-router?dti=0&lc=en-CA

Figure 149 - 4G router (with antennas attached) in operation

78.1.2 4G Results and Assessment

Latency between the Sensor Array/Feedback System and the Control Model virtual machine was assessed by performing pings. 100 ping requests were sent, and the statistics are shown in Table 20.

Table 20 - Ping statistics for the 4G network. Collected by sending 100 pings from the Sensor Array/Feedback System to the Control Model

		Ping round trip time (ms)		
Network	**Packet Loss (%)**	**Average**	**Maximum**	**Minimum**
4G	0	81	138	28

Overall, the Closed Loop LRI system performed well using 4G. The network appeared robust and stable, and worked well in the industrial environment. No data loss was recorded in the Data Visualisation System, and the Closed Loop Control System worked effectively.

Some radio signal black spots were noticed in the facility, meaning this could restrict the ability to deploy the Closed Loop LRI system in different areas. However, this issue could be easily rectified by relocating current radio cells or adding more in areas with poor signal coverage.

It is likely the system worked well on 4G as the number of sensors and controllers used was relatively low. The system was a proof of concept; stress testing the network with 10s-100s sensors/controllers was not in scope. However, one of the key requirements for a closed loop control system (as outlined in Introduction: Why 5G?) is low latency and high reliability. The latency seen over 4G was around 81ms, which is sufficient for the system currently; however, if the system was developed to include control of pressurised injections this latency may not be adequate. Pressure can change rapidly in an injection, so sensor data and commands need to be sent quickly to ensure accurate control and maintain safety.

Safety is also the driving factor for reliability, as if the control model can't communicate with the real-world control system temporarily this is a major issue. The reliability of the 4G network appeared sufficient, however this must be tested over a much longer period before it can be properly verified.

78.2 5G Discussion

78.2.1 5G Test Setup

For the 5G trials Airspan AirSpot 5G routers were used (shown in Figure 135). Their set up within the Closed Loop LRI system can be seen in Figure 143. Two routers were used, one each for the Sensor Array and the Feedback System. These provided the connection for both systems to the Control Model virtual machine.

78.2.2 5G Results

As with 4G, latency between the Sensor Array/Feedback System and the Control Model virtual machine over 5G was assessed by performing pings. The statistics are shown in Table 21, and the 4G statistics are also shown for ease of comparison.

Table 21 - Ping statistics for the 5G and 4G networks. Collected by sending 100 pings from the Sensor Array/Feedback System to the Control Model

		Ping round trip time (ms)		
Network	**Packet Loss (%)**	**Average**	**Maximum**	**Minimum**
4G	0	81	138	28
5G SA	0	33	47	17

Network statistics generated by the Accedian[9] Skylight Analytics system are viewable in Figure 150, Figure 151, and Figure 152. This system sat on the core switch in the 5G network and was able to monitor all data sent over the network. What is immediately noticeable in these figures is that the Closed Loop LRI system lost connection to the 5G network on numerous occasions. A major outage happened between around 15:00 and 16:00, while smaller outages occurred at around 16:20, 17:20, and 17:30. This outage caused significant issues and their effects are detailed in 5G Assessment. The cause of the outage was the 5G routers losing connection to the network. The outages resulted in a **network reliability rating of 85.6%** (as defined in Network Metrics).

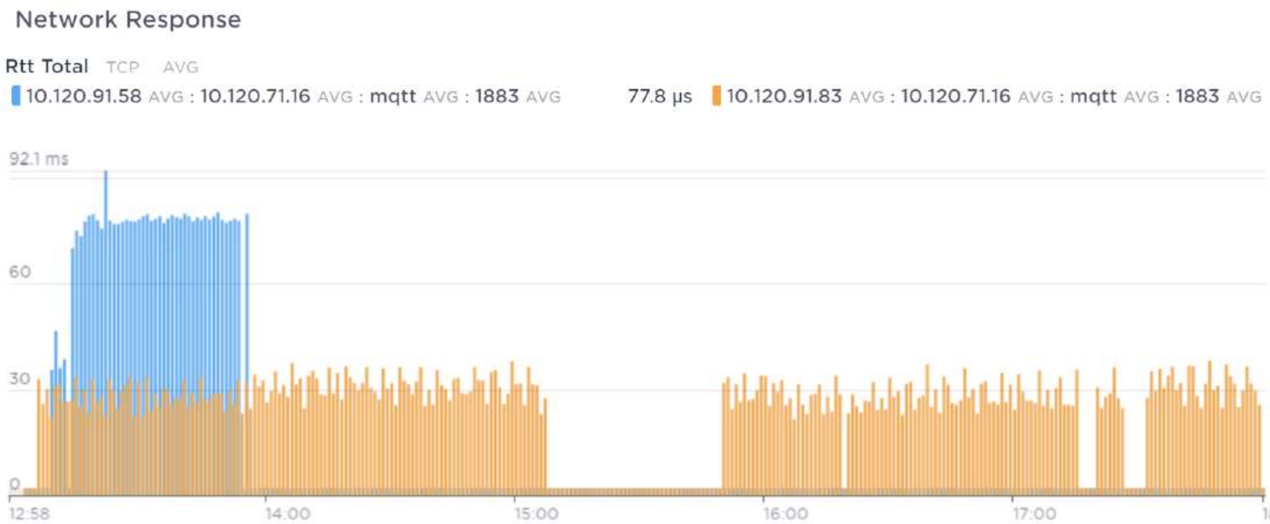


Figure 150 - Latency for data packets sent between Sensor Array (orange bars) and Feedback System (blue bars) to Control Model

[9] https://accedian.com

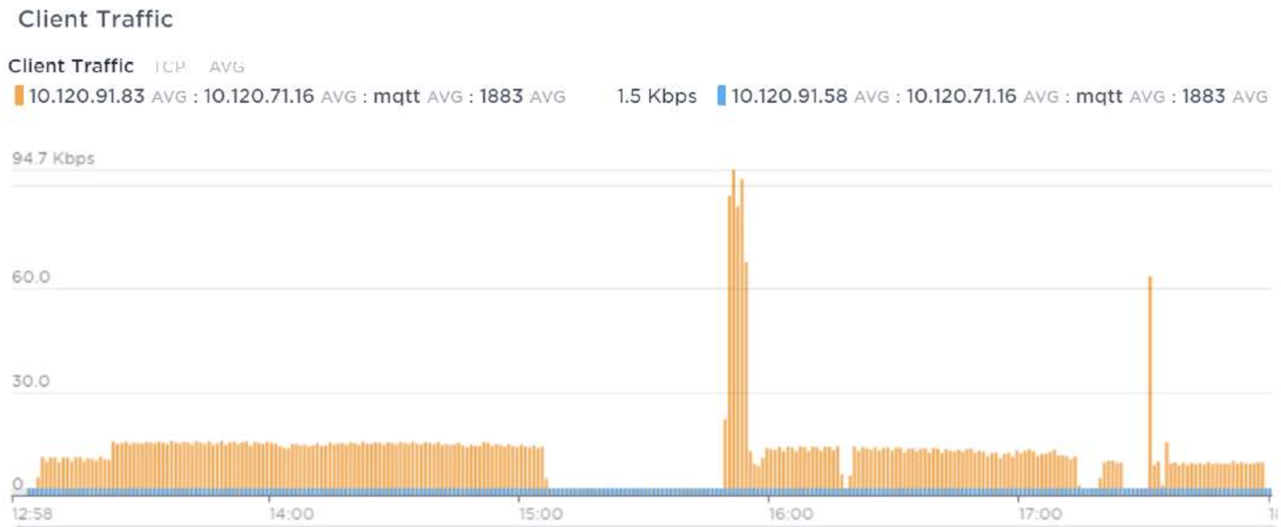


Figure 151 - Volume of traffic (data) *received by* Control Model *from* Sensor Array (orange bars) and Feedback system (blue bars)

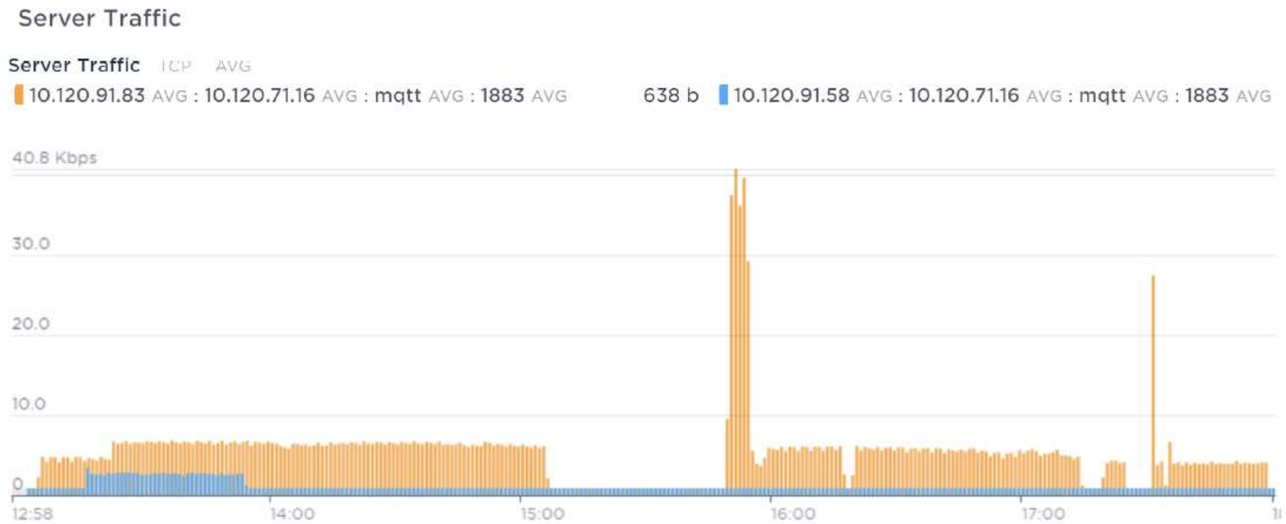


Figure 152 – Volume of traffic (data) sent *from* Control Model *to* Sensor Array (orange bars) and Feedback system (blue bars)

The Feedback System was designed to only be in operation during the injection phase of the manufacture. This phase was between 13:15 and just before 14:00. Therefore the Feedback Systems' (blue) bars in the figures stop after this point.

Figure 150 shows the latency for data transfer between the Sensor Array and Control Model was around 30ms, which aligns with the ping data recorded in Table 21. The latency from the Feedback System to the Control Model appears to be significantly higher (around 75ms); however, this does not match what was seen. It is suspected that the higher latency recorded is a feature of the MQTT message protocols acknowledgment system, as real-world latencies were closer to 30ms.

The volume of traffic between the Sensor Array and Control Model is shown in Figure 151. During normal operation the volume of data appeared to be around 15 Kbps, this low volume was expected. After the major network outage between 15:00 and 16:00 the Sensor Array reconnected and appeared to send a large amount of data.

The traffic volume sent by the Control Model to the Sensor Array and Feedback system is seen in Figure 152. Again, these sub-10 Kbps volumes were expected as the data packages traversing the network were relatively small.

78.2.3 5G Assessment

78.2.3.1 5G Benefits

Overall, the Closed Loop LRI system worked well over 5G. Prior to the point where connection to the network was lost, the network achieved very low latencies allowing for rapid transfer of data and commands. The Closed Loop Control system (Sensor Array/Feedback System/Control Model) was able to work as designed and was fully executed before connection was lost.

5G does have the potential to work well in a manufacturing environment - the latencies achieved were impressive, and signal coverage was good. The edge computing on the servers also worked well and enabled high system flexibility.

78.2.3.2 5G Issues and Future Work

The main issue with the 5G network was its reliability. The Data Visualisation System (Sensor Array/Dashboards) worked well while the connection to 5G was live, however major problems occurred when the connection was dropped. The drop out not only caused a total loss of data recording during the outage window but had knock on effects to the quality of the data collected even after the connection was re-established (due to the nature of the sensors).

Reliability is the primary challenge that must be addressed before this kind of system could be used in industry. The drop in connection during the 5G manufacturing trial was not unexpected. It has proved incredibly challenging to develop the ultra-high reliability supposedly achievable with 5G. One of the primary reasons for this is that 5G devices (such as routers) are still immature, especially when used on 5G SA networks. A reliability of 85.6% is poor – network reliability is usually categorised as 99.9% and higher. If a more comprehensive closed loop control system was developed which used 5G as its means of communication, any loss in connection would at best lead to a loss of data or a scrapped part, and at worst could result in serious safety hazards.

Additionally, this project was not able to assess the mMTC capability of 5G. This feature allows thousands of individual devises to connect simultaneously to a 5G network in high density. This kind of setup would be needed where the number of sensors/controllers was increased, for instance in the LRI manufacture of large structures. mMTC therefore requires further testing in a manufacturing environment before it can be verified.

Finally, prior to the implementation of a private 5G network in a manufacturing setting, a comprehensive signal coverage study should be performed. This must include assessing potential areas of signal interference such as large electrical machines or steel framework. It is much easier to plan and implement correct signal coverage than to try to retrospectively fix coverage after the network is installed.

78.3 5G Conclusions

5G has the characteristics to meet many of the key challenges involved with implementing closed loop manufacturing systems. Through the industrial real-world testing of a 5G network, this project has found that the low latencies needed by closed loop manufacture can be achieved with 5G (~30ms). Further, the edge compute capability worked well for running control models.

The main challenge identified for using 5G on these kinds of use cases is developing ultra-high reliability. 5G-enabled devices and the SA network technology itself cannot currently provide the level of reliability needed for safe control. That said, as device and 5G private network technology improves, the remaining barriers to using 5G in a closed loop manufacturing setting should be removed. Progress is already being made in this area; more 5G devices are coming to market that should work effectively on SA 5G networks.

Finally, as the use case was unable to test 5G mMTC, it should be subject to a detailed future investigation to understand if it can be realistically achieved in industry.

79 TOSHIBA 5G NSA

As outlined in Assessment Methodology the purpose of the Toshiba 5G NSA network was to test the viability of using a 5G network – built using COTS hardware and Opensource software – in an industrial setting. The Closed Loop LRI system was used as the test bed for this assessment. This section details the build, test, and results of this investigation.

79.1 Introduction

Toshiba have provided a separate 5G Non-Standalone (NSA) network in the NCC. The 5G implementation that Toshiba BRIL (Bristol Research Innovation Laboratory) have been experimenting with is based on the open-source project Open Air Interface (OAI).

OAI is led by the OpenAirInterface Software Alliance (OSA) based in the Eurecom research centre in Sofia, France. The purpose of OAI is to provide an open platform for telecommunication research by providing software to realise a 3GPP compliant open-source approach to LTE (Long Term Evolution), 5G NSA and 5G SA stacks.

79.2 How was it Built

The Toshiba network installed in the NCC is of the NSA configuration. A block diagram is found in Figure 153.

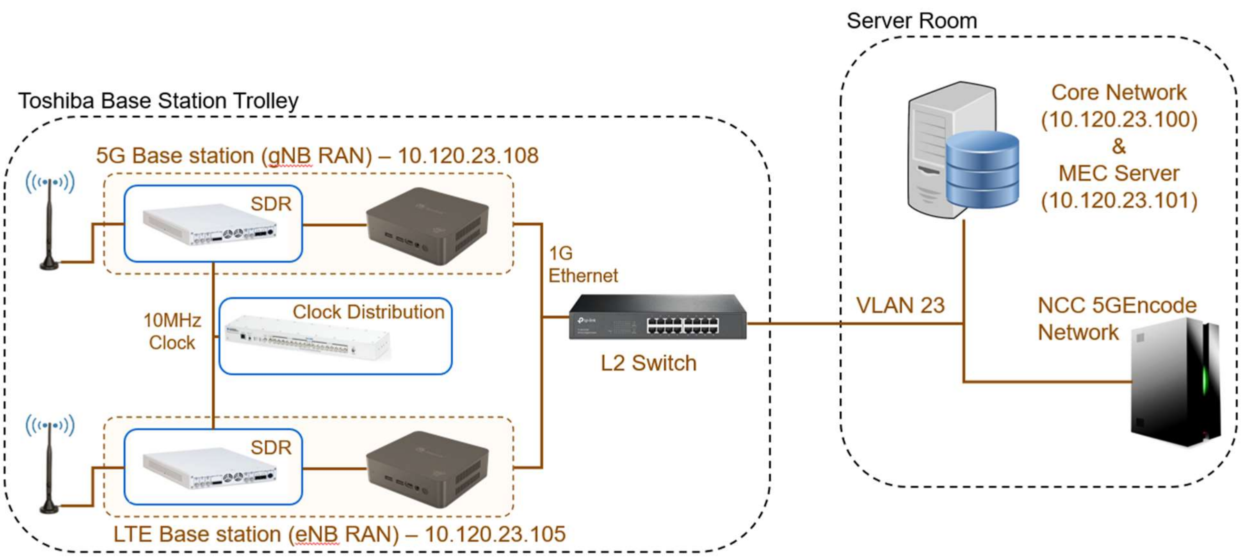


Figure 153 - Diagram of Toshiba's NSA Network

The network is split into 2 parts, Base Station and Server Room.

The Base Station consists of the following:

eNB RAN (Radio Access Network) – Radio for LTE communication - PC & SDR
gNB RAN – Radio for 5G NR communication - PC & SDR
Clock Distribution – Synchronising hardware for the eNB and gNB
The Server Room contains the following.

Core Network – Database for registration and endpoint of the Protocol Data Unit (PDU) session
Multi-access Edge Compute (MEC) systems – For running low latency application code
The parts of the network are made up of commercial off the shelf (COTS) components, such as research grade Software Defined Radio's (SDR), clock distribution units and standard server and PC hardware. The hardware used is detailed below:

79.2.1 Software Defined Radio

The SDR is responsible for the RF layer of communication, it communicates with the host PC via either USB 3 or a fast ethernet link. There are multiple SDRs that are compatible with the OAI platform depending on performance needs. We will focus on the National Instruments Ettus USRP series as they have the most support from the OAI project.

For the NCC setup the Ettus USRP B210 was chosen as this has support from the OAI project and is at a fair price point. The B210 has a USB3 interface, and it is capable of up to 40MHz bandwidth using ¾ sampling. Both the eNB and gNB will have 1 USRP B210 each.

Figure 154 - National Instruments USRP B210

79.2.2 Synchronisation

The eNB and gNB USRP radios are required to be synchronised when used in an NSA network configuration. A recommended way of achieving this for an OAI NSA based system is to use either a GPS Pulse Per Second (PPS) receiver, or a 10MHz accurate clock. A synchronisation product from Ettus is the OctoClock-G. The OctoClock-G can synchronise up to 8 devices using either the GPS PPS or its internal 10MHz clock if a GPS signal is unavailable.

Potentially if the radios are situated far away from each other to make connecting via the OctoClock-G unsuitable, a GPS module can be added to the USRP's which will allow the radios to synchronise via GPS PPS. However, this solution requires an antenna that can receive GPS signals that are traditionally hard to receive indoors.

Figure 155 - National Instruments Octoclock-G

79.2.3 Base Station PC's

For each base-station radio there is a requirement for a high-powered PC to perform the processing on the radio data. Each PC ran the Ubuntu Linux 18.04 operating system and had the OAI-RAN software installed. As the OAI-RAN software is a real time system it is preferred that a low latency kernel is installed, however in later versions of the software a standard Linux kernel is also usable. For better stability, the PC should have CPU frequency scaling turned off to prevent delays caused by CPU power management. The PC used must be of an Intel X86 architecture as the OAI-RAN software uses certain CPU instructions built into the processor.

79.2.4 eNB PC

The eNB in the Toshiba NSA base station is powered by a custom made mini-ITX form factor PC. The PC is running an Intel Core i7-8700 with 16GB RAM and a 256GB NVMe SSD. The eNB software is less resource intensive and this hardware ran it easily.

79.2.5 gNB PC

The software that runs on the gNB is much more resource intensive than the eNB software. As the software is also still in development it is advantageous to have additional computing power for when advanced features such as MIMO are implemented in the future.

The suggested PC configuration from OAI for the gNB is at least an 8 core Intel i7 processor and 16GB RAM, but preferably a modern Intel i9 with 32GB RAM. The PC that was chosen to meet the specs is the Intel Core i9 Ghost Canyon Extreme NUC Mini - BXNUC9i9QNX3. The i9 Ghost Canyon is a top spec NUC featuring an Intel i9-9980HK processor, it has been fitted with a 256GB NVMe SSD and 32GB RAM.

The PC was chosen for its high performance in a small form factor. Keeping the PC cool is an issue due to the intensive processing required by the OAI-gNB software. The NUC has a custom designed cooling solution from Intel which will keep the PC at optimal levels of performance.

Figure 156 - Intel Core i9 Ghost Canyon Extreme NUC Mini - BXNUC9i9QNX3

79.2.6 Core Network & MEC Server

The Core Network of the Toshiba 5G NSA network is based off the OAI Core Network project. This provides the necessary components such as Home Subscriber Server (HSS) Database, Mobile Management Entity (MME) and the Serving & PDN Gateway (SPGW). These components allow User Equipment (UE) to register with the network and transfer data to the wider network on the NCC.

A Dell Power Edge R640 server was used as the host for several Virtual Machines (VM's) which ran the Core Network and MEC applications. The server has the capability of running numerous edge applications at the same time. The advantage of having MEC applications and the Core Network on the same server is that it lowers latency and data can be accessed easily through the same network interfaces.

Another application from OAI called FlexRAN has been installed on the server. FlexRAN can be used to adjust certain parts of the system, read status of base stations, and do network slicing. Unfortunately, FlexRAN only works on LTE and has not been updated yet for the 5G network.

79.2.7 Software

As mentioned in the previous sections the software running on the network is based on the OAI project. Table 22 details the software versions used including git tags and repository information.

Table 22 - OAI Software Used

Network Component	Software Used	Git Version Tag	Link to Repository
Core Network	OAI-HSS	v1.1.1	https://github.com/OPENAIRINTERFACE/openair-epc-fed/tree/2021.w06
	OAI-MME	2020.w47	
	OAI-SPGW-C	v1.1.0	
	OAI-SPGW-U	v1.1.0	
eNB RAN	OAI-LTE RAN	2021.w10	https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/2021.w10/doc/TESTING_GNB_W_COTS_UE.md
gNB RAN	OAI-NR RAN	2021.w10	

Some of the core network components have been depreciated such as the MME, so it is advantageous to investigate upgrading the core to some of the latest versions.

There is also an OAI project that implements an SA system which will negate the need for an eNB base station and the clock distribution unit. However, the software is not as mature as the NSA and therefore has not been used for the Toshiba system.

79.2.8 User Equipment (UE)

To connect with the network a capable UE is needed. For the 5G Encode network Toshiba has purchased a Quectel RM500Q-GL USB dongle. The USB dongle shows up as a QMI device on Linux machines and can be used as a network interface.

Each UE needs a SIM that is registered with the network. For the Quectel dongle it was discovered that only certain Public Land Mobile Network (PLMN) registrations would allow the dongle to access the 5G network, even if LTE were working correctly.

For Toshiba's network in the NCC the PLMN of 001 01 was chosen as this is accepted by manufacturers as a test network setting. PLMN ID's for private networks are still under standardisation within 3GPP and associated bodies.

79.2.9 Frequency Bands

The Toshiba NSA network requires 2 licences from Ofcom to legally broadcast in the NCC. Toshiba has acquired 2 licences from Ofcom, 1 for Band 40 LTE (10MHz at Centre Frequency (Fc) 2395MHz), the second for Band N77 5G (80MHz at Fc 4155MHz). With testing it has been discovered that although it is possible to connect the Quectel device in LTE only Band 40, it does not work as an anchor band for the NSA configuration.
For our test for the LRI interface the NCC have allowed Toshiba's network to broadcast on their LTE Band 3 licence as this configuration works with
the Quectel dongle. The broadcast frequencies used are in Table 23.

Table 23 - RF Frequencies Used During LRI Use-Case

Radio	Frequency Band	Centre Frequency (Fc) Broadcast	Bandwidth
eNB (LTE)	Band 3 (FDD)	1845MHz Downlink 1750MHz Uplink	5MHz
gNB (5G)	Band N77 (TDD)	4155MHz UL/DL	40MHz

79.2.10 Other Network Capabilities

Toshiba's 5G network can support network slicing, in the form of radio resource slicing, as discussed in Appendix B – Radio Resource Slicing.

79.2.11 Integration with LRI Use-Case

The integration of the Toshiba NSA network and the LRI use-case was achieved as shown in Figure 157 below.

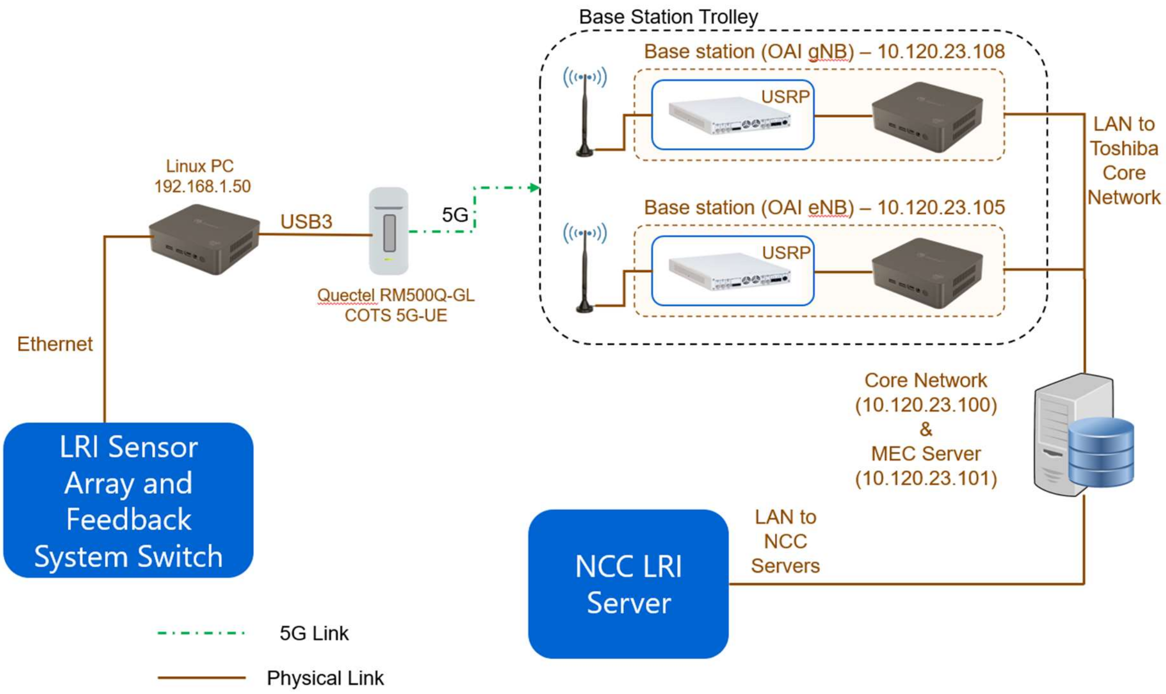


Figure 157 - Diagram of Integration Between Toshiba's NSA Network and the LRI Use-Case

The Linux PC on 192.168.1.50 acts as a bridge between the LRI and Toshiba 5G networks. The devices in the LRI network that need to send data to the LRI servers set their gateway to route via the Toshiba Linux PC. The Toshiba Core Network can directly see the LRI use-case servers, as such the packets are able to be routed out of the network to the LRI servers without issue.

79.3 5G NSA Network Performance

The Toshiba network was utilised during a test infusion of the LRI system as described in the Use Case Testing section.

The LRI use-case is the first test of the Toshiba NSA network in an industrial setting. All the testing prior to the installation at the NCC has been done in lab conditions. Some of the main differences between the factory and lab conditions are that there are many more sources of RF interference (including other cellular networks and industrial communication protocols from manufacturing equipment), more personal devices from workers and lots of RF blocking material in the area such as metal machinery and ducting.

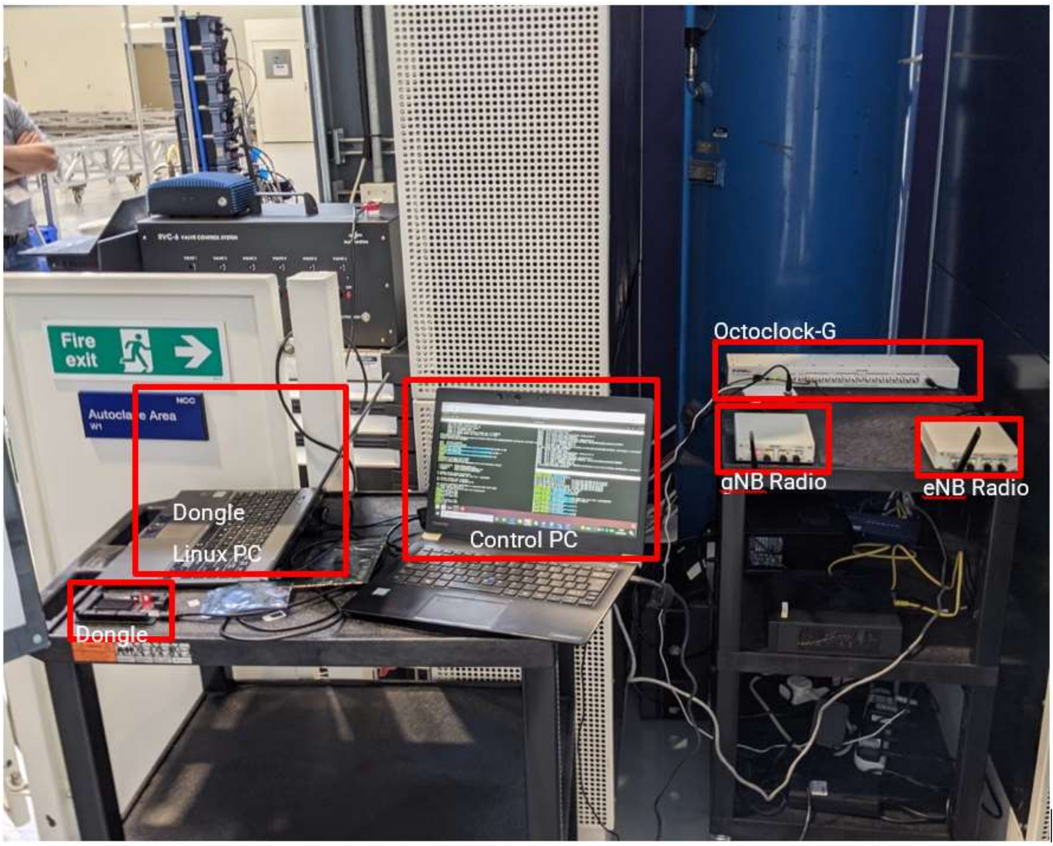


Figure 158 - Picture of LRI Use-Case Setup

79.3.1 Test Performance

The LRI test with Toshiba's NSA 5G network went well. The closed loop control of the infusion valves was successfully run over the Toshiba 5G network.

Unfortunately, after about 1 hour 20 minutes the 5G base station crashed. As the network is an NSA system, the device was switched over to the Toshiba LTE network where it was still able to transmit data, albeit with lesser downlink and latency performance than 5G. After 10 minutes on the LTE system the connection to the Quectel dongle was dropped by the network.

It is suspected that the reason for both the 5G base station crashing and LTE dropping the device is that some unexpected devices attempted to roam on the network. Although the other devices did not gain access to the network, it did manage to disrupt the scheduling of the connected device leading to it being dropped by the base station. The LRI test was swapped to run on the NCC 4G network for the overnight cure and minimal amounts of data was lost.

Whilst the test was running, several data metrics were logged on the network as detailed below.

79.3.2 Latency

A ping test was performed during the test with a period of 1 ping every second. Figure 159 shows the results of the overall test.

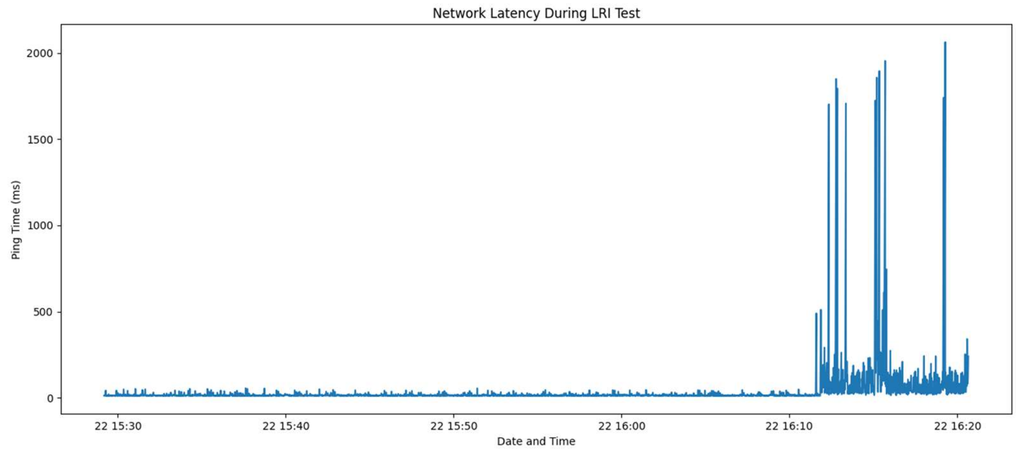


Figure 159 - Graph of Latency During LRI Test

The erratic behaviour towards the end of the test at about 16:12 was when the 5G base station and resulting switchover to LTE occurred. Table 24, Figure 160, and Figure 161 below shows results of the ping test before and after the 5G crash.

Table 24 - Table of Latency During LRI Test

Metrics	Data Before 16:10	Data After 16:10
Avg Ping	14.1ms	129.1ms
Max Ping	54.9ms	2064.0ms
Min Ping	8.6ms	9.6ms
Standard Deviation	6.0ms	268.7ms

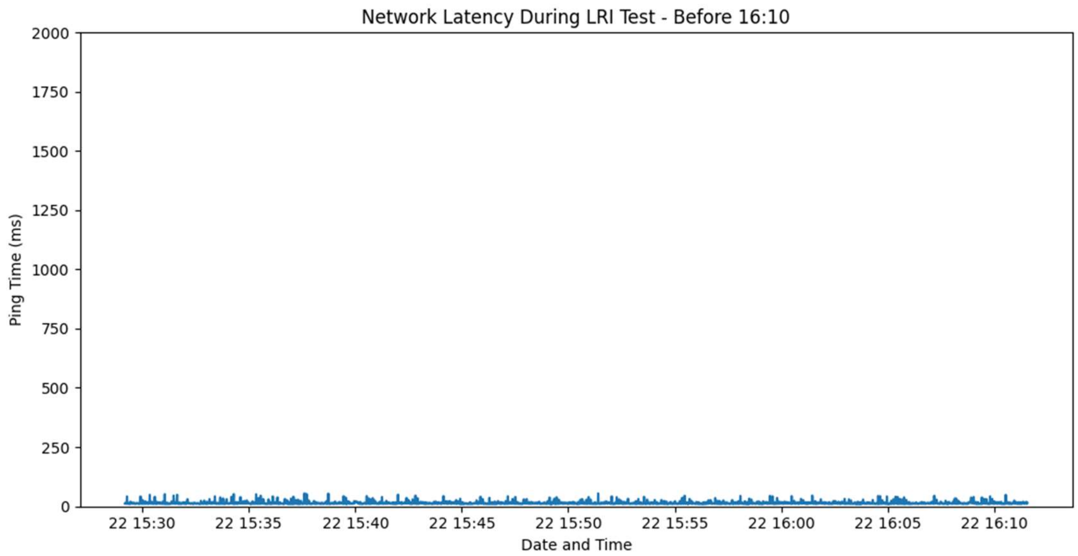


Figure 160 - Latency During LRI Test Before 5G Crash

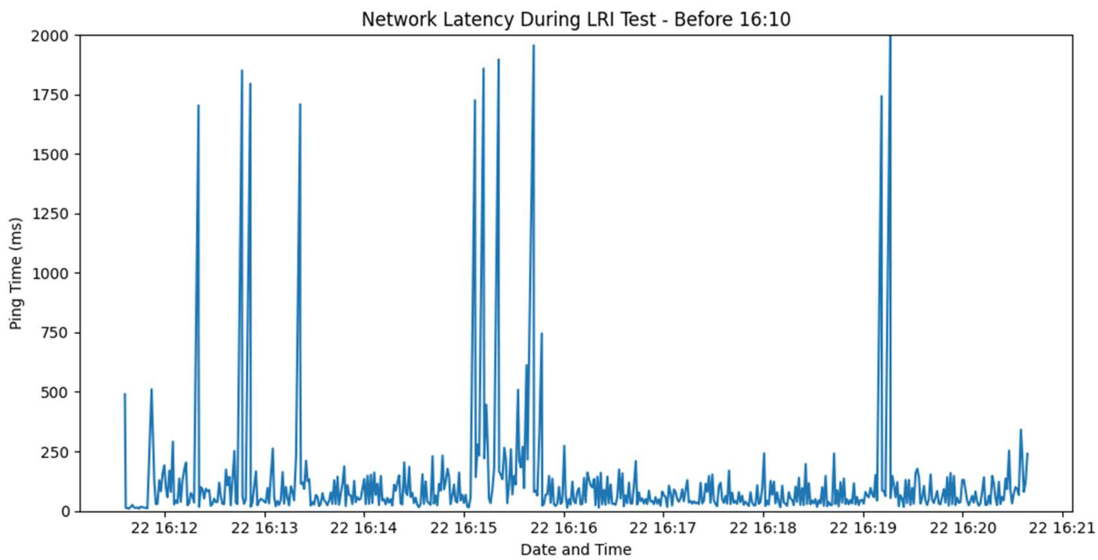


Figure 161 - Latency During LRI Test After 5G Crash

It has not been determined if the spikes in latency are related to the air interface interference or if there is a processing delay on the PC side of the network.

79.3.3 Network Speed

The bandwidth performance of the network has been measured in the Toshiba BRIL lab using an iperf3 test between the Linux machine with the Quectel 5G dongle and the Core Network endpoint. Performance is shown in Table 25 below.

Table 25 - Lab Iperf3 Performance

Mean Downlink	22 Mbps

Mean Uplink	0.8 Mbps

The low uplink performance comes from the slot configuration of the OAI system on the gNB. Unfortunately, the software version that was used on the test did not allow for easy configuration of the DL/UL slots and became unstable when not in the default configuration of 7DL/2UL slots.

79.3.4 Transferred Data, Stability & Packet Loss

Figure 162 shows the total data transferred during the LRI test on the 5G network.

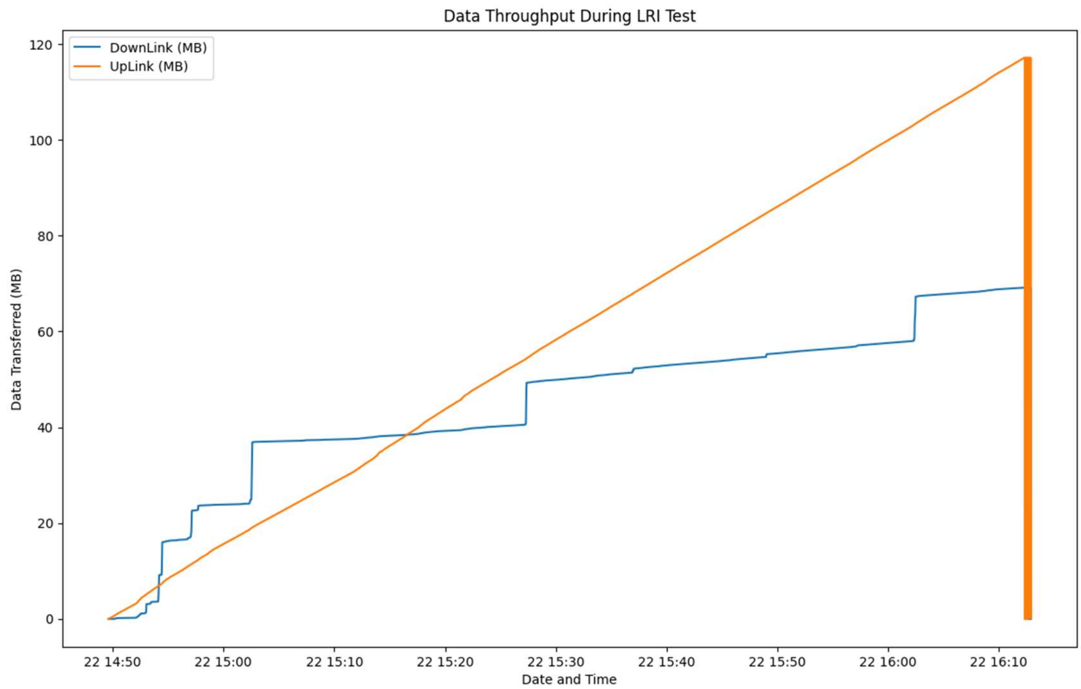


Figure 162 - Graph of Data Transferred During LRI Test

The erratic behaviour towards the end of the graph is when the gNB crashed. The uplink is a steady linear increase due to a constant amount of data being sent from the LRI equipment to the server over the network. The downlink shows more of a step function at various times. These would correspond with the closed loop control sent from the server to the system.

With regards to the RF signal the network performed robustly in the industrial environment with minimal radio interference from unknown radio sources. Although range was limited, this could be improved with amplification of the radio signal. As mentioned above in Test Performance there is a need for further software development to address the stability of the network. This should be focused on the roaming issue, as it cannot be assumed that other devices in the area will not attempt connection.

With regards to the environmental concerns, there did not seem to be any discernible difference between the NCC and BRIL's lab setup with latency and bandwidth, nor did there seem to be any packet data loss during the LRI closed loop test.

79.4 Conclusions & Lessons Learned

Looking at the specific use-case testing in the NCC environment it was interesting to see the differences between a lab environment and a busy factory. Issues that were expected such as range and RF interference did not seem to be a problem for the network. However, legitimate device interference from employees' personal devices attempting to connect and roam to the network did cause some significant problems with stability.

The roaming issue had been overlooked previously as the majority of Toshiba BRIL's OAI testing has been performed in controlled conditions with single devices. Adding unpredictable actors into the system had a negative effect on parts of the system that are not production ready yet. It is suspected that the main cause of the issue was the version of the OAI gNB software that was used. The software is less mature than its LTE counterpart and is still in active development. Updating the gNB software to a later version will be investigated for future tests.

The Toshiba NSA network was currently not very well ruggedised for industrial environments. For one-off testing this can be controlled by limiting exposure to chemicals, dust, and other electrically damaging debris. However, a suitable enclosure should be sourced if the base station were to be more permanently installed in a harsh environment.

There are definite limitations of basing the network from an open-source software project. OSA have provided numerous tutorials and guides on the system, however they still require a working understanding and knowledge of low level 5G/LTE systems, as well as experience with Linux and networking that may not be applicable to everyone. The lack of warranty and the technical barrier to entry of getting the system up and running can prove daunting if inexperienced.

With the issues stated above it is clear that there are several improvements necessary before the network can be taken into a full deployment in an industrial environment. However, the technical achievement that the OSA have reached should not be understated. With more years of maturity and development OAI is an incredibly promising project that will have reaches far outside the research community that is developing it. Toshiba has found benefits from the open and programmable nature of the OAI network. It has allowed for the same hardware to be used for different licence bands, and as the code is open source there is opportunity to build upon the codebase with new technology for research.

As a parallel exercise Toshiba BRIL is also investigating a vendor provided 5G SA network solution based on the O-RAN architecture to understand how the new open architecture complements the 3GPP specification. Though the OAI open-source solution is far cheaper than a vendor provided system, stability issues and the barrier to entry currently present in the software make it hard to recommend OAI as more than a research tool.

80 APPENDICES

80.1 Appendix A – Systems Engineering and Requirements Development Process

80.1.1 The Systems Engineering and Requirements Capture Process

As outlined in the introduction, the LRI process is complex, highly manual, and dependent on the skill of the manufacturing operator. Numerous variables such as resin temperatures, infusion pressures, fabric permeability, resin viscosity and many others effect the quality of the final composite component. Because of its complexity very little has been done to practically automate it and bring greater intelligence to the process.

A Systems Engineering (SE) approach was used in the design and development of the Closed Loop LRI system. To start with the scope of the system was left open to capture the full requirements for a closed loop LRI process. During this phase cost, time to implement, and available resources were not considered; this was done later when choosing which requirements to implement. The stages of the SE approach are shown in Figure 163.

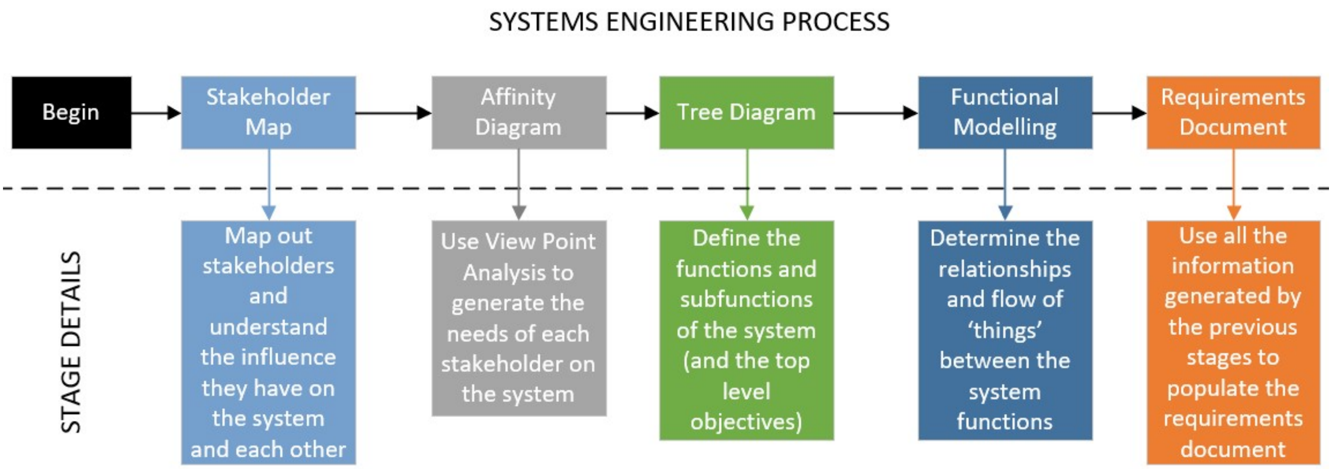


Figure 163 - The Systems Engineering process

The SE approach used in this project was done pragmatically based off the available time, meaning some stages of the more formal SE process were not performed. The details of each stage are as follows:

- **Stakeholder Analysis** – this is used to determine the different groups or 'things' that have an influence or interest in the system. Once stakeholders are generated they are collected into groups of similar interests (e.g. system designers, system users, suppliers). The influence that these stakeholder groups have on the system and each other are then mapped out in a Stakeholder Influence Map.

