Worcestershire 5G Testbed and Trials

Final Report

• Foreword – Mark Stansfeld – Chair Worcestershire LEP and Worcestershire 5G

The Department for Digital, Culture, Media & Sport (DCMS) 5G Testbeds and Trials (5GTT) Programme is the cornerstone to the government's ambition for the UK to be a leader in the next generation of mobile technology, 5G. The 5GTT programme has been a 'catalyst' in accelerating the adoption by the wider business and 5G ecosystem and in helping position the UK as a 'thought leader' on the international stage.
Worcestershire, where the Industry 4.0 5G testbed is located has long held a vision for a 'connected, creative, dynamic economy to the benefit of all' and the role of connectivity, both physical and digital, is a key enabler to driving both productivity and social benefits for residents. Figures vary as to what these enablers contribute, but it is commonly accepted that 5G is likely to be a significant contributor in the new economy.

The Worcestershire 5G Consortium consisted of world class manufacturers, equipment vendors, cyber security experts, Mobile Network Operators (MNO), leading system integrators, academia and public bodies. All were committed to working together on the role that 5G can play in driving productivity in manufacturing. In the Midlands, manufacturing is a critical sector and accounts for 20% of the region's GVA. The consortium was committed to investigating the hypothesis that the adoption of 5G with industry 4.0 principles in manufacturing would lead to a potential 1% improvement in productivity and operational efficiency.

Our results showed that up to 2% efficiency gain may be possible through the adoption of 5G services which supports a recommendation for additional investment in manufacturing 5G based solutions to help drive future efficiency gains. Such levels of productivity gain, *if* extrapolated to a UK level, would be equivalent to a contribution of £2.6 billion. Manufacturers' ability to generate efficiency savings is not only dependent on the availability of 5G, but also on other technology such as Augmented Reality, and – critically – on the identification of applications for those technologies. We remain at an early stage in the development of 5G and other technologies and there is no single application that would work for all manufacturers; each manufacturer needs to consider how it might be able to leverage new technologies including 5G to address their specific circumstances.

The W5G testbed has been underpinned by technology infrastructure which is increasingly mature, stable, secure, and commercially available and there is now an opportunity to take the learnings to the next level and commercialise our findings. We are at the beginning of this journey and success at regional and national level requires all players within the ecosystem to collaborate to drive the development and adoption of 5G and Industry 4.0 applications, including;

- Further evolution of the capabilities of 5G through the 3GPP standards initiative, to deliver 5G capabilities that enable more and more Industry 4.0 use cases;
- The development of sensors and edge devices at an affordable cost to allow the 5G network to be fully exploited;
- Development of 5G / industry 4.0 "in a box" solutions for the wider SME sector to buy and adopt, delivering on plug and play capability;

- A new commercial model for operators to offer the enterprise sector, making 5G progressively more attractive from a financial perspective;
- A role for manufacturing industry representative bodies to raise awareness of how 5G can drive productivity improvements.

Through our relationship with the Midlands Engine, and our proposed Open Test Facility hosted at Malvern Hills Science Park we are now uniquely positioned to reach out to a wider industry base and further accelerate this progress.

I would like to thank all the consortium members for their ongoing support, but also DCMS for the 5GTT Programme that has shone a light on the role 5G can play in both business and in people's lives with industry, health, mobility, and rural communities applications, to name a few, and a recognition that there will be many more areas of benefit, in areas as yet unidentified.

It has been a great honour for me to Chair the Worcestershire 5GTT and see Worcestershire establish itself as a leader and exemplar in how 5G can play a significant role in delivering increased productivity gains in manufacturing.

Executive Summary

In March 2018 DCMS chose the Worcestershire 5G (W5G) consortium as one of six early stage 5G Testbeds and Trials (5GTT) projects. It was selected to drive the manufacturing industry to better understand the opportunities and challenges of deploying new technologies based on the developing international standards for future 5G networks, the first cellular technology with features specifically designed for industrial and wider enterprise and commercial use.

The primary purpose of the W5G testbed was through a research and design approach, to assess and quantify how 5G New Radio (5GNR) can facilitate Industry 4.0, including the enablement of cyber-physical systems, "secure by design" within an industrial setting – to both demonstrate potential for and measurable efficiency benefits that in turn would deliver increased productivity gains. We set out with a hypothesis of evidencing the potential to achieve at least 1% improvement in productivity and operational efficiency.

