5G-encode

Lessons Learned

Final Report

Mar 2022

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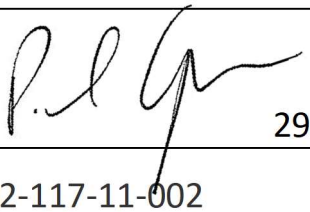
Internal authorisation	Paul Cooper	 29 Mar 2022
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1	Initial issue
1-1	Added Haptics feasibility study findings

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.

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.

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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

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.

5G NETWORK AND INFRASTRUCTURE

Skills

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

IT Network

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.

RAN

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

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.

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 license is granted.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

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.

USE CASE CHALLENGES

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.

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.

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.

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.

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.

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.

Liquid Resin Infusion and Automated Preforming Control

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.

Network outages

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

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.

Haptics Robot Teleoperation Feasibility Study

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.

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.

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.

PROJECT EXECUTION

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.

Project Execution

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.

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.

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.

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.

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.

DCMS PROCESSES

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.

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.

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.

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.

Project Close out

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.

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 1: Asset register xlsx issues

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 2: Full list of Lessons Learned