- **Affinity Diagram** – A tool called Viewpoint Analysis is used to systematically determine the needs each stakeholder has on the system (using the Stakeholder Map). This ensures a holistic approach to generating the system requirements without an overfocus on one or two stakeholders. These needs are then collected into groups that are similar - or share 'affinity' – in a diagram, and this outlines the key functionality of the system.

- **Tree Diagram** – The requirements from the affinity diagram are taken and organised in a tree structure outlining top level functionality and sub-functionally at different levels. The diagrams top level functions are used to determine what sub-systems will need to be developed. **NOTE – requirements must be written as functions, not solutions.**

- **Functional Modelling** – The Tree Diagram is useful for determining whole system and sub-system functionality; however it gives a siloed view. Therefore, there is a need to understand how each sub-system will interact with each other - Functional Modelling is used to determine this. A diagram is made mapping out the inputs and outputs every sub-system has on each other, and this is used to generate additional requirements based off their interactions.

- **Requirements Document** – The functionality outlined in the Tree and Functional Modelling diagrams are transferred into a formal requirements document.

It's important to note that during this process no solutions are proposed yet. The requirements document consists only of system functions, in other words "what the system has to do to meet the top-level requirement – closed loop LRI".

80.1.2 Requirement Selection

As previously stated, the requirements capture process was left open to understand the functionally needed for a full Closed Loop LRI system. Once the requirement set was developed, the scope of the Closed Loop LRI system was narrowed by choosing specific requirements to implement. This was done by selecting the system requirements that met the overall requirements of the programme (5G ENCODE), and that would be deliverable within the bounds of the project (budget, time, resource). Additionally, a technology assessment was performed to understand what sensors, controllers, and software could be realistically procured/developed within the project.

It was not within the scope of this programme to implement a compressive closed loop system to monitor and automate every element of the LRI manufacturing technique. The aim of this programme was to take the first steps towards a fully closed loop LRI process by **targeting specific elements of the technique to monitor and automate**. In addition to the benefits this initial automation would bring, the architectures, underlying systems, and knowledge base that would enable a fully closed loop system to be built in the future were also developed.

80.2 Appendix B – Radio Resource Slicing

Toshiba’s 5G network is fully capable of radio resource slicing functionality. Slicing of radio resources is crucial for providing strict performance guarantees in private/local deployments, particularly under multi-service co-existence scenarios.

The slicing functionality is achieved through a programmable software-defined RAN platform which provides necessary APIs for defining slice requirements and controlling radio resources at the base station. Slicing takes place at application level, i.e., each application (and associated users) is allocated a radio slice which has been customized to its requirements. Dynamic relocation of users from one slice to another is also supported.

Toshiba has recently demonstrated the concept of a private 4G/5G network with radio resource slicing. The demonstration considers three distinct applications: closed-loop control, event-triggered control, and video streaming, and shows the importance of slicing for providing performance guarantees. Further details about demonstration and radio resource slicing strategy are available in the following reference.

Jaya Thota and Adnan Aijaz. 2020. Slicing-enabled private 4G/5G network for industrial wireless applications. In Proceedings of the 26th Annual International Conference on Mobile Computing and Networking (MobiCom '20). Association for Computing Machinery, New York, NY, USA, Article 75, 1–3.
DOI: https://doi.org/10.1145/3372224.3417325
Public copy: https://arxiv.org/pdf/2008.04866.pdf

81 – ASSET TRACK. AND NEUTRAL HOSTING –

82 ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK Government's biggest investments in 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It also is designed to validate the premise that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that UK industry makes the most of the 5G technology and ultimately remains a global leader in the development of robust engineering capabilities when implementing complex composites structures manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLLC/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the Southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and small and medium enterprises (SMEs).

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

83 EXECUTIVE SUMMARY

This document describes how 5G ENCODE work package 3 was delivered, and the use cases were developed and executed, and the contribution consortium members made in delivering use case 2 (AR/VR) and use case 5 (Neutral Hosting and a possible O2 Interconnect opportunity).

The requirements placed in Telefonica UK (TUK) from the Consortium Agreement included allocation of test spectrum for in-building use if needed, consultancy and SIM cards to support possible public network utilization. The project also asked TUK to investigate the provision of neutral hosting integration, whilst outside the agreed scope of the project TUK agreed to investigate what was possible.

Whilst it was not included in the original Consortium Agreement, TUK were asked if they could support neutral hosting solution. TUK whilst not contracted to deliver a solution investigated what was possible in the timescales. Following that investigation TUK found that they were unable to support outdoor Use Case 2 (AR/VR) for 5G Encode Phase 2. The project had to find another solution and selected a lower cost core and RAN solution that would be managed by the project. TUK had also investigated a Nokia based standalone solution where the RAN and core were supported by TUK, but again the costs were significant and were deemed to be too high.

TUK's analysis clearly showed that connecting private networks to their public network was not possible within the planned project budget and timescale, due to complexity of the integration task, license obligations and security concerns. TUK reviewed three solutions that the project could adopt. The Joint Operators Technical Specification (JOTS) seemed the most realistic, but this was still complex to integrate when the private network was not provided by the public mobile operator and with a cost that was beyond the budget of the project. In the end it was simply not possible to deliver a JOTS solution to the timescale of the project, consequently, the integration idea was abandoned.

It should be noted that TUK were only a minor partner in this project from the beginning and never intended to deliver the network solution. And this was reflected in our modest claim for this project.

In the 5G Discussion section of this document the technical and logistical lessons learned are discussed along with recommendations for future projects to consider.

84 ABBREVIATIONS

APC	Automated Preforming Cell
AR	Augmented Reality
CTIL	Cornerstone Transmission Limited
eMBB	Enhanced Mobile Broad Band
IoT	Internet of Things
JOTS	Joint Operators Technical Specification
LRI	Liquid Resin Infusion
LSA	Licensed Spectrum Allocation
MEC	Mobile Edge Compute
MMTC	Massive Machine Type Communication
NCC	National Composites Centre, UK
RAN	Radio Access Network
SIM	Subscriber Identity Module
SME	Small and Medium size Enterprises
SWOT	Strengths, Weaknesses, Opportunities and Threats
T&D	Test and Deployment
TUK	Telefonica UK
UoB	University of Bristol
URLLC	Ultra-Reliable Low Latency Communication
VLAN	Virtual Local Area Network
VR	Virtual Reality
WECA	West of England Combined Authority

85 INTRODUCTION

As per the collaboration agreement (Appendix B), TUK's role in 5G Encode was to assist in Test & Development spectrum acquisition, network design and evaluation of technology vendors.

This was however revisited later to as follows.

- Consultancy - Spectrum T&D licenses, to help & assist in network design and evaluate technology vendors.
- SIMs to allow the use of TUK Public O2 4G / 5G for the external route testing from UoB to NCC.
- Possible adoption of the private network or joining of the neutral hosted solution at the end of the project (RAN connection to O2 core via VLAN) to ensure a smooth transition ideally needs to be Ericsson or Nokia.

Following was out of scope:

- No external Private Network Deployment/Coverage beyond NCC premises.
- No external Network Multi Domain Orchestration (MDO) beyond NCC premise.
- Telefonica had not yet deployed a public 5G SA core, therefore, testing of MDO was not possible within the life of the project.
- No connectivity to the TUK public core of any test network. Due to the complexity of integrating a private network in a public network. Something 5G DRIVE looks to solve.
- Everything that is not explicitly covered above in the opportunities is out of scope.

Figure 1 below details the work packages and use cases where TUK contribution was planned in the 5G ENCODE project. TUK's involvement was planned in work package 3 to enable parts of use cases 2 and 5.

Usecase category	Usecase #	Usecase	Details	TUK Involvement
Use Case 1 – AR/VR	WP3.1.1	Application 1: VR 360 Video training	Training video streamed to remote students in real-time to give a real-world experience.	No. TUK already participating in similar usecases in other POCs
	WP3.1.2	Application 2: AR training	3D overlays in real space to guide the user in real world scenarios.	
	WP3.1.3	Application 3: VR and haptic controlled robots	Remote control of off-site robot arm. VR and Haptic interfaces for the real-time user experience.	
Use Case 2 – In-building & Outdoor High value manufacturing Asset Tracking	WP3.2.1	Indoor @NCC-HQ and @NCC-I	Visibility of asset location within factory boundaries, the Continuous track of time sensitive conditions, Maintaining traceability and pedigree of assets and Establishing asset-equipment relationship.	Yes, TUK is providing spectrum for indoor use
	WP3.2.2	Outdoor @Telefonica/O2 Public Network	Asset location outside factory boundaries and continuous tracking, Initiation of Material Passport, Enablement of in process quality control technologies, and Recyclability and reuse of assets.	Yes, TUK will be supporting outdoor tracking

Usecase category	Usecase #	Usecase	Details	TUK Involvement
Use Case 3 – Preparation for manufacturing sensor deployment	WP3.3.1	Closed Loop Manufacturing in LRI (Liquid resin infusion)	The current monolithic control system will be disaggregated, split over 5G wireless connectivity, partly virtualized in a virtual machine hosted on project's MEC/compute platform. These steps will enable the insertion of an AI/ML based decision engine and a visualisation application.	No
	WP3.3.2	Automated Preforming Technology (APC)	5G transformation of the ProFactor Verification End Effector. It is a commercially available verification system that integrates with a robot and features sensors. These sensors are coupled to a high-powered PC, which hosts the ProFactor application for the analysis of the sensor information for accurately detecting defects.	No
Use Case 4 – Toshiba	WP3.4.1	TBC		-
Use Case 5 – Neutral Hosting and O2 Interconnect	WP3.5.1	NCC providing service to MNO (for MNO's customers)	Adoption of the private network or joining of the neutral hosted solution at the end of the project	Y
	WP3.5.2	MNO providing service to NCC (linked to WP3.2.2 Outdoor Tracking)		Y

Figure 164: Work Package 3 Use Cases where TUK planned to contribute

86 5G ENCODE PHASE 1

In this phase a 4G cellular private network was implemented in two separate NCC premises named NCC and NCCi. Each industrial use case executed within the constraints of the 4G technology to create baseline network performance measures and understand design changes needed to be successful in a 5G cellular deployment. TUK had minimal involvement in phase 1.

The Phase 1 network was managed as separate domains, each associated with a location. The following domains were provisioned:

- NCC Building (NCC): A fixed deployment, with distributed access to each of the project locations, but with a centralised infrastructure, managed by NCC and visualised using Zeetta's solution.
- NCCi Building (NCCi): A portable deployment, located in the relevant manufacturing cell, managed locally by Zeetta, and visualised in their solution.

The Phase 1 network was to be a subset of the Phase 2 deployment. Phase 1 was designed to test use cases in a cellular environment and identify where processes in the use cases needed to change and identify limitations of the 4G LTE cellular network. The manufacturing use cases exercised in phase 1 were as follows:

- Use Case 1 – Distributed Training. In this use case there were two parts to the training: a virtual reality and augmented reality training. For the virtual reality training session, a camera located in the NCC workshop was used by the trainer to deliver content to a class of trainees in other parts of the NCC. The training session was delivered using virtual reality 360-degree camera with two-way interactive component for trainees to ask questions of the trainer. The virtual reality training was followed by an augmented reality trainee exercise to assemble a component ready to be used in the liquid resin infusion use case.

- Use Case 2 – Asset Tracking. In this use case RFID sensors were deployed around the tracking area. Each RFID sensor used the private cellular network to transfer location of detected RFID tags to the central hosting platform in the Enterprise LAN. In Phase 1 of the project the RFID sensors detected the transition of passive RFID tags entering the building and when passing specific locations within the building. Materials and assets to be tracked were fitted with a passive RFID tag that triggers the sensor when passing. The use case tracked materials from the Solvay supplier factory, through the public network, arrival at the NCC and then inside the NCC location. The use case also tracked tools inside the NCC location.

- Use Case 3 – Ultra low latency in production processes. In this use case two production processes were executed to demonstrate the business case for 5G:

Liquid Resin Infusion (LRI) and Automated Preforming Cell (APC). Whilst each industrial process has different network performance needs each needed to collect data form IoT sensors, transfer the data to a mobile edge compute (MEC) function and receive change commands returned.

The outcomes of each use case being exercised are recorded in the detailed report for each use case.

The aspects of phase 1 where TUK had offered to help:

- Spectrum license requests
- Consultancy
- Public network SIM card allocation

Licenses to radiate 4G in the LTE spectrum were acquired from OFCOM by NCC. The project informed TUK that support for Use Case 2 (Asset Tracking) out of building was not needed, this was a decision by the project to ensure the planned timescale and budget was met. As part of use case 2 (Asset Tracking) 2 SIM's were provided to the project team for testing out of factory tracking.

87 5G ENCODE PHASE 2

In this phase a 5G Open RAN (ORAN) Standalone (SA) cellular network was implemented in two separate NCC premises and the Millennium Square in Bristol. Each industrial use case was executed with the network performance and updated application performance characteristics measured. In phase 2 the Millennium Square location was used to exercise and show case the VR and AR use cases in a public space using an outdoor Nokia solution provided by the University of Bristol.

- NCC Building (NCC): A fixed deployment, with distributed access to each of the project locations, but with a centralised infrastructure, managed by NCC and visualised using Zeetta's solution.
- NCCi Building (NCCi): A portable deployment, located in the relevant manufacturing cell, managed locally by Zeetta, and visualised in their solution.
- UoB 5G Testbed in Millennium Square, Bristol: An extension of the existing deployment, managed by existing UoB systems.

The Phase 2 network extended the Phase 1 network to include 5G RAN. The network design included a shared Home Subscriber Server (HSS) hosted by the 4G network being reused to provide 5G network access. To separate data service traffic for subscribers different Access Point Names (APN) for 4G and 5G were used. The manufacturing use cases were repeated in phase 2 as follows:

- Use Case 1 – Distributed Training. In this use case the quality and latency of the video stream and two-way interactive service in a static situation were the success criteria for the deployed 5G.

- Use Case 2 – Asset Tracking. In this use case coverage, uninterrupted data transmission and mobility were success criteria for the deployed 5G.

- Use Case 3 – LRI and APC production processes. In this use case latency and high-volume data transmission in a static situation were success criteria for the deployed 5G.

The results of each of the above use cases are captured in the detailed final reports produced in separate documents.

TUK was asked if they would be prepared to support use case 2 as materials left the supplier facility travelled through the public network and arrived at the NCC (WP 3.2.2 – Out of factory Asset Tracking). The Solvay final report documents 5G cellular in a controlled materials factory, the NCC final report documents the 5G cellular enablement of asset tracking in a production environment.

The original intention was to use TUK 5G Standalone (SA) public network, including a selection of outdoor sites covering the surrounding areas of NCC premises, providing better positioning accuracy outdoors than possible with LTE. Hence, continuous tracking of materials transfer from the private network in the supplier facility (Solvay premises) onto the public network support (TUK) and then into a destination private network (NCC).

However, due to internal roadmap and 5G SA readiness timelines, TUK proposed using an isolated private network with 5G SA core and outdoor RAN solution for the 5G ENCODE project to reduce the requirements needed to create a neutral hosting environment (options proposed specified in Appendix A). Unfortunately, this proposal created a delay to the project schedule with that would affect multiple collaborators and a cost that exceeded the planned project budget. To attach and host a private network from a public network needed processes to be agreed to manage; security, RAN technology characteristics, users and entitlements and inter network billing, these were not within the agreed scope of work for TUK. The project team decided to use RAN from Airspan and a DRUID Core and forgo public network hosting. Out of office asset tracking used a GPS based tracking alternative solution.

87.1 WP3.2.2 – Out of factory Asset Tracking

A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis to support Use Case 2 (WP3.2.2 Asset Tracking) was completed. As a result the alternative GPS based solution was selected to deliver the 5G network in Q4 2021 and maintain the launch planned for 30 November 2021.

88 5G DISCUSSION

TUK does not have ability to deploy an outdoor private network, in the Vodafone deployment area of the country, as it restricted by the terms of its Joint venture (CTIL). TUK offered public sims cards as a viable alternative. This would allow for the transfer of users from the indoor private network to O2 public outdoor network as required by use case 2 for 5G Encode Phase 2 was not completed due to the project's decision to de-risk the timelines.

This significant increase in scope for TUK required significant additional budget approval, approval was obtained for an inbuilding solution. The project team discussed this with the engineering team at Zeetta and determined it was not going to be possible for them to take on the extra work of integrating the Nokia solution within the budget and timescales of the project. Various options were discussed to understand whether other activities could de-prioritized to enable the TUK proposal, but it was determined by the project that was not going to be possible.

Adoption of the 5G Encode RAN, and integration with TUK Core following Neutral Hosting model was not completed. It was discussed with UoB and Zeetta that they will go through the Joint Operators Technical Specifications (JOTS), and that this is Telefonica's preferred approach for Neutral hosting (though the specifications only cover indoor LTE and doesn't address outdoor deployments, 5G or distributed RAN architecture). Adaptation of NH solution to include distributed RAN and 5G was not aligned to project's timelines.

To improve the ability to adopt and use neutral hosting in a public network operator environment more time is needed in project schedules for interoperability, licence obligations and security testing of products not in the approved mobile network operator catalogue e.g. new core and RAN elements.

The activities needed to adopt integrate private and public networks using JOTS need more work than was planned for in 5G ENCODE.

It is recommended that for future projects a SWOT is conducted very early in the project to give the public mobile operator time to plan any needed integration.

It is for this very reason TUK now Virgin Media O2 put for forward a proposal called 5G DRIVE as part of the DCMS FRAN Competition, to allow for a simplified model of adoption. Allowing private networks to be simply integrated into a public network.

With the approved it is hoped that the integration issues; staffing, OPEX, CAPEX budget, Security, Regulatory requirements and Public Network Service Protection encountered in this project will be a thing of the past.

More information on project 5G Drive can be found here https://uk5g.org/discover/5G-projects/5G-Diversification-Projects/5g-drive/

89 APPENDIX A

The following deployment options were considered during the initial planning.

1. TUK temporary mobile private network deployed at the NCC headquarters building, with coverage contained within the building itself.

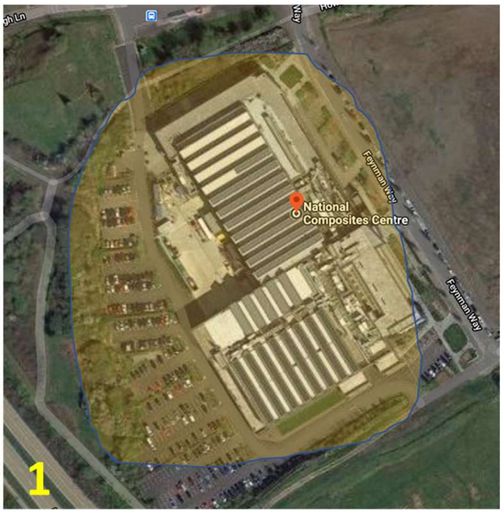


Figure 165: MPN deployment at NCC headquarters

2. TUK temporary mobile private network deployed in NCC headquarter building with outdoor coverage transfer between NCC and TUK public network.

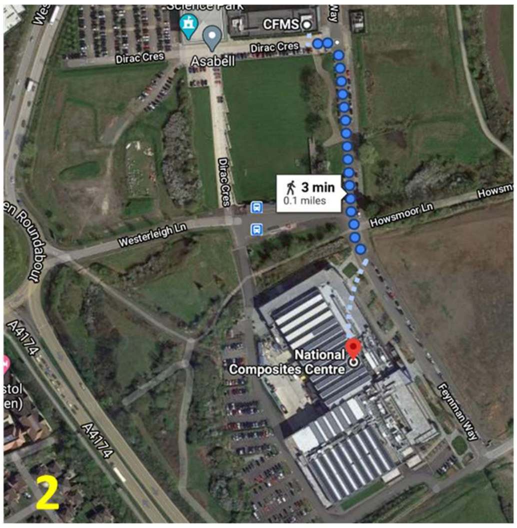


Figure 166: TUK MPN deployment at NCC premises with outdoor coverage by CFMS

3. TUK temporary mobile private network deployed at NCC and NCCi premises with outdoor coverage between both premises provided though TUK public network.

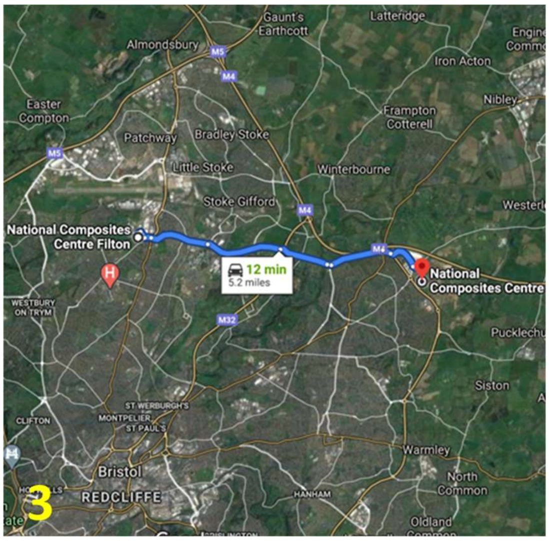


Figure 167: TUK MPN's connected over public network

90 APPENDIX B

Telefonica 5G spectrum management plan in case 5G standalone operation needed TUK spectrum or with LTE anchoring in case of Non-Standalone operation. In the event that Licensed Spectrum Allocation (LSA) spectrum needed to be used in the range 3.8-4.2 GHz this would be subject to TUK internal clearance.

Option	RAID	Advantages	Caveats
1-3) TUK deploys a temporary 5G SA (option 2) based private core with outdoor RAN coverage: • contained within NCC premises or between NCC and CFMS • using TEF 5G Frequency or LSA from Ofcom • PLMN ID 23402 or 999 (or use specific SUPI range) to avoid TUK customers attaching to the network	• A1: TUK will be accountable to manage this network (assumed turnkey solution from TUK vendors) • A2: NCC/Zeetta will apply and use LSA spectrum (i.e. not use TUK spectrum for their indoor private network) • A3: Will need SIMs with PLMN ID 999 or 23402. It is assumed that SIMs (or SIM writer) will be provided by this TUK Private Network vendor. • A4: Interference to TUK Macro network will be controlled by limiting power of the PV NW RAN • A5: This will be a release 15 SA network (Core and RAN) • R1: Once the Macro network is 5G enabled in Bristol, there is a risk of interference to this TUK provided private network outdoor coverage – Probability is Low. Regardless, Martin Gilbert (Regional Radio Manager) will need to be kept in loop. • R2: Higher than committed costs – Probability is High • D1: Devices used by 5G Encode project may need to support 23402 and/or 999 PLMN IDs; and 5G SA. • D2: Approval from Beacon partnership team.	• 6-12 months POC type deployment including turnkey deployment, integration and support by the vendor, hence an isolated deployment from TUK perspective with no need for integration with TUK network. • Assumed TUK is responsible to run and manage this network, then no need to apply for T&D licenses, which saves time and effort. • Providing ability for the project to test MDO and indoor/outdoor asset tracking.	• Additional equipment and resourcing cost than committed by TUK initially. • The project will have dependency on this network deployment by TUK preferred vendors, which might lack in features or present interoperability issues with the NCC deployed Druid Raemis Core and IP Access RAN.

Figure 168: TUK spectrum management plan

– NETWORK PROBING –

5G-encode

92 EXECUTIVE SUMMARY

5G-Encode is a £9 million collaborative project partially funded by the Department for Digital, Culture, Media, and Sport (DCMS) with the aim of developing clear business cases for 5G applications in the composites manufacturing industry. Solvay was a partner in the industrial use case evaluating asset tracking of time sensitive materials.

The asset tracking evaluation work package was delivered in collaboration with Plataine Ltd which provided the TPO application and the NCC, Bristol which provided the test bed for the private 5G technology evaluation. The NCC test bed was delivered together with Zeetta Networks, Toshiba, Mativision, Plataine, Siemens, Telefonica, Accedian and the High-Performance Networks Group from the University of Bristol as partners.

Accedian has been a long-standing provider of network and application performance monitoring to both Service Provider and Enterprise markets and they had recognised the new opportunities that 5G would offer to Industry. Research by the CapGemini Research Institute concluded that "2 out of 3 industrial companies believe that guaranteed quality of service is critical for their digital transformation" and with 5G holding the key to unlocking digital transformation for manufacturers, both in the UK and around the world, monitoring the performance of both the 5G network and the applications driving the 5G use cases of mMTC, eMBB and URLLC, is a critical success factor.

Project Encode provided Accedian with an ideal opportunity to validate the value of its performance monitoring and test generation virtual platform, Skylight Analytics, to in the manufacturing industry by supporting their digital transformation journey and helping companies to realise the performance and reliability benefits of 5G.

Within Project Encode, Skylight was deployed at the National Composites Centre (NCC) and delivered granular and accurate real-time visibility, anomaly detection, and analytics on the performance of 5G-ENCODE's private 5G network and the applications that run over it. Skylight was able to support the project's goal to accelerate the realisation of the benefits of 5G for their key business use cases; in-factory and in-transit asset tracking, virtual 360-degree video training and closed loop manufacturing in Liquid Resin Infusion. The key results being:

4. The simplification of fault identification and resolution to enable non technically skilled staff to identify use case impacting issues and also what the issue was and what the possible root cause was.
5. The presentation of highly accurate and granular performance data to enable technical staff to trouble-shoot use case impacting issues to reduce downtime
6. The ability to proactively identify performance degradations that would lead to negative impact on the use cases.

93 ABBREVIATIONS

AI/ML	Artificial Intelligence / Machine Learning
API	Application Programming Interface
eMBB	Enhanced Mobile Broadband
KPI	Key Performance Indicator
mMTC	Massive Machine Type Communications
uRLLC	Ultra-Reliable Low Latency Communications

94 INTRODUCTION

94.1 Project Objectives

The prime objective of Accedian within the Encode project was to provide a performance monitoring capability, Skylight, which enables Manufacturers to ensure that the performance benefits promised by 5G live up to expectations and lead to the successful delivery of the use cases that underpinned the business case for investment in Private 5G.

We also wanted to show that Skylight could be used by non-technical people to derive operational value for the organisation.

94.2 Purpose of 5G

From Accedian's perspective 5G is just an enabler of the Manufacturing use cases and is no different to a 4G or Wi-Fi network connection or indeed a wired connection, other than that the Encode 5G environment is disaggregated rather than a black box solution.

However, there is a difference when it comes to the value of performance monitoring, which increase with 5G due to the stringent nature of the network performance requirements for some private 5G use cases and applications. These applications have special requirements in terms of latency, packet loss and bandwidth, which make it critical to monitor these performance factors.

The disaggregated nature of the Encode 5G environment also creates challenges with understanding performance across multiple functions and multiple vendors.

Skylight delivers value in three ways; visibility, insight and action:

94.3 Visibility

Skylight provides the ability to measure the performance of the connectivity in a very accurate and granular way. This is done using sensors. These sensors can be deployed as physical sensors or software sensors, in the form of virtual software or containers to generate a multitude of KPIs that determine the performance of the network connectivity. We can also deploy capture sensors that provide application delivery performance metrics.

The combination of these sensors means that Skylight can provide complete end to end visibility of both the underlay and overlay network performance, irrespective of whether the network is wireless or wired or whether the applications are hosted in a private or public cloud or indeed a hybrid environment.

94.4 Insight

However, visibility in itself isn't enough. It's all well and good Identifying that an issue exists is useful, but the real value is knowing what the issue is, where it is and most importantly what its impact is on end user experience.

KPI's on their own may only be useful to users with the appropriate skills and knowledge to analyse them and deduce what they are indicating if there is an issue that will impact end user experience.

Skylight uses metadata to add context to the KPI's and then uses AI/ML methodologies such as anomaly detection and pattern matching to add intelligence to turn them into something meaningful, such as the root cause of the issue. A simple example would be that Skylight could identify an issue with packet loss but using geographic metadata to determine that the issue was in a particular location and then additional metadata would lead us to the exact location of the device

94.5 Action

With the insights now available, what can a user do with the information? Skylight has very powerful dash-boarding capabilities to enable visualization of performance KPIs and create insights in multiple ways to meet differing requirements of individual user groups, such as Operations or Capacity Planning. These dashboards can provide a high-level view of performance that can indicate specific issues based on threshold breaches. This allows users, based on their role profile, to drill down into the underlying details to determine the root cause.

These dashboard views should not be confused with a similarly named features documented in the single and multi-domain service management report where a 'single plane of glass' feature is used to visualise the network devices.

Additionally, Skylight can feed the created KPIs and insight, via APIs, to other third-party systems to trigger further actions. This could be for something simple like the creation of a trouble ticket, but it could also be part of a more complex closed loop automation process.

95 WHAT WAS DEPLOYED

In order to meet the objective described previously we selected the following operational use cases on which to base the solution design:

- End-to-end Slice performance visibility across the 5G private and 5G public networks
- End user QoE monitoring
- Enable SLA compliance across entire infrastructure
- Advanced troubleshooting for operational efficiency
- Accurate performance data feedback loop for automated network orchestration

To deliver the above use cases we also took the following key design decisions:

- To implement both active network testing and passive application monitoring
- To deploy sensors where appropriate to measure the performance across the end-to-end network all the way to end devices and applications and on both sites

The following components were implemented:

- Virtual Machines (on Hyper-V and KVM):
- Sensor Control
- Sensor Capture
- Orchestrator
- Roadrunner
- License Server
- Skylight Analytics (SaaS)
- Sensor Agent x 2 (Docker)
- Roadrunner x 2 (Docker)
- TWAMP reflector agent x 3 (Android)
- Hardware components:
    - SFP-C x 6
    - ANT x 1

Please see figure 1 below, which illustrates the topology of the solution deployed. Figure 2 provides more detail on each component.

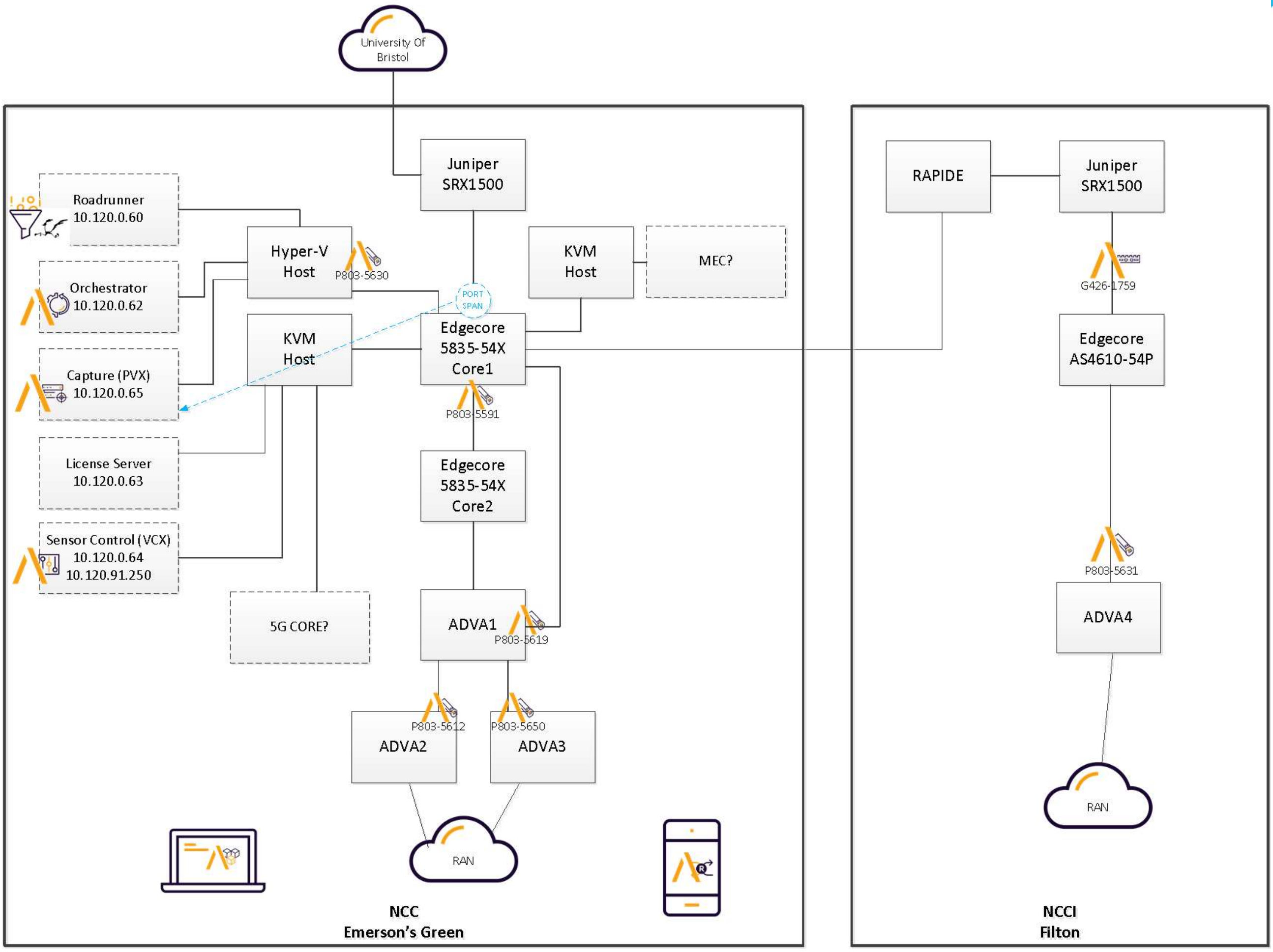


Figure 169: Skylight solution topology showing the position of the solution components

Component	Deployment Target / Scope	Technical Function	Capability
SFP-Compute and ANT modules	Physically installed in or connected to ADVA switches and EdgeCore switches	TWAMP and Flowmeter	Network performance and bandwidth assurance
Sensor Agent	Docker container on workstations	TWAMP	Network performance assurance
TWAMP reflector	App on Android handsets	TWAMP	Network performance assurance
Sensor Capture	Mirror / SPAN feed from Core switch	Wire data analysis	Application delivery assurance
Sensor Control, Orchestrator, Roadrunner, License Server	Virtual Machine on Hyper-V and KVM	Module discovery, configuration, management, data collection, APIs	Network performance and bandwidth assurance with full orchestration
Analytics	SaaS	Data visualization portal / APIs	Network performance, application delivery and bandwidth assurance with visualization, AI/ML data processing & 3rd party ingestion

Figure 170: Explanation of the role of each of the components

96 IMPACT ON ENCODE USE CASES

In general terms, there are three generic use cases for 5G and they are mMTC, eMBB and URLLC. Skylight enables organizations to understand how the 5G network is impacting the delivery of these use cases by providing ultra-granular visibility of network performance (the underlay) as well as visibility of the performance of the applications (the overlay) that run over the network to drive these use cases. Skylight was used in the Liquid Resin Infusion (LRI) use case report to validate network traffic estimated with network traffic passed by the transported network. The data was not of high volume but needed to be delivered with minimal latency for valve and oven controls used during the infusion process to execute correctly.

A recent report from Analysys Mason (Analysys Mason Private 5G enterprise survey) says that reliability and security are the most important 5G requirements for the manufacturing sector. Support for low-latency time-critical applications is important to manufacturers, along with high network bandwidth and throughput and support for a wide range of endpoint devices.

High reliability 82%
Highly secure 78%
Support for low-latency, time-critical apps 75%
High bandwidth/throughput 73%
Diversity of endpoint devices supported 73%

Specifically, to Encode, the key impact that Skylight will have on the four use cases are as follows:

1. Skylight enable NCC users to proactively identify both stability and performance issues that will impact the successful delivery of the various use cases and provide insight into what the root cause is so that the appropriate action can be taken.
2. Reduces the technical skills required to identify issues and their root cause through the use of thresholds and alerts and also visualizations
3. Provides a single, agnostic, view of network and application performance irrespective of the vendors implemented in the network or whether a private, public or hybrid cloud environment is being used.

To support the above we have provided example screen shots and labels in the Appendices to demonstrate how Skylight enables non-technical resources to identify issues and their root causes.

97 IDENTIFIED LIMITATIONS

As a result of the project, we identified a number of limitations in the current Skylight product that we can now address moving forward:

1. User Equipment (UE) TWAMP endpoint capability currently limited to Android phones and workstations capable of running Docker
2. Android reflector is not currently GA
3. Android reflector reflects TWAMP from Sensor Agent only (and cannot reflect from SFP-C) due to callback requirement
4. Capture Sensor does not dissect MQTT or LLRP L7 transactions

There were also a number of constraints within the NCC environment that impacted the expected deliverables:

1. LLDP messaging caused issues in the 5G network, LLDP had to be configured as a pass-through in the SFP-C modules, so the probe was not detected as a network device
2. Un-supported hypervisors (Hyper-V) were used to host some VMs due to hardware capacity
3. Time constraints and 5G network stability did not allow for the addition of enhanced features such as closed loop automation
4. No end device or connectivity available for measuring over private-public-private 5G to validate “splicing” technology.
5. Very low latency in 5G core platform which may not be representative of production Private 5G deployment. Limitation on “realism” of data displayed in Skylight

98 FUTURE DEVELOPMENTS

The key areas of focus for development to support 5G Private Network use cases is our sensor agent program. Our objective, as seen in Figure 3 below, is to enable ubiquitous coverage by creating agents to sit in any environment.

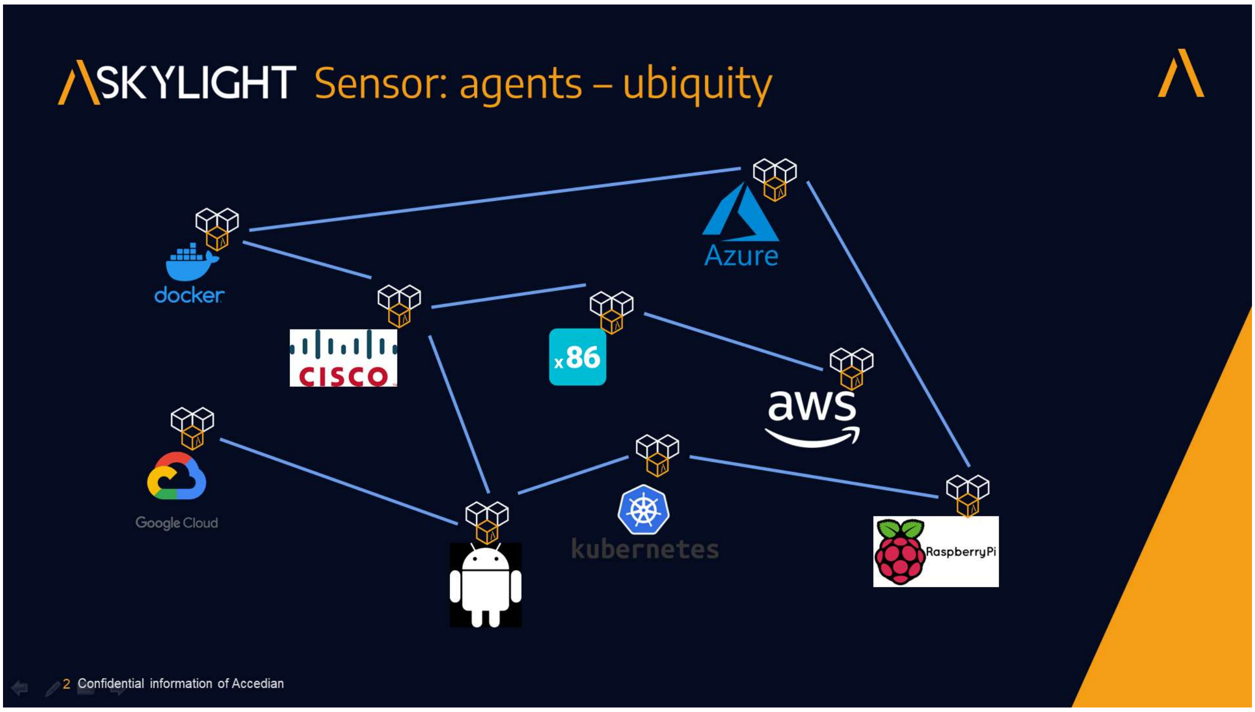


Figure 171: Illustration of proposed sensor agents

Skylight Sensor Agents – Current

- 21.06 GA
    - Actuate: RFC5337 TWAMP sender, reflector
    - Throughput: RFC6349 TCP agent, limited
- Demo / PoC versions:
    - ARMv8 actuate and throughput
    - Reflect: PM reflection binary x86 and ARMv8
    - Trace: path tracing, limited
    - Android reflector

Skylight Sensor Agents – Up-and-coming Enhancements

- 21.12 (in final SQA)
    - Actuate: added support for UDP echo and ICMP echo session types
    - Throughput: added support for baseline results and multiple test definitions
    - Reflect: simple unmanaged binary reflector app for linux 64bit (x86)
    - VRF support for deployment on Cisco
    - post-GA validation of performance on Cisco HW platforms (5500 and 540)
- 22.04
    - Throughput: new visualization of TCP tests in Analytics
    - Actuate: adding roundtrip metric support, TWAMP-control NAT support
    - Trace: multi-test support and configuration loops (scheduling) – no new visualization
    - ARMv8 (64-bit) GA for throughput, actuate, trace and reflect
    - Domain: demo version for DNS testing

99 CONCLUSIONS

5G technology will revolutionize manufacturing not only with much needed additional security for critical applications, but also by delivery of dedicated resources with assigned guaranteed quality of service.

In response to a 2021 IDC global survey, 50% of manufacturers cited lack of automation and analytics to optimize their environment as a top barrier to building a resilient digital infrastructure.
In the same survey over 40% of manufacturers reported problems with performance, security, and connectivity with mission-critical workloads and 43% saying that having difficulty with finding the staff/training/skills to meet the needs of evolving network requirements, is one of their organization's biggest business challenges.

The Analysys Mason Private 5G enterprise survey points out that "The network will need tools to monitor each application's performance and ensure that those metrics are in line with the KPIs."

Our involvement in the 5G-ENCODE project, enabled us to take a step closer to delivering a solution that enables organizations to realise the value of 5G through the visibility and assurance of the performance of the network and critical applications and of the end user experience. A particular example where Skylight was able to identify how a network outage impacted the LRI use case has been highlighted in their report.

Also, asset tracking is a low data volume solution that is not reliant of ultra-low latency, however, coverage is key so NCC used Skylight to look for rhythmic transmission of small bursts of data. In the samples taken no issues were detected but please refer to figures 7,8 & 9 in the Appendices.

In addition, we have provided sample screen shots from the Skylight solution implemented for Encode in Appendix A to demonstrate how Skylight enables non-technical resources to identify issues and their root causes. I've also attached the IDC snapshot report in Appendix B.

100 APPENDIX A

Skylight dashboards

This section provides information regarding the dashboard views configured for the 5G-Encode Project and associated use cases. The red text provides annotation of capabilities provided.

The final 2 screenshots present information provided to a specific 5G-Encode use case owner in order to understand the traffic activity in their own environment.

Encode Overview dashboard – Network Performance Assurance section

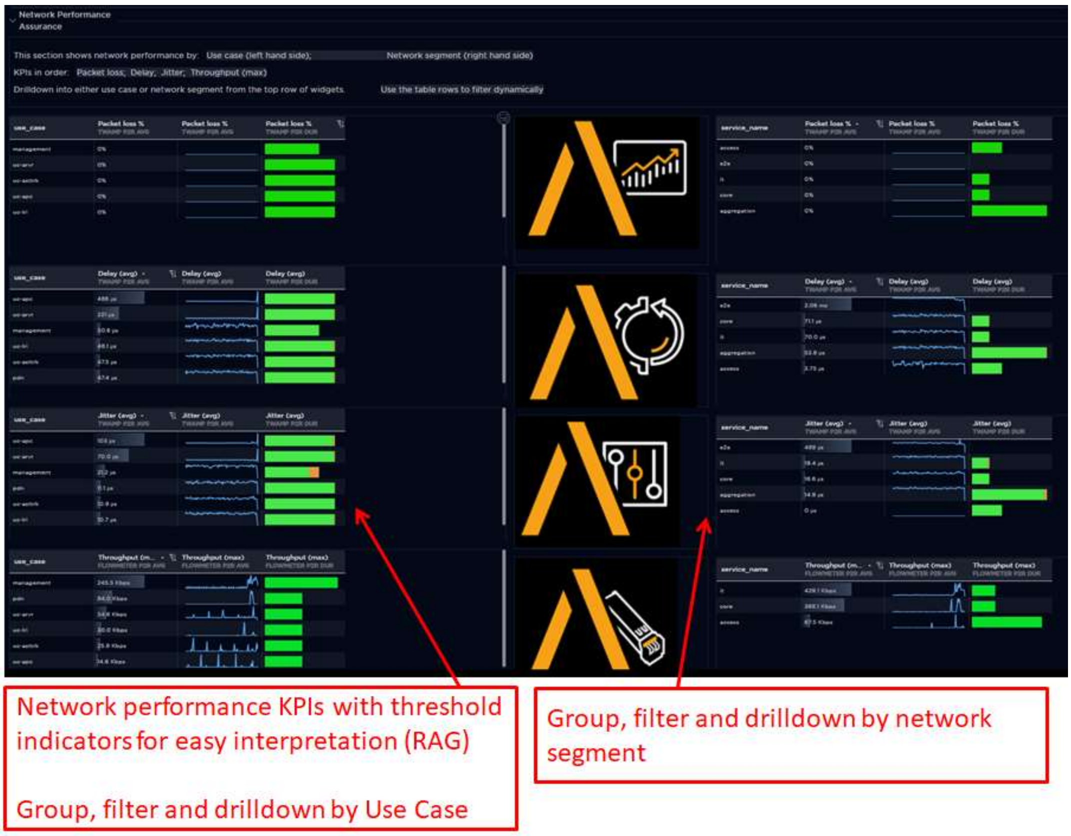


Figure 172: Network Performance Assurance

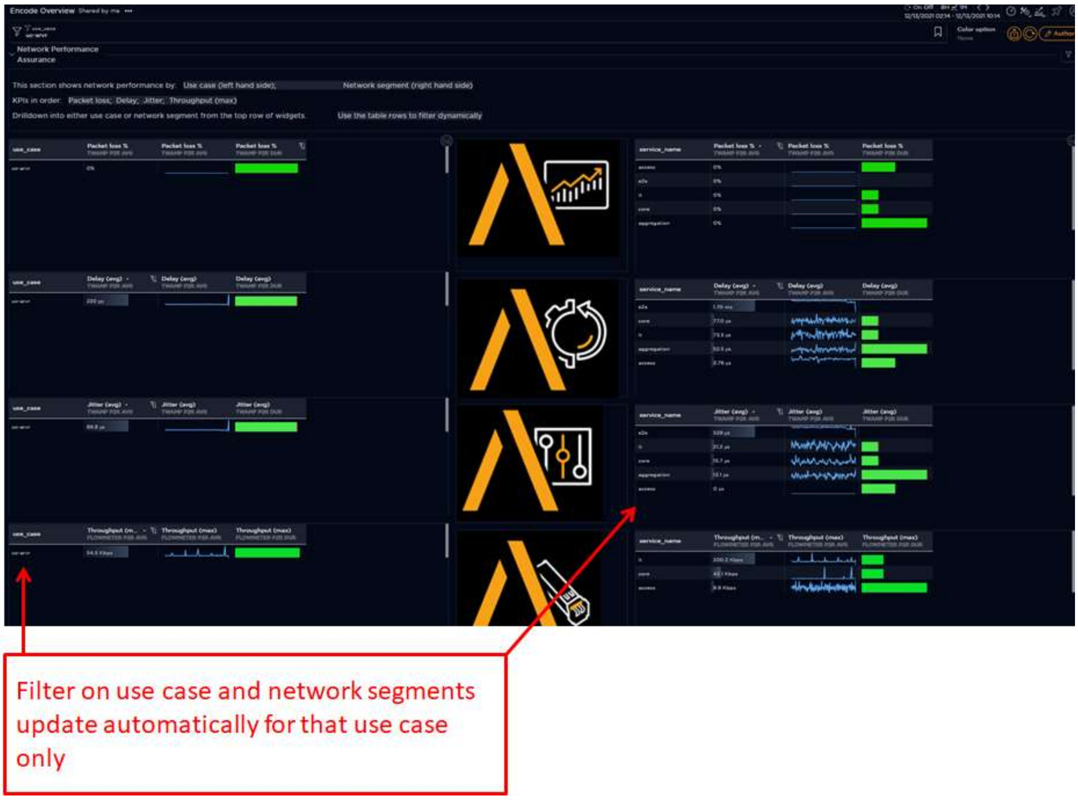


Figure 173: Filtering network segments

Aggregation Segment dashboard

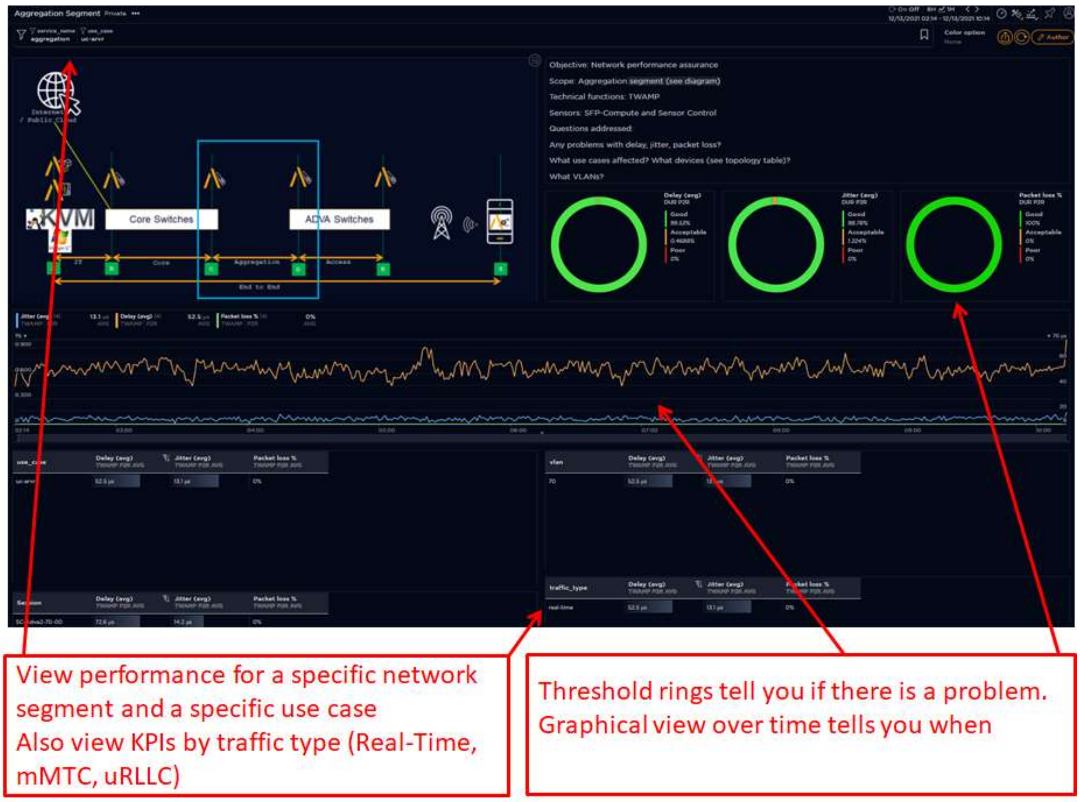


Figure 174: Network Segment Performance

Asset Tracking Use Case dashboard – Network Performance Assurance section

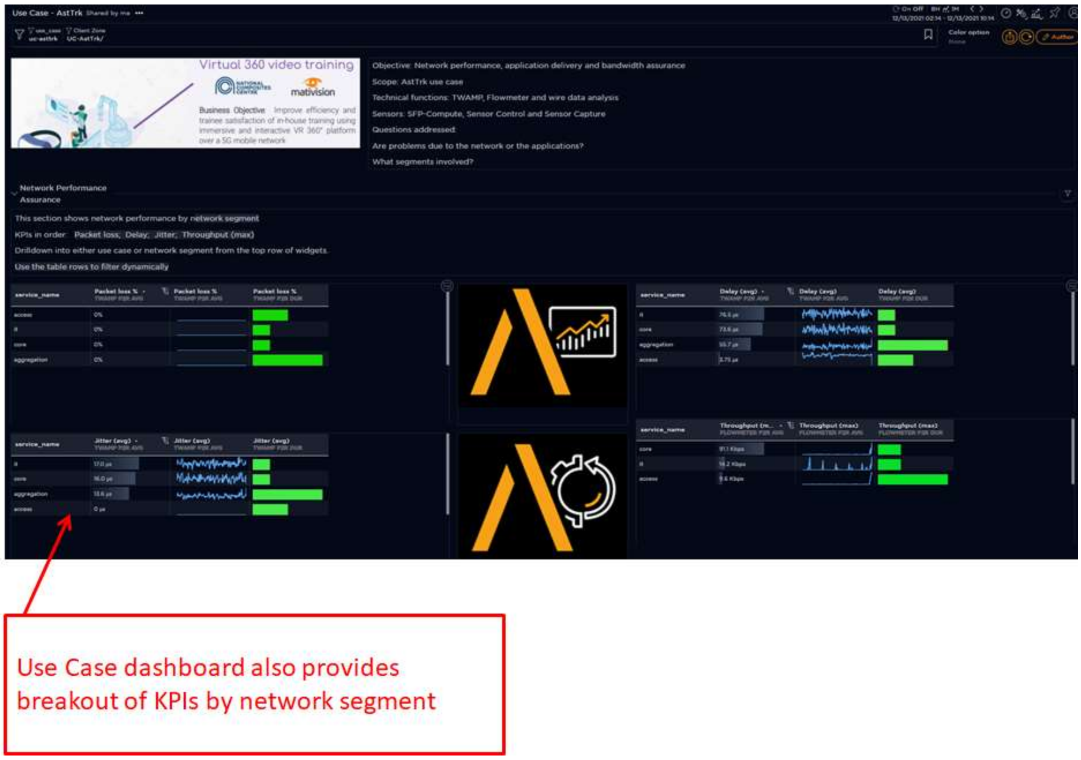


Figure 175: Asset Tracking Use Case Dashboard

Asset Tracking Use Case dashboard – Application Delivery Assurance section

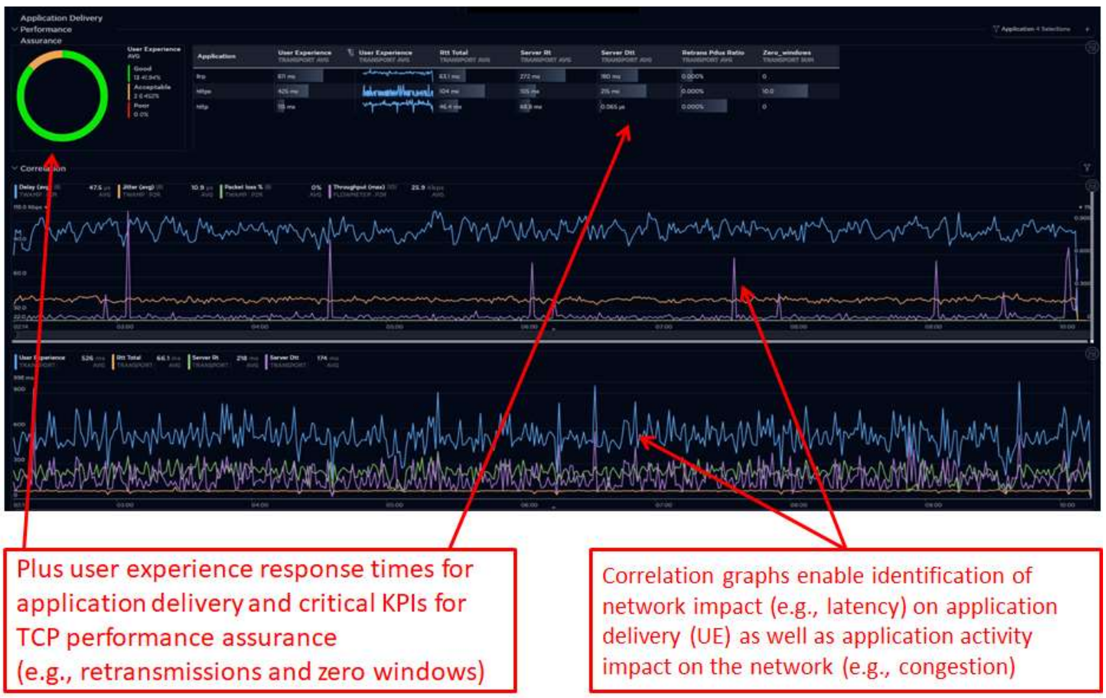


Figure 176: Asset Tracking Use Case Application Assurance charting

Conversations dashboard – filtered for Asset Tracking Use Case

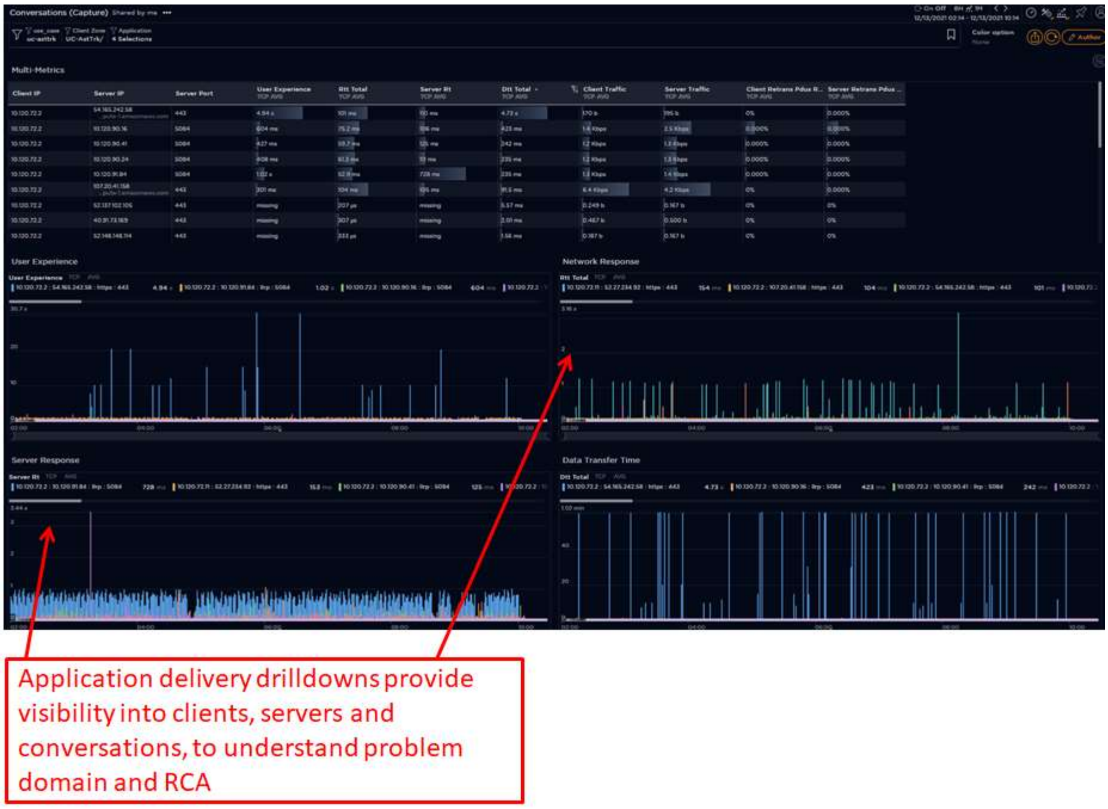


Figure 177: Asset Tracking Use Case filtered data

Bandwidth Usage dashboard

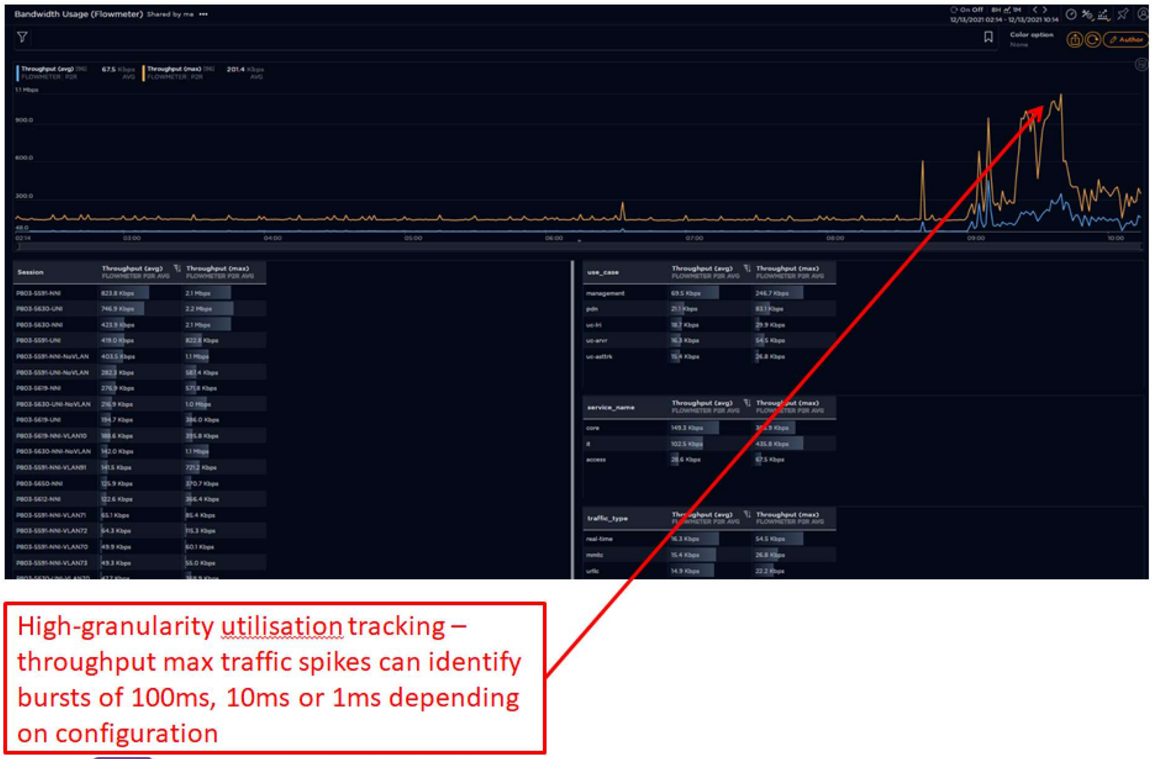


Figure 178: Asset Tracking Bandwidth Usage visualization

Analysis mode on selected data set

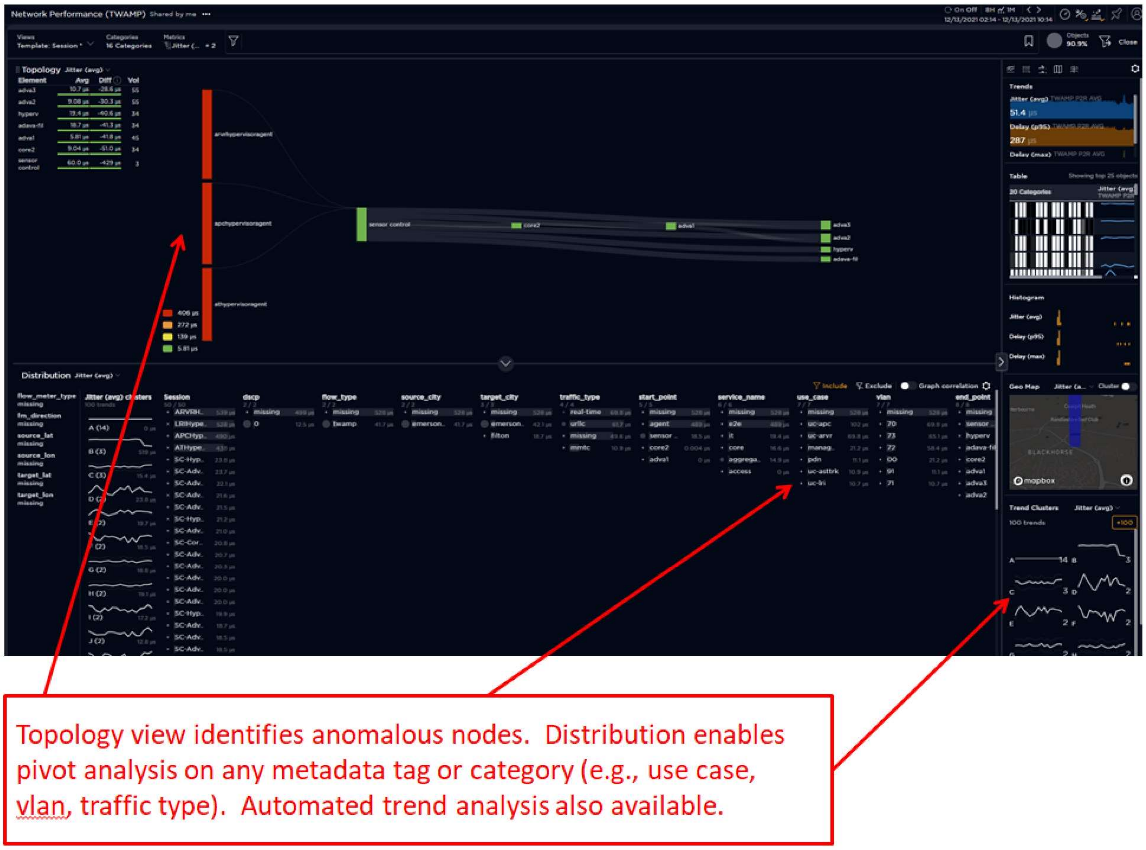


Figure 179: Dataset analysis for issue determination

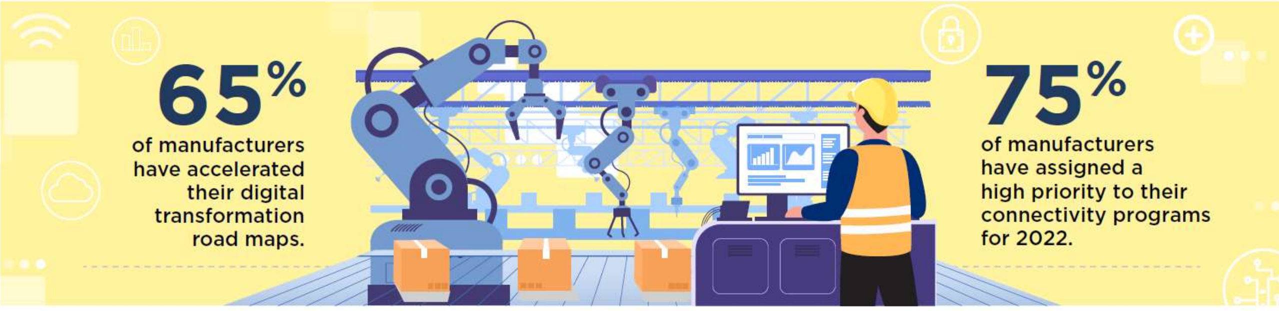
Conversation's dashboard filtered for LRI MEC server and exported as PDF

Figure 180: PDF export of conversations data

The Network in Manufacturing: 2022 and Beyond

Critical to Innovation, Efficiency, and Productivity

- **Over 40% of manufacturers reported problems with performance, security, and connectivity with mission-critical workloads.**
- **43% of manufacturers cited difficulty in finding staff, training, and skills as their biggest business challenges related to managing the network.**



n=167 Source: IDC's *Future Enterprise Resiliency & Spending Survey*, Wave 7, August
n=159 Source: IDC's *Future Enterprise Resiliency & Spending Survey*, Wave 4, May

Manufacturing organizations face the challenge of advancing along multiple digital business fronts while operating with already tight budgets driven by a difficult 2020–2021 economic environment. In a series of recent IDC surveys, manufacturers consistently ranked the following as top business priorities: digital innovation, operational efficiency, and employee productivity. It is no coincidence that further IDC research in 2021 indicates that **65% of manufacturers have accelerated their digital transformation road maps** by more than 25% as they move toward 2022 — with almost half of those companies accelerating their DX road maps by more than 50%!

Manufacturers recognize the importance of the network infrastructure to digital success. A 2021 global IDC survey indicated that **75% of manufacturers have assigned a high priority to their connectivity programs for 2022.** A network that provides for consistent, high-quality, and resilient services — and protects connected resources, users, devices, and information — is an absolute necessity in today's hyperconnected manufacturing environment, where data in motion is central to success.

Critical Focal Points for Network Management in Manufacturing

Comprehensive end-to-end network intelligence and insights enable the continuous monitoring and proactive management necessary to meet the evolving demands associated with top digital business priorities. From private network and public cloud services to end-user experiences and smart device exchanges, complete visibility and control assures consistent network service levels, a strong security posture, cost-effective resource use, and ready digital rollouts.

Digital innovation

IDC research indicates that **48% of manufacturers are increasing investment in Internet of Things (IoT) solutions over previously planned levels.** This raises network connections, traffic volumes, and potential vulnerabilities dramatically. At the same time, the global supply chain problems seen across all industries have manufacturers reforming their partner ecosystems. Here, heightened connectivity and interactions with both supply and distribution partners raise external networking and security requirements. Network visibility and control are vital to innovation, whether focused on internal or external systems, services, and processes.

Operational efficiency

Pervasive secure connectivity and high-impact exchanges among critical manufacturing systems, workers, facilities, and partners guarantee all work in concert, providing for maximum return and resiliency. Network access, threat protection, high performance, and resource (e.g., budget, systems, and services) optimization are prime determinants of success. Here, visibility and control are paramount to network integrity and cost-effective connectivity and operations — no matter the location or demand or endpoint.

Workforce productivity

IT staff hortages, limited cross-IT teamwork, and IT/OT convergence are driving major technical workforce reformation for manufacturing organizations. Digital pressures keep rising, while IT/networking budgets and staffing levels are constrained. Detailed network intelligence and insights boost networking staff roductivity and impact in such key areas as problem resolution and network optimization. In addition, improved network visibility and control bolster the effectiveness of other IT teams (e.g., SecOps, DevOps) and promote teamwork across IT through shared network data, views, and toolsets.

While driving forward movement along top business priorities, it is also important to note that heightened network visibility and control help manufacturing organizations overcome significant barriers. In response to a 2021 IDC global survey, **50% of manufacturers cited lack of automation and analytics to optimize their environment as a top barrier to building a resilient digital infrastructure.** In this same survey, other top barriers included cost-effective cloud services management (47%) and performance and security issues with many critical workloads (41%).

The Impact of Network Analytics in Manufacturing

Improved network visibility and control drive significant tactical and strategic benefits to manufacturing organizations. Network analytics solutions stand front and centre in delivering end-to-end visibility and control across the network infrastructure. When done right, network analytics deliver the following key benefits:

Reduction of downtime, slowdowns, and security threats: Over 40% of manufacturers reported problems with performance, security, and connectivity with mission-critical workloads. Detailed network data and associated analysis of that data provide early warnings based on traffic behaviour for developing problems and threats and direct precise corrective actions. Gains in infrastructure integrity, application performance, data availability, and connected automation heighten operational efficiency, workforce productivity, and product output and quality — critical to customer satisfaction and business profitability.

Acceleration of digital transformation and innovation: As manufacturers undergo digital transformation, it is critical for the network — and network monitoring and management systems — to readily adapt to dramatic increases in smart devices and machinery, data collection and distribution, new and dynamic workflows, remote work activity, and supply and distribution partner interactions. Complete visibility and control over network components, connected resources, data in motion, and even developing threats drive more predictable results and positive returns from new network technologies, connections, and exchanges.

Improved IT/OT staff roductivity and teamwork: Manufacturers are having difficulty finding the staff/training/skills to meet the needs of evolving network requirements, with 43% saying it was their organization's biggest business challenge related to managing the network. Getting the most from not only the network staff ut also the broader IT staff nd, increasingly, the OT staff s a critical success factor for manufacturers. Offering a single source of network intelligence and in-depth insights across NetOps, SecOps, DevOps, and OT groups boosts technology worker productivity and impact, which in turn boosts digital infrastructure resiliency and readiness.

Enabling reliable real-time communications and collaboration: Remote work, partner interactions, customer exchanges, IoT solutions, and data in motion are all accelerating out of the pandemic. End users and smart end devices all require consistent network service to meet the rising expectations of the time-sensitive, highly interactive, and ever-more-virtual digital manufacturing environment. Detailed end-to-end and core-to-client network visibility and control enable the delivery of the best possible digital experience for all — users and machines.

Accedian_IDC
InfoSnapshot_CA483

ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK's biggest investments in using 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It is designed to validate the idea that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that the UK industry exploits the 5G technology and remains a global leader in the development of robust digital engineering capabilities when implementing complex composites manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (uRLLC/eMBB/mMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-ENCODE project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and SMEs.

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), application performance as measured by probes (Accedian), world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

EXECUTIVE SUMMARY

5G connectivity services are being explored not only by the incumbent global mobile network operators but also by enterprises looking to have more secure and flexible mobile connectivity solutions for their various connectivity requirements. In an already complex enterprise IT environment, 5G will yet add another level of complexity for those having to manage their networks.

Abstracting away the underlying complexity of provisioning and managing a multi-site and multi-technology enterprise network environment provides great value for enterprises. As Network engineering teams managing these enterprise networks might not have access to the expertise typically required to fully manage this ever-growing complexity, solutions to simplify daily operations are of critical importance.

Zeetta NetOS and Zeetta MDO provide this level of abstraction for the case of single site and multi-site enterprise networks respectively. These tools provide network administrators with a single dashboard for management of various network services - including 5G PCN services - allowing end to end services to be deployed seamlessly across various network infrastructure devices and application servers.

At 5G-ENCODE, Zeetta deployed a cloud based Multi-Domain Orchestrator and demonstrated the benefits of using this application by creating a multi-domain end-to-end connectivity slice that was automatically provisioned across different network domains, reducing the time required to enable service connectivity and avoiding manual intervention in the various network devices.

ABBREVIATIONS

3GPP	Third Generation Partnership Project
API	Application Programming Interface
AWS	Amazon Web Services
eMBB	Enhanced Mobile Broadband
gNB	Next Generation NodeB (5G Radio Node)
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
LLDP	Link-Layer Discovery Protocol
MDO	Multi-Domain Orchestrator
mMTC	Massive Machine Type Communications
MPN	Mobile Private Network
NCC	National Composites Centre
OMS	Operations and Maintenance Solution
OPEX	Operational Expenditures
OSPF	Open Shortest Path First
OSS	Operation Support Systems
PCN	Private Cellular Network
PDN	Packet Data Network
PTP	Precision Timing Protocol
QCI	Quality of Service Class Identifier
QoS	Quality of Service
RAN	Radio Access Network
SA	Stand Alone
UE	User Equipment

uRLLC	Ultra-Reliable Low Latency Communications
VLAN	Virtual Local Area Network
VPN	Virtual Private Network

103 INTRODUCTION

103.1 Zeetta's solution to network complexity

The configuration of networks is complex, with the introduction of 5G this is getting even more complex, therefore ways to reduce the time, cost and errors is required. DevOps engineers will require simplified ways to manage these networks for 5G to be a feasible solution.

Zeetta's products simplify the deployment, monitoring and management of Private Cellular Networks as they enable a single-pane-of-glass control and management of network devices operating in licenced and unlicensed spectrum.

This project has required Zeetta to create a new product to orchestrate services across different network domains and assure end-to-end availability and compliance.

This report will show how Zeetta's products have simplified the configuration of Private Cellular Network services to ensure 5G can be adopted at the earliest opportunity.

103.2 Project Objectives

The main project objectives are:

4. **Support for 4G and 5G 3GPP networks**
    a. Zeetta Automate software: Topology aggregation and service orchestration across IEEE and 3GPP network technologies.
5. **Multi-Domain Orchestrator (MDO)**
    a. Zeetta Multi-Domain Orchestrator (MDO): Pre-production prototype of cloud-native service orchestrator provisioning end to end connectivity (aka. Network Slicing) across multiple administrative domains (via multiple Zeetta Automate instances).
    b. Zeetta Multi-Domain Orchestrator (MDO): Create a model that supports traffic management across aggregated IEEE and 3GPP network topologies.

103.3 Overview of Use Case

The main purpose for the **single domain service management** is to:

- Provide a single pane of glass management interface to control the various multi-vendor network devices/nodes that are part of the 4G/5G service on a single administrative network domain. This enables service orchestration via a single GUI for the provisioning of the end-to-end service, including specifying the Quality-of-Service parameters, as opposed to manually provisioning each device.
- Being able to visualise the topology of all the devices in the network and to see in Zeetta Automate when a device or link is down.
- Zeetta Automate will automatically compute the path between end points when provisioning a 4G/5G Private Cellular Network service.
- Zeetta Automate will apply the necessary configurations to the various network devices along the path.

The main purpose for the **multi-domain service management** is to:

- Enable network slice orchestration via a single cloud-based GUI for the provisioning of the end-to-end service across multiple and independent administrative network domains, including the IP Layer 3 connectivity between the respective domains.
- The Multi-Domain Service Management provides the user the ability to validate the feasibility of the network slices across the respective network domains by analysing the existing configuration at each domain against the design.
- The ability to visualise the topology of all the devices across multiple domains and to see in Zeetta Multi-Domain Orchestrator (MDO) when a device or link is down.

104 SINGLE DOMAIN NETWORK SERVICE MANAGEMENT AND ORCHESTRATION

104.1 Single Domain Service Management

Zeetta's solution to single domain network service management is NetOS. Within a single network domain, NetOS provides a single point of management and orchestration of network services. It allows network administrators to provision various end-to-end services within the network. Examples of such services include provisioning of Layer 2 connectivity between end points, setting up Wi-Fi services as well as 5G PCN services to provide connectivity for 5G enabled end devices.

Within the 5G Encode Project, NetOS was deployed at the National Composites Centre Headquarters (NCC Main Site) and at a second location we refer to as NCCi (as will be described in section 3.1.1).

104.1.1 Single Domain Service Management

At the main NCC site, Zeetta Networks Engineering team, together with NCC Engineers, designed and implemented a complete Open RAN 5G SA Private Cellular Network operating with an Ofcom Shared Spectrum Licence within the n78 frequency band (3.6GHz). The processing elements of this network, were physically installed at the NCC datacentre, including all the required Layer 2 and Layer 3 network equipment and the PTP timing HW required to provide the required timing synchronisation for the 5G gNB. This Network was integrated with an already existing 3GPP 4G PCN. The radio units were installed in locations within the NCC workshops themselves and connected to the NCC datacentre.

The Figure below shows a diagram of the 5G SA deployed at the main NCC site.

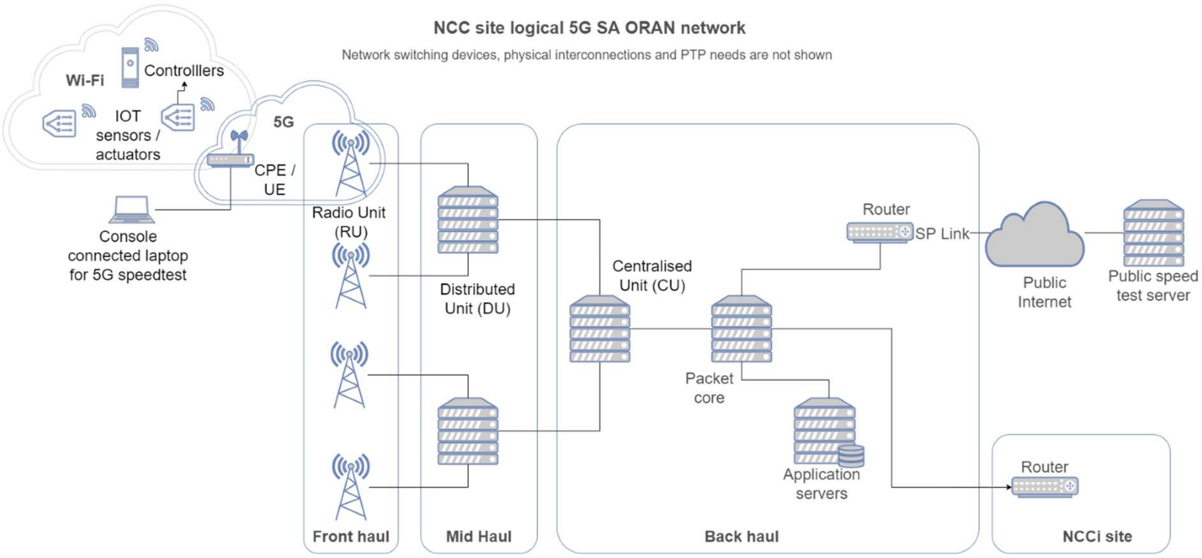


Figure 181 - NCC 5G Network Diagram

At the main NCC site, NetOS was configured to adopt all the network devices, which includes Juniper Router and Firewall, Edgecore Switches, ADVA switches and the 5G Core - supporting a multi-vendor network environment. A screenshot of NCC's NetOS dashboard is shown below.

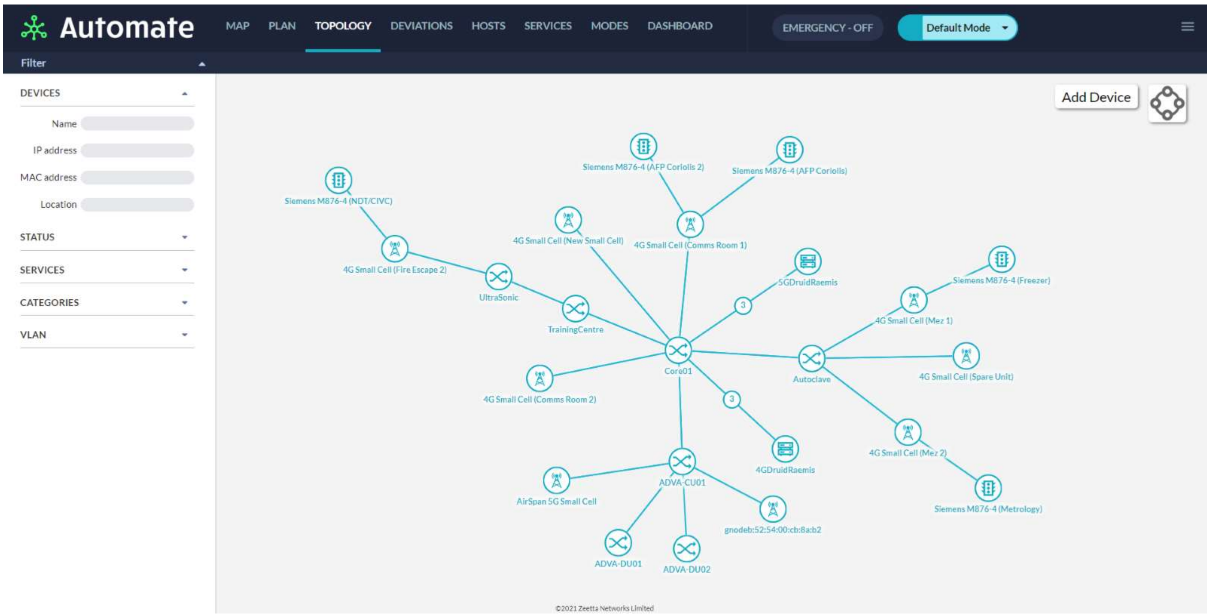


Figure 182 - NCC NetOS Topology View

The dashboard enables network administrators to visualise all the network from a single interface, to easily identify any disconnected devices, to automatically provision end-to-end services that may involve several devices depending on the device endpoints selected when defining the service.

The NetOS internal path calculation feature automatically selects the complete path between the respective end points and applies the required configuration to all the network devices and all the switch ports along the path (which can vary from just a single switch to various switches interconnected by Layer 2 trunk links).

NetOS uses APIs to interact with the various network elements to read and/or write configuration data. The network topology creation process is assisted with LLDP data that NetOS reads from the devices to establish all the existing physical connections. Logical connections are dealt with via the multi-domain service management functionality described later in this report.

The PLAN view available through the NetOS GUI is used to physically locate the various network devices, as shown below.

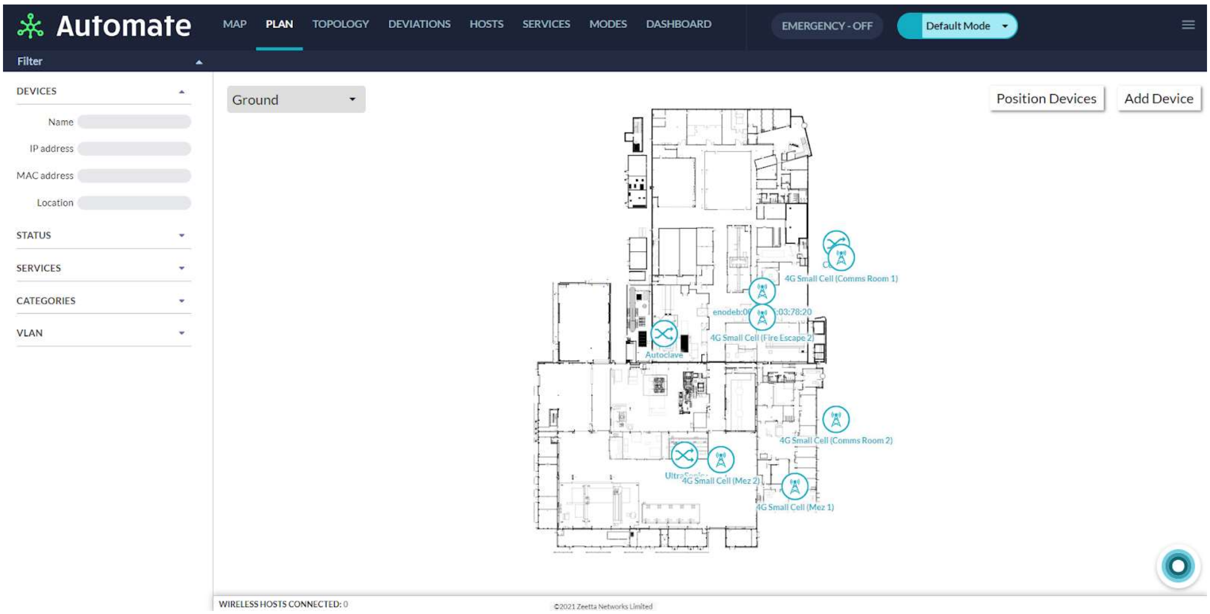


Figure 183 - NCC NetOS Plan View

104.1.2 Single Domain Service Provisioning – 5G PCN Service

Many types of service can be created through the Services tab. In this section we describe the creation of a 5G PCN service using NetOS.

This process starts with assigning a name and optional description to the Service.

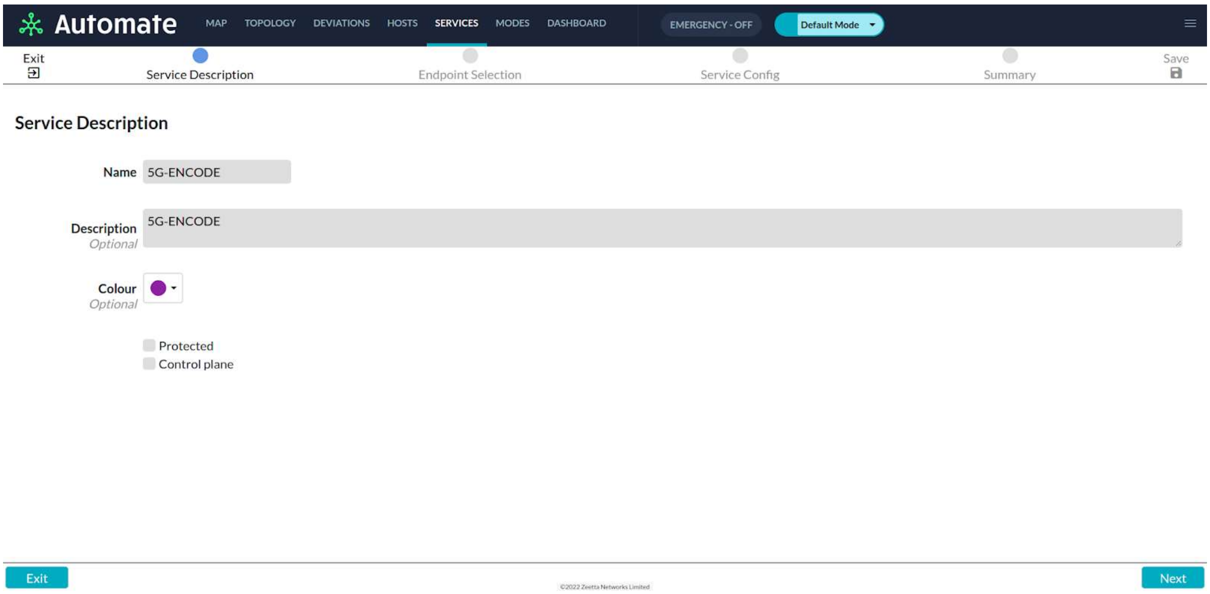


Figure 184 - NetOS defining the service description

The next step is the selection of the endpoints that should be part of the 5G service. This will include the respective 5G core interface and the UEs that should be part of this service, which is the 5G UEs that will be able to attach to the 5G service being created. NetOS automatically identifies the switch port where the required 5G core interface is connected to and will also add the specified VLAN to it.

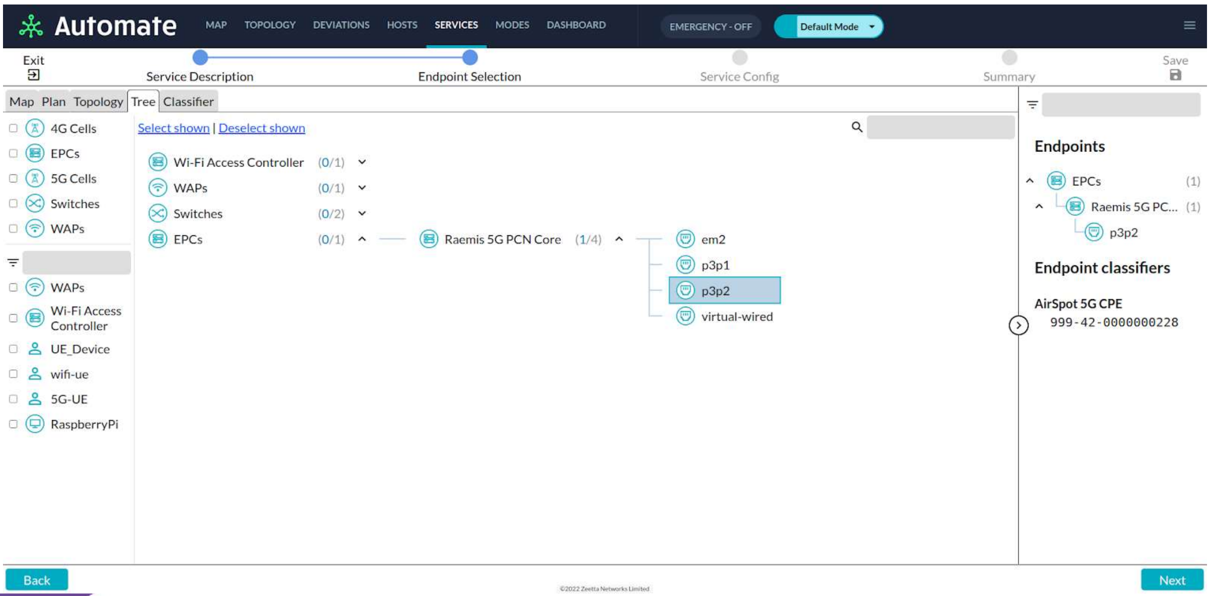


Figure 185 - NetOS defining the service end points

In the Service Config section, the user selects the VLAN this service will be using and specifies the packet data network (PDN) name for this 5G network. The quality-of-service (QoS) settings associated with the PDN being created are also specified in this section. These include QCI, the priority and AMBR 5G network parameters.

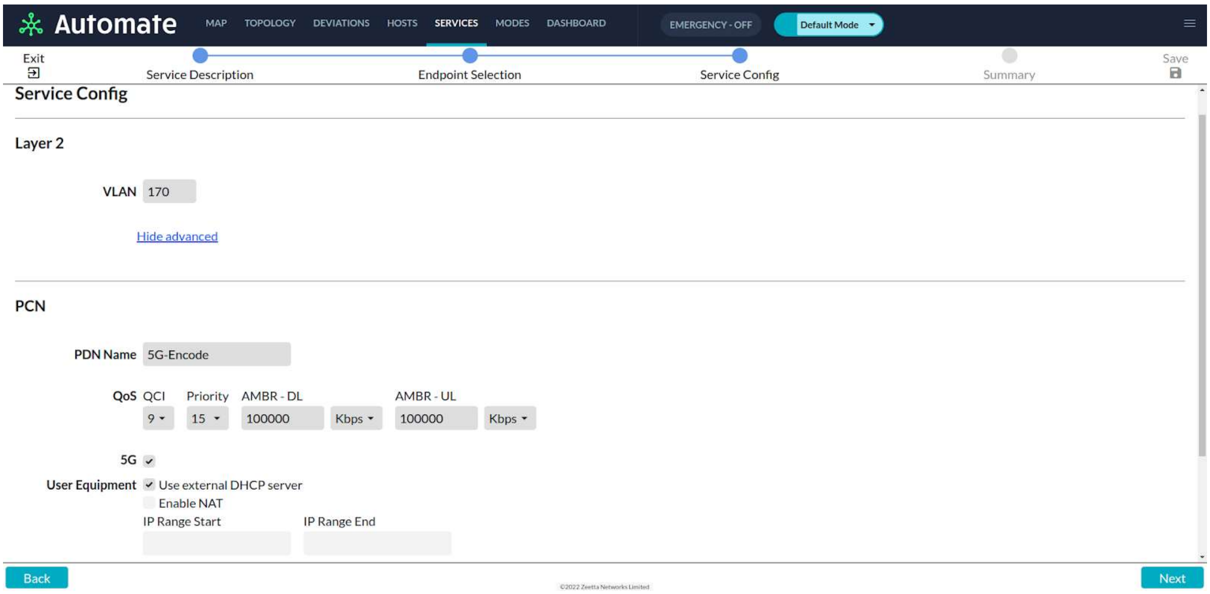


Figure 186 - NetOS defining the PCN parameters

From this point onwards the service creation process is complete, and the user will then be able to activate and deactivate the service as required. This step is only reached after NetOS validation of the data provided, thus avoiding any potential configuration conflicts before any data is sent to the various network devices to be changed when implementing the service.

When activating the service, all the PDN related parameters will be automatically provisioned on the 5G core application server, and the specified VLAN identifier will be configured on the switch port that is connected to the 5G core server.

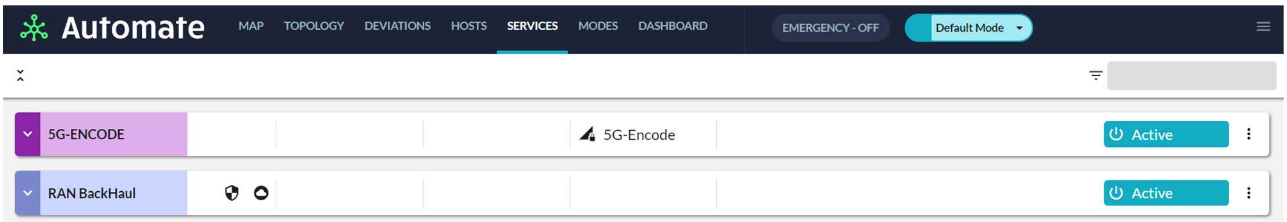


Figure 187 - NetOS overview of 5G related service

The figure above shows the activated 5G related services. The RAN Backhaul control service was created previously, to provide control plane connectivity between the 5G Core and the gNB. This control plane service applied the necessary Layer 2 VLAN configurations to the switch where the 5G Core and gNB were connected to.

After the PCN service has been activated, all UEs that were included as end points will then be able to attach to this 5G PDN and access any services available through it.

This 5G PCN service can be filtered in the topology to show the Layer 3 link from the UE device to the 5G Core with the connecting switch, as we can see in the figure below.

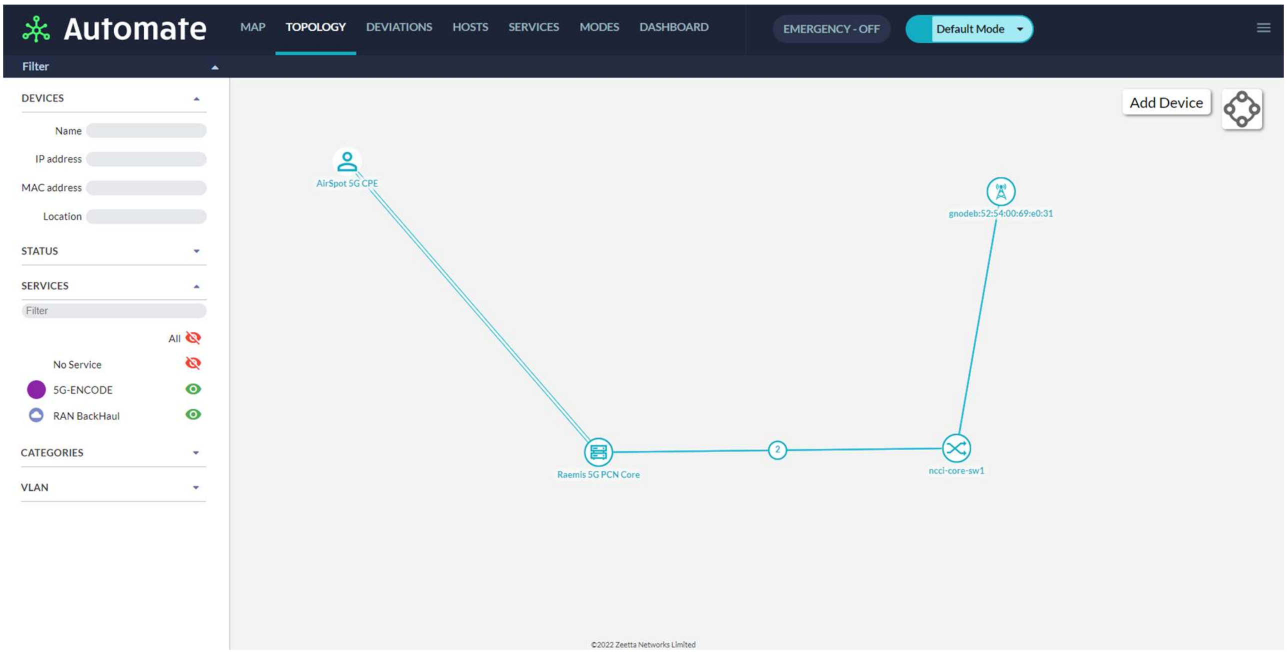


Figure 188 - 5G services filtered in the topology view

In this section we have demonstrated, from a single management interface the network administrator is able to provision the various network devices that are part of the services (e.g. in the case described above, these include the 5G Core server and the infrastructure switch) without having to separately and manually logging to each device.

105 MULTI DOMAIN NETWORK SERVICE MANAGEMENT AND ORCHESTRATION

105.1 Multi-Domain Service Management

MDO provides a single point of management and orchestration of network services across multiple network domains. It allows network administrators to provision various end to end layer 3 slices inter-connecting the different network domains (which are typically located at different physical locations).

Within the 5G Encode Project, MDO was deployed in an AWS cloud instance, with WireGuard VPN access provisioned to provide secure connectivity to the NCC and NCCi networks.

105.1.1 Deployment of Secondary Network Domain - NCCi

To support the multi-domain service management use case, Zeetta Networks designed and deployed an additional network - including a secondary 5G SA setup - that was installed in a different physical location also belonging to NCC, a site named NCCi. This network is connected to the main NCC site via an existing fibre link between the two buildings.

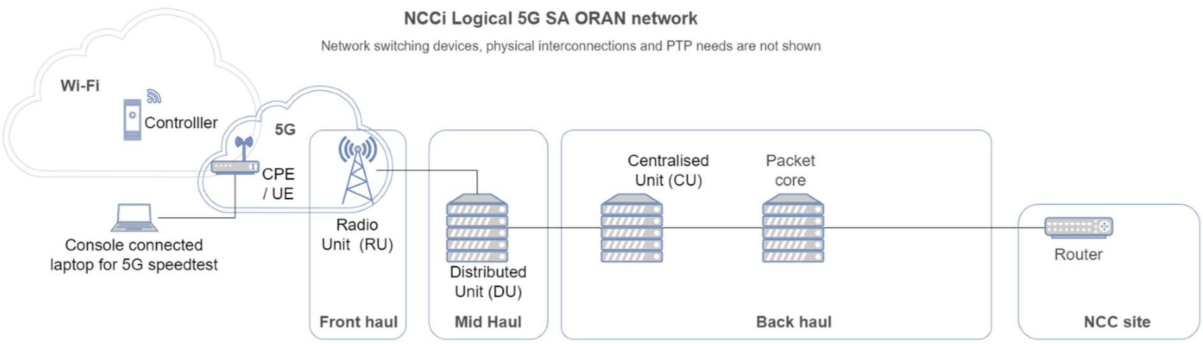


Figure 189 - NCCi Network Diagram

The above diagram illustrates the NCCi 5G SA network. The Open RAN 5G gNB was interconnected by a carrier grade PTP enabled aggregation switch and is connected to the 5G core server. An additional server was deployed to host the NetOS instance dedicated to this network. A Wi-Fi controller was also deployed in this network, along with a Wi-Fi Access Point, thereby providing a multi access technology environment.

Figure 190 - NCCi Rack

The NetOS instance at NCCi was configured to adopt all the network devices, as can be seen in the picture below. These include all the layer 2 and layer 3 devices, 5G Core and Wi-Fi devices.

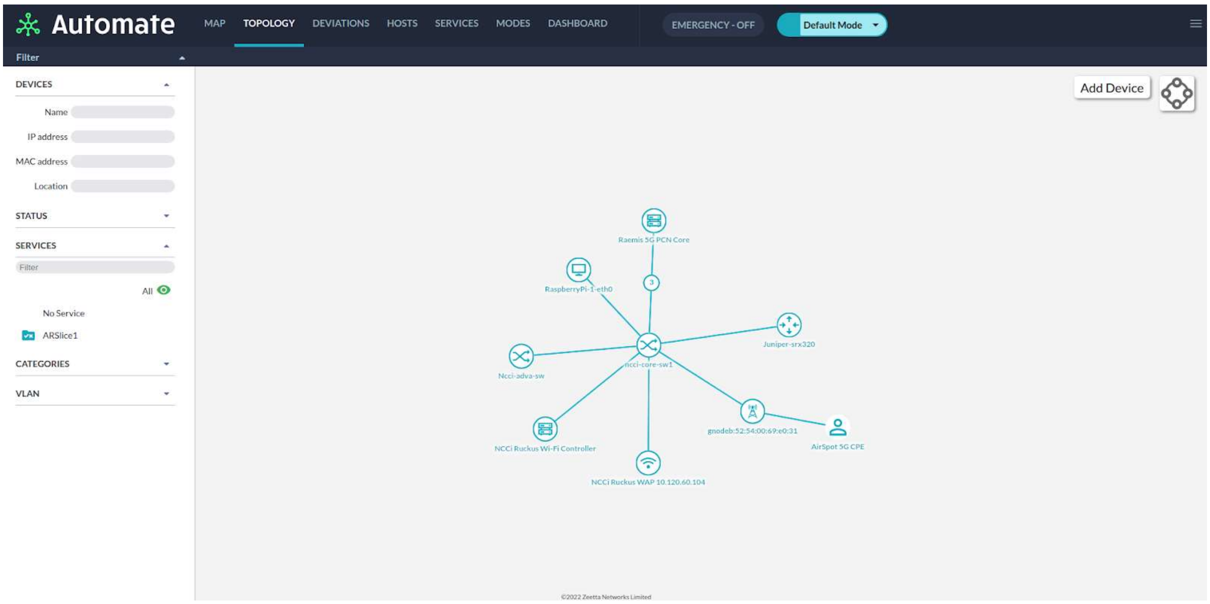


Figure 191 - NCCi Topology View

105.1.2 Multi Domain Slice Across Different Domains

For the multi domain service management use case, Zeetta MDO (Multi Domain Orchestrator) was deployed on the AWS cloud. Both the NCC NetOS and the NCCi NetOS instances are connected to MDO via a WireGuard VPN, for secure communication. This VPN interface allows MDO to collect network topology information from both network domains as well as to push configurations to be applied at each domain. These configurations are sent to each domain in the form of NetOS services.

The diagram below illustrates the MDO setup on AWS, showing that network administrators can interact directly with MDO to manage the multi-domain services. WireGuard needs installing in each location to connect.

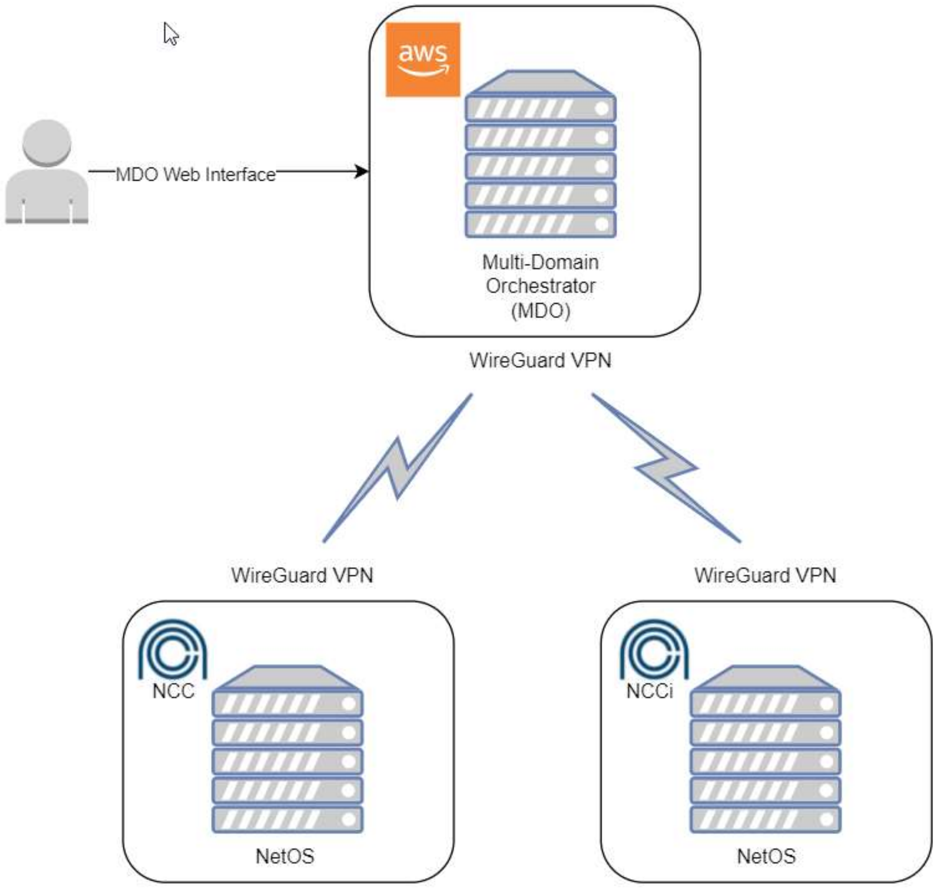


Figure 192 - Connectivity of MDO with NetOS instances

This diagram shows MDO hosted on AWS, interconnected to the two NetOS instances (NCC and NCCi) through a WireGuard VPN connection.

MDO solution allows the users to manage services across the various network domains, including the design and automatic provisioning of inter-domain Layer 3 slices, providing Layer 3 connectivity between end points from different domains.
Within the NCC-NCCi setup, an example of how this technology can be used is in the deployment of a 5G mediation slice between the two 5G core instances from each domain. This would allow 5G users that are configured in one of the 5G cores to use the other 5G core for network registration purposes, thereby allowing the 5G UE the possibility of roaming between the two 5G PCN networks.

MDO Layer 3 slices involve the use of various technologies and provide effective 'slice isolation' by deploying dedicated virtual routing instances at the point of entry for each network domain. This provides enhanced network security and effective Layer 3 routing isolation between multiple slices, as each slice will only have access to its own routing table, preventing

The Layer 3 slices are composed of a Layer 3 inter-domain link that is established between the gateway routers from each domain, along with any Layer 2 intra-domain links required to reach the respective endpoints. At each domain, NetOS's path calculation feature determines the exact path to reach the endpoint and configures all the devices along this path. Inter-domain routing configuration is also automatically provisioned by configuring OSPF routing protocol to run between virtual routing instances at each network domain.

All these configurations are automatically provisioned to the respective devices at both network domains.

The diagram below illustrates an end-to-end Layer 3 slice that was deployed between the NCC and NCCi sites, including the inter-domain Layer 3 link and the intra-domain Layer 2 switch connections. This slice was specifically provisioned to provide Layer 3 connectivity between the two end devices that are at each end of the diagram - at the left-hand site there is a host physically located at the NCC main site and on the right-hand side there is a 5G connected host physically located at NCCi.

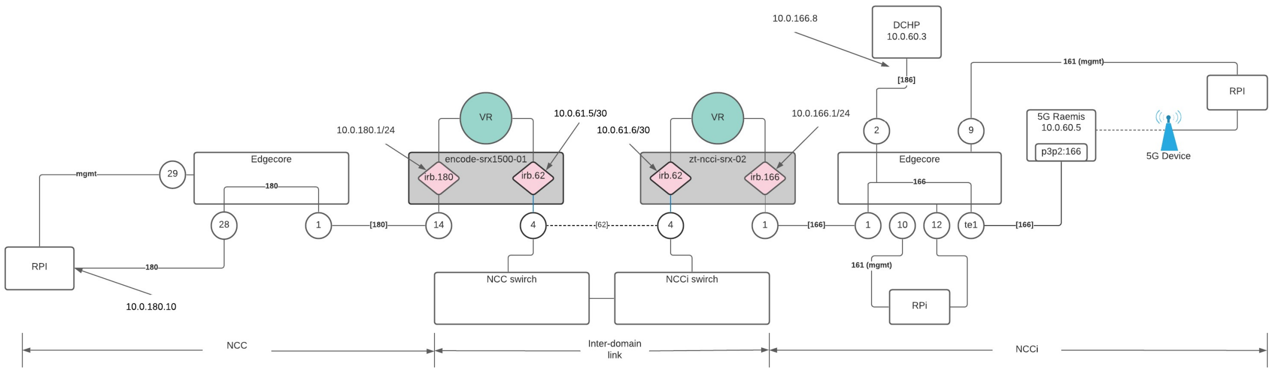


Figure 193 - Inter-domain Layer 3 slice

The process of Layer 3 inter-domain slice design and activation follows a similar structure to the single domain NetOS services described above in this report. The user first provides the VLAN identifiers and IP subnet network addresses to be used at each network domain, as well as the data required to implement the inter-domain link between the gateway routers.

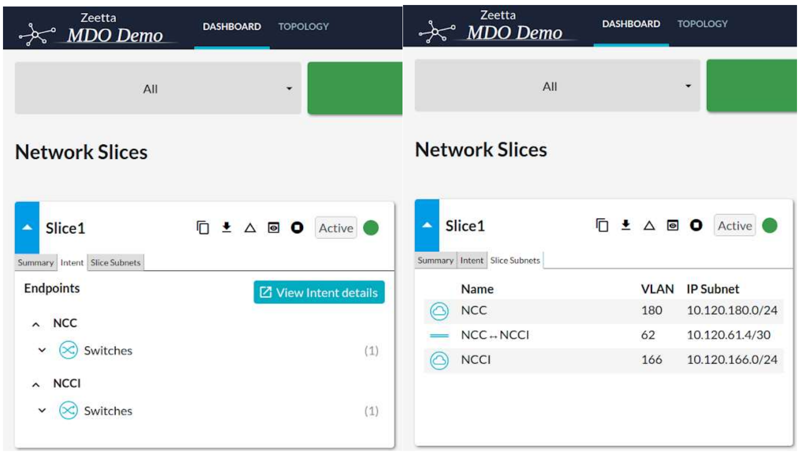


Figure 194 - MDO Slice provisioning

From the information provided, MDO builds the slice blueprint, detailing all the Layer 3 and Layer 2 network device configurations. The user can then review all the data before MDO applies the configuration to the network.

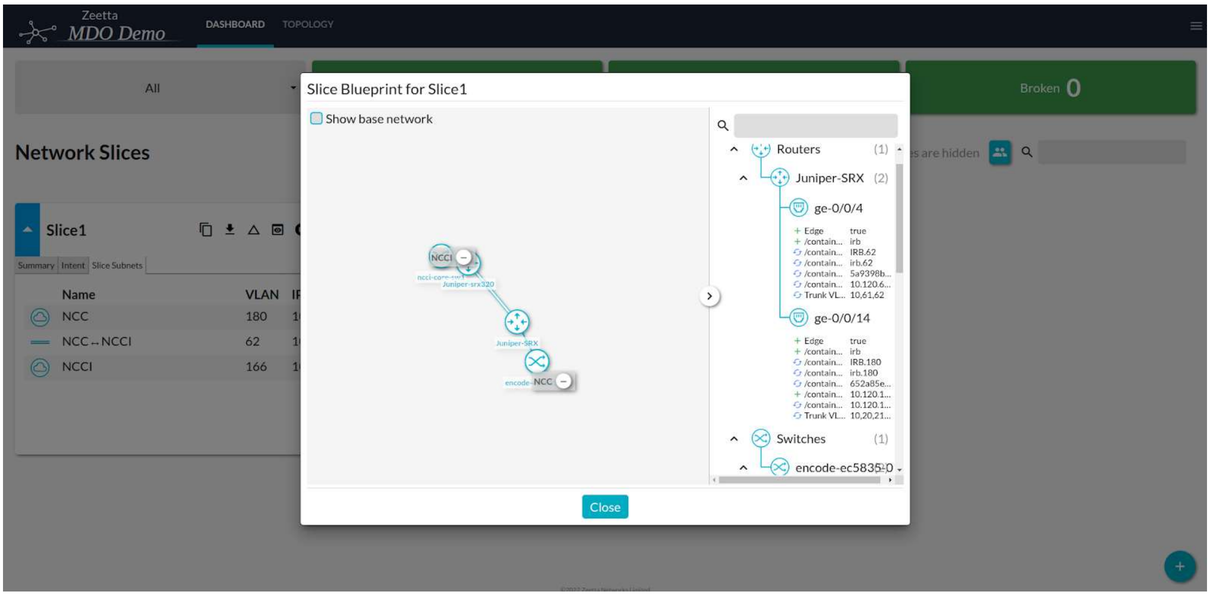


Figure 195 - Slice blueprint

After reviewing all the data, the user can then activate the slice, which will instruct MDO to create the required NetOS services. At each domain, NetOS will then automatically install the respective services and automatically activate them - the user can manage the multi domain service via a single interface. There is no need to login to each NetOS instance.

Following the slice activation, MDO topology view allows the user to have an overall view of the slice interconnecting the two domains

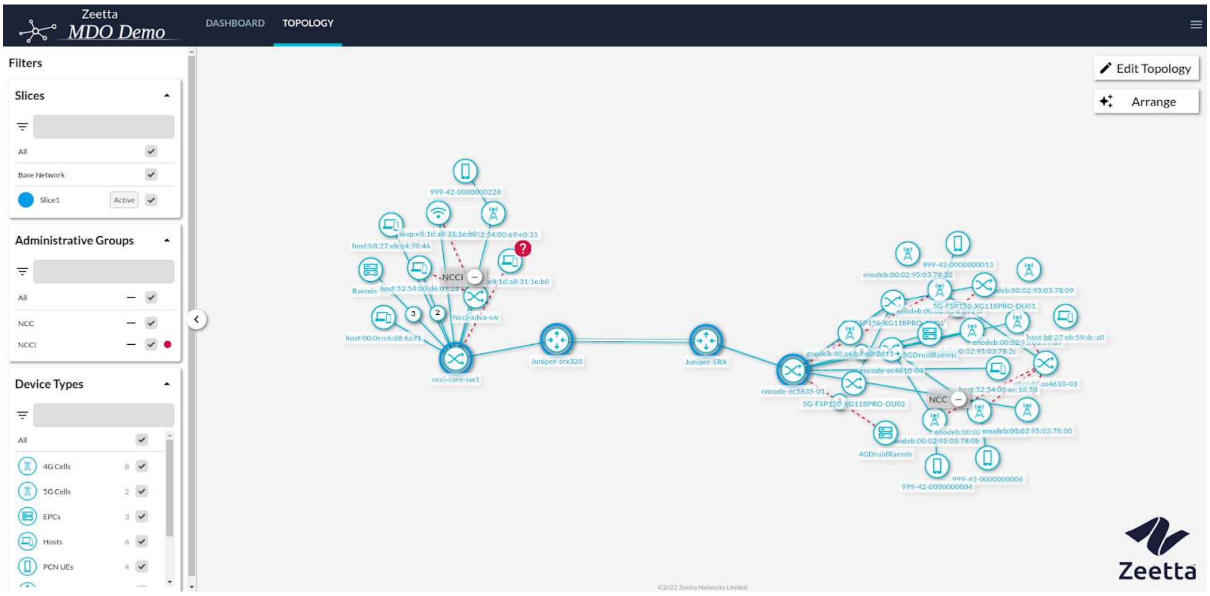


Figure 196 - MDO Inter domain Layer 3 slice topology view

From a single cloud-based GUI, MDO was able to deploy inter-site connectivity as well as provide detailed network topology visualisation, by leveraging data aggregation capabilities of each NetOS instance.

106 CONCLUSIONS

Enterprise IT networks are continually evolving. Significant evolutionary steps included moving from a fully cabled network to a cable and Wi-Fi network. The most recent evolution is the adoption of mobile private networks (MPN). Enterprise modernisation to include MPN is set to accelerate with the more flexible service features introduced in 5G.

With each evolutionary step Enterprise IT networks have become more complex to manage creating a need for easy-to-use solutions that simplify and reduce the user interaction needed to implement changes that affect multiple elements in a network such as configuring a service that includes a high number of network endpoints.

Benefits

Lowering operational cost - The need to schedule, manage and coordinate the activities of specialists for each device type has been removed. Device specialists may still be required in the Enterprise. These employees can be redeployed to focus on monitoring and supporting the network with a reduced need for specialist support to implement configuration requests. For example, using a traditional approach to plan, deploy and verify a Layer 3 slice service across various network domains would take several staff days. By using the innovative solutions developed for this project, much less effort to plan and execute change is needed with most of the activity being spent on planning. The need for the end user to be trained on a specific PCN solution is reduced. The user issues service updates from NetOS using the four-step wizard to set up the change to be made. NetOS provides an abstraction of the underlying 5G service parameters that simplifies the input needed from the end user.

Multi-Domain slice management simplifies network management – Traditionally, each enterprise location is treated as an IT domain and each domain administered locally. The IT operation for cross domain slicing (service management in each domain) is simplified and similar benefits to the previous paragraph are yielded.

Detecting change - For enterprise IT departments tasked with managing multi-domain and multi-technology networks, being able to visualise network topology deviations enables support agents to see changes as they occur and investigate if the change is planned or unplanned. Detecting issues in a complex network consisting of multiple device vendors in multiple network domains can be time consuming when the network cannot be visualised on a single topology view. In the 5G technology the topology can be configured to show changes on the 5G core, gNodeB and devices attached to the gNodeB.

Deployed hardware savings – Whilst the NetOS platform is typically deployed within the Enterprise domain to minimise security risks, the multi-domain slice manager (MDO) is deployed in the public cloud. Using a public cloud for applications with smaller compute needs is beneficial as the cost of ownership is usually cheaper than buying and owning equipment.

Challenges

Neutral Hosting – this feature in the product scope was not realised as the entitlement and billing system did not mature in time for the mobile network operator to fully engage on this topic during the 5G ENCODE program. This created an issue for MDO to demonstrate network 'splicing,' the ability to create a slice between mobile network operator and the enterprise. To address this challenge the MDO network design and slicing use case were modified such that the two domains were interconnected using a leased line.

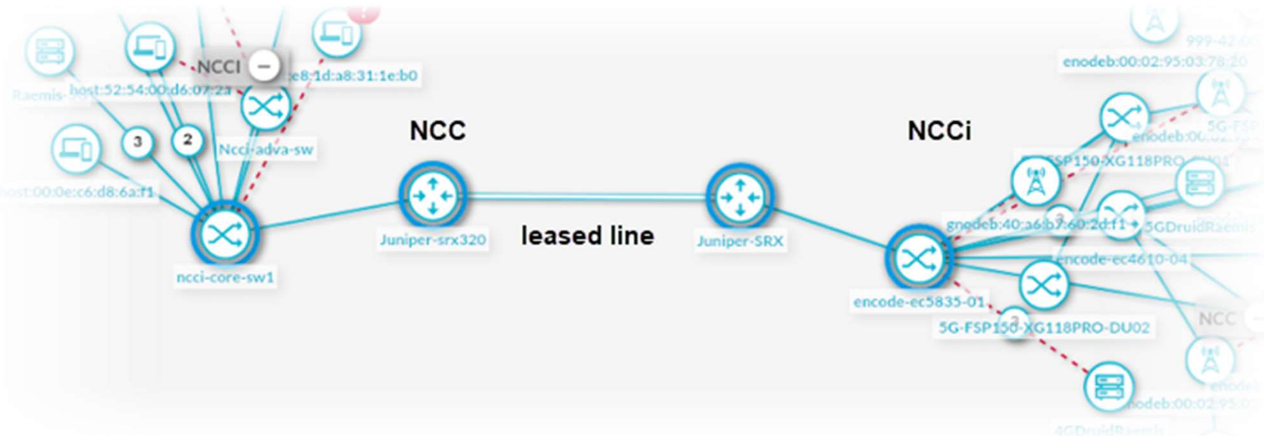


Figure 197: leased line replacing mobile network operator

ADVA FSP150-XG118PRO driver development – this device is classed as a carrier grade Ethernet Demarcation Device; this means it was more complex to adopt and manage than a simpler enterprise network switching device. This device was recommended for use in the network design as it supports the precision timing protocol (PTP) for synchronising the 5G RAN. The engineering and development effort required to understand and develop a solution for this device was greater than expected and needed careful management in the program schedule.

Connectivity issues and 5G maturity – the network deployed for the project was 5G SA ORAN based in SR15. Multiple suppliers involved in this project continued to rapidly develop their solutions during the deployment phase. These developments required updates to the NetOS solution to ensure connectivity to the network was preserved. This created additional unplanned work for the development team that needed careful management to ensure the program remained on schedule.

Conclusions

There is a need for solutions that simplify network visualisation and automate the management of ever changing and increasingly complex networks. Complexity arises when enterprises need to start managing services in multiples of:

- devices
- technologies
- domains

Simplifying and abstracting devices, technologies and domains from network designers reduces the effort required to implement changes.

The need for domain and technology knowledge is not completely removed as designers will still need some basic knowledge of the network design to enable them to translate configuration change requests into actionable changes.

In complex networks new challenges are introduced when determining if the services using that network are operating as expected. The network administrator needs a solution whereby any change and the impact of that change can be detected and identified quickly. For this, a 'single pane of glass' view on the network devices and domains in use is essential. Changes to identify are:

- device states that have changed
- connecting link states that have changed

This ‘single pane of glass’ view should not be confused with a similarly named feature documented in the network probing report where a dashboard is used to visualise probe results.
Creating an environment whereby change can be seen quickly is key to effective response planning in an operational network. Network status changes can be in the form of planned or unplanned. Planned status changes are known events in the network and can be acknowledged as expected changes. Unplanned status changes often indicate outages in the network and its services that will need further investigation. It should be noted that, a common topology view onto the complete network does not replace the vendor specific operations support systems needed to investigate and troubleshoot specific devices.

The MDO and NetOS solutions used and introduced in the 5G ENCODE project address the following network management issues:

1. device visualisation
2. service status change detection
3. configuration change simplification

To understand the benefit of these solutions, studies were conducted to understand:

- revenue unlocked
- cost saved
- cost avoided

Revenue unlocked – in this project future revenues were not measured. It is expected that with the cost savings introduced (next paragraph) the need for services and service updates in the network will grow as new solutions adopt 5G network slicing and cross domain services required to support slicing. This growth will create revenue in the applications consuming slices and services.

Cost saved – introducing the functionality to change multiple devices, using different technologies across various network domains introduces an estimated 66% saving in engineering compared to the effort needed to complete the same changes manually e.g. resources needed from three persons to one person to complete similar activities.

Cost avoided – The ability to visualise multiple domains with different technologies and numerous devices in a common topology view (‘single pane of glass’) reduces OPEX costs. Network administrators no longer need to use vendor specific OSS solutions when detecting network-wide issues during extended network outage events. The estimated costs avoided grow as network complexity increases (domains, devices, and technologies). In the figure below, the levels of investigation effort for each scenario were tuned using data captured from this project (Appendix A).

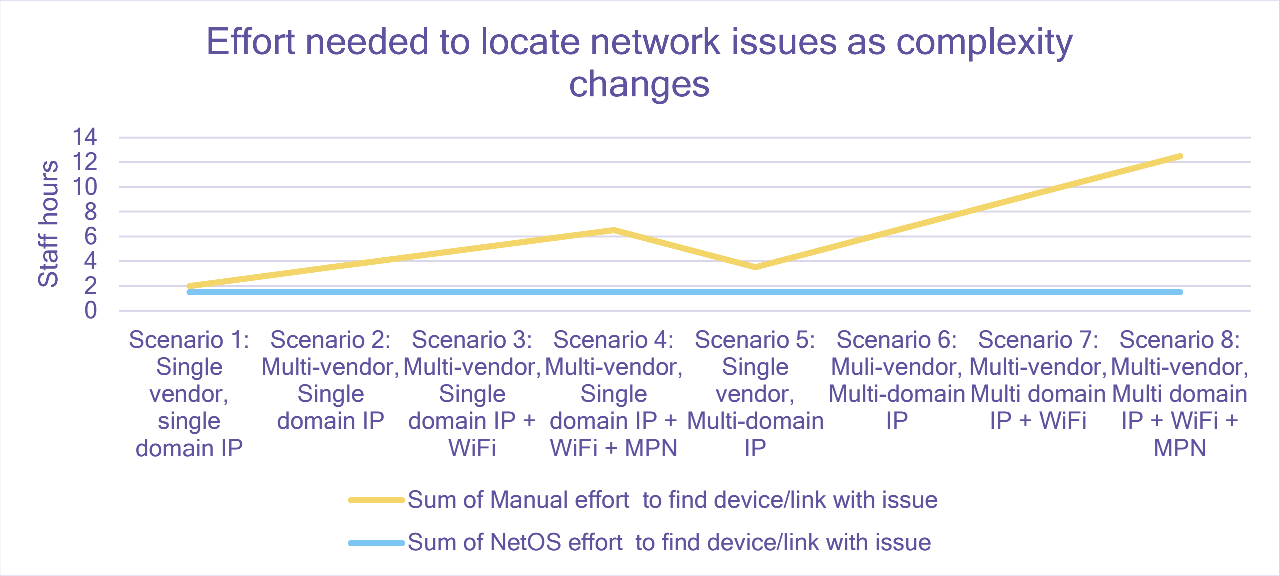


Figure 198: Effort to find network issues with and without NetOS or MDO

For each scenario identified in the figure above, there are assumptions for the number of technology vendors in the network. These assumptions are based on differing Enterprise network configurations. The assumptions are as follows:

- two IP vendors - switch vendor and router vendor
- one Wi-Fi vendor
- one MPN vendor

The effort in resolving problems increases with number of vendors and network complexity.

This project has demonstrated that there are clear benefits of having a consolidated network management tool to visualize and manage various connectivity services, including 5G, in an Enterprise.

107 APPENDIX A

					Without NetOS (Manual effort to investigate a network issue)						With NetOS			Cost Avoided (%)
Scenario	Technology	Device Vendors	Domains with equipment	Domains & Devices	Detect and start issue processsing	Per team start up time	Form working group and task investigating team	Per Vendor Search Time	Time spend searching without NetOS	Manual effort to find device/link with issue	Detect and start issue processsing	Open NetOS and locate issue	NetOS effort to find device/link with issue	% time saved
	IP	1	1	1		0.5	0.5	1	1					
Scenario 1: Single vendor, single domain IP	Sub-Total	1	1	1	0.5		0.5		1	2	0.5	1	1.5	25%
	IP	2	1	2		0.5	1	1	2					
Scenario 2: Multi-vendor, Single domain	Sub-Total	2	1	2	0.5		1		2	3.5	0.5	1	1.5	57%
	Wi-Fi	1	1	1		0.5	0.5	1	1					
	IP	2	1	2		0.5	1	1	2					
Scenario 3: Multi-vendor, Single domain IP + WiFi	Sub-Total	3	1	3	0.5		1.5		3	5	0.5	1	1.5	70%
	Cellular	1	1	1		0.5	0.5	1	1					
	Wi-Fi	1	1	1		0.5	0.5	1	1					
	IP	2	1	2		0.5	1	1	2					
Scenario 4: Multi-vendor, Single domain IP + WiFi + MPN	Sub-Total	4	1	4	0.5		2		4	6.5	0.5	1	1.5	77%
	IP	1	2	2		0.5	1	1	2					
Scenario 5: Single vendor, Multi-domain	Sub-Total	1	2	2	0.5		1		2	3.5	0.5	1	1.5	57%
	IP	2	2	4		0.5	2	1	4					
Scenario 6: Muli-vendor, Multi-domain IP	Sub-Total	2	2	4	0.5		2		4	6.5	0.5	1	1.5	77%
	Wi-Fi	1	2	2		0.5	1	1	2					
	IP	2	2	4		0.5	2	1	4					
Scenario 7: Multi-vendor, Multi domain IP + WiFi	Sub-Total	3	2	6	0.5		3		6	9.5	0.5	1	1.5	84%
	Cellular	1	2	2		0.5	1	1	2					
	Wi-Fi	1	2	2		0.5	1	1	2					
	IP	2	2	4		0.5	2	1	4					
Scenario 8: Multi-vendor, Multi domain IP + WiFi + MPN	Sub-Total	4	2	8	0.5		4		8	12.5	0.5	1	1.5	88%

Figure 199: Table showing effort needed to investigate issues increasing as network complexity increases

108 – HAPTIC ROBOT TELEOPERATION –

109 ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK's biggest investments in using 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It is designed to validate the idea that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that the UK industry exploits the 5G technology and remains a global leader in the development of robust digital engineering capabilities when implementing complex composites manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLL/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the Southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and SMEs.

The project consortium, led by Zeetta Networks, brings together leading industrial players (e.g., Siemens, Toshiba, Solvay), a Tier 1 operator (Telefonica), disruptive technology SMEs covering all aspects of network design, deployment, and applications (Zeetta Networks, MatiVision, Plataine), a world-leading 5G network research group (High Performance Networks Group in the University of Bristol) and the NCC representing the high value manufacturing industry.

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111 EXECUTIVE SUMMARY

In this work, haptic robot control protocols were integrated into a teleoperation solution where an industrial robot located at the Bristol Robotics Laboratory is operated from the National Composites Centre. The need for robot teleoperation within the industry remains for use-cases of which the environment is too hazardous for direct human operation and too complex for automation.

For further steps to be made in robot teleoperation there need to be intuitive systems designed that allows an operator to control the robot with confidence. A system is proposed that uses hand tracking, haptic feedback, and an immersive experience to actuate a robotic arm from a distance for which optical fibre and network cables are used to facilitate the network needs.

The robotic actuation using the combination of a haptic hand tracking device and a haptic protocol that allows the operator to move the robot by moving his/her hand. The immersive experience using a stereo camera to capture the robot's environment and a Virtual Reality (VR)-headset to make this content visible for the operator. The teleoperation is cabled to function as a benchmark in this feasibility study.

The network consists of a combination of optical fibre, CAT 6 Ethernet and universal serial bus cables. The main connections within the network are limited to a 1 Gbps maximum throughput. During testing of the solution it was measured that the maximum data throughput was 27 Mbps. The current 5G networking capability allows for an uplink of 57 Mbps and a downlink of 410 Mbps.

112 ABBREVIATIONS

2D	Two-Dimensional
3D	Three-Dimensional
3G	Third Generation Mobile Network
4G LTE	Fourth Generation Long-Term Evolution Mobile Network
5G	Fifth Generation Mobile Network
AP	Access Point
APC	Automated Pre-Forming Cell
AR	Augmented Reality
CPE	Customer Premises Equipment
DCMS	Department for Digital, Culture, Media, and Sport
DL	Downlink
eMBB	Enhanced Mobile Broadband
IoT	Internet of Things
IP	Internet Protocol
Kbps	Kilobits Per Second
KPIs	Key Performance Indicators
LRI	Liquid Resin Infusion
Mbps	Megabits Per Second
MMTC	Massive Machine-Type Communications
NCC	National Composites Centre
NCC HQ	National Composites Centre Headquarters
NCCi	National Composites Centre – Filton Site
NR	New Radio
NTP	Network Timing Protocol
P2P	Peer-to-Peer

PTP	Precision Timing Protocol
RAN	Radio Access Network
SA	Standalone
SMEs	Small and Medium-Sized Enterprises
TCP	Tool Centre Point
UEs	User Equipment
UL	Uplink
UoB	University of Bristol
UPF	User Plane Function
URLL	Ultra-Reliable Low Latency
VMs	Virtual Machines
VR	Virtual Reality
WECA	West of England Combined Authority

113 INTRODUCTION

Robot teleoperation is used in numerous industries, this is currently often conducted through control pendants that require extensive training before it can be safely operated. In this project an alternative solution for the teleoperation of an industrial robotic arms has been trialled.

The need for robot teleoperation within the industry ranges far and wide. The use-cases for this research project are focussed on the use of an industrial 6-DoF (Degree of Freedom) robotic arm. These industrial robotic arms come with extensive safety protocols. An example of teleoperation of robotic arm use is when the environment proves to be too hazardous for a human being and too challenging and/or too perilous for an automated system. Industries where this may occur include nuclear decommissioning and industrial welding.

The current needs of robot teleoperation are met using a number of different solutions. Typical solutions use a 3D mouse attached to a control pendant which is directly controlled, often through cable, to its respective robotic system. Such a pendant allows the operator to either steer the Tool Centre Point (TCP) in Cartesian coordinates (in world or local axis) or the individual joints of the robot. This form of operation is conventionally done with the operator in the vicinity of the robotic system keep a good overview of the movement. The conventional pendant solution, therefore, is not usable when operation is required in a hazardous environment that requires active control.

Two challenges can immediately be identified that need to be surpassed to take the next step in industrial robot teleoperation. The first challenge is to develop an intuitive method for active actuation of the robot arm during operation such that the operator can perform all required operations with confidence. The second challenge relates to the situational awareness of the operator during robot teleoperation. The operator needs to be aware of what is always happening and the options they have available to update each operation. The first challenge was solved in a previous project [1] where research has been done on how intuitive different methods of haptic teleoperation are, including hard and soft measures. This project builds upon the haptic research conducted before and adds direct active robot control over an extended distance, whereas this time, the second challenge is tackled through an immersive solution and a direct cabled teleoperation network.

Multiple collaborators are needed to complete this research project. The teleoperation will be conducted between two geographically separate facilities. The robot side is in Bristol Robotics Laboratory (BRL) which has conducted extensive research on teleoperation and has a state-of-art leader-follower teleoperation system. The application side is at the National Composites Centre (NCC) and its digital programme DETI (Digital Engineering Technology & Innovation). A high-speed high bandwidth cabled connection has been created by the South Gloucestershire Umbrella project between both facilities. This connection is referred to as "dark-fibre." 5G-ENCODE is the main funding body of this project and has enabled this research to be undertaken.

5G-encode

DETI
DIGITAL ENGINEERING
TECHNOLOGY & INNOVATION

Figure 200: Project enablers

brl
Bristol Robotics Laboratory

NATIONAL
COMPOSITES
CENTRE

Figure 201: Project collaborators

113.1 Motivation

Teleoperation of robotic systems is a great method for actuating robotic systems that operate in complex environments. Autonomous robots have made major steps in both industrial and commercial use-cases. However, when robots are required to perform intricate non-repetitive tasks in complex environments the actuation still relies on human control, as the human ability to interpret complex environments remains ahead of known autonomous technology.

To accommodate the need of robotics teleoperation solutions BRL designed a leader-follower set-up that consists of two Franka Emika robot arms (see figure 1.3 a). An operator moves the leader robot of which the motion is subsequently followed by the identical second robot resulting in active teleoperation control. The follower robot returns information to the leader robot when it has contact, to give a form of feedback to the operator. This is done by the leader follower not allowing itself to be pushed further in the direction of the contact. In a different project, a Franka Emika robot arm is equipped with a stereo camera of which the feed is visualised in a VR-headset which is worn by the operator. In this scenario, the operator can look around and be more aware of the robots working environment (see Figure 202).

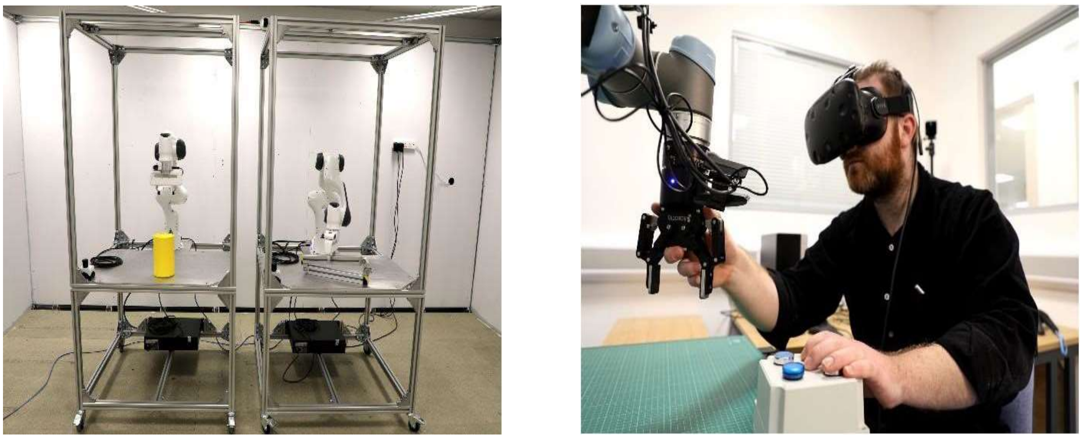


Figure 202: Bristol Robotics Laboratory teleoperation

In future projects, alternatives will be needed when larger industrial robotic arms are used as the operator will not be able to manually guide a large robotic arm and this solution can encounter issues with transforming the output of the smaller leader to a different larger follower robot. Hence, there is the need to further study robotic teleoperation control system so that the final solution is unaffected by the size of the robot being actuated.

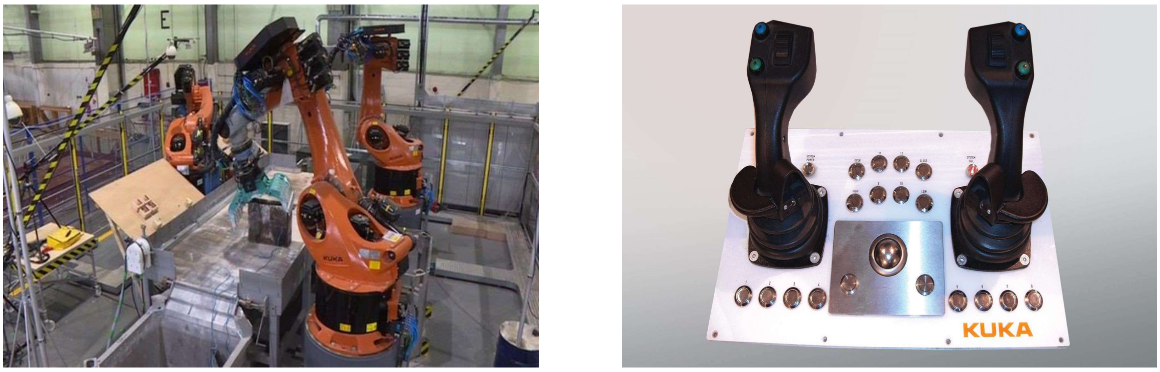


Figure 203: KUKA Nuclear decommissioning solution

The need for teleoperation control unaffected by robot size becomes clear with one of the largest use cases for this research. Nuclear decommissioning is forecasted to have a market value of 121 billion pounds as part of the UK future clean-up. This market value is estimated to realise across 120 years creating a sizable and long-lasting market. This use case involves work with dangerous substances that render the environment hostile and not suitable for human presence without specialised protective gear. The current solution for the need of teleoperation in nuclear decommissioning involves the use of a nearby (at same location) controller (see Figure 203).

To increase operational efficiency, it is necessary to find more intuitive methods of teleoperating 6-DOF industrial robot arms. These systems will perform complex tasks in equally complex and hazardous environments. An additional use case is that of welding operators and inspectors which can also benefit from the research done in this project. Besides the safer work environment, the added benefit of decoupling the operator is an easier start-up and even the potential to teleoperate robots from all over the world.

Research needs to be done regarding the network requirements to realise teleoperation of robotic systems. During this project, a robotic teleoperation network is set-up to determine the network requirements. This initial network uses cables throughout for the trials to be conducted. The steps that have been taken to realise this are discussed in this report.

113.2 Aims & Objectives

This project focusses on the implementation of intuitive haptic control protocols and the creation of an active robotic arm teleoperation network to determine the feasibility of 5G implementation.

The aim of this project is to understand and generate knowledge relating to remote operation of robotic arms in an industrial context summarized in the following project statement: "To determine the feasibility of 5G connectivity elements in a robotic arm teleoperation scenario where haptic control is used"

The general objective statement describes the elements that require to be completed for the aim to be achieved: "To create an active robotic arm teleoperation network that allows the operator to actuate the robot arm using existing haptic control protocols whilst being made aware of the robot's surroundings"

From both general statements, a list of aims, and objectives is created. This list will be referred to throughout the report to gauge the research success:

Aims

- Review the network statistics in the wired teleoperation trial
- Review current 5G options for robot teleoperation
- Evaluate the pros and cons of 5G implementation

Objectives

- Enable interfacing with existing haptic devices
- Implement control of robotic arm
- Implement stereo camera feed
- Create a virtual reality solution
- Create a teleoperation network
- Record network statistics during wired teleoperation trial

The research aims & objectives are chronically ordered, however, before these objectives can be tackled it is of importance to discuss the choices made and the steps that have been taken in the duration of this project. A technical description follows which evaluates the solutions found to address each objective. With this given, it is possible to achieve the research aims through discussing the results.

114 SOLUTION SELECTION

In this chapter relevant studies are researched and described with the aim to determine which solutions need to be used for different parts of the project. An important part of the project has been to get the right equipment for the right use-case. In this chapter the decision forming is focused on narrowing the scope of the project as the core of this research remains the network requirements and with that the feasibility of 5G implementation.

The haptic device is the main input of the solution and allows the operator to direct the robot arm with their hand. Once the operator's input is gathered it is necessary to translate this to an output on the robot. This translation is done using haptic protocols to which prior research has been done [1]. From this research a single protocol is chosen to limit the scope of this project. A VR-headset is necessary to create the immersive experience needed to give the operator a perspective of depth during teleoperation. Multiple VR-headset devices are currently available on the market and the decision process is described. As part of the immersive experience there is also a camera is required to view the robot.

114.1 Haptic robot control

New terminology was introduced during the literature review of the "Haptic Control Protocols for Simulated Industrial Robot Control" research [1] when it comes to haptic control. The terminology was designed to clearly describe the haptic protocol from a standardised point of view allowing for research undertaken on different hand recognition devices to be easily compared.

Hand recognition device	**Protocols**	**Feedback**
Kinect	PtPp [2], PtJv [3], PtPv [3], JtJp [4]	Not natively
Leap motion controller	PtPp [5][6][1], PtPv [1]	Lower hand, position only
Data glove	PtPp [7][8], JtJp [8]	Full hand, movement only

Table 26: Haptic protocols per device [1]

The meaning of the haptic protocol abbreviations can be determined in sections. The first capital letter describes the hand input and the second capital letter describes the robot output. Where P stands for "Pose" and J for "Joint". The smaller letter at the end describes the form of output whether this is done through "position" (p) or "velocity" (v) commands. Hence Pose to Pose position (PtP) based haptic protocol uses the Cartesian coordinates of the operator's palm and translates these to position commands for the robot's TCP pose. Pose to Pose velocity (PtPv) based protocol uses the same Cartesian coordinates of the operator's palm but now translates this to a velocity vector placed on the robot's TCP pose. Pose to Joint velocity (PtJv) based control protocol changes the joint angle of a selected robot joint by a rate that depends on the position of the operator's hand. Joint to Joint position (JtJp) based protocol maps the different robot joints to different joint angles of the operator.

Three types of devices (Kinect, Leap and data glove) have been identified that have gained the most haptic robot control research. These devices are described and compared in order to explain which device is best for the project. It should be noted that this is undertaken to give a good overview of devices available on the market, however, individual prices have not been considered as these can fluctuate.

114.1.1 Kinect

There have been several versions of the Kinect device. The latest solution from Microsoft is called Azure Kinect (2019) which builds on its predecessors Kinect V2 (2014) and V1 (2010). The first two Kinect versions were aimed at the consumer market for use as an accessory to the XBOX game console. The device mapped the user's body which allowed the user to interact with the game by moving. Hardware with an ability to recognise body positions proved to be a very useful tool in research projects and consequently was used in a range of research projects including computer vision and robot teleoperation. The latest edition of the Kinect has seen a change in aim as this product is now focussed on the research in industrial applications.

Figure 204: From left to right: Kinect v1, Kinect v2, Kinect v3 [9]

The Kinect has been implemented in a solution for real-time remote robot teleoperation [2]. Here the depth images of the Kinect are used to segment the active arm from the rest of the picture. This allows for the index finger and the thumb to be efficiently tracked in 3D space. A PtPp (Pose to Pose position) based controller is implemented where the hand pose of the operator is used to direct the robot's TCP position and direction. Hand tremors are a natural phenomenon that can result in unwanted robot moves. During the same research it was found that the use of different modes (e.g. coarse and precise) is useful for robot operation. Another research project [3] used a velocity-based protocol and inadvertently found that this solved some of the operational issues. Firstly, operator's joint limitations only prevent faster motion as opposed to limiting the all-out controllable robot workspace which would be the case in position-based control. Secondly, using a velocity-based protocol limits the effect hand tremor has as any involuntary movements are not directly mimicked.

114.1.2 Data gloves

A device that is worn on the hand which measures hand motion and translation by use of tracking sensors. The hand movement is translated to a digital instruction. These devices do not require any computer-vision based systems which can reduce the computational power requirements. However, these devices may require calibration and can be expensive and bulky when set-up.

A data glove solution was introduced by HaptX which uses an additional Vive tracker. This device combination gives the operator an intuitive way of operating a robot arm that is equipped with an anthropomorphic hand [8]. The Vive tracker allows for a PtPp based control protocol where small increments in motion are translated to the robot's TCP position.

The anthropomorphic robot hand has tactile sensors which are translated within the data glove giving the operator haptic feedback in the form of touch. The anthropomorphic hand end-effector itself is controlled by the data glove using a JtJp protocol where the operator's hand joint Cartesian coordinates are mimicked.

Data gloves have proven to be good for tracking movement of individual fingers. However, to track the hand position in space requires additional sensors. Custom made and calibrated equipment is needed to accommodate different hands. It is only possible to apply resistance on finger movement and not the movement of the hand itself.

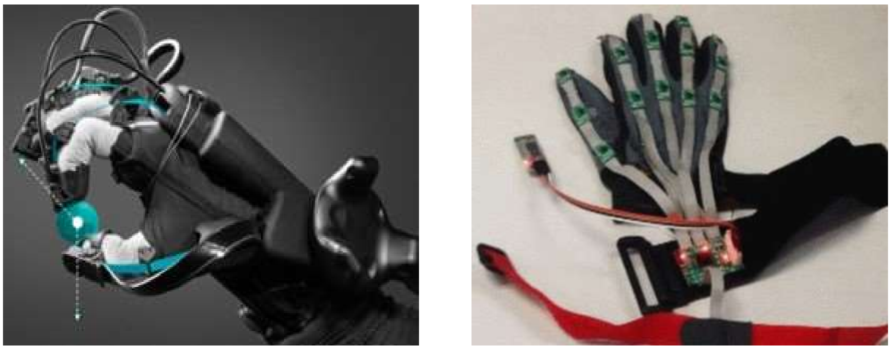


Figure 205: Data gloves – HaptX [8] & YoBu [7] (left to right)

114.1.3 Ultraleap motion controller

A compact optical hand tracking device designed to be used on a desk. The operator places his/her hand above the sensor and the dual infrared cameras are able to track the position of the hand in real-time.

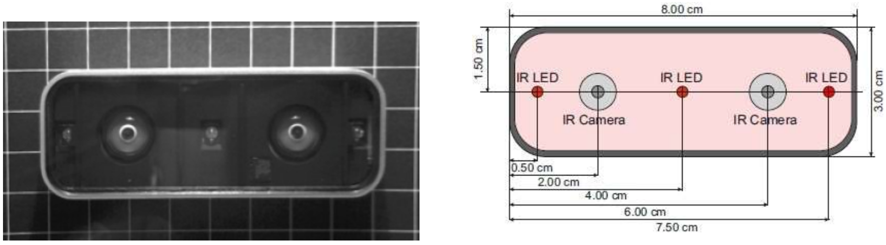


Figure 206: Ultraleap motion controller [10]

The device is designed by the company Ultraleap with the main focus to recognise hands and their relative position. It has an operational frequency of 120Hz; however, no quantitative accuracy measures have been given. One of the first studies on the Leap motion sensor was conducted to quantify the performance of the device, for both static and dynamic accuracy [10]. An industrial robotic arm was used to determine an average static position error lower than 0.2mm and an average dynamic error of 1.2mm.

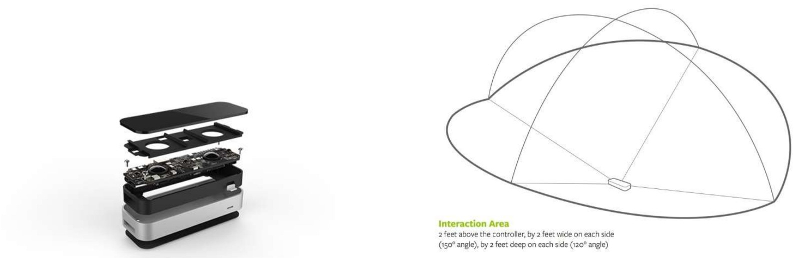


Figure 207: Ultraleap motion controller

Due to the standard desk placement of the device the field of view of the device can become a limiting factor. Both infrared cameras have an optimum distance of 60 cm above the sensor and have a field of view of 140º by 120º. The resulting workspace is a cone that morphs into a sphere that has an effective radius of approximately one metre.

The device tracks the movement from one point of view and therefore can struggle with specific hand positions, gestures and fingers that are hidden behind the palm as was found in multiple studies [11][12]. Direct sunlight and other infrared light are found to detrimental on the hand recognition ability [13].

The Ultraleap motion controller and its use-case for robot teleoperation has been less researched than the Kinect. This is, in part, related to the hype that surrounded the release of the first Kinect, potentially overshadowing the Ultraleap motion controller. This does not make it a less viable option. The Ultraleap motion controller outperforms the Kinect when it comes to hand recognition and tracking.

One prior research, dating back to 2015, has shown that an Ultraleap motion controller was used to control a robotic arm [6]. In that report, a UR10 robotic arm was simulated using control based on PtPp haptic protocol. During this research it was found that a low-pass filter helped reduce the effect of hand tremor or other noise related issues in the control process.

114.1.4 Robot teleoperation method

First, it is of importance to conclude which haptic device is most suitable to be used for haptic control in a teleoperation robot arm use case. A relatively high amount of research has been conducted using one of the different Kinect versions. However, it should be noted that these devices have been designed to track not just the hand and is, therefore, not necessarily the best option for a hand tracking only use-case. Data gloves enable both precise hand and finger positioning which allows for grasping control. However, these features can only be capitalised on when specific anthropomorphic hand end-effectors are used which, on top of the already expensive data glove, come with an expensive price tag. In addition, the data glove has the drawback of requiring an extensive setup and does not allow for hand positioning feedback. The Ultraleap motion controller is the device of choice as it outperforms the Kinect and the Vive tracker when it comes to hand tracking.

The Ultraleap motion controller has further advantages as it is small in size and easy to set-up for operation. When the Ultrahaptics STRATOS Explore, device is added to the solution it can also give haptic feedback. This is a high-end mid-air haptic feedback device that uses a set of 256 transducers that can project a tactile sensation on the hand through ultrasonic waves.

Figure 208: UltraHaptics Stratos Explore

Some common challenges have been found with different haptic protocols. These are discussed below to give a clear overview before explaining how the proposed solution solves these issues. Firstly, that of human joint limitations, both JtJ and to a lesser degree PtP have their workspace limited due to this natural occurrence. Operational difficulties arise when the operator is not able to position their hand in the right manner for the robot to perform a particular action. Secondly, the problem of hand tremor which can result in involuntarily movements of the robot that has a detrimental effect on the operational performance. Our hands are never perfectly still, and this phenomenon mainly impacts protocols that try to mimic the hand's movement like the ones that are position based.

Numerous types of robot control protocols have been found. All can be applied for haptic robot control, however, not all are necessarily sensical when operated just by hand movements. A gesture type PtPp based control protocol has been designed before for the Ultraleap motion device [6]. During the prior research [1] two types of protocols were designed for the Leap motion hand controller. The first is also a PtPp based controller, however, this time the palm position is directly used from the Leap SDK. The second protocol is a PtPv based controller which, during the research, was found to outperform its competition on both objective and subjective measures.

In short, the PtPv based haptic control uses the operator's relative palm position and translated to a velocity vector on the robot TCP position. This protocol allows for unlimited movement of the robot TCP and is naturally unaffected by the operator's joint limitations. This protocol is also impervious to hand tremors as it will move the robot in a specific direction with small changes due to hand tremors removed from the actual robot movement.

114.2 Streaming camera

Given that the operator is not in the same room as the robot itself, it is important that the robot is visualised to the operator. There are multiple options to do this, however, there are some requirements and useful notes that help limit the number of options which will be discussed here.

Firstly, it is of importance to determine what type of camera set-up is useful. The main types to choose between are a standard digital camera, 360◦camera and a stereo camera. The standard digital camera comes with many options and allows for high quality capturing and many options as to type of cable and video signal. 360◦cameras allow for a full capture of the environment with the drawback being that the sense of distances can be distorted. A stereo camera gives the opportunity to give a sense of depth if combined with a VR-headset. Especially when operating a robotic arm for a pick & place use-case it is important to be able to see such depth. Henceforth, there is only the need to look into stereo cameras for this project.

There are a number of stereo cameras on the market, however, many cameras are focussed on the 3D mapping potential that a stereo camera can realise. The two main products that focus on high quality imagery on top of having the distance between cameras in such a way that it can be used by VR-headset are produced by Stereolabs and Suometry.

Figure 209: Camera options, Suometry system & ZED camera (left to right)

Both options were suitable for this project as both can create an immersive experience and give the operator a sense of depth. It was important to also consider which option could better integrate into the already existing virtual teleoperation solution. The existing solution uses Unity which is a 3D game engine to create the virtual environment and simulate the robot movement.

The Suometry "360°stereo video camera developer kit" comes with the main benefit that it allows stereo vision for the complete 360-degree field. It also allows for higher framerates at similar resolutions. However, the zed camera comes with a Unity plug-in and has been proven to work with VR by the project collaborator BRL [16]. Hence, the ZED camera 2 has been chosen as the device to be used for this project.

114.3 VR Headset

A head-mounted device that can provide a virtual reality experience for the operator. VR headsets are widely used for commercial use-cases like video games and have more recently also been used for simulators, research and industrial design use-cases.

The headset needs to be able to communicate with a desktop wirelessly which reduces the number of VR-headsets available. The main competition is between the Oculus Quest 2 and the Vive Pro 2. Both devices can give an excellent immersive experience. The HTC Vive Pro 2 has a higher resolution (4896 x 2448 px) compared to the Oculus Quest 2 (3664 x 1920 px), however, both resolutions are higher than the highest camera resolution at 30 fps (3840 x 1080 px). On top of that the HTC Vive Pro 2 requires additional equipment to make the experience wireless which is natively supported by the Oculus Quest 2 through the newly added feature "Air-Link".

Figure 210: VR-Headset options, Oculus Quest 2 & HTC Vive (left to right)

With all the pros and cons weighed it was decided that the Oculus Quest 2 was the best option. This device is a VR-headset created by “Meta Platforms” and is a standalone headset with inside out tracking which results in minimal set-up time. The device runs an Android-based operation system and is compatible with a desktop computer, through the use of proprietary Oculus VR software, when connected over either USB or Wi-Fi.

During the project it was found that the Oculus Quest 2 headset is not natively compatible[10] with the ZED unity plug-in. This results in the plug-in not automatically creating the needed gameobject (ZedRigDisplayer) and assigning the correct assets (ZEDMixedRealityPlugin.cs). However, this does not mean that the camera and the headset are not compatible with one another. This additional gameobject in the headset can simply be removed which only results in limited in-game options but will give the same end-result of an immersive experience with a sense of depth.

[10] https://support.stereolabs.com/hc/en-us/articles/360011975694

115 TECHNICAL DESCRIPTION

This chapter documents the development process and research undertaken in this project.

It is necessary to further describe the workings of the control protocols as used within the teleoperation solution. The devices needed to interface with the created teleoperation solution are described. The created network is described in detail which is the foundation for the research that is done.

To understand the simulation facets, it is of importance to have a clear understanding of how the control set-up is created. This set-up was proven to work in a previous project [1] where the solution was simulated. This limited the number of variables in the project thus decreasing project risk.

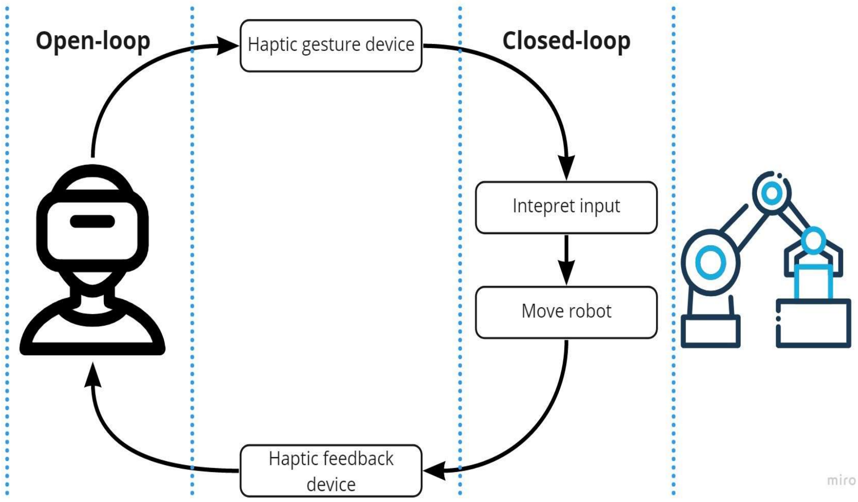


Figure 211: Haptic Control Set-up

The control setup illustrated in

Figure 211 shows how the control related devices are involved in the process of actuating the robot arm. The operator's side is essentially an open loop as the system has no direct influence on the actions of the operator. The robot side is, in contrast, a closed loop as the system handles the movement of the robot from the input data given. The operator interacts with the haptic tracking device which is interpreted by the algorithms embedded in the solution which in turn moves the robot. The application itself interacts back to the operator through the haptic feedback device by means of tactile sensation. It should be noted that the haptic feedback is on an application level and, therefore, does not use information coming back from the robot itself. Plans to integrate a touch sensor to the end-effector which can be relayed back to the operator through the haptic feedback device have been discussed, however, this is considered out-of-scope for this project.

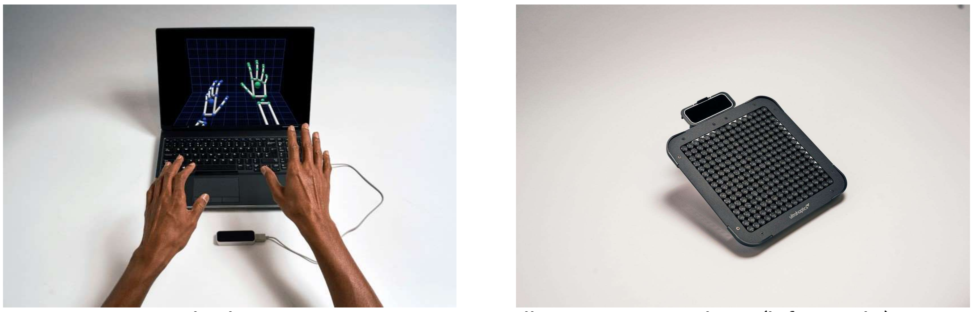


Figure 212: Ultraleap Devices, Motion controller & Stratos Explorer (left to right)

The haptic gesture device chosen is the Leap Motion Controller. An optical hand tracking device that creates a virtual model of the hand through what is called "skeletal tracking". This allows for finger positions to be estimated when not directly visible. The haptic feedback device that is paired with the leap motion controller is the Stratos Explore. A haptics development kit that is able to create mid-air tactile feedback through the use of an array of transducers.

115.1 Haptic Protocols

The haptic control protocols are key to the success of this solution. As part of the solution selection multiple haptic protocol options were reviewed and a protocol to use decided. Additionally, a decision has been made as to which haptic protocol will be used. In this section the haptic protocol is described in more detail.

The figure below shows both the input given by the operator and the output that will be given to the robot's TCP. The device has a virtual centre point that is effectively 20cm above the centre of either the Ultrahaptics device or the Leap motion sensor. A velocity vector is drawn between the virtual centre point and the operator's hand position (e.g. middle of palm). This velocity vector is then transferred to the robot's TCP which means that the further the operator's hand is from the centre point the faster the robot will move in that direction.

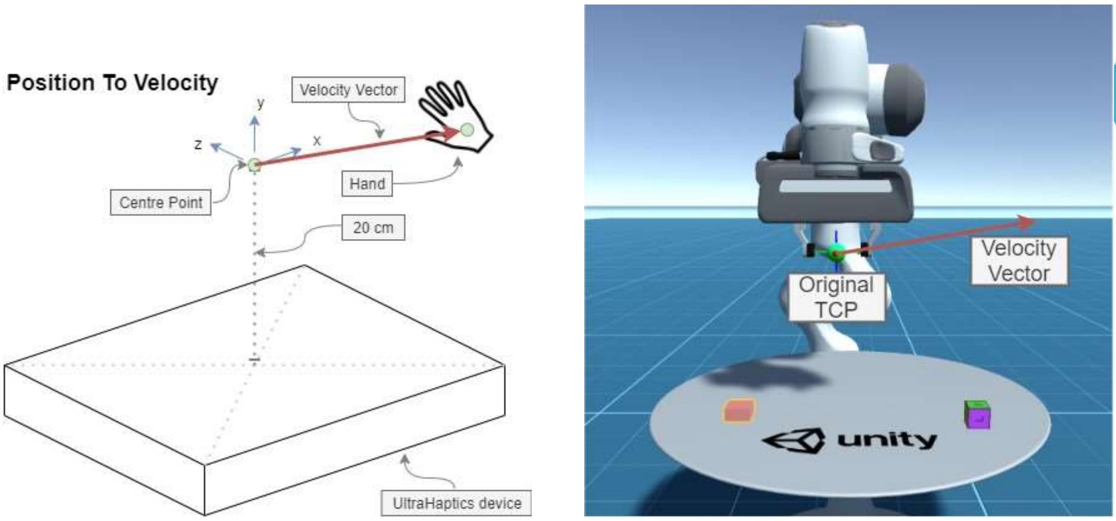


Figure 213: PTV Control [1]

The rotation is directly transferred from the operator's hand to the TCP on the world axis again in a velocity fashion. This is considered to be a pitch-roll-yaw rotation system where the rotation of the hand affects the TCP's rotational velocity. For instance, when the hand is pitched upwards the TCP will pitch in the same fashion. The higher the pitch of the operator's hand the higher the pitch-like rotational velocity of the TCP.

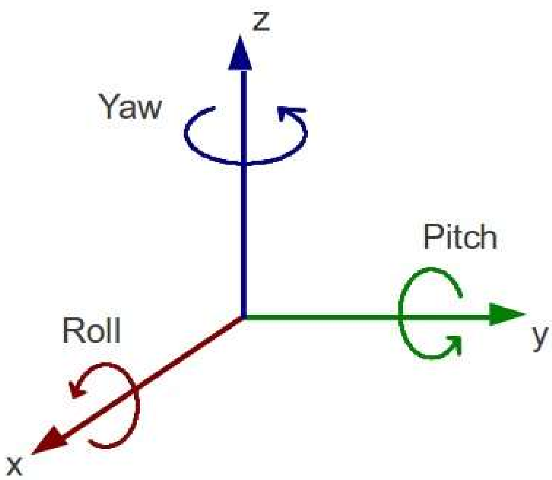


Figure 214: Pitch Roll Yaw diagram

The PtPv based controllers struggle less with the problem of the operator's joint limitations as well as sensory workspace issues. Additional scaling is used where the input of the operator is scaled and with that directly increasing the output on the robot arm. This is in direct correlation so when the scale-factor is set to two the velocity vector on the robot arm would be twice as high for any given input of the operator. This scale-factor can be actively changed by the operator in operation allowing.

115.2 System interfacing

There are a total of five separate systems that require interfacing with the application. In this section the devices in the systems are discussed as well as their interfacing solution and accompanying limitations.

It should be noted that not all system connections have an influence on the network which is at the core of this feasibility project. Only the robot system and the camera part of the immersive system influences the network. In the network section of this chapter this is discussed in more detail.

115.3 Haptics System

There are two devices that make up the haptics system. One is the Leap motion controller which tracks hand movement, and the other is the Ultrahaptics device that uses the tracked hand information and a set of transducers to create haptic feedback. Both devices come with their proprietary software development kits (SDK). This is used to interface with the relevant device and is described below.

Leap Motion

The Leap Motion Controller comes with an SDK that features a C-based API (Application Programming Interface) called LeapC. This API allows for higher-level scripting languages to access the tracking data of the Leap motion controller. There are different versions of the tracking software available depending on the development operating system (OS) used. The most recent version available is Version 4.1.0 for Windows. This tracking software is installed in order to access the SDK and its internal API. The Leap Motion C API is used as an intermediary between the application created and the Leap Motion service. The most important functionality required for this project is the hand tracking information. The Leap Motion system uses a right-handed Cartesian coordinate system of which the origin is found at the centre of the sensor's topside.

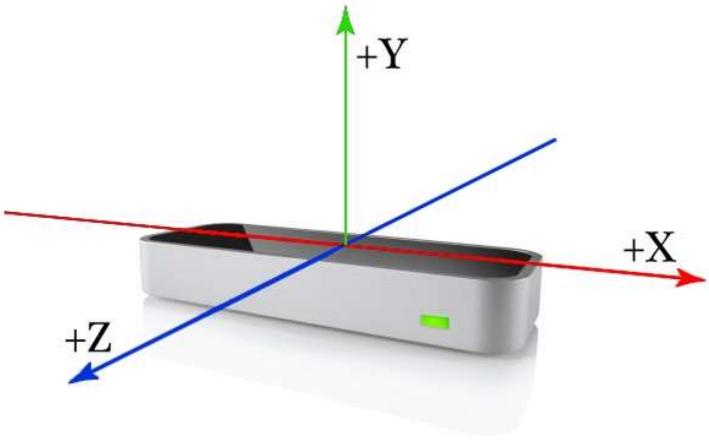


Figure 215: Leap Motion cartesian system

Before the tracking information is accessed a connection is created using the SDK. These steps can be skipped if the Unity plugin, created by Ultraleap is used. The Core unity module is all that is needed as this holds the crucial Leap service provider. This script is added as a component to a gameobject in Unity and is the class that communicates with the Leap service. This gameobject is subsequently addressed by all other scripts to gain valuable tracking data.

UltraHaptics

The UltraHaptics device SDK comes with drivers for the transducer array as well as C# and unity libraries. A unity component is included that is added to a gameobject within Unity, similar to the leap service provider. When this gameobject is active, the UltraHaptics device is given instructions to creates a certain tactile sense. In this instance, this would result in a focused point sensation that represents the device centre point as discussed in chapter 3.1. Further research into the API and the Unity integration needs to be done to determine potential avenues for haptic feedback.

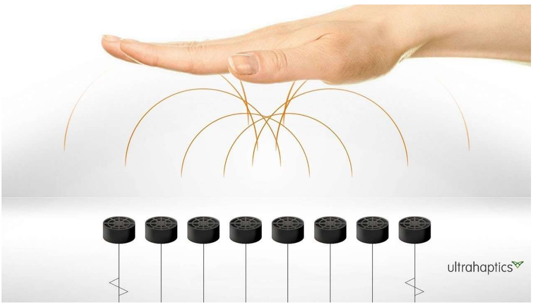


Figure 216: UltraHaptics mid-air tactile sense

Unity Implementation

A section called *hand portal* is created within Unity. Here the haptics system is both integrated as well as visualised, this involves a hand representation as well as overall control.

The hand portal shows important information regarding the inputs from the operator and how they are transferred to the target object (e.g. Robot TCP). The hand portal is a number of facets that can all be clustered into four groups (e.g. *Hand Controller*, *Input Drawer*, *Hand Object*, *Target Object*) that make up the logic. The figure below shows the two groups *Input Drawer* and *Hand object* in-session representation. The hand object is represented by a sphere that has a coarse form when disconnected and becomes circular over the connecting period. The input drawer representation holds the connect status as well as the dead man's switch, connection timer, control protocol text and input details.

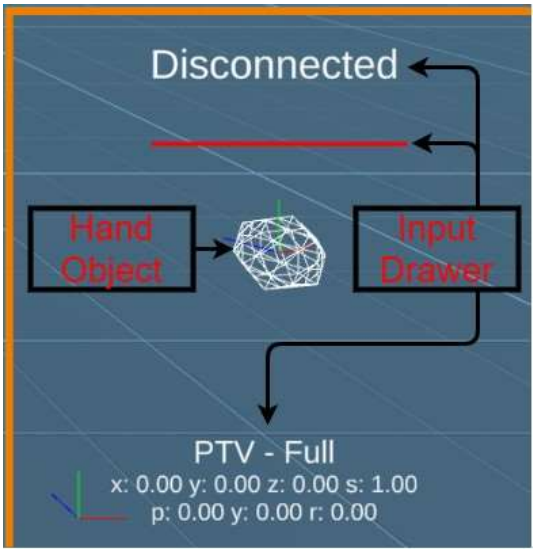


Figure 217: Hand portal in-session annotation

The *Hand Controller* outputs several information streams to the other groups as can be seen in the figure below. As variable inputs, it has the leap plug-in and keyboard which allows for interaction with the leap motion controller and added operator input, respectively. It also has a set of notable internal variables which are either used by the other groups or tells the hand controller which game objects to interact with.

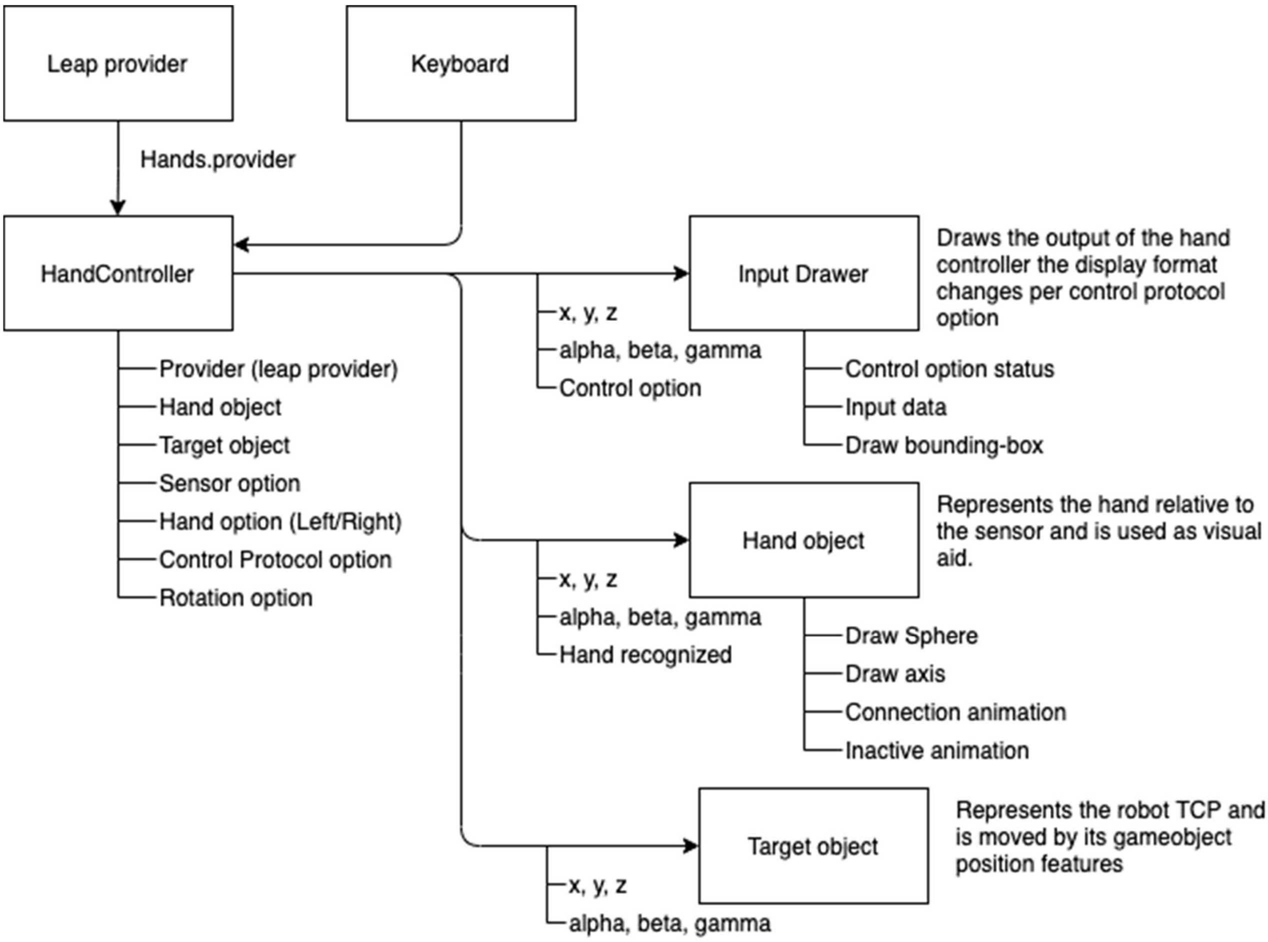


Figure 218: Hand portal architecture diagram

It should be noted that the keyboard inputs are crucial during the pick & place operation as they can change settings on the go and most importantly function the dead man's switch. Figure 3.21 shows the control layout of the keyboard.

The finite state machine of the HandController is managed by the ControlStatus for which there are three options: Connected, Disconnected and Connecting.

This segment lays the foundation of how the operator seizes control. In short, the intuition behind this system is that the operator does not want to be in control as soon as a hand is recognised or when they are not aware, as this can result in dangerous situations. The figure below shows the finite state machine set-up. First, a check is needed to determine whether the dead man's switch is pressed (e.g. space bar). This is standard procedure for human robot control and brings two benefits. Firstly, the operator is aware that control can be given to them. Secondly, control is quickly terminated on releasing the dead man's switch.

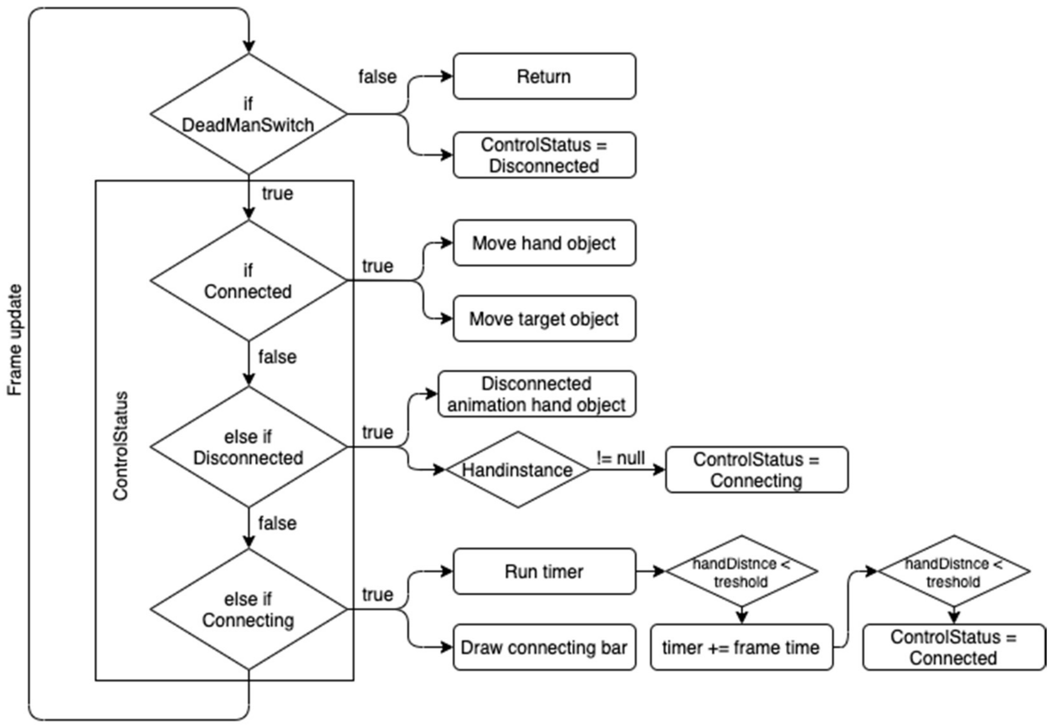


Figure 219: Hand controller finite state machine architecture diagram

The figure below shows how the position and rotation control is separated for both PTP and PTV and, therefore, addressed separately. It should be noted, that in this project, only PTV (a PtPv based haptic protocol) is used. However, it is still important to determine what control protocol mode is being used (e.g. Both, Position only or Rotation only) as this determines whether both position and rotation control is used or just one of the two.

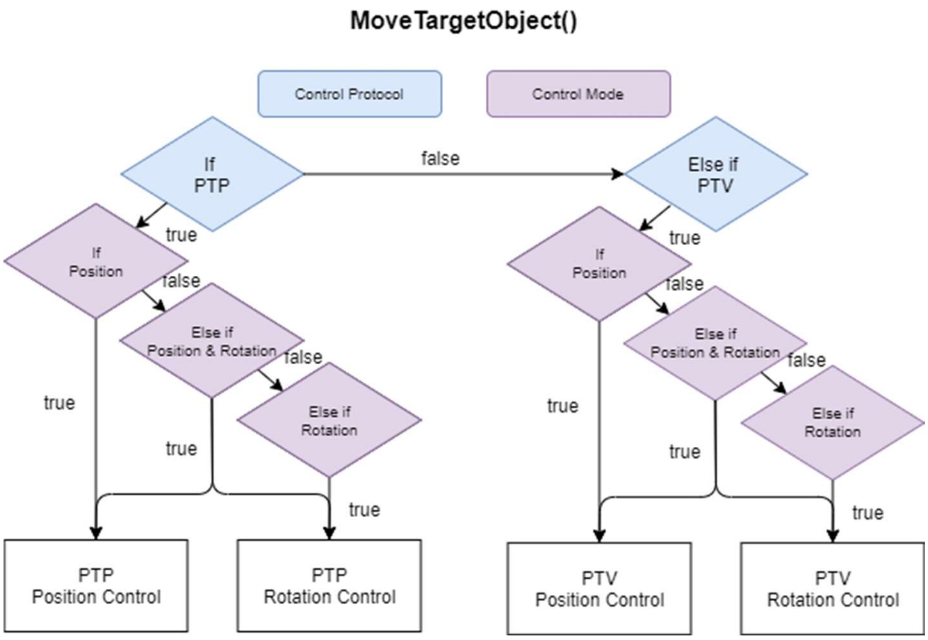


Figure 220: Move target object

The importance of being able to only translate or rotate should not be underrated. During the prior research [1] it was found that participants often struggled to recognise the small rotational changes they were asserting whilst being focused on translating the TCP. This often meant that the small changes overtime became considerable and once the position was reached the end-effector had to be corrected on rotation.

115.3.1 Robot system

The robot system consists of two parts. The first part is the virtual part where the robot arm is simulated. This virtual part is realised in Unity and both visualises the robot arm as well as performing the inverse kinematics of the robot arm. The inverse kinematics calculate the robot joint angles from the given TCP which is moved around by the operator. The joint angles are then sent through a TCP (Transmission Control Protocol) connection to the actual robot arm which is the second part of the robot system.

Figure 221: Franka Emika Panda robot

Virtual robot arm

Unity is originally a cross-platform game engine developed by Unity Technologies designed for game development. However, the strong ability to create 3D environments and the inert connection with powerful and efficient C# code it is also possible to cater for robotics use cases.

To realise inverse kinematics within the Unity simulation a plug-in is used. Bio IK is a generic geometric kinematic solver that allows for the inverse kinematics to be set up for any kinematic chain. The robot arm is set up in such a way that each link is its own gameobject. The base is the main parent, and each subsequent link is the child of the link prior, up to the gripper (see figure 3.12). The centre-point between the two gripper-fingers is set to be the TCP. Bio Ik works by adding a behaviour component to each link and telling the joint rotation limitations. It is of importance that the origin point of the gameobject is concentric with the joint's centre of rotation. With the robot links set up the TCP, which is placed last in the chain of gameobject children, is set to follow a target object. The inverse kinematics solver will then determine the joint angles and rotate the gameobjects accordingly.

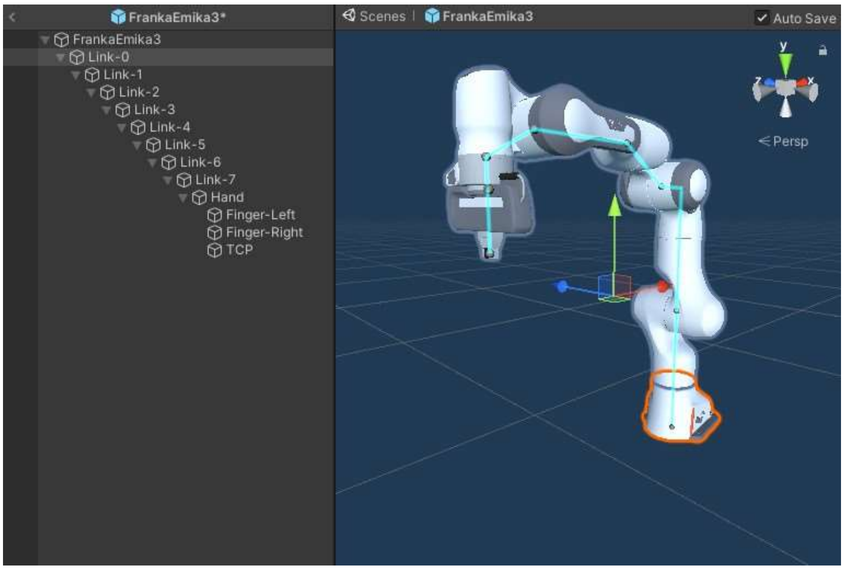


Figure 222: Franka Emika Panda robot inverse kinematics set-up

Physical robot arm

This robot arm is the same as its virtual counterpart and located at Bristol Robotics Laboratory. The Franka emika robot arm has a control module which is connected to the Linux based computer that has been dubbed the "robot computer." The function of the robot computer is to connect with the TCP server hosted by the application, interpret the joint angles and subsequently give the robot movement commands.


Figure 223: Bristol Robotics Laboratory set-up

115.3.2 Immersive system

This section discusses all the elements that relate to the immersive side of this project. The immersive solution contains two separate devices one that is used to capture the environment and one to display the captured feed. The project selection of immersive devices is discussed above. It was decided to use a stereo camera referred to as ZED 2 and the Oculus Quest 2 VR-headset. The ZED camera implementation is described first in the following sections as this set-up is used by the VR-headset.

ZED Camera

The integration of the ZED camera and its feed comes in two parts. There is a sender side which makes the camera feed available to the local network and a receiver side which connects to the sender. It is important to get the correct software prior to configuration of the solution. For this project version 3.6.5 of the ZED SDK was used. To use this SDK another piece of software, NVIDIA CUDA, was needed that allows for accelerated GPU processes.

Sender

Connecting the camera and opening the feed for the local network is done by using one of the examples given by Stereolabs. The example uses the ZED SDK and allows a live video stream over local IP network. The feed is encoded to limit network bandwidth requirements.

The camera feed needs a minimum FPS of 30 to be usable within the immersive experience. From Stereolabs documentation, it can be seen that this comes with a maximum resolution of 1080p and an advised bitrate of 12500 [kbits/s]. These values are manually set within the example code.

Receiver

By using the ZED SDK for both the sending as well as the receiving side of the camera feed there is no inherent problem with implementing the feed differently compared to when an USB connection is used. The ZED API must be told to use a stream as input and the associated IP-address needs to be given but apart from this the solution will behave as if the camera has a direct connection.

For the integration within Unity the ZED Unity plugin is used. This plugin comes with multiple examples for use as well as prefab configurations. The main Unity prefabs that are being used in this project are the so-called "ZED Rig Mono" and "ZED Rig Stereo". The mono variant is used in both the main screen to perform a connection check and give a quick view of the camera feed as well as in the camera teleoperation scene where it is used to show the robot during operation. The stereo variant is used for the VR headset solution where the feed of each camera is overlayed on the corresponding eye plane.

An additional behaviour script was added on top of the existing prefab to allow for the integration of the ZED camera within the general application. This was done by having the ZED Rig Mono on inactive until connection is needed for which it is first ensured that the settings of the ZED manager are correct. When it comes to the VR solution the ZED camera is always running, however, the Oculus environment is overlayed giving the illusion of the camera being turned off. It should be noted that turning of the receiver side within Unity can come with issues potentially not allowing the camera feed to be shown again even-though the camera is reconnected. Turning off the camera prefab which includes leaving a scene whilst the ZED camera prefab is not connected can also result in the application stalling and taking an extended time to perform the requested action.

VR-headset

With the Oculus Quest 2 VR-headset selected for use it is possible to use specific functionality related to this device. In this case an SDK is provided to expedite the Unity development. Using this SDK it was possible to add device embedded features as controller input and visualisation as well as adding a general pipeline implementation for building the VR experience.

The Oculus headset is designed to run android applications; however, it can also be used as a standard VR-headset where the application is run from a desktop to which the headset is connected. For this project, the application was run on the desktop to ensure connectivity with the robot and the camera as well as assuring the high computation needs were met when decoding footage. Air-link was used to wirelessly connect the headset to the desktop. This feature was added as an experimental streaming solution as part of software version 28 in April 2021. More information on connecting the headset with the desktop over air-link is available on the oculus website. Another option is to use a direct cable which is referred to as "Oculus-link".

Figure 224: Oculus VR-Headset

The SDK already uses an open standard called OpenXR. This standard allows one application to operate with different VR-headsets. This can be especially interesting when the teleoperation solution is used more broadly as it would allow operators to use any VR-headset available to them.

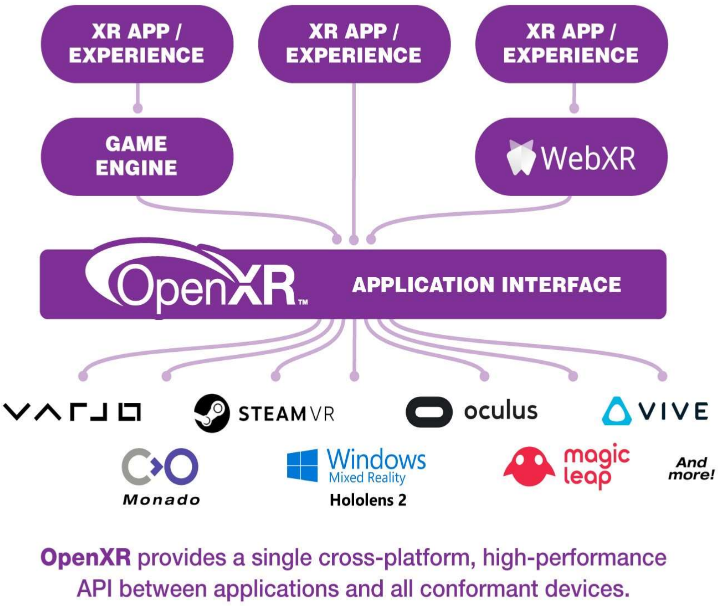


Figure 225: OpenXR

115.4 Application

A short overview is given of the application in order to make clear where the more in-depth technical descriptions apply to. The application was created in Unity and consists of six different scenes. Each scene was a created environment where the operator can perform certain actions. The figure below shows how each scene was connected.

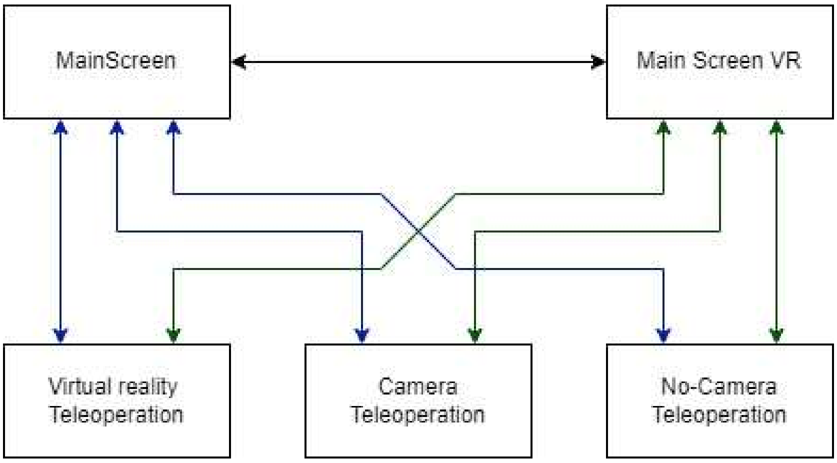


Figure 226: Scene overview diagram

115.4.1 Main screen

This is the first screen the operator will see when starting up the application. Effectively the heart of the application. From here it is possible to acquire more information on the project, go to the training environment, check device connection status, and go to one of the three teleoperation environments.

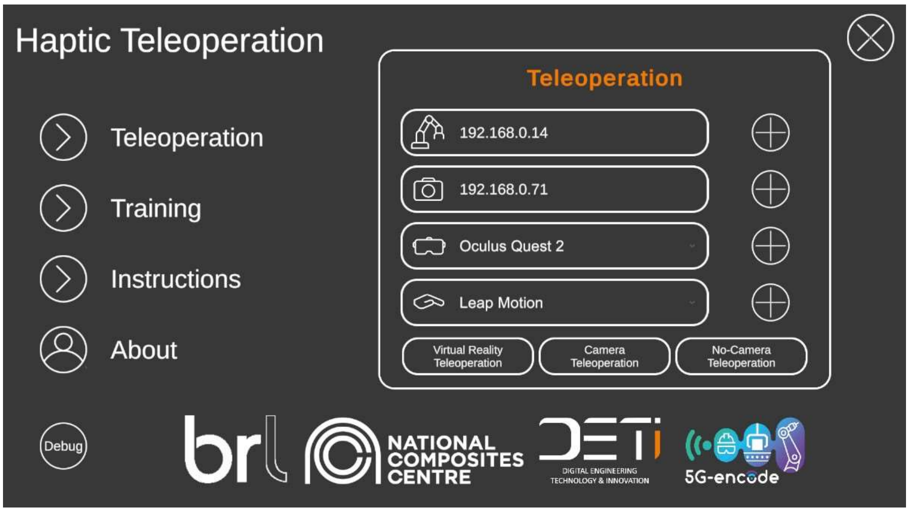


Figure 227: Main screen

Before any teleoperation is conducted it is of importance to fill out some device related information and automatically check the connection status of the device. The robot connection requires the TCP server host IP-address to be entered (currently IP-address of device running application), the camera needs the IP-address of the device that makes the camera available to the network, the VR-headset needs to be specified as well as the haptic device.

Next to each input field a button runs a particular script when. The functionality of the button is to save the input given, check it and eventually use it to make sure that the device can be connected to. The figure below shows the logic that enables this.

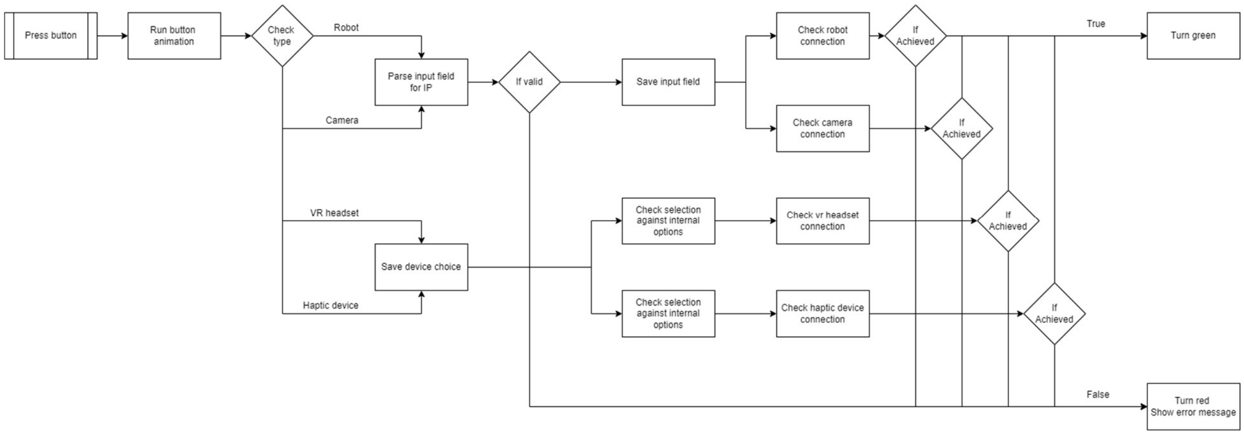


Figure 228: Connection button flow chart

The start event is one of the four buttons being pressed. The type is then checked to determine what kind of input is to be expected. There are four input fields, hence there are also four types. When it comes to the IP-addresses it is first checked whether it can be parsed and, therefore, is a valid IP-address. When it comes to the robot IP an additional check is done to determine whether the IP-address can be correlated with the DNS (Domain Name System) host info of the device. The input value is saved and automatically a check for connection is started. When this is conducted successfully both the button and the input field is turned green to indicate success. For the camera connection an additional screen is shown (see figure below) where the IP-address of the camera connected device is displayed as well as other variables.

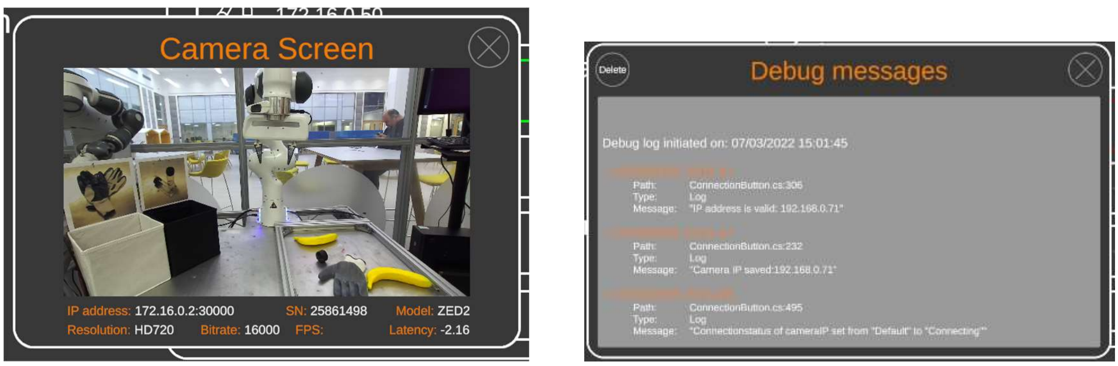


Figure 229: Camera screen & Debug screen (left to right)

Another screen that can be accessed from the main screen is the debug screen. Here all general debug log information can be read as well as any errors that might pop-up during operation. This is especially beneficial during test trials as this would mean that the errors are stored in one place and can be accessed from within the application. Normally the application is run from within the Unity Editor which gives a broad range of debug tools, however, from the Unity editor threaded TCP connections work very slowly and it was measured to take more than two minutes to achieve connection whereas that otherwise would take seconds.

115.4.2 Menu Screen

Each teleoperation scene has a menu screen that can be is accessed through the “esc” button on the keyboard. This screen shows the saved input values as well as the current status of the four devices. It also gives the operator a way back to the main screen.

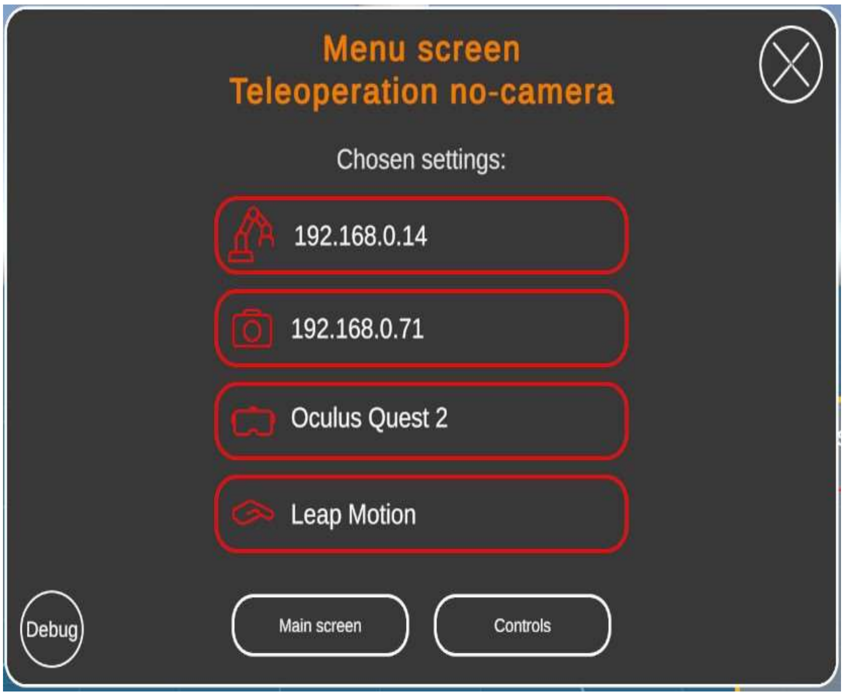


Figure 230: Menu screen

115.4.3 Controls

The figure below shows the control layout of the keyboard. This screen is reached by either going to the main screen and pressing the instructions button or accessing the menu screen from within a scenario (escape button) and press the controls button.

Figure 231: Keyboard controls

Main keys

- Key1 Escape: Opens menu screen
- Key2 Spacebar: Engages/Disengages dead man's switch

Control scale

- Key3 Z: Decrease control scale by 0.1
- Key4 X: Increase control scale by 0.1

Rotational

- Key5 R: Changes haptic control mode to rotation only
- Key6 F: Changes haptic control mode to rotation & position
- Key7 V: Changes haptic control mode to position only
- Key8 C: Toggles through the haptic control mode options

115.4.4 No-Camera teleoperation

The most basic scene where the digital robot representation is visualised show the desired robot configuration. This scene is an advancement of the free-roam environment development during the prior research [1]. Only two devices are necessary to allow this scene to work. A robot connection to perform teleoperation and a leap motion device to give instructions to the virtual robot.

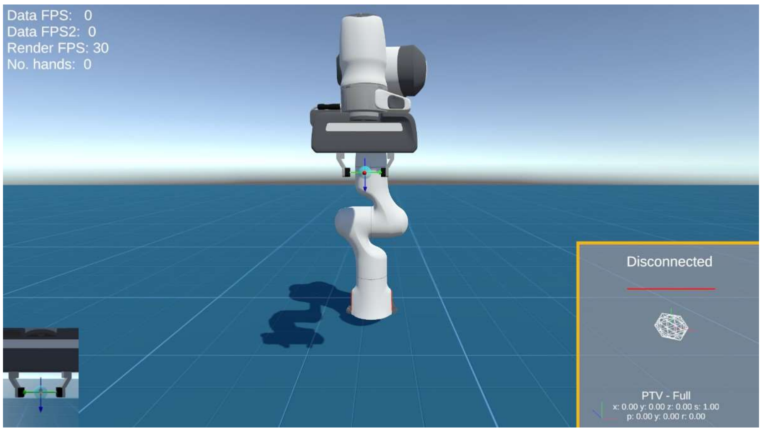


Figure 232: No-Camera teleoperation

It should be noted that it is not recommended to start robot teleoperation when it is not possible to see the robot arm. However, this scenario was created as part of the testing trials to determine the different bandwidths requirements for different configurations of the application. This set-up allows for the bandwidth of just the robot arm commands to be captured. It should also be noted that before acquiring teleoperation access multiple preparation steps had to be taken at the robot side. If the robot happened to be live and the applicable code was also running a key press was still needed for every teleoperation request before access is granted.

115.4.5 Camera teleoperation

This scene adds a direct camera connection and visualises this on screen. From here it is possible to conduct standard teleoperation using the leap hand tracking device like before, however, now it is also possible to see the robot through the camera feed displayed on the screen. This is the first step towards the goal of creating a fully immersive experience.

Figure 233: Camera teleoperation

When using this scene, it is possible to operate the robot arm adequately, however, it is relatively difficult to determine depth. In the trial this scene makes it possible to determine the bandwidth used when both utilising the camera as well as the robot.

115.4.6 Virtual reality teleoperation

This scene uses all devices that are integrated in this application. The robot arm connection allows for teleoperation, the leap motion device gives input to the virtual robot arm, the ZED camera shows a live feed of the robot and the VR-headset displays this feed. The camera feed is directly projected onto the VR eyes allowing the operator to gain a sense of depth. It should be noted that the camera is stationary, therefore, the camera is not able to turn when the operator turns his/her head. This can make the overall operator experience uncomfortable.

Figure 234: VR teleoperation menu screen

There are two modes when it comes to this scene. One is the dedicated camera feed where the operator will see just the feed itself. During this any head movement will not change what the operator is seeing. The other mode is where menu screen is visualised. The operator is placed in a minimalist room with a desk and a sizable menu screen behind it. On top of the desk the virtual robot is placed giving the operator even whilst viewing the menu screen a sense of what the robot's state is.

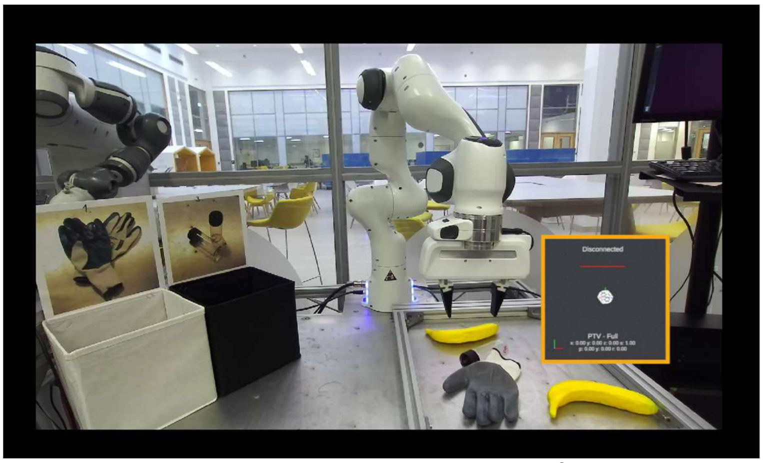


Figure 235: VR teleoperation camera feed

115.5 Network

An important part of robot teleoperation is the network capability. There are multiple devices incorporated in this solution and all of them have different network bandwidth requirements. All individual network links have a common need to be low latency.

In this section the network architecture is described along with its theoretical limitations. The network is used to determine the network requirements and options for future 5G deployment.

115.5.1 Current network architecture

The figure below shows the architecture of the network. Four major individual links are identified from this diagram. To lower potential risk for the project these links were tested on their own before being integrated in the whole project.

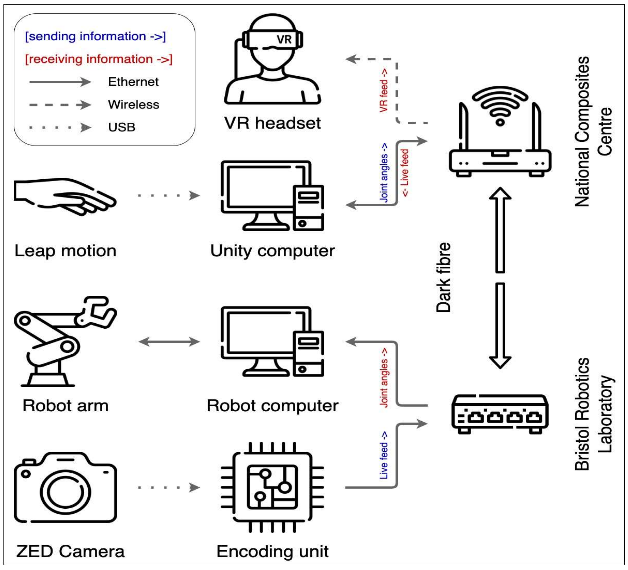


Figure 236: Network diagram

The four major links define what can directly affect the operator's experience and are considered inside the research scope of this feasibility project. It should be noted that a link can consists of multiple connections of which one or more can be the bottleneck effectively enforcing a maximum bandwidth.

- C1: Robot - Unity Computer
- C2: Camera - Unity Computer
- C3: VR-headset - Unity Computer
- C4: Dark Fibre

This meant that before the robot connection with the Unity computer was integrated, it was tested on its own locally before being tested in combination with the dark fibre connection and eventually being integrated in the complete network set-up. These steps were taken for all identified major connection links.

These connections are also a major part of the feasibility study as each comes with different network bandwidth requirements that could have potentially influenced network latency. Before these requirements were established it was important to have the limitations identified from the current trial network set-up. The table below shows all the theoretical maximum bandwidths associated with the connection between the devices.

Connection	Facilitator	Max bandwidth
VR headset - Wi-Fi access point	2.4 Ghz Wi-Fi	300 Mbps
Leap motion - Unity computer	USB 2.0	480 Mbps
Unity computer - Wi-Fi___33 access point	Cat 6 Ethernet	1 Gbps
Robot arm - Robot computer	Cat 6 Ethernet	1 Gbps
Robot computer - Network switch	Cat 6 Ethernet	1 Gbps
ZED camera - Encoding unit	USB 3.1 Gen1	5 Gbps
Encoding unit - Network switch	Cat 6 Ethernet	1 Gbps
BRL - NCC (Dark Fibre)	OS2 9/125 (1310nm) Single Mode	10 Gbps

Table 27 : Network table theoretical maximum bandwidth

The figure below places the theoretical max bandwidth connections on top of the network diagram. The individual links are limited by different bandwidths. All connection links that were part of this feasibility study (C1 & C2) have a maximum network bandwidth of 1 Gbps.

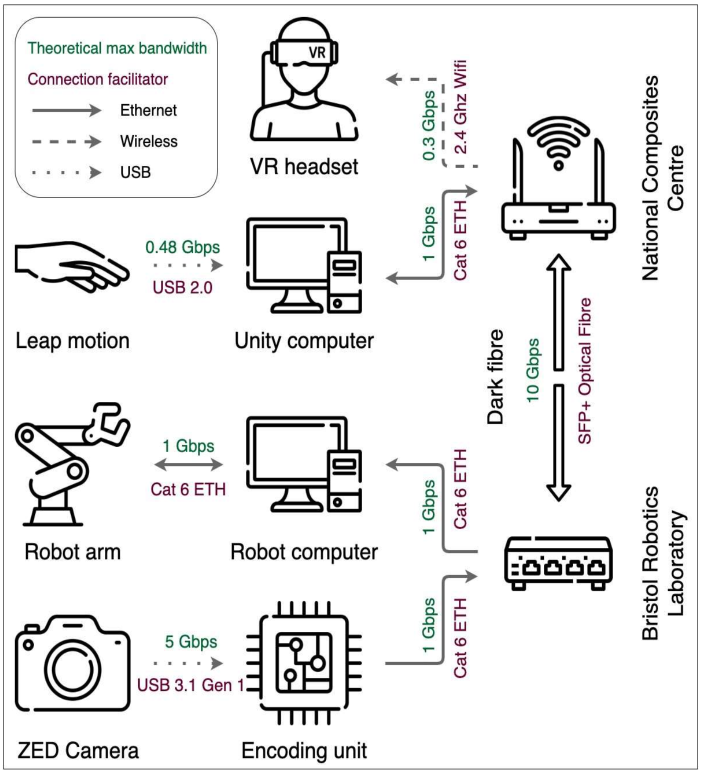


Figure 237: Network diagram max bandwidth

115.5.2 Consideration for using 5G

It is important to determine how 5G capability can be added to this project before assessing feasibility of adding 5G to the network. The current 5G network bandwidth capability (taken from network report issued to DCMS Jan-2022) is stated in the table below.

Throughputs	Values [Mbps]
Uplink	57
Downlink	410

Table 28: 5G-Network Throughputs

Currently there are two switch type devices used which allow for the cabled dark fibre network to be extended to the specific devices. These switch type devices could be replaced with 5G nodes to make all connections wireless. The implementation of the two nodes into the network architecture is visualised in the diagram below. On top of that the revised speeds are overlayed on the connections to get a clear understanding of the capability.

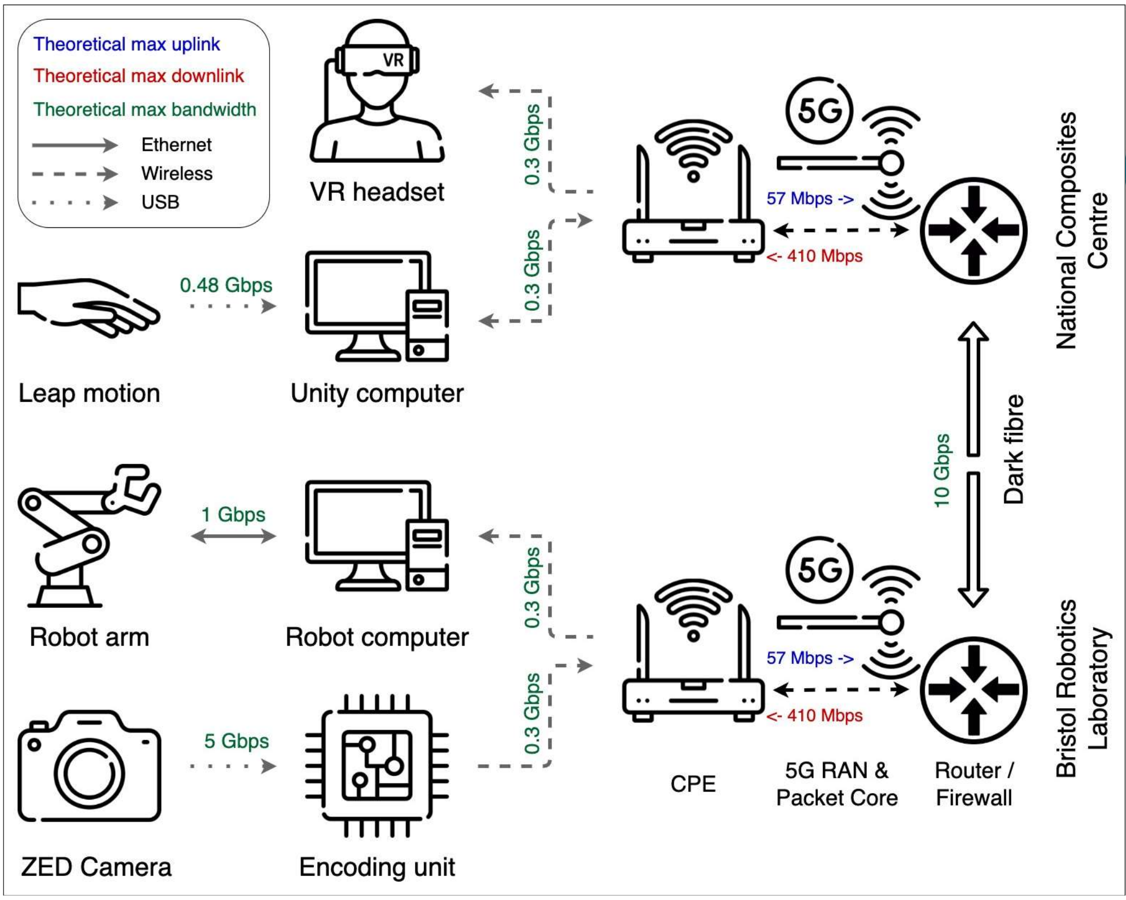


Figure 238: 5G-Network diagram max bandwidth

It should be noted that the throughputs described in Table 28 is per device. This means that every device connected to the 5G node can use up to the specified bandwidth. These bandwidths are considerably lower than that of the cabled trial network. This shows the necessity of doing a trial to test network bandwidth and confirm requirements. The ZED camera footage live stream will have the need for high uplink throughput, meaning there is a major concern that the 5G, as deployed in this project, cannot meet the uplink requirements of the camera. The ability to test the network prior to 5G integration has identified limitations and greatly reduced the risk of this project and created requirements for any future projects using this type of camera.

With the implementation of 5G determined and described it is now possible to start looking at the pros and cons of adding such a capability. The benefits are very dependent on the location of the implementation hence the assessment is split between the National Composites Centre and Bristol Robotics Laboratory.

Node location	Pros	Cons
National Composites Centre	• Full wireless operation • Enhanced freedom of movement • Flexible working area • Not location restricted	• Lower uplink • Lower downlink • Potential wireless interference
Bristol Robotics Laboratory	• Wireless camera placement • Mobile robot teleoperation plug & play	• Lower uplink • Lower downlink • Potential wireless interference

Table 29: Location and activity description

At the National Composites Centre, the main benefits relate to the increased freedom of operation. This includes being able to start conducting the operation from anywhere within the 5G network range instead of having to be connected to a specific Ethernet cable. Wireless operation also allows the operator to be untethered which gives more freedom of movement and can impact the operational performance positively. The overall time it would take to start operation of which setting-up connectivity could also be reduced.

At Bristol Robotics Laboratory, benefits are found when it comes to placement of the devices. Currently the camera location is limited by the length of the cable and can only be set-up in a limited space. Having the ability to place the camera anywhere due to the wireless connection is not only beneficial for camera placement but also opens the opportunity to investigate actively moving the camera for better overview of the environment. Further benefits could be found when a mobile robot arm system is being using wireless connectivity as this could give extended freedom and enable a plug & play form of teleoperation.

The 5G implementation to the existing teleoperation network aligns well with the use-cases envisioned in the main 5G-Encode work packages. From the AR/VR use case 5G enabled advanced human machine interfacing using a wireless high-bandwidth low-latency network connection. These results for video relay are likely to be seen in a future haptics use case trial.

116 RESULTS

During the trial tests from multiple data points were captured to identify the network performance. This makes it possible to start determining the minimal network requirements for this use case. The following network parameters were tested whilst using the current teleoperation network.

- Uplink bandwidth
- Downlink bandwidth
- Ping latency
- Ping lost percentage

Bandwidth parameters were determined using software called NetPerSec installed on the computer hosting the solution applications. This software gives an overview of the current uplink, downlink and average network traffic observed on the network port in the computer. These last two parameters were determined by running a continuous ping command whilst running the certain test scenario. The ping results were saved in a text file prior to processing in an excel file. All raw results data are in Appendix A. It should be noted that after going over the results it was found that the average numbers taken by NetPerSec were rolling averages and not the average value over time. This led to the need to interrogate the screenshot and take an estimate of the average value that would be closer to reality.

A total of seven test scenarios were determined for which each network parameter described was measured. Firstly, it was necessary to benchmark with all applications on the machine turned off. The same was then done with the application running in idle mode which in our case is just showing the main screen. Separate tests were then completed for the robot and the camera before a combined test of both operating together. It should be noted that different uplink speeds were being captured when the robot was moving opposed to not moving, hence, both were captured.

Entries	Robot move	Duration	Average	Max	Average	Max
Benchmark	N/A	10 min	3.80	12.67	3.65	10.34
Application idle	N/A	10 min	3.05	12.49	3.45	13.45
Camera only	N/A	10 min	20840	24790	4.34	14.82
Robot only	Not moving	5 min	20.27	23.70	38.00	44.00
	Moving	5 min	20.74	29.47	7.55	44.18
Robot & Camera	Not moving	5 min	22510	26950	57.78	70.40
	Moving	5 min	22140	25190	4.38	50.28

Table 30: NetPerSec network bandwidth

The table above shows the results of the network parameters of which a few findings can be discussed. It was seen that when the application is idle it is not using the network connection. It was also determined that the camera feed is the main consumer of network bandwidth. This was expected; however, it was beneficial to have determined the network bandwidth to understand network bandwidth consumption in detail.

There is a big difference in uplink bandwidth consumption dependent on whether the robot is moving or not. Investigation found that before messages can be sent through the TCP connection a check is being done as to whether the receiving end (robot computer) is waiting for a new command. The current code that is connecting to the robot arm and translating the commands does this in a sub-optimal way. For each command that would move the robot beyond a small threshold the robot arm is told to move to a certain joint angle configuration. The issue is that the robot is asked to take 0.75 seconds regardless of how big the requested movement is. For comparison, the normal loop time is 0.03 seconds but when the robot is moved this goes up to 0.078 seconds. This resulted in choppy robot movement and a connection that was not available most of the time when the robot was in operation. This means that less messages were being send and consequently less bandwidth used.

From the values taken during trial tests the network diagram shown before was adjusted with now actual required bandwidth values.

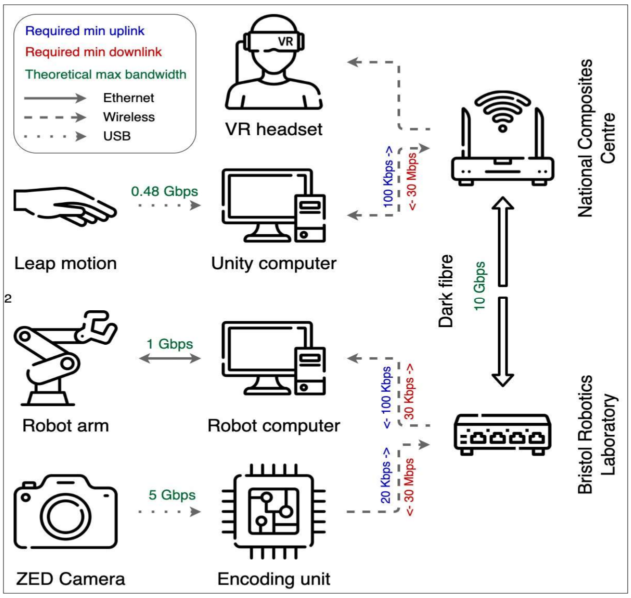


Figure 239: Network diagram required bandwidth

The ping latency results shown in table 5 shows that the current network is very stable as expected from a fully cabled network. No packets were lost, and the latency values were extremely low throughout the period of testing. These measurements create a benchmark to compare an integrated 5G network with.

Entries	Robot status	Send [#]	Lost [%]	Min [ms]	Max [ms]	Avg [ms]
Benchmark	N/A	617	0	0	5	0
Application idle	N/A	706	0	0	22	0
Camera only	N/A	615	0	0	8	0
Robot only	Not moving	313	0	0	27	0
	Moving	310	0	0	16	0
Robot & Camera	Not moving	307	0	0	15	0
	Moving	310	0	0	15	0

Table 31: Ping latency

117 CONCLUSIONS

In this work, haptic robot control protocols were integrated into a teleoperation solution where an industrial robot located at Bristol Robotics Laboratory was operated from the National Composites Centre. The need for robot teleoperation within the industry remains for use-cases where the operating environment is too hazardous for direct human operation and too complex for automation. To make further steps in robot teleoperation there is a need to develop intuitive systems that allow an operator to control the robot with confidence. A system was proposed that used hand tracking, haptic feedback and an immersive experience to actuate a robotic arm from a distance for which optical fibre and network cables were used to facilitate the network needs. The aim for this feasibility research project was stated as follows.

“To determine the feasibility of 5G connectivity elements in a robotic arm teleoperation scenario where haptic control is used”

In order meet the aim of this project a teleoperation solution was created. This required the creation of a teleoperation network, a haptic robot arm actuation solution and an immersive experience. These were all successfully created within the duration of the project.

To control the robotic arm a haptic hand tracking device was used. A haptic protocol developed in a previous research project was used to translate the input of the operator to the output of the robot. The so-called PTV (Position to Velocity) translates the position of the operator’s hand to a velocity vector placed on the robot’s tool centre point. The virtual robot arm follows the movement of the desired tool centre point (TCP) and actively calculates its joint angles using inverse kinematics. These joint angles are then sent to the physical robot using a direct “Transmission Control Protocol” connection.

The immersive experience used is enabled by a combination of stereo camera and VR-headset. The stereo camera had its feed encoded and directly streamed to the computer that ran the operational control application. This feed was then encoded by the computer and used within the application. The VR-headset allows for the operator to gain a sense of depth of field which directly impacts the operational performance.

The teleoperation network consisted of differing networking bandwidth capabilities. In an effort to reduce the project schedule risk the network was cabled, and a benchmark created from which future 5G integration can be tested. In the centre of the network is an optical fibre connection that connects Bristol Robotics Laboratory to the National Composites Centre. This connection was able to have a bandwidth of up to 10 Gbps. The rest of the major connections were limited by CAT 6 Ethernet cables and standard issue network adaptors meaning that the overall max bandwidth of most parts on the network was 1 Gbps.

To determine the solution's network requirements a number of tests were conducted. During these tests all systems that make up the teleoperation solution were used. This means that a camera was sending footage from Bristol Robotics Laboratory to remote operator whilst that operator was actuating the robot arm from the National Composites Centre. During these trials a maximum bandwidth of 27 Mbps was measured. The current 5G networking capability allows for an uplink of 57 Mbps and a downlink of 410 Mbps. It is concluded that the current 5G capacity meets the requirements of this solution and potentially has capacity for some other users on the radio interface in use.

An additional demonstrator was created as an extra deliverable on top of the project deliverable. This demonstrator shows the solution working to pick and place items in a nuclear decommissioning operation.

[1] Emiel Evert Hendrik Bos. Haptic control protocols for simulated industrial robot control, 2021. 1, 4, 8, 10, 11, 15, 22

[2] Guanglong Du, Ping Zhang, Jianhua Mai, and Zeling Li. Markerless kinect-based hand tracking for robot teleoperation. *International Journal of Advanced Robotic Systems*, 9, 2012. 4, 5

[3] Goran Vasiljevic, Nikola Jagodin, and Zdenko Kovacic. Kinect-based robot teleoperation by velocities control in the joint/cartesian frames. volume 45, 2012. 4, 5

[4] Jose Avalos and Oscar E. Ramos. Real-time teleoperation with the baxter robot and the kinect sensor. volume 2018-January, 2018. 4

[5] D. Bassily, C. Georgoulas, J. Gu¨ttler, T. Linner, and T. Bock. Intuitive and adaptive robotic arm manipulation using the leap motion controller. 2014. 4

[6] Sunjie Chen, Hongbin Ma, Chenguang Yang, and Mengyin Fu. Hand gesture based robot control system using leap motion. volume 9244, 2015. 4, 7, 8

[7] Bin Fang, Di Guo, Fuchun Sun, Huaping Liu, and Yupei Wu. A robotic hand-arm teleoperation system using human arm/hand with a novel data glove. 2015. 4, 6

[8] Jeremy A. Fishel, Toni Oliver, Michael Eichermueller, Giuseppe Barbieri, Ethan Fowler, Toivo Hartikainen, Luke Moss, and Rich Walker. Tactile telerobots for dull, dirty, dangerous, and inaccessible tasks. 2020. 4, 5, 6

[9] Michal T¨olgyessy, Martin Dekan, Lubo˘s Chovanec, and Peter Hubinsky´. Evaluation of the˘ azure kinect and its comparison to kinect v1 and kinect v2. *Sensors (Switzerland)*, 21:1–25, 1 2021. 5

[10] Frank Weichert, Daniel Bachmann, Bartholom¨aus Rudak, and Denis Fisseler. Analysis of the accuracy and robustness of the leap motion controller. *Sensors (Switzerland)*, 13:6380–6393, 5 2013. 6

[11] Giulio Marin, Fabio Dominio, and Pietro Zanuttigh. Hand gesture recognition with leap motion and kinect devices. 2014. 7

[12] A. H. Butt, E. Rovini, C. Dolciotti, G. De Petris, P. Bongioanni, M. C. Carboncini, and F. Cavallo. Objective and automatic classification of parkinson disease with leap motion controller. *BioMedical Engineering Online*, 17, 2018. 7

[13] Bin Hu and Jiacun Wang. Deep learning based hand gesture recognition and uav flight controls. *International Journal of Automation and Computing*, 17, 2020. 7

[14] UltraLeap. Introducing leapuvc: A new api for education, robotics and more. https://blog. leapmotion.com/leapuvc/, 2018. [Online; accessed 14-Sep-2021]. 7

[15] UltraLeap. How to build your own leap motion art installation. https://medium.com/@LeapMotion/building-a-leap-motion-art-installation-38062e085955, 2015. [Online; accessed 14-Sep-2021]. 7

[16] Mehdi Sobhani, Manuel Giuliani, Alex Smith, and Anthony G Pipe. Robot teleoperation through virtual reality interfaces: Comparing effects of fixed and moving cameras. volume 2657, pages 1–9. CEUR-WS, 2020. 9

119 APPENDIX

NetPerSec Results

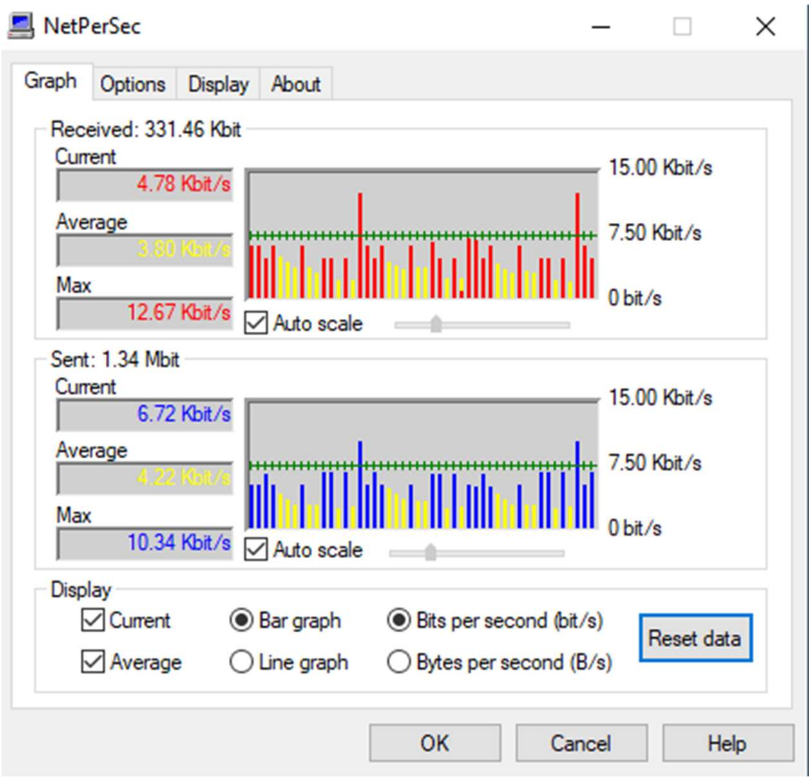


Figure 240: NetPerSec baseline

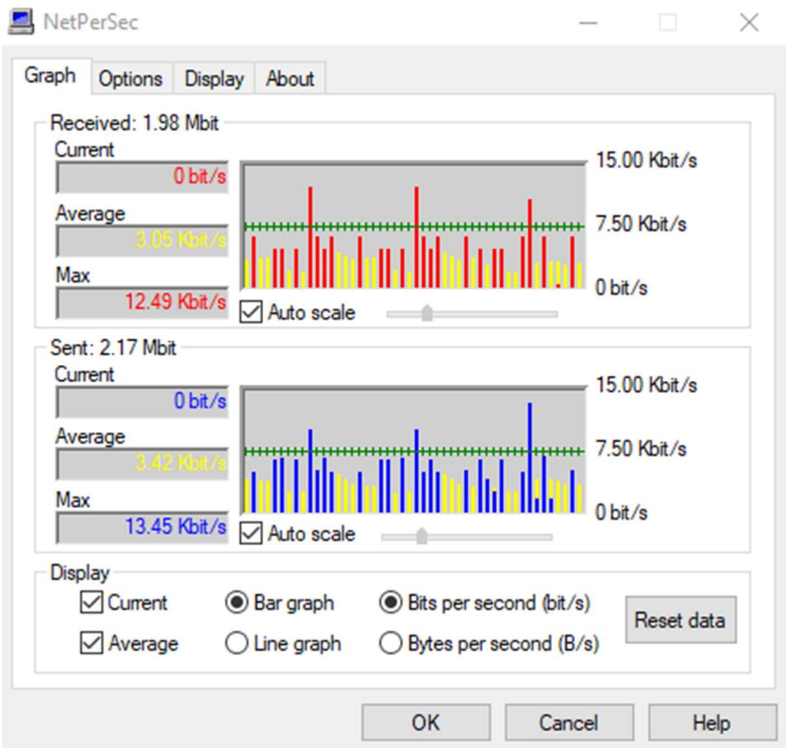


Figure 241: NetPerSec application idle

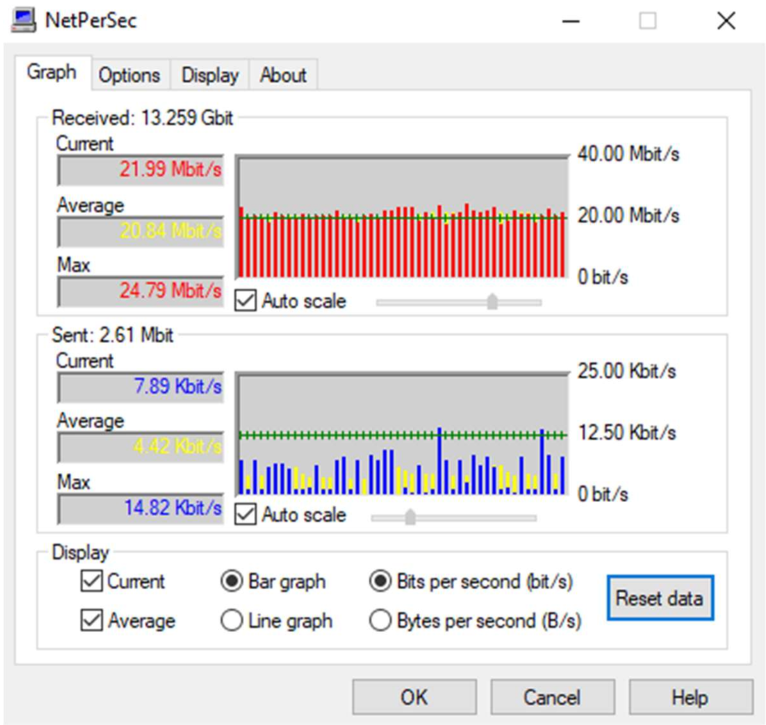


Figure 242: NetPerSec application camera

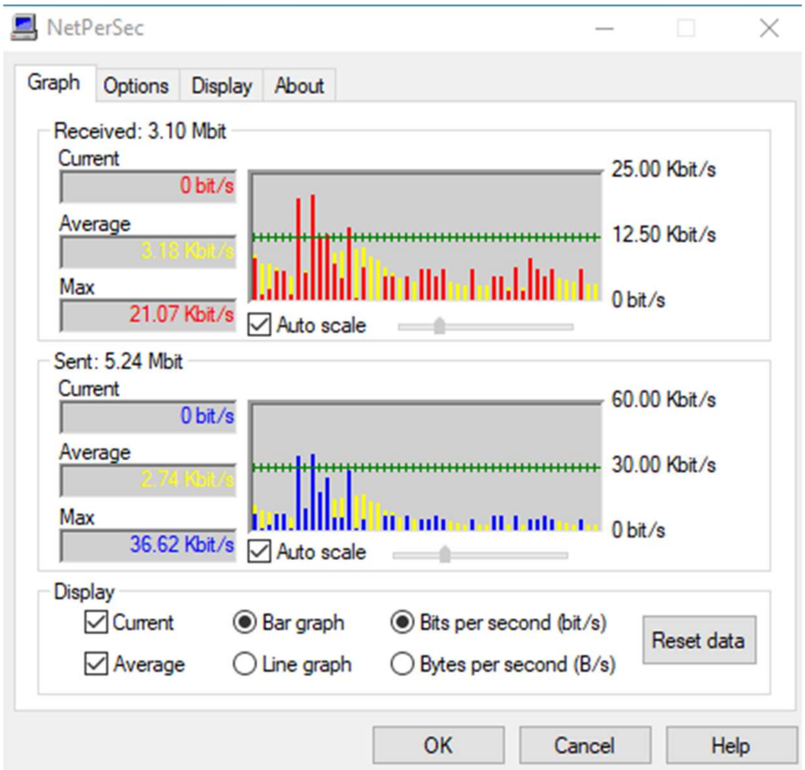


Figure 243: NetPerSec robot moving no camera

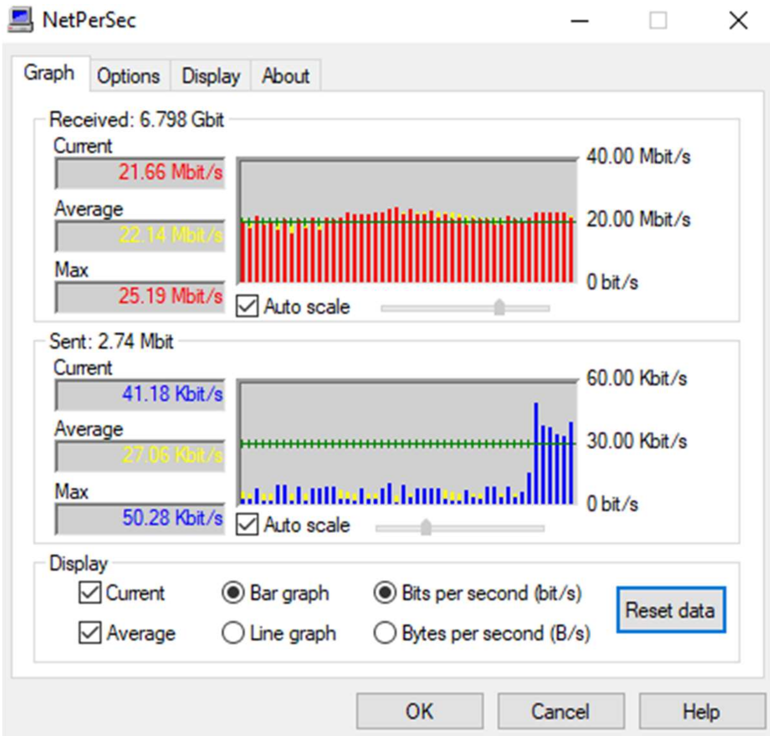


Figure 244: NetPerSec robot moving camera

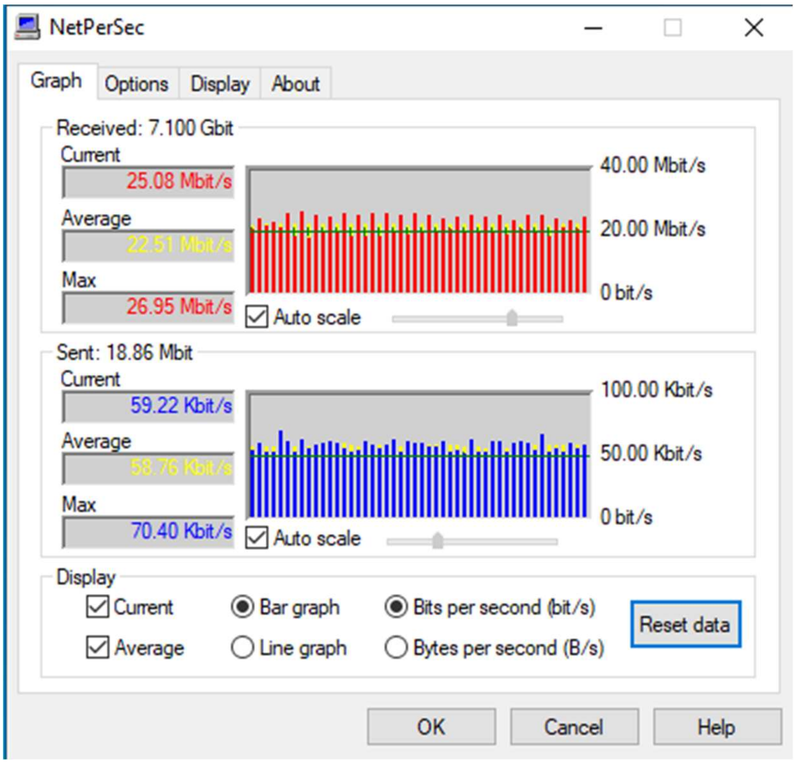


Figure 245: NetPerSec robot not moving camera

120 PLATFORM COMMISSIONING

121 ABOUT 5G-ENCODE

The 5G-ENCODE Project is a £9Million collaborative project aiming to develop clear business cases and value propositions for 5G applications in the manufacturing industry. The project is partially funded by the Department for Digital, Culture, Media, and Sport (DCMS), of the UK government as part of their 5G Testbeds and Trials programme. The project is one of the UK's biggest investments in using 5G to modernise manufacturing.

The key objective of the 5G-ENCODE project is to demonstrate the value of 5G as part of industrial use case delivery within the composites manufacturing industry. It is designed to validate the idea that using private 5G networks in conjunction with new business models can deliver better efficiency, productivity, and a range of new services and opportunities that would help the UK lead the development of advanced manufacturing applications.

The project will play a key role in ensuring that the UK industry exploits the 5G technology and remains a global leader in the development of robust digital engineering capabilities when implementing complex composites manufacturing processes.

The project will highlight how 5G features such as neutral hosting and network slicing can be applied to transform a private 5G network into a dynamically reconfigurable network able to support a wide range of applications (URLL/eMBB/MMTC) including industrial applications of Augmented Reality/Virtual Reality (AR/VR), asset tracking of time sensitive materials and automated industrial control though IoT monitoring and big data analytics. Such a dynamic network would enable new business models and creation of bespoke virtual networks tailored to specific applications or use cases.

A state-of-the-art test bed was deployed across three sites centred around the National Composites Centre in the Southwest of England. In support of the West of England Combined Authority (WECA) industrial strategy, the NCC plans to keep the test bed as an open access facility for the experimentation and development of new products and services for the composites industry after the completion of the 5G-Encode project. The location and nature of NCC's business would ensure the creation of an industrial 5G ecosystem involving multiple industry sectors and SMEs.

1. INTRODUCTION

This report contains the journey of specification, design, and implementation of the Open Radio Access Network (ORAN), 5G Stand Alone (SA) Private Cellular Network (PCN) installed at the National Composites Centre (NCC), Emersons Green, Bristol, and is targeted at IT professionals. This 5G SA PCN provides the foundation to the government backed Department of Digital, Culture, Media, and Sport (DCMS) 5G-Encode research project which has the overall goal to enable industrial use case demonstrators that springboard 5G technology within a manufacturing environment.

2. JOURNEY

This section contains an insight into the implementation from a System Integrator's perspective (in this case the Infrastructure & Security Lead for the NCC Digital Business Unit) to deploy the 5G SA PCN. For each stage there is a deep dive of the process used to move from conception to vendor selection and deployment. Documented, in this section, are the challenges, workarounds and solutions faced during the integration.

2.1. Requirements

At conception, it was very apparent that a 5G PCN had a more moving components than its 4G PCN predecessor and as such vendor support (in this case Airspan Networks) was critical in ensuring the architecture was correct. This is due to the Open RAN nature of the deployment, which sees collaboration between non-proprietary equipment makers to create an end-end solution based on interoperability and open standards. Provided the equipment meets open RAN standards it should be compatible with equipment from other vendors that share these standards. Open RAN is favourable in private networks as it can create a more cost-effective and innovative solution when distinct functions are sourced from independent specialist suppliers.

Airspan Networks consulted with the lead partner on the Encode Project (Zeetta Networks) to fabricate the High-Level Design (HLD) to identify and plan all hardware and software components needed. The Low-Level Design (LLD) was then created ready for system integration. The following section contains both the HLD and the LLD as well as all components selected for deployment.

2.2. Architecture

Airspan's ORAN architecture supports the split architecture as depicted in Figure 1 where a gNodeB is composed of the following network functions:

- Radio Unit (RU): Handles the digital front end and the parts of the PHY layer
- Distributed Unit (DU): Located in proximity (in sense of timing) to the RU and handles the RLC, MAC, and parts of the PHY layer.
    - DU is a virtual network function that runs over commercial off-the-self servers.
- The Centralised Unit (CU):

- Centralised Unit - Control Plane (CU-CP): A logical node hosting the Radio Resource Control (RRC) and the control plane part of the Packet Data Coverage Protocol (PDCP) of the gNodeB-CU for a gNodeB (5g New Radio base station). The gNodeB-CU-CP terminates the E1 interface connected with the gNodeB-CU-UP (User Plane) and the F1-C interface connected with the gNodeB-DU (Distributed Unit).
- Centralised Unit - User Plane (CU-UP): A logical node hosting the user plane part of the PDCP protocol and the Service Data Adaption Protocol (SDAP) protocol of the gNodeB-CU for a gNodeB. The gNodeB-CU-UP terminates the E1 interface connected with the gNodeB-CU-CP and the F1-U interface connected with the gNodeB-DU.
- Both CU-CP and CU-UP are virtual network functions that run over commercial off-the-self servers.

Figure 246: Open RAN Split Architecture

- The front-haul between the RU and the DU is using Split 7.2a per O-RAN definition.
- The mid-haul between DU and CU is Split 2 (F1 interface) as defined by 3GPP.
- The back-haul between CU and the 5G Core (5GC) includes N2/N3 interfaces as defined by 3GPP.

Coverage requirements of NCC headquarters in Emersons Green, Bristol, drove the scale requirements of the Radio Access Network (RAN). The budget for equipment was considered to minimise investment where possible.

A remedial survey was carried out based on experience with the 4G deployment to indicate the most suitable locations for the 5G radio units (RU) and determine the number of RUs required to cover the workshop spaces with 5G connectivity. Environmental Radio Frequency (RF) interference was also taken into consideration and an overlap was also considered in this process for resilience. The chosen radio locations are shown below in Figure 2.

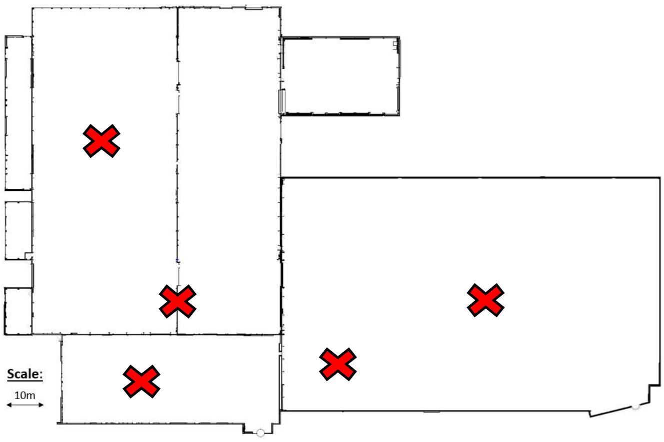


Figure 247: Floor Plan of the Workshop Area at NCC Emersons Green, Bristol

After establishing Radio Unit locations, the system requirements to manage these RUs was designed and equipment procured. The HLD was updated after consultation with Airspan Networks.

2.2.1. High Level RAN Overview

The HLD displayed in Figure 3 below allows for 4 x Radio Units connected to the relevant back-end components that make up the RAN. There is a maximum of a 2 to 1 relationship between the Radio Units (RUs) and the Distributed Units (DUs) and all DUs talk back to a single Centralised Unit (CU) in a tiered format.

A decision was taken to not to provide full coverage in one area of the workshop to reduce RAN infrastructure cost. The RU removed from the coverage plan being planned for a future installation activity as the RAN product matures and this RU can be supported within the infrastructure purchased for the 4 x RUs planned for initial deployment.

NB: The requirement for complete coverage at NCC Emersons Green transpired to be 5 x RUs so the decision to carry 1 x RU for future use meant that coverage in one area was sub-optimal. This would not affect use case execution.

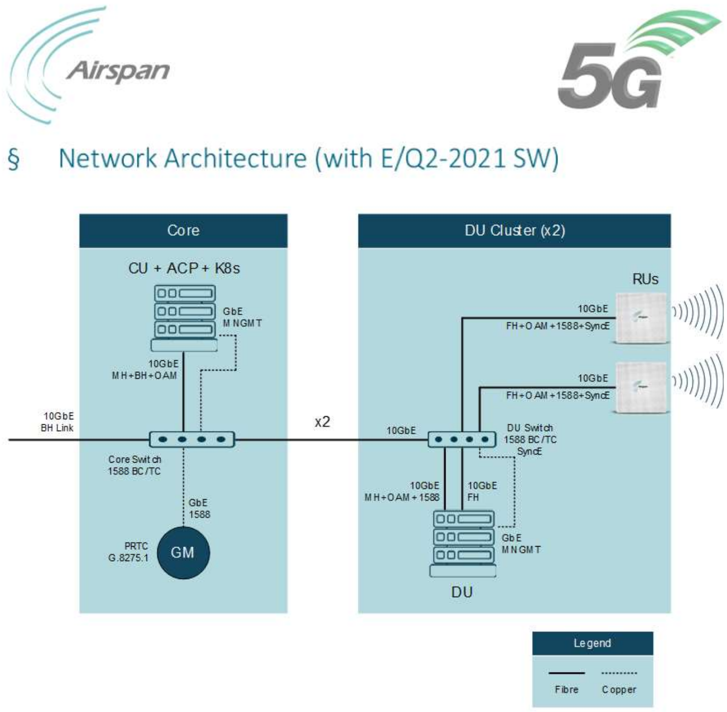


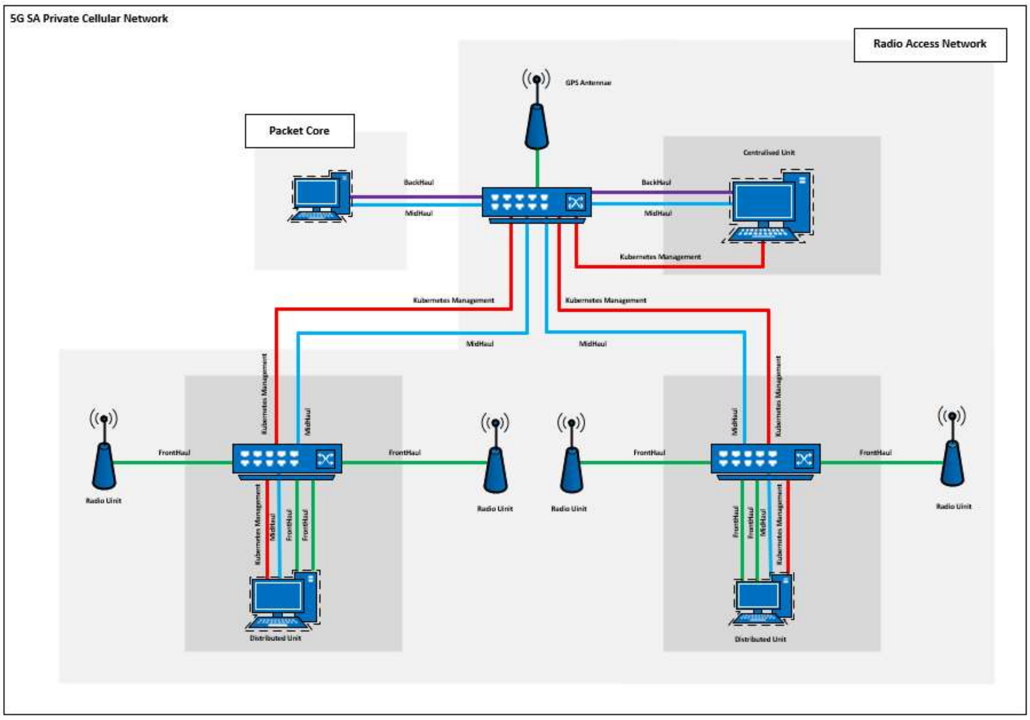
Figure 248: 5G RAN High Level Design Provided by Airspan Networks

A set of hardware requirements accompanied this design to allow for all relevant software to run in an optimised manner, this is discussed in a later section.

2.2.2. Low Level RAN Overview

The LLD iterations in Figure 4 to Figure 8 expand on the previous section and add the related network segments to allow for intercommunication between 4 x RUs and the supporting Distributed Units (DUs), Centralised Unit (CU) and Packet Core. IP Addressing can be any RFC1918 address schema. For the purposes of the project the concept of front, mid and backhaul addressing was implemented, and the IP addresses shown in Figure 5 used. Precision Time Protocol needs are discussed in later sections.

Note: The LLD was created in collaboration between Zeetta Networks and NCC. It is presented in a layered approach to enable easier reading, larger diagrams can be found in the appendices.



Legend:

- Kubernetes Management:
- Front-Haul:
- Mid-Haul:
- Back-Haul:

Figure 249: RAN LLD Provided by Consortium (Network Segments)

A larger diagram can be found in Appendix A.

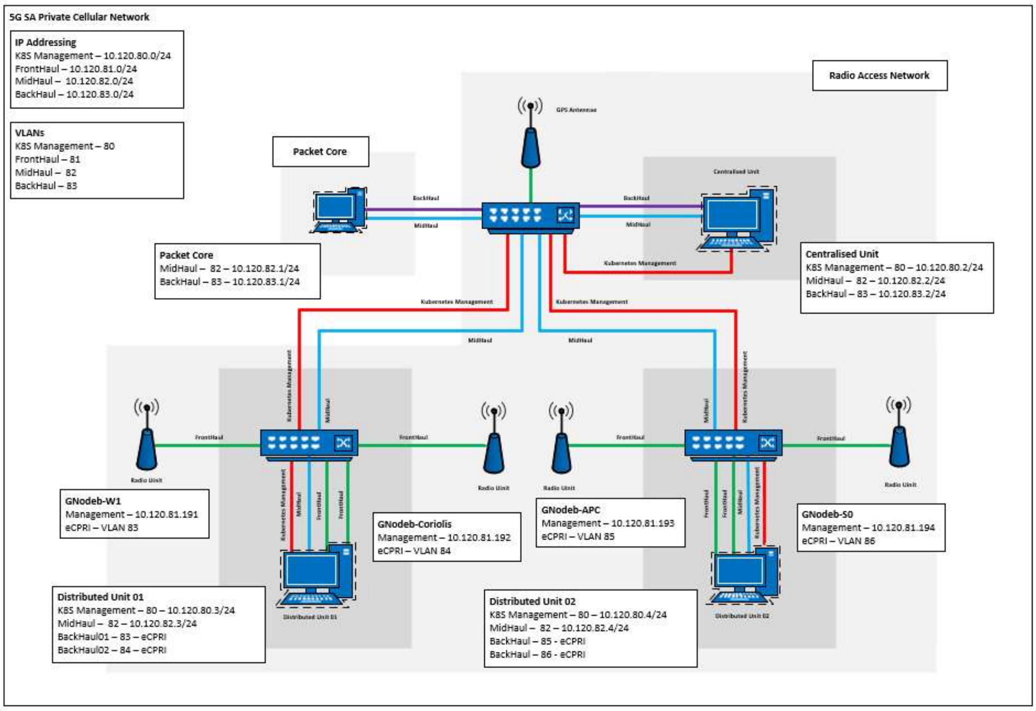


Figure 250: RAN LLD Provided by Consortium (VLANs & IP Addressing)

A larger diagram can be found in Appendix B.

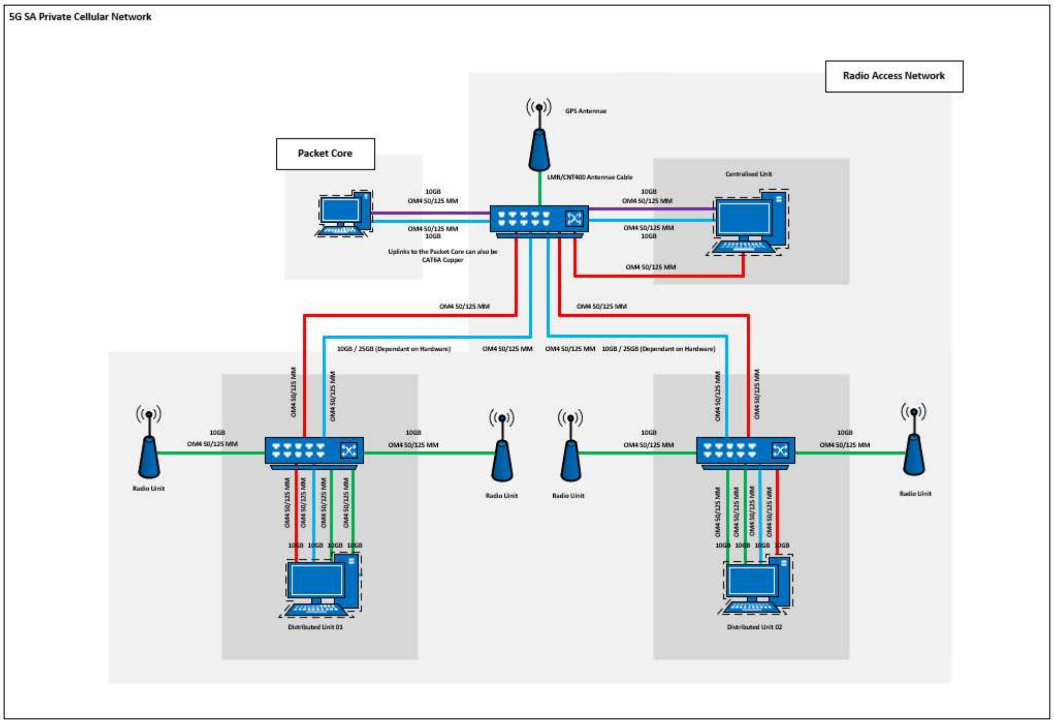


Figure 251: Physical Connectivity

A larger diagram can be found in Appendix C.

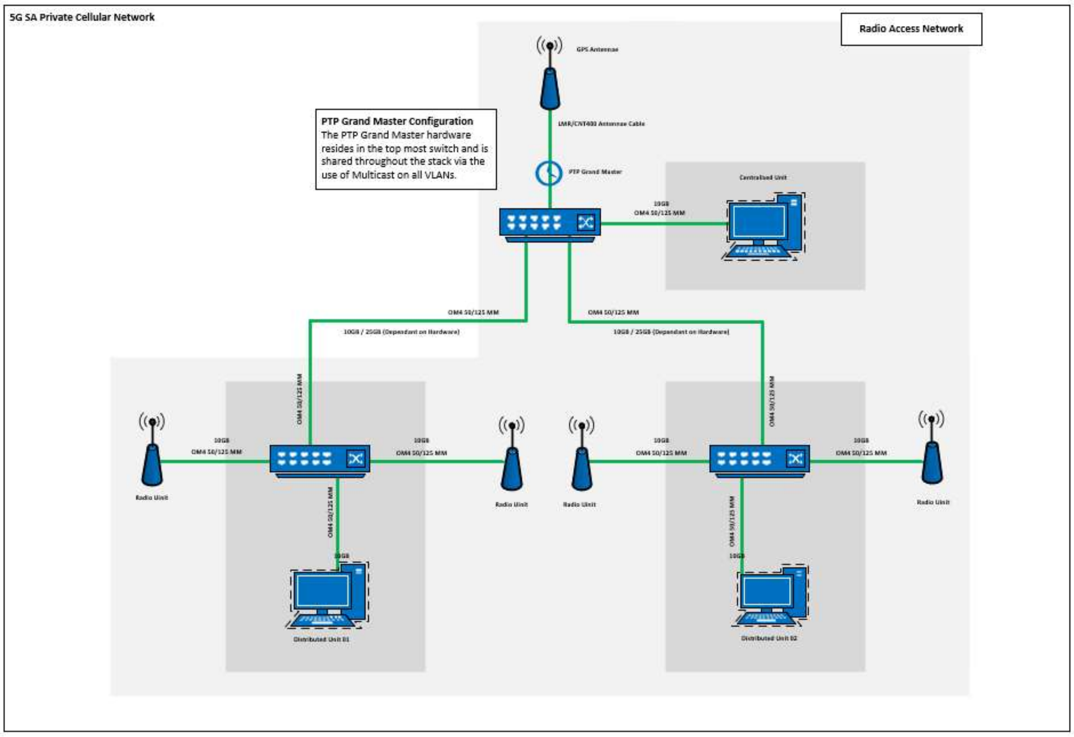


Figure 252: RAN with PTP Clock Integration

A larger diagram can be found in Appendix D.

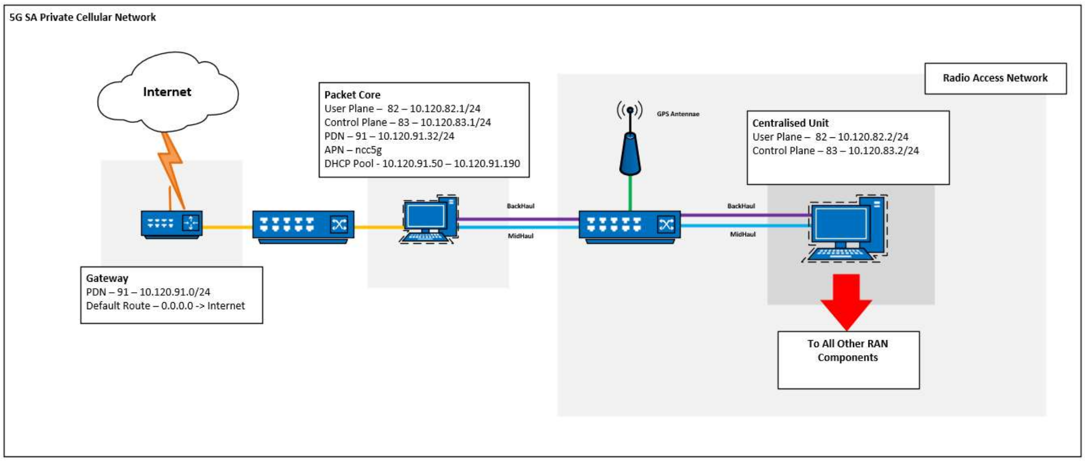


Figure 253: Packet Core Integration

A larger diagram can be found in Appendix E.

Hardware and software selection was limited to vendor interoperability and supported configurations and as such are discussed in later sections.

2.3. Hardware Selection

The following section lists out the hardware specification for each of the components required to deliver the overall solution.

2.3.1. Compute Function

The RAN vendor, Airspan Networks, listed the following server hardware for their supported configuration for the deployment at NCC Emersons Green:

- 1 x Centralised Unit
  - 1 x Dell R740 Chassis
  - 1 x PowerEdge R740/R740XD Motherboard
  - 2 x Intel Xeon Gold 5218R 2.1G, 20C/40T, 10.4GT/s, 27.5 M Cache, Turbo, HT (125W) DDR4-2666
  - 1 x Chassis with up to 8 x 2.5" SAS/SATA Hard Drives for 2CPU Configuration
  - 1 x PowerEdge 2U LCD Bezel
  - 1 x Riser Config 5, 6 x8, 2 x16 slots
  - 12 x 16GB RDIMM, 3200MT/s, Dual Rank
  - 1 x iDRAC9, Enterprise
  - 2 x 960GB SSD SATA Read Intensive 6Gbps 512 2.5in Hot-plug AG Drive, 1 DWPD, 1752 TBW
  - 1 x PERC H330 RAID Controller, Low Profile

- 1 x Dual, Hot-plug, Redundant Power Supply (1+1), 750W
- 1 x Trusted Platform Module 2.0
- 2 x Intel XXV710 Dual Port 10/25GbE SFP28 Adapter, PCIe Full Height
- 1 x Intel X550 Quad Port 10GbE BASE-T, rNDC

- 2 x Distributed Units
  - 1 x Dell R740 Chassis
  - 1 x PowerEdge R740/R740XD Motherboard
  - 2 x Intel® Xeon® Gold 6240R 2.4G, 24C/48T, 10.4GT/s, 35.75 M Cache, Turbo, HT (165W) DDR4-2933
  - 1 x Chassis with up to 8 x 2.5" SAS/SATA Hard Drives for 2CPU Configuration
  - 1 x PowerEdge 2U LCD Bezel
  - 1 x Riser Config 6, 5 x8, 3 x16 slots
  - 8 x 32GB RDIMM, 3200MT/s, Dual Rank
  - 1 x iDRAC9, Enterprise
  - 1 x 960GB SSD SATA Read Intensive 6Gbps 512 2.5in Hot-plug AG Drive, 1 DWPD, 1752 TBW
  - 1 x PERC H330 RAID Controller, Low Profile
  - 1 x Dual, Hot-plug, Redundant Power Supply (1+1), 750W
  - 1 x Trusted Platform Module 2.0
  - 2 x Intel XXV710 Dual Port 10/25GbE SFP28 Adapter, PCIe Full Height
  - 1 x Intel X550 Quad Port 10GbE BASE-T, rNDC
  - 1 x Silicom eASIC ACC100 FEC Accelerator, PCIe Full Height

Note: Vendor recommended SFP/SFP+ modules are installed in all network cards.

2.3.2. Switching

The lead partner, Zeetta Networks, listed the following LAN hardware for the interconnectivity between RAN components:

- ADVA FSP150-XG118PRO

The above device is classed more as an Ethernet Demarcation Device as it can manage traffic flows at a lower level than your “out-of-the-box” switch. The device has 8 ports and is designed to provide connectivity specifically designed for 5G implementations with the additional facility to provide edge compute capacity where required.

Note: All upstream connectivity from the 5G stack uses standard switching and vendor recommended SFP/SFP+ modules installed in all network hardware.

2.3.3. Timing

The lead partner, Zeetta Networks, listed the following time clock hardware for the 5G stack:

- Oscilloquartz OSA5401

The above device is a Small Form-Factor Pluggable GNSS receiver and plugs into the above referenced network hardware to provide GPS based precision timing compliant with G8275.1 on the LAN to synchronize the RAN devices. The features embedded in the ADVA FSP150-XG118PRO then share this time synchronisation across other units via multicast on all VLANs. The antenna for the device is attached to a 120m cable via risers inside the fabric of the building to the roof for reliable GPS connectivity.

2.3.4. Radio Units

The RAN vendor, Airspan Networks, listed the following RU hardware for their supported configuration for the deployment at NCC Emersons Green:

- Airspan AirVelocity 2700

Airspan Networks AirVelocity 2700 has the following features required to facilitate 5G connectivity:

- 4T4R Tx/Rx Paths
- Up to 100 MHz Bandwidth
- 2+ Gbps
- CBRS Supported
- Split 7.2x

All connectivity provisioned to the radios is 10GB leveraging specific LC SFP+ Modules and are listed as the following:

- Multi-Mode - Finisar FTLX8574D3BCL
- Single-Mode - Finisar FTLX1475D3BCL

All RU SFPs at NCC Emersons Green use Finisar FTLX8574D3BCL (Multi-Mode) modules for connectivity.

2.4. Software Selection

The following section details the Operating Systems, pre-requisites and operational software required to enable the RAN and Packet Core to function as a complete Private Cellular Network. All Operating Systems are Linux based with a Kubernetes (K8S)/Kernel-based Virtual Machine (KVM) overlay.

2.4.1. Operating Systems

Operating Systems are installed on the hardware specified in section 2.3.1 and are part of the build document supplied by the RAN vendor. All Operating Systems are Linux based and are a CentOS version. CentOS 7 is the long term supported distribution that runs as the underlying Operating System to a Kubernetes cluster and host Operating System for KVM hypervisor.

CentOS 8 is used to underpin Airspan's ACP software that controls all containers relating to the Virtual Radio Access Network (vRAN) deployment (CU and DU software). This part of the deployment is a virtual machine configuration.

2.4.1.1. Challenges

Specific Operating System versions were quoted by the RAN vendor (Airspan Networks) and not the current release. As such a legacy version was obtained and installed. Special considerations were required to ensure these operating systems are deployed on a security compliant network with minimal attack vectors e.g. the installations were restricted from accessing the internet and other parts of the wider LAN.

2.4.2. Packet Core

The Packet Core is installed on a virtual machine upstream from the Radio Access Network. The Packet Core selected by the lead partner, Zeetta Networks. was a Druid Raemis 5G SA system with HSS+ enabled. HSS+ allows for the SIM database to be referenced on an the already existing 4G Packet Core as opposed to having its own integrated SIM database. This means that devices can use a common SIM to authenticate to and access either the 4G or 5G RAN. The Packet Core uses Back-haul and Mid-haul connectivity to manage the user control plane and route the user data plane through the RAN to the internet and edge compute resources.

The packet core is installed on the latest CentOS 7 Operating System on a virtual machine on separate hardware to the previously discussed 5G stack.

2.4.2.1. Challenges

Druid's support team were engaged at through both the Packet Core integration and subsequence RAN integration phases of the project to diagnose and resolve encountered issues.

SIMs using the Public Land Mobile Network (PLMN) ID of 001 01 were imported into the 5G packet core and used on some CPE/UE devices to enable the successful attach and data flows for devices with 5G SA limitations that included being limited to that PLMN ID. This configuration issue is discussed further in section 2.7.

Note: A PLMN ID is comprised of two parts; a 3-digit Mobile Country Code (MCC) and a 2-digit Mobile Network Code (MNC)

2.4.3. RAN

RAN software provided by Airspan was selected for the project by Zeetta Networks considering availability, capability and cost. This software is installed on hardware platforms with Operating Systems as discussed in 2.4.1. The construct of this software is a combination of physical installations sitting on bare metal hardware, Kubernetes containers and virtual machine deployments. The physical installation on both CU and DU hardware was preceded by a substantial pre-requisite list with specific versions of software needed to prevent impact on the performance of the solution when in use, a significant element was the Kubernetes configuration.

Kubernetes is installed with network plugins (specifically Flannel & Multus) to allow for clustering of the three servers listed in section 2.3.1 and to run containers that are pre-configured for specific functions throughout the deployment. All containers are monitored and configured from the Airspan Control Platform (ACP).

ACP was installed to run on a virtual machine located on the Centralised Unit hardware. It is a tiered web application with a Linux derivative of a Microsoft SQL back end containing all configuration data. The version of Microsoft SQL will depend on the scale of the deployment and the retention requirements of logs and metrics. This project utilised Microsoft SQL Express.

2.4.3.1. Challenges

The software is a constantly evolving product due to the immaturity of the Open RAN technology. The installation and configuration consistently encountered multiple challenges in both stability and performance of the product. The pre-requisite software configuration required modification on multiple occasions to enable optimisation of the hardware and new releases of the vRAN to be installed. During the project the product evolved into significantly more stable and reliable solution that is installed today. These issues are described in more detail in section 2.5.4.

2.4.4. Monitoring & Statistical Analysis

Monitoring & statistical analysis was performed via two functions:

1. Cellular statistics were generated by the ACP platform and visualised by the engineering team at Zeetta Networks

2. Live network metrics were captured and provided by Accedian using their Skylight product

Accedian used a hybrid approach that allowed for a mixture of in-line hardware probes, port mirroring configuration, docker based software probes and Android applications used on UE devices. The probes enabled an end-to-end transparent picture of network metrics and availability to be visualised.

To visualise the network, in-line hardware probes were implemented on every uplink between the back-end hardware. Probe detection was configured on each link to create full transparency. A port mirror was configured on the uplink to the gateway for application detection on ingress/egress traffic on the 5G VLANs and the associated metrics for uplink/downlink speeds. Software probes were located inside each use case VLAN allowing for part of the end-to-end visualisation and the Android software allowed for metrics to be generated on the end device (in this case a UE) to visualise real-time 5G metrics.

All data to be analysed was sent to a centralised Accedian software installation that processed receiver data and sent to an online portal for visualisation and presentation to the end user.

2.4.4.1. Challenges

Due to the mainstream hardware vendor support of the software, there were compatibility issues with the upstream hardware from the 5G stack to detect some of the metrics. Specific models of EdgeCore hardware running PICOS (open networking stack) could not negotiate a connection with the SFP modules resulting in the inability to monitor traffic outside of the core. As such an alternative piece of equipment (an Accedian ANT) was installed in-line to mitigate the issue and capture the required metrics.

Further hurdles were faced when deploying some elements of the core server that all probes talk back to due to available hypervisor technology, other issues such as nested virtualisation also reared their head and are discussed in 2.5.5.

2.4.5. Software Defined Networking

The Software Defined Network solution was provided by lead partner, Zeetta Networks. The solution encompassed all aspects of the network allowing for VLAN creation, visualisation, and service control functionality. This developed as the project progressed to encompass routing and the ability to create APNs within the Packet Core. Solution upgrades were delivered as functions were completed. A separate instance of this solution was integrated into the remote NCCi site, at Filton. This instance along with a small 5G network was used to demonstrate a new SDN capability Multi-Domain Orchestration (Management of multiple sites from a centralised cloud-based platform).

2.4.5.1. Challenges

The routing between NCC Emersons Green and NCCi Filton had to be provisioned on an already "in-service" link so due diligence was necessary to enable connectivity. This was a timely process due to resource allocation within the NCC IT department.

Access during periods where COVID infection rates were high, and some employees were off work due to infection hindered the deployment timescales.

Features available at the time of implementation only covered Open Systems Interconnect (OSI) model Layer 2 configurations.

2.5. Deployment

The following section provides deployment information throughout the journey, specific configuration of components that overcome hurdles and the final configuration that is currently operational.

2.5.1. Computer Hardware

The DU servers suffered repeated stability issues. Investigation revealed the hardware specification of the DU server recommended by Airspan conflicted with hardware capabilities of the R740 platform provided by Dell. Airspan Networks specify a set number of cores within their requirements documentation for the DU server and later iterations of the documentation state that the deployment requires a single processor configuration, this was not possible due to the number of slots required to allow for network connectivity and an (Field Programmable Gate Array) FPGA card.

2.5.1.1. Challenges

The system was installed in a resilient configuration and subsequently altered to the Airspan recommended configuration. The consequences of this alteration created some constraints in system robustness that need documenting. These are as follows: with the requirement to leverage multiple PCIe risers within the specified chassis it was necessary to have multiple processors. This did not align with the Airspan single processor configuration as per the documentation as the removal of one of these processors would result in loss of functionality of a Peripheral Component Interconnect Express (PCIe) riser causing a network card installed in the riser to move to an offline state. An increased number of PCIe risers within an R740 platform requires an additional CPU to be brought on-line. Loss of connectivity to a card would result in loss of either the Front-haul, Mid-haul, or Kubernetes Management networks. The Airspan configuration required that all ports carrying the enhanced Common Public Radio Interface (eCPRI) protocol to arrive onto the riser hosting the FPGA Card. To enable other links to be connected to the platform these were positioned on the other riser hosted by the second CPU.

DU Processor upgrades were required to accommodate the overall number of cores on a single processor as opposed to the correct number of cores split across both processors. The processor configuration also had to accommodate the number of PCIe risers required to support 4 x SFP modules, a storage controller, and an FPGA card. Airspan Networks supported a dual processor configuration for a virtual “all in one” deployment that accommodated the previously mentioned core requirement, so these chips were specified (upgraded from Intel Xeon Silver in a dual socket configuration to Intel Xeon Gold dual socket configuration) and installed.

Post-processor upgrades the configuration also allowed for redundancy across network interface cards for the radio units (split eCPRI interfaces per network card). When the radio eCPRI interfaces were brought online the radios were showing what appeared to be an out-of-sync time source. Further investigation proved that when a single radio was online the issue was not present. The issue was escalated to Airspan Networks to which it was discovered that both eCPRI interfaces needed to be configured on the network card on the same riser as the FPGA card and separating these will cause a slight time delay. Figure 9 below displays the layout of an R740, the final layout of the hardware configuration for the 5G vRAN DU application is also displayed.

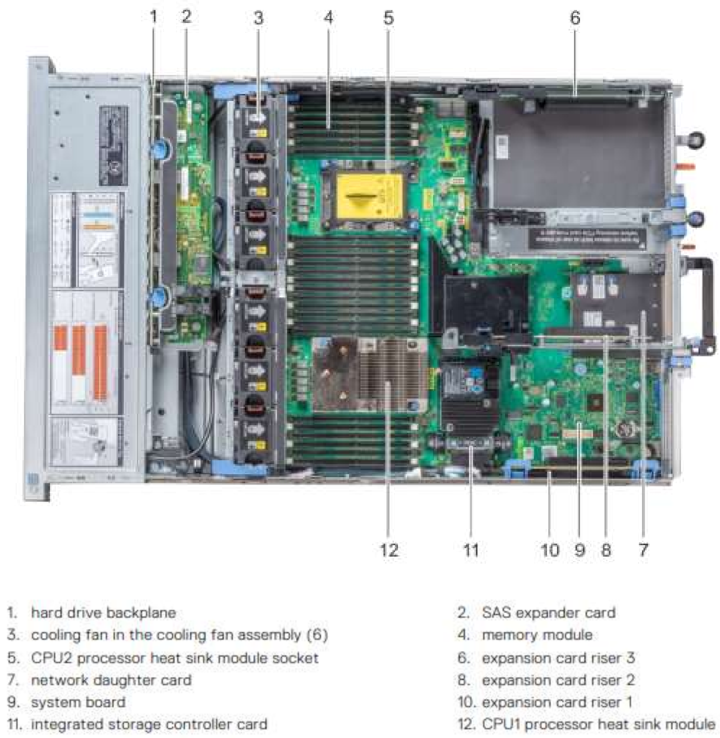


Figure 254: Dell R740 DU Physical Layout

Airspan Specific Hardware Configuration:

Hardware Location Reference	Item Description	Use
12	CPU1 Location	Processing power for container software
5	CPU2 Location	Processing power for container software
6	Expansion Card Riser 3 – Dual Port SFP+ Intel NIC	Mid-Haul & Kubernetes Management networks
10	Expansion Card Riser 1 – Dual Port SFP+ Intel NIC	eCPRI to Radio Units (1 per Radio Unit)
8	Expansion Card Riser 2 – PERC H330	RAID controller for hard disk redundancy

NB: All other RAN computer hardware specification is as recommended by Airspan Networks.

2.5.2. Network Hardware

The ADVA FSP150-XG118PRO is a Telco grade switch designed to work with 5G environments, as such this style of switching is new to most enterprise network engineers. Specialist configuration support and engineer training was required.

2.5.2.1. Challenges

Due to the niche nature of the above product, the lack of understanding made troubleshooting issues (namely the Precision Time Protocol (PTP) time synchronisation issue) in a timely manner challenging and requiring engagement of professionals from all suppliers.

2.5.3. Operating Systems with Kubernetes & KVM Hypervisor

2.5.3.1. Centralised Unit (CU)

As stated previously, the CU server is built on a CentOS 7 platform with KVM Hypervisor installed on it. It also acts as a worker node within a Kubernetes cluster. The installation is based on CentOS7 1908 with "Infrastructure Server" and "Development Tools" selected on installation. The pre-requisite installation files provided by Airspan Networks make up the rest of the bare metal installation.

NB: all versions of the software and pre-requisites are to be kept "as is" until further mainstream releases of containers are provided by Airspan Networks.

2.5.3.1.1. Kernel Virtual Machine (KVM) Hypervisor

KVM is installed as part of the pre-requisite installation and configuration. This component allows for virtual machines to run on the bare metal and function as a hypervisor. Airspan Networks recommend that the Kubernetes Master (the unit that controls all containers and workers within Kubernetes) run on a virtual machine on the CU hardware.

This virtual machine requires network connectivity to the Kubernetes Management network and due to the selection of operating system it is necessary to create a network bridge for interaction between the host and the virtual machine.

2.5.3.1.2. Kubernetes (K8S)

Kubernetes is required to underpin the containers running on the network that form the vRAN. The Kubernetes Control Plane virtual machine can talk to the worker nodes via a management network and communication between the pods are facilitated via the use of the Flannel and Multus add-ins. These plug-ins allow expansion and interactivity of virtual networking functions inside Kubernetes and take advantage of SR-IOV capabilities within the network interface cards leveraged as part of the hardware specification.

NB: The virtual network capabilities manifest themselves to the Operating System as additional network adapters with specific class A subnets associated with them.

Figure 10 below displays the architecture of the Kubernetes Cluster:

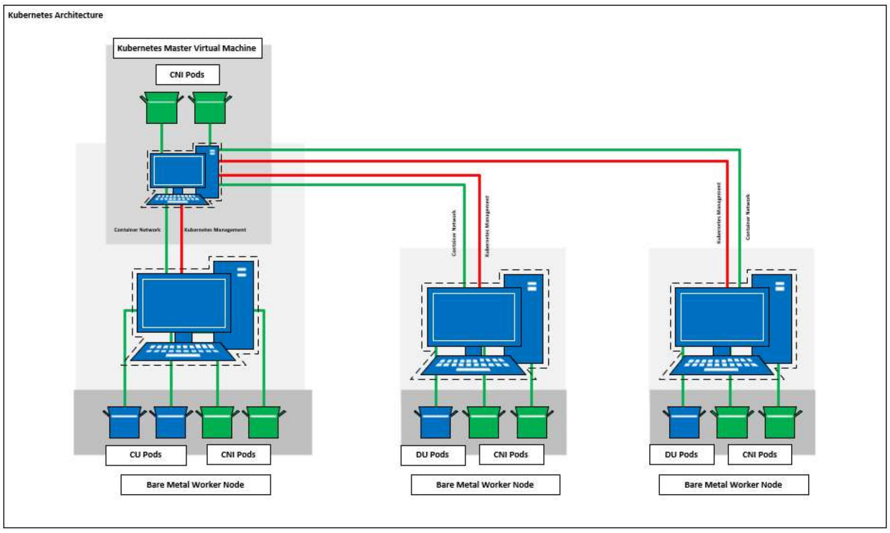


Figure 255: Kubernetes Cluster

Blue: Containers provided by Airspan Networks

Green: Container Network Interfaces (CNI) via Flannel & Multus Add-ins

NB: A larger diagram can be found in Appendix F.

After Kubernetes is installed to the Kubernetes Master virtual machine the add-ins are installed and the pods containing CNI configuration start. Each worker node added to the Kubernetes Master will then have pods deployed to it supporting the CNI and will start as soon as the node becomes available on the Kubernetes Management interface (this is always the interface that adds the node to the cluster).

When all nodes are added and pods containing CNI functionality start, the node switches to a “Ready” status and is available for the addition of pods containing third party applications.

2.5.3.2. Distributed Unit (DU)

The DU server is also built on a CentOS 7 platform. The installation is based on CentOS7 1908 with "Infrastructure Server" and "Development Tools" selected on installation. The pre-requisite installation files provided by Airspan Networks make up the rest of the bare metal installation.

NB: all versions of the software and pre-requisites need to be kept "as is" until further mainstream releases of containers are provided by Airspan Networks.

The DU servers have the most intensive workload of all servers in the deployment and post installation, are required to be added to the Kubernetes Cluster as worker nodes. When the third-party pods are deployed that make up part of the Virtual Radio Access Network (vRAN), they commandeer physical interfaces defined inside configuration files to send eCPRI traffic to the Radio Units. These physical interfaces are hidden from the base OS when active. The container software also leverages the FPGA card installed in the hardware via a direct access mapping (physical hardware presented to a virtual component) to deliver optimum performance on the Front-Haul networks.

2.5.3.3. Challenges

Throughout the entire deployment the underlying hardware required configuration to allow for single processor functionality in a unit that required dual processors to accommodate the number of expansion cards to support the correct number of attached radios. During deployment unexpected behaviour was experienced from multiple components. This unexpected behaviour includes instability of Kubernetes pods, resource spikes that eventually caused Operating System failure and intermittent connectivity to Radio Units. Investigation of the stability issues resulted in processor upgrade to the DU servers to be a match to an alternative, more powerful Airspan configuration. After processor upgrades the same behaviour was observed until a pre-requisite component, named "tuned", was configured to emulate a single slot processor for Kubernetes components whilst leaving all other available cores for the Operating System to leverage.

This resolved most of the issues although container restarts still happened intermittently, and Operating System freezes caused by resource consumption also occurred from time-to-time. The workaround for this was to enable Watchdog (a method of physically restarting a server via the use of an IPMI interface if a response from the host Operating System is not detected over a set period) to allow for recovery in the event of an issue being present. Containers were also restarted in a controlled manner via a cron job running on the Kubernetes Master VM that re-deployed DU containers every morning.

NB: As the software matures these issues will eventually evolve into a stable solution.

2.5.4. Timing

A key difference between 4G and 5G networks is timing. For the radio to achieve the higher capacity and lower latency offered by 5G the network timing precision is increased. In 4G network timing protocol (NTP) was sufficient to support the system. For 5G NTP does not meet the timing precision required, thus Precision Timing Protocol (PTP) needs implementing. To implement PTP all devices in the radio subsystem need the capability to support the protocol. The OSA5401 Grand Master Clock required configuration inside the ADVA FSP150-XG118PRO to allow for a time source to be made available across all 3 pieces of hardware in a Master/Slave architecture.

2.5.4.1. Challenges

The PTP Grand Master Clock was not plug and play, it required extensive configuration when leveraged across multiple pieces of hardware, as such ADVA Professional Services were engaged to configure the OSA5401. The method used to broadcast the PTP in accordance with Airspan documentation was multicast and this was configured to broadcast on all VLANs. Due to the accuracy requirement of timings for 5G deployments it was also necessary to take into consideration the length of cable (120m at NCC Emersons Green) and the material of the core of the cable. Both factors require inputting into an equation that calculates an offset to guarantee accuracy of the time source. When operational, Airspan DUs and RUs verified that timing was correct via the CLI.

2.5.5. Airspan ACP

Airspan ACP is installed on CentOS 8.4.2150 and is a minimal deployment on a virtual machine within the CU hardware. The network configuration needs to reflect the Kubernetes Management network so that ACP can talk to all nodes inside the Kubernetes Cluster. After patching, the Linux version of Microsoft SQL Server is installed on the OS and configured with an instance to which the System Administrator (SA) password needs to be configured. Post installation, the Airspan ACP software is installed using the SA credentials to build the database back-end to the web front-end upon installation.

As soon as this process has been completed ACP needs to be licensed and configured. Each node in the Kubernetes cluster is added to ACP so that the containers can be configured and leveraged to form the complete end-to-end Radio Access Network.

Figure 11 below displays where Airspan ACP sits in the architecture of the Kubernetes Cluster.

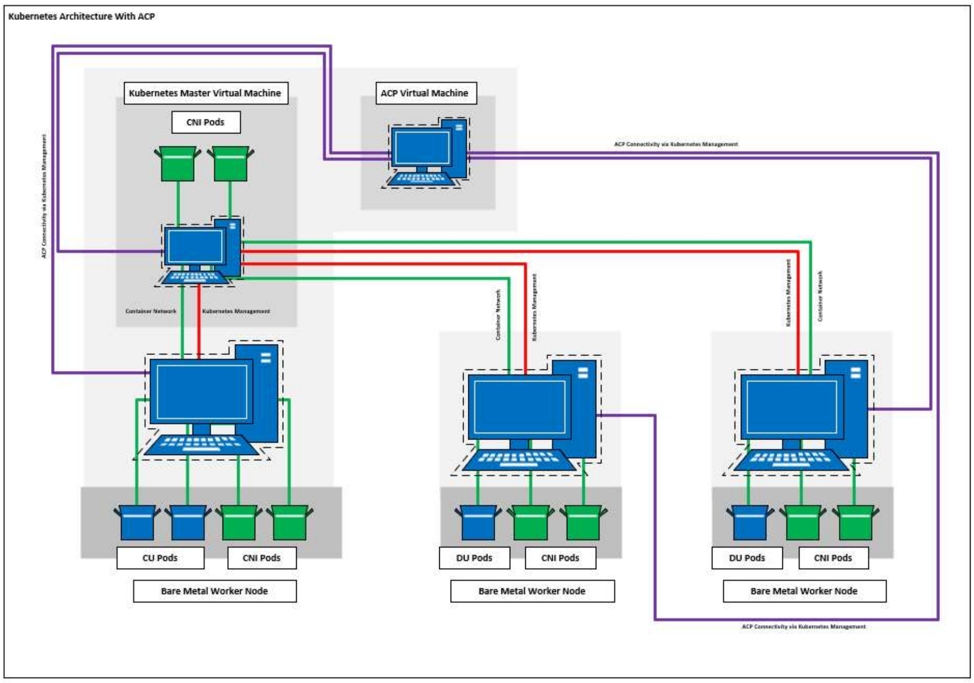


Figure 256: Kubernetes Architecture with ACP

Purple: ACP Connectivity via Kubernetes Management Network for ACP to control all pods contained within worker nodes.

NB: A larger diagram can be found in Appendix G

2.5.5.1. Challenges

No challenges were observed when installing ACP.

2.5.6. Packet Core

The packet core leveraged on both the 4G and 5G deployments is developed by Druid and the product is Raemis. The Raemis packet core operated on the up-to-date release of CentOS 7 and can be patched regularly without issue. The installation is script based and installs by pulling information from the internet.

Post installation configuration is required to allow the packet core to see the RAN. This is in the form of a Control Plane and User Plane L2 connection made available between the packet core and the CU containers (diagrammatical representation in Figure 8; earlier in the document). Connectivity is provisioned via 2 physical interfaces present on the host OS and selected during initial configuration of the Raemis software.

Note: The RAN User Plane and RAN Control Plane Network Interface Cards need to be configured as purely L2 connectivity, so default routes need to be removed during initial configuration.

The CU server is then detected as a gNodeB, screenshot displayed in Figure 12 below:

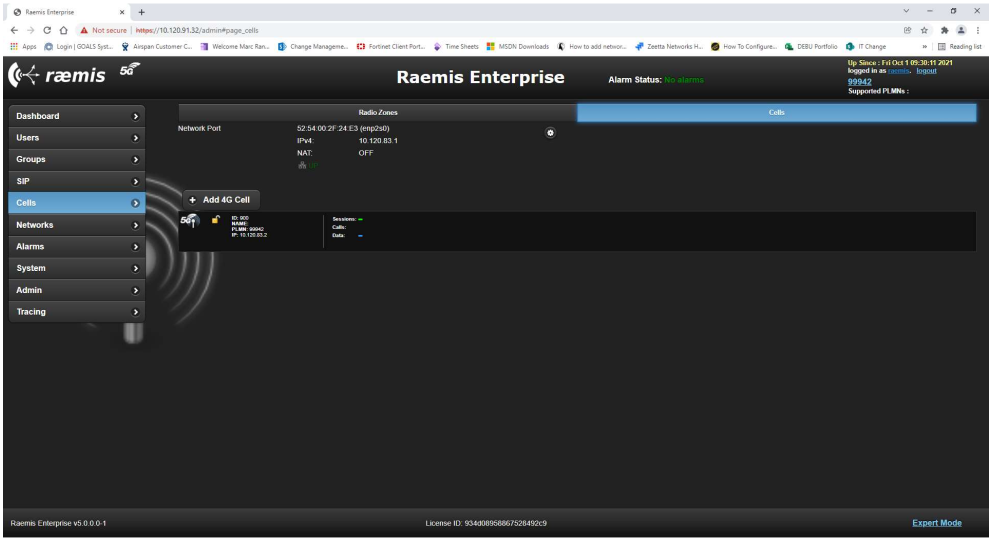


Figure 257: gNodeB Inside Raemis

Note: If the control plane is connected but the user plane is not then the gNodeB will be present but there will be no data flow from the remote devices that are attached to the packet core.

After the RAN is provisioned, it was necessary to configure an APN and attach it to the third and final physical network interface within the software. A default route is required on this Network Interface Card to be able to access resources both LAN and WAN side.

Figure 13 below displays the configured Network Interface Cards inside the Raemis software

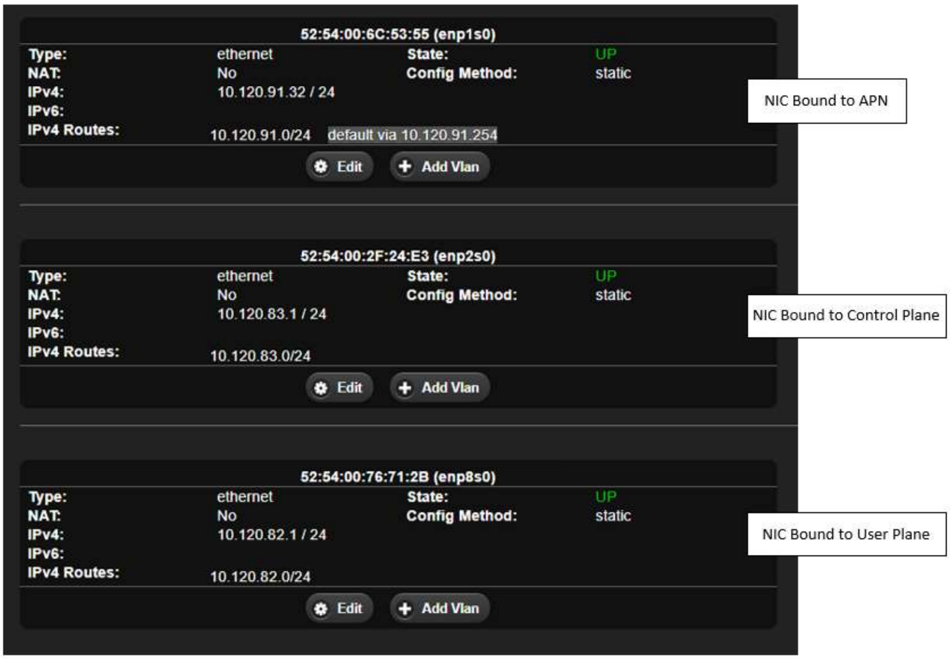


Figure 258: Raemis NIC Configuration

As observed above, the Network Interface Card associated with upstream connectivity has a default route. This card can be seen in Figure 14 bound to the APN "ncc5g" with associated core services connectivity.

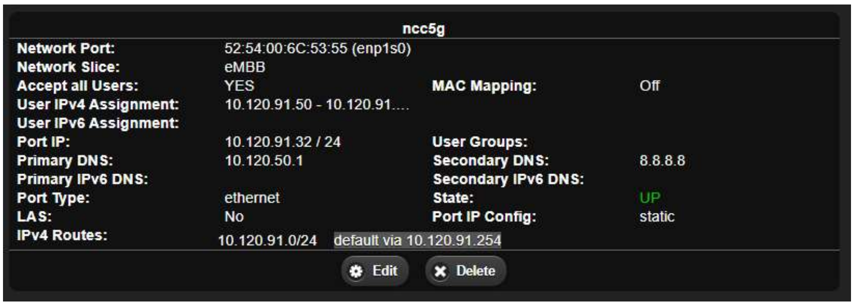


Figure 259: APN Configuration

When a device attaches with the configured APN and its associated registered SIM card it is allocated an address within the designated range and connects to the network.

Note: Licensing dictates the number of APNs, Networks, gNodeBs and Registered SIM Cards available within the software.

Additional features within the software enable a shared SIM card database (HSS+) located on the 4G core (PLMN ID is also 999 42) used to maintain a single set of SIM cards for network access.

2.5.6.1. Challenges

No issues were observed whilst deploying the Packet Core although as the project progressed it was apparent that support was required to confirm connectivity issues with the 5G RAN vendor. Collaboration between both vendors ironed out issues with User Plane and Control Plane configuration to achieve a fully functional system.

Further issues were observed with Customer Premises Equipment (CPE) and User Equipment (UE) devices attaching to the RAN and Packet Core. These issues were also external to the RAN and Packet Core software and related to 5G cellular interfaces specific to these products not recognising the test PLMN ID of 999 42. This was test PLMN used in the NCC 4G that was re-used for NCC 5G. To devices with constraints to attach to the 5G RAN it was necessary to use a SIM card with the PLMN ID of 001 01. Many of the devices also required specific configuration to enable 5G SA network detection and attach protocols. Once configure for 5G SA attach and with a recognised PLMN i.e. 001 01 available on the installed SIM these devices attached to the 5G RAN.

Note: not all devices once configured would attach to the 5G RAN thus it is recommended that care is taken in the selection of devices for use on a 5G SA networks at this time.

2.5.7. Monitoring & Statistical Analysis

Network Probe

The deployment of the Accedian platform involved installation of in-line multimode SFP+ modules to a multitude of third-party vendor hardware. EdgeCore 10GB Enterprise Fibre Optic switches accepted the modules but the 1GB Copper switches with 6 x SFP+ expansion modules would not accept the modules. ADVA switching and Dell server hardware observed no issues and the SFP+ modules functioned as expected.

The construct of the system was extensive involving 5 x virtual machine deployments for components to manage hardware/buffer/analyse and send the metrics to a cloud-based platform for visualisation. These virtual appliances were supplied in specific formats and leverage a proprietary configuration shell. Configuration of the in-line SFP+ modules, the ANT traffic interception devices and port mirroring statistical analysis (for application aware traffic logging) are completed via the web portals on the individual appliances after post setup tasks have been completed.

Furthermore, the base system configuration, is that each probe that sits in-line on the network required an IP address to be able to provide an end point within a required network segment. A Single probe can sit in multiple VLANs and have multiple IP addresses associated with it for complete transparency. In the case of the Encode project, each use case has a separate network segment associated with it meaning probes can be positioned in a full end-to-end configuration giving full transparency on traffic flows and LAN side metrics.

The port mirroring configuration (PVX Sensor) for application detection was deployed on the uplink between the core switch and default gateway.

Figure 15 below displays the topology of the Accedian Networks monitoring and statistical analysis platform:

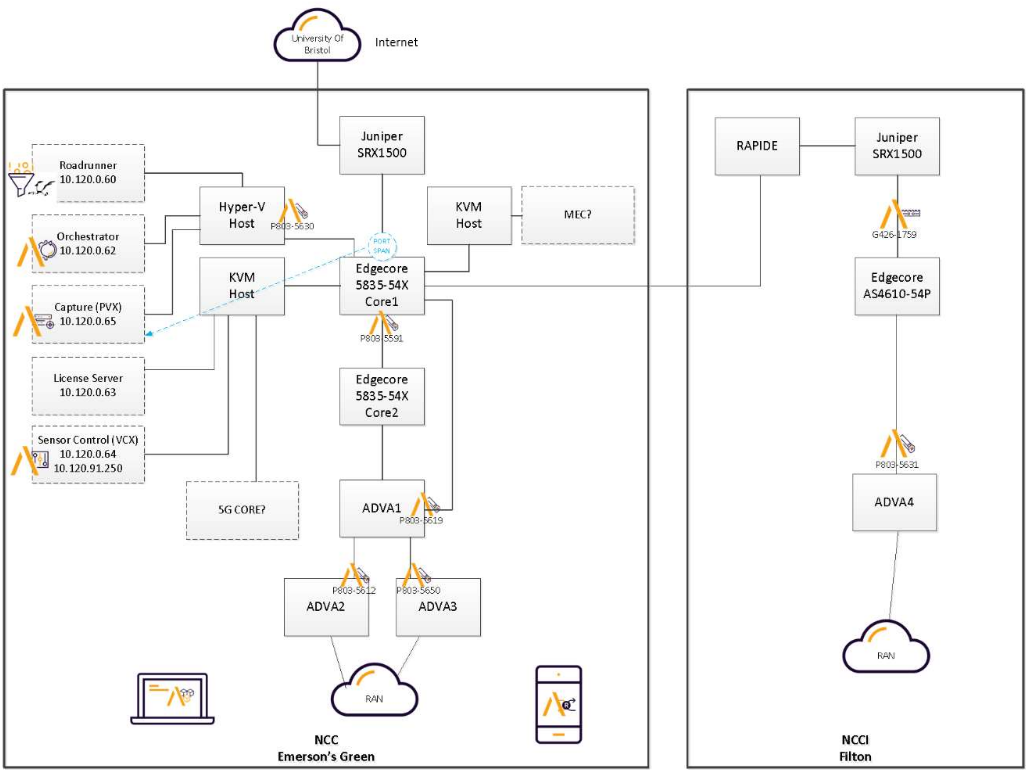


Figure 260: Accedian Topology

Note: All virtual appliances can be found on the left-hand side of the diagram.

- SFP+ In-line probe
- ANT Traffic Interception Device

- Android Probe
- Docker Based Software Probe

All cellular specific statistics were generated within the Airspan ACP platform and processed by Zeetta Networks. These metrics are created from statistical counts points included in the software of the CU and DU elements. These metrics are collated and sent to ACP as a single XML file at the end of each collection period. The default collection period of every 15 minutes was used for network metric processing and collection. The collected metrics are stored in ACP as XML files, loaded by ACP and visualised on screen as tables of text and numeric data. These tables were exported in CSV format and transferred to Zeetta for chart preparation and initial analysis. Charts and pre-analysis for each use case were returned to each NCC use case lead for further analysis and use in understanding the benefits of 5G.

Note: Similar 4G metric files were generated every 60 minutes. 5G metrics can be set to be generated every 60 minutes, the team decided to retain the 15-minute interval for metrics generation.

Cellular

When considering cellular network level metrics, it must be remembered that the metrics reflect all activity on the network in the collection period. Therefore, distinguishing metric data that were created as a result of executing a use case from all other network related metrics data is not possible. To mitigate this use cases were planned such that the only network activity during the use case was generated by the use case itself. This created network metrics that were as close as could be to expected results from the use case. In busier, or mature, 5G networks, the network metrics created by the RAN will represent overall network performance and not metrics specific to a use case.

2.5.7.1. Challenges

Network Probe

Due to all use case demonstrators utilising Virtual Machine deployments on a multitude of Hypervisor platforms it was necessary to enable nested virtualisation to allow for the software probes to install and function within a containerisation environment. Some of the use case demonstrators leveraged VDI style shared graphics devices for 3D rendering which caused the nested virtualisation to malfunction when certain Microsoft Windows features were enabled. As such a probe running directly on a use case demonstrator server or workstation was not possible so a workaround was required. The Accedian container software was deployed like the hardware probes in the sense that additional interfaces within the host Operating System facilitated connectivity tests within use case network segments ultimately producing the required LAN side network metrics.

Cellular

When considering cellular network level metrics, it must be remembered that the metrics reflect all activity on the network in the collection period. Therefore, distinguishing metric data that were created as a result of executing a use case from all other network related metrics data is not possible. To mitigate this use cases were planned such that the only network activity during the use case was generated by the use case itself. This created network metrics that were as close as could be to expected results from the use case. In busier, or mature, 5G networks, the network metrics created by the RAN will represent overall network performance and not metrics specific to a use case.

The above approach used to network metrics as close as would be expected to the results from the use case had a consequence that without other network traffic the capacity of the 5G network in a multi-use environment was not measured e.g. interruption as a result of other traffic and capacity limits of the network resulting from multiple users were not observed.

2.6. Testing

Throughout the entire deployment the metrics varied depending on what version of the RAN software was deployed. This affected stability, latency, and throughput. As the software evolved it was apparent that a stable baseline would be reached with the Q3 2021 release of the vRAN from Airspan Networks. Stability was achieved from the Radio Units whereby packet loss was consistently less than 1% in what could be considered as “close to optimal” RF conditions. Latency was observed as sub ~10ms and throughput was observed at ~410Mbps downlink and ~57Mbps uplink.

Testing was performed on both CPE and UE devices compatible with 5G SA connectivity. These values were consistently observed throughout testing for use case demonstrators throughout December 2021.

Note: Please refer to the Airspan 5G SA roadmap for 2022/23 as the performance of the system is significant.

3. CONCLUSION

After the hardware platform was built and handed over to the Airspan Networks professional services team, it was necessary to modify and upgrade components within the configuration throughout the deployment to achieve a stable and performant solution. Intermittent issues were observed through the project that were resolved with software releases. These releases were installed quarterly throughout the project, which created delay in multiple use case delivery timescales. This highlighted that the RAN software was not initially production ready.

Performance and stability of the technology increased with each software release. The RAN vendors roadmap outlines incremental releases that a ~1GB downlink throughput would be achieved within the next 12 months. Uplink speeds remain at ~10% of the downlink throughput, although there is potential to modify the uplink and downlink throughput, which was discussed in the concluding phases. Latency is currently ~10ms and this is will also be improved to a lower value as part of the RAN vendor roadmap.

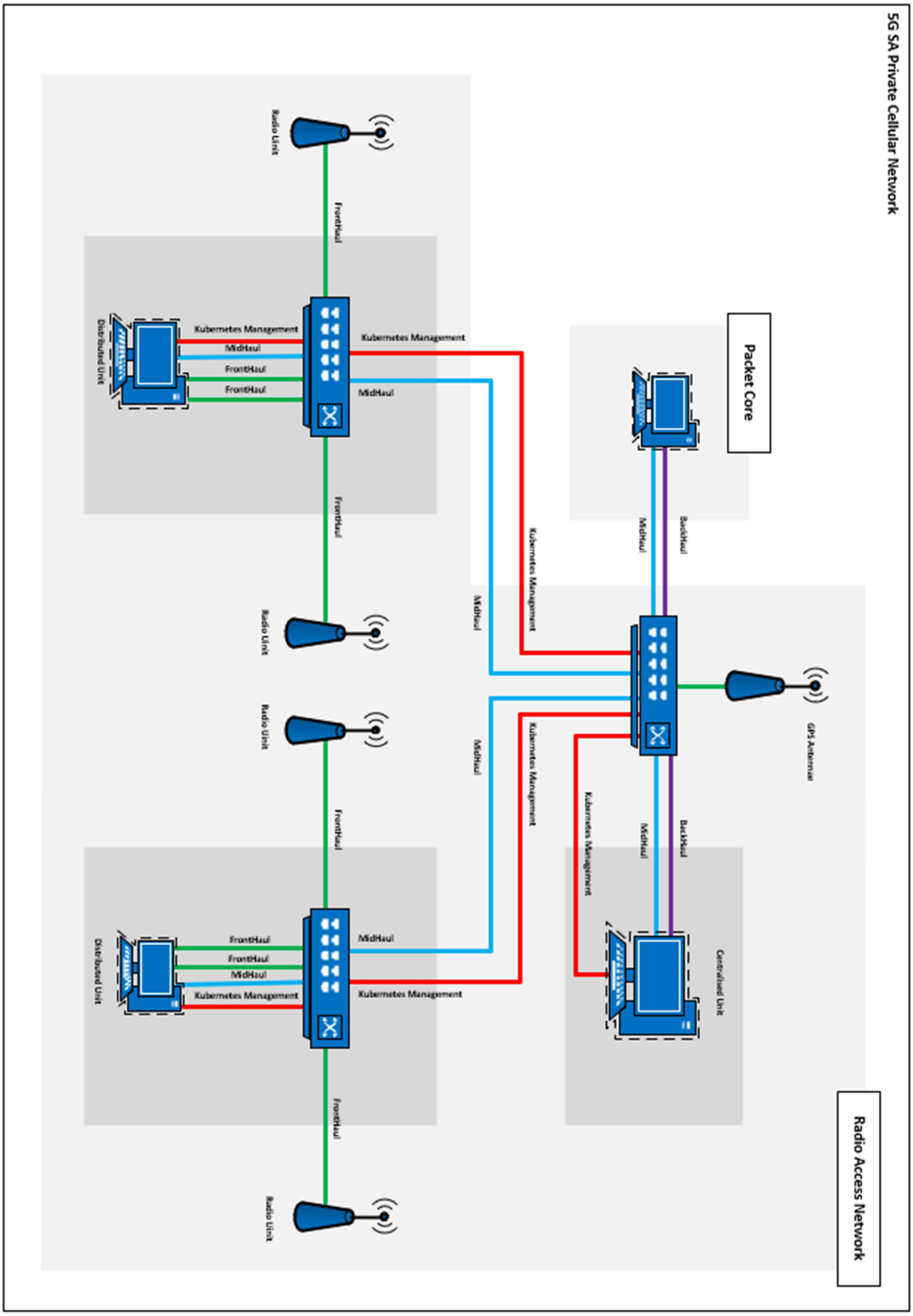
Note: Performance is dependent on radio conditions and, consequently, subject to environmental variation.

5G is still in the early adoption phase by most third-party hardware suppliers, limiting end user devices that are available. The uptake of the technology is expected to continue to grow and as devices mature the need for advanced configuration to force the hardware to connect to the technology be retired. For this project the challenge that every device is different and needed specific engineering or SIM configuration did add delays to the timescale for deliverables.

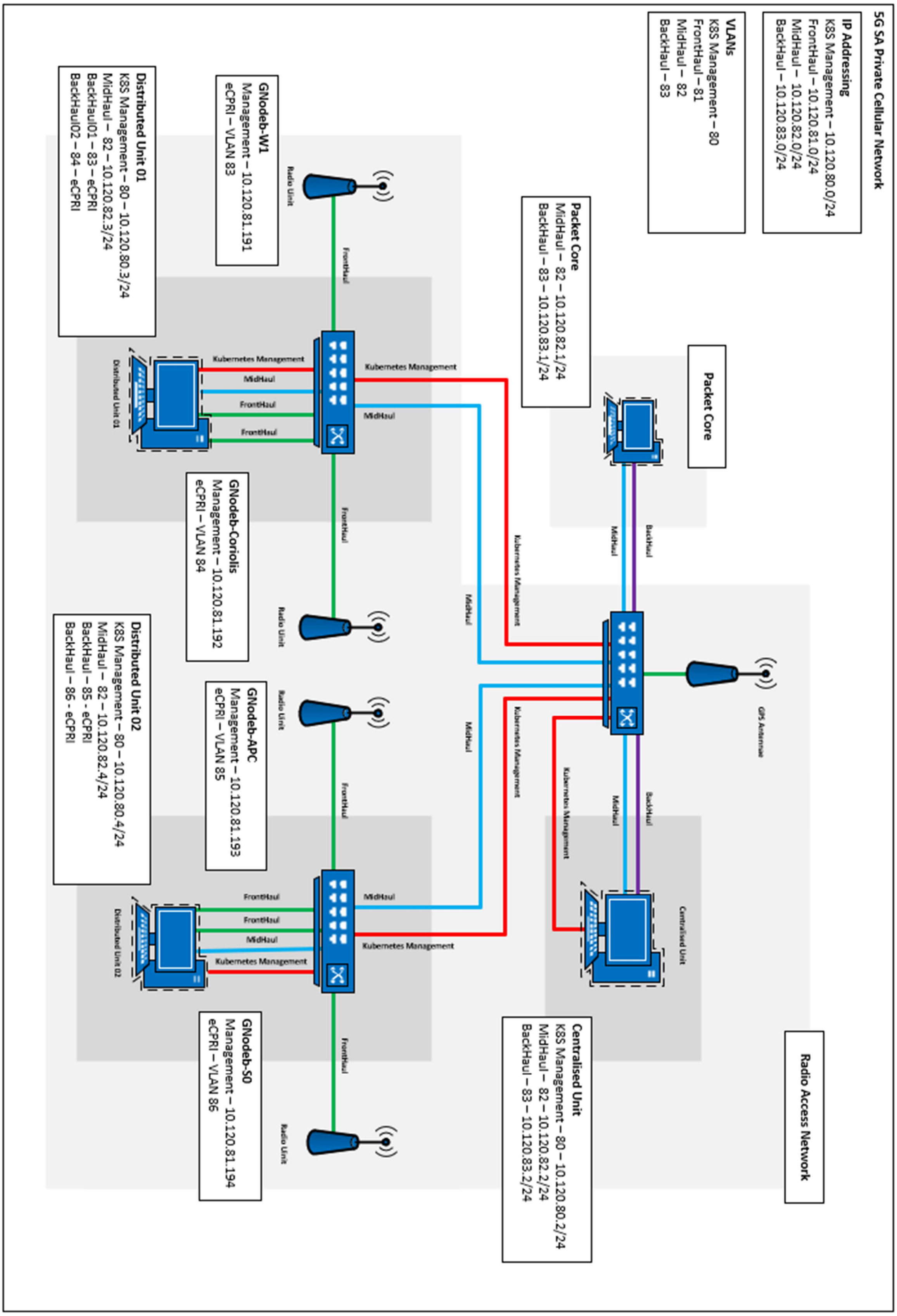
In conclusion, the software from the selected RAN vendor should perform at gigabit speeds during 2022 based on their roadmap. This will help to achieve what is expected downlink from a technical perspective within a 5G SA network. Uplink RAN performance will improve through 2022 as per the RAN vendor roadmap, however, the hardware limitations of the currently deployed radio units will constrain the uplink performance. The technology shows promise to far exceed what is currently available with its 4G derivative and will benefit from maturing over the next 12 to 24 months.


RU
Fronthaul
Split 7.2
O-RAN
DU
Midhaul
Split 2
(F1-C & F1-U)
CU
(CU-UP &
CU-CP)
Backhaul
NG
(NGU & NGC)
5GC

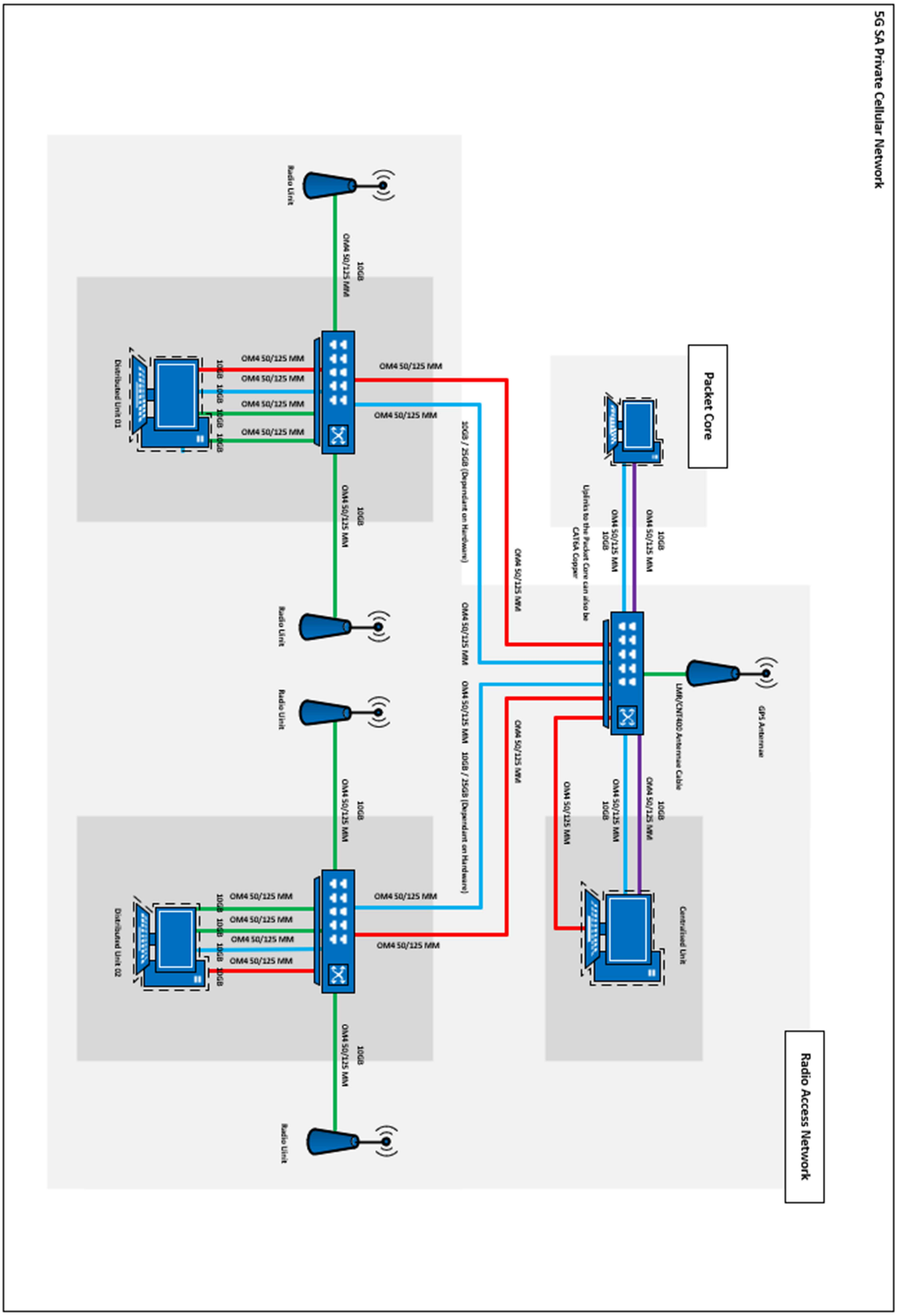
123 APPENDIX B – RAN LLD PROVIDED BY CONSORTIUM (NETWORK SEGMENTS).



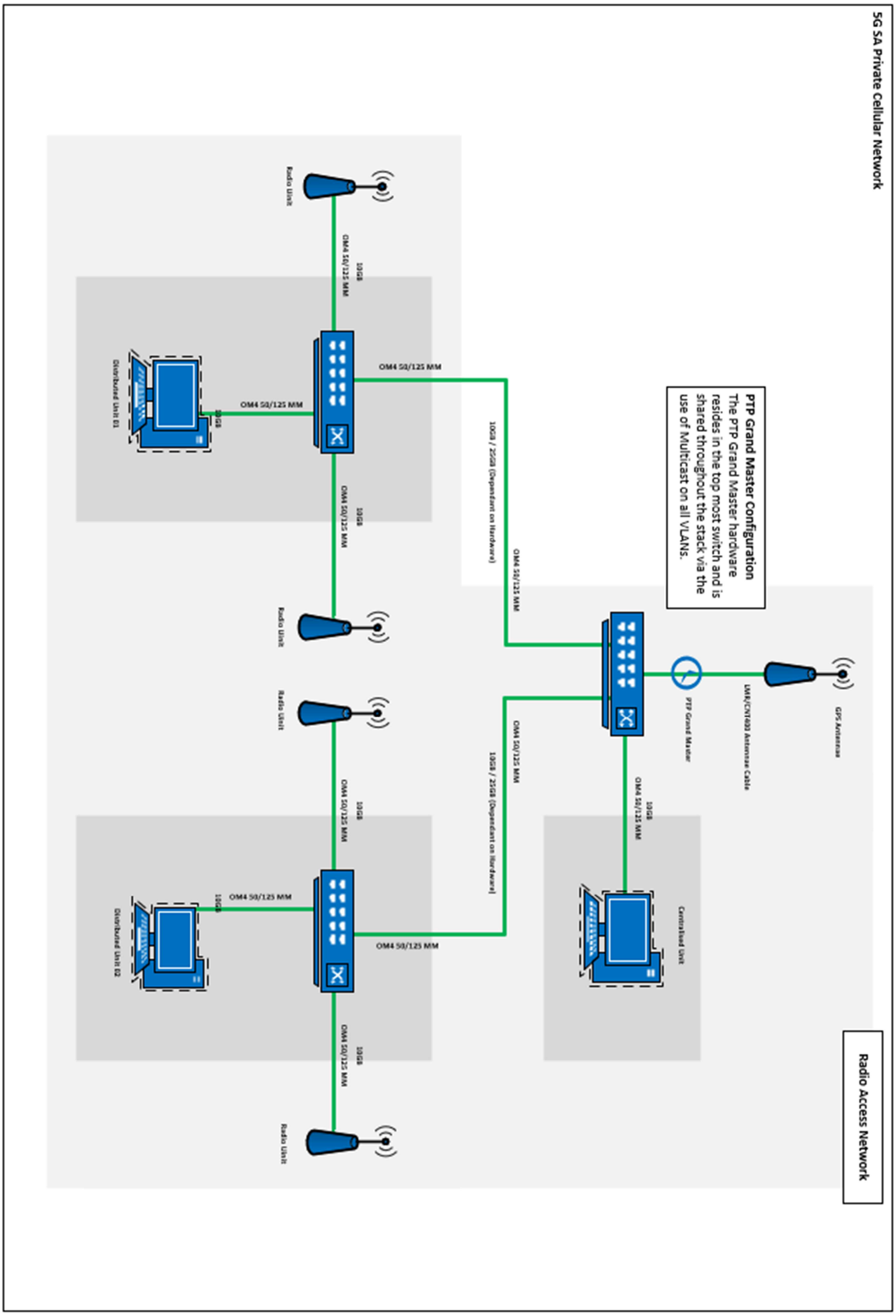
124 APPENDIX C – RAN LLD PROVIDED BY CONSORTIUM (VLANS & IP ADDRESSING).



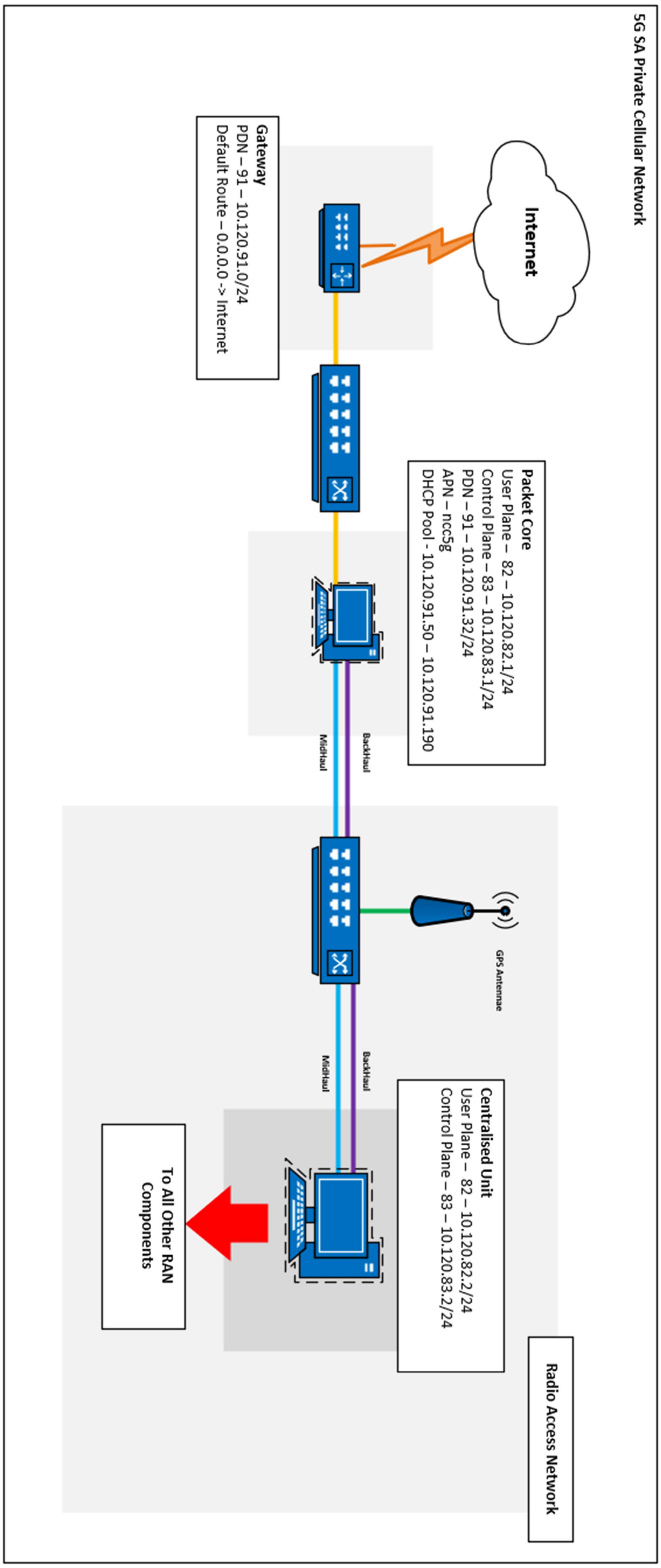
125 APPENDIX D – PHYSICAL CONNECTIVITY.



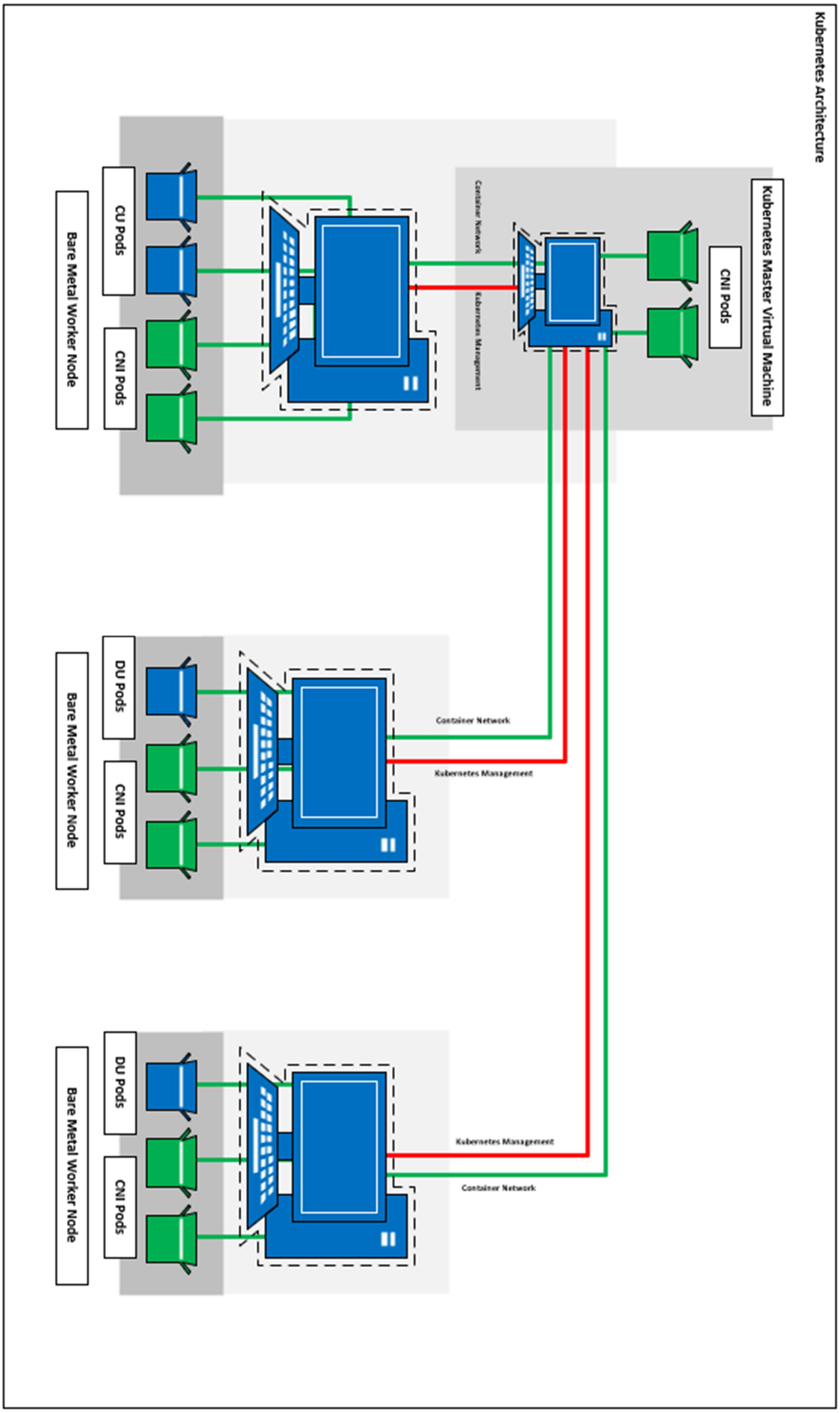
126 APPENDIX E – RAN WITH PTP CLOCK INTEGRATION.



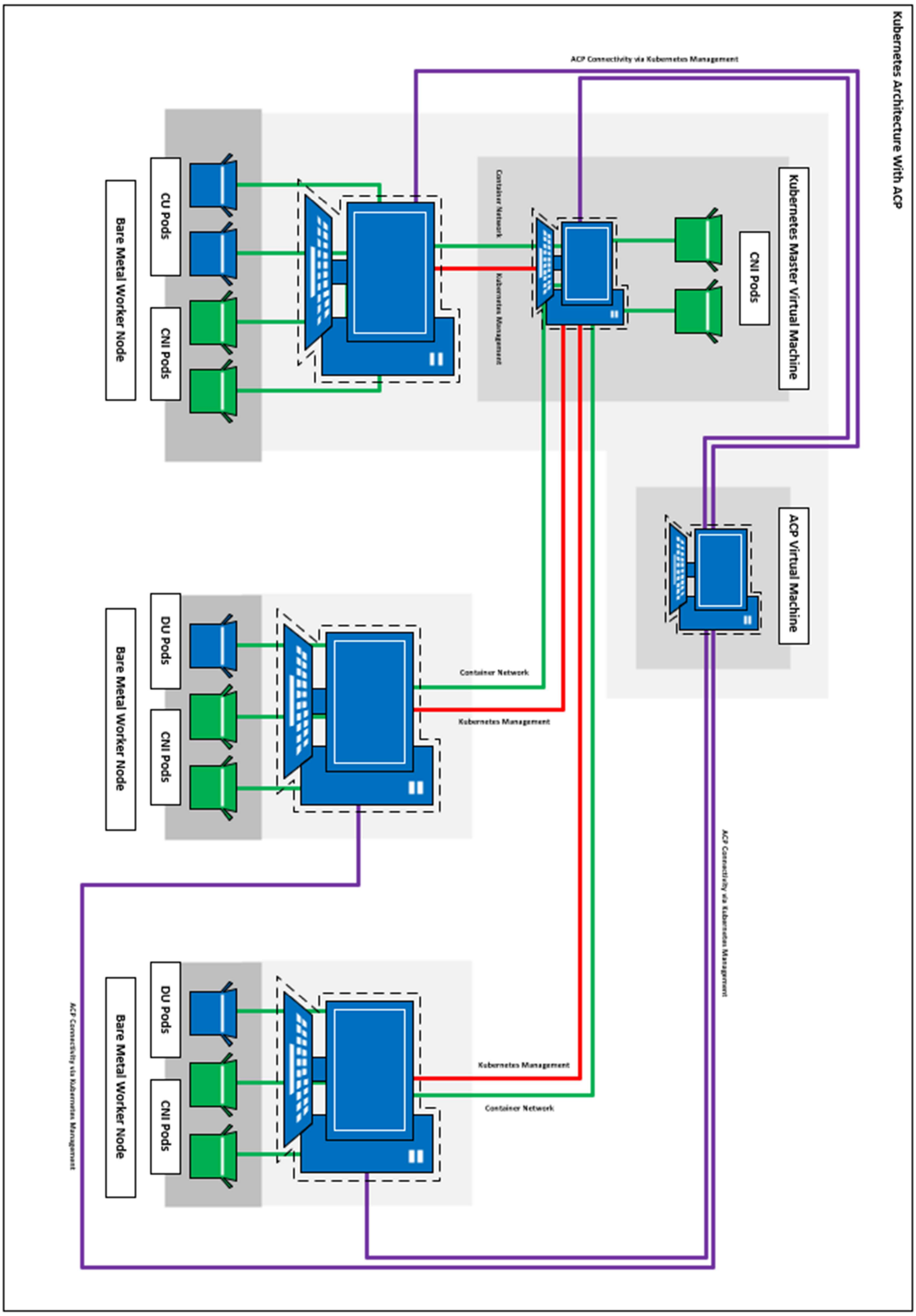
127 APPENDIX F – PACKET CORE INTEGRATION



128 APPENDIX G – KUBERNETES CLUSTER



129 APPENDIX H – KUBERNETES ARCHITECTURE WITH ACP



END