Building a connected, creative and dynamic economy

The 5G Testbed and Trails Programme has afforded Worcestershire a once-in a lifetime opportunity to take early-mover advantage within the 5G ecosystem.

The work delivered through W5G forms part of a much wider programme in Worcestershire aiming to build a connected, creative and dynamic economy for the county; sitting at the centre of the wider national 5G ecosystem underpinned by DCMS, and supported by mobile network operators, industry bodies and other key players.

Collaboration is key

> "Industry adoption of 5G will not be possible without committed collaboration between all players in the manufacturing and connectivity value chain. This collaboration is the catalyst for overcoming current challenges and creating the space for 5G enabled innovation."
>
> **(Made in 5G, 5G for the Manufacturing Sector, June 2019)**

The collaboration of the W5G consortium is an exemplar involving world-class industry leading manufacturers, vendors, mobile network operators, systems integrators, cyber security experts, academia and local government; has been key to the success of W5G. Outside of the consortium we have collaborated with other leaders in the 5G ecosystem to deliver sector specific reports, which are duly referenced within this report.

Our experience and results add up to significant progress and practical delivery against many of the biggest challenges to 5G adoption identified by industry.

Driving Productivity

The W5G networked locations included the Worcester Bosch and Yamazaki Mazak Corporation factories in Worcester which have tested Industry 4.0 use cases covering condition monitoring, visual monitoring and augmented reality. However, these use cases are just a start, the tip of the iceberg. Advanced manufacturing presents great diversity of challenge and opportunity, including harsh and challenging operating environments, critical safety and security considerations and its own operational language and context. These aspects drive both cultural as well as technological change. 5G provides a platform for potential transformation in manufacturing, delivering greater production efficiency, flexibility and scalability.

Our use cases evidenced the potential for productivity returns up to 2% through improved operations and plant efficiency.

Our results and learning potentially underpin partner investments in smart factories of the future, targeted on the need to address a wider set of use cases. W5G to date has primarily focused on production operations and those that directly support it, but the scope for potential improvements is much wider extending into monitoring and management across the supply chain. Furthermore, it may be possible to modify our Remote Expert use case for use as a live field training aid in many sectors.

Network Performance – Industry 4.0 Imperative

The W5G Consortium has delivered several **firsts for manufacturing**-based networks in the UK.

- First deployment of 5G Non Stand Alone Architecture (5G NSA), operating alongside 4G at close to its theoretical limit.
- First instance of an enterprise-led implementation of private 5G NSA
- First in-depth 'security by design' review and development of a 5G Manufacturing network

Four Industry 4.0 use cases, developed and tested using next generation technologies, confirmed the need for a high performing 5G network to support factory wide automation compared to the best performing alternative networks. Whole factory implementations require the speed, latency and device density that can only be delivered by a 5G network. Investment in multiple networking technologies is likely to be sub optimal.

Continued advancement in technology, connectivity, devices, and standards will only continue to make the case for 5G more attractive and commercially viable. Mutual dependency across the value chain increases the motivation for success.

"5G can lift Industry 4.0 to the next level and Industry 4.0 may be the killer application for 5G"

(Dr Andreas Mueller – Head of Communications and Networking Technology at Bosch, Chairman 5G Alliance for Connected Industries Association, ACIA)

Table 1 below summarises the key use case conclusions.

Use Case & Question	Industry 4.0 Lead	Conclusions
Augmented Reality-enabled remote training ('Remote Expert', UC1) – Is 5G required to enable effective interactive live streaming and communication between experts and remote field engineers?	Mazak	● Commercial 4G was found to be suitable only for short sessions, with the user experience (i.e. a high number of disconnections) precluding lengthy interaction ● Many scenarios were manageable with the high quality private 4G network installed in Mazak's premises. However, image quality was significantly improved in 5G compared to 4G, with 5G achieving image resolution between HD and UHD, which 4G was unable to achieve. The higher image resolution in 5G is likely to provide a better platform for AI capabilities. ● Widespread availability and access to 5G would be required to deliver the kind of benefits possible from the use of this kind of technology
Preventative maintenance – spindle (UC2) *(Proof of Concept)* – Could 5G enable automated remote monitoring and control of the spindle in operation? Specifically, might it be feasible to send remotely a "stop" command to a	Mazak	● Neither the private 4G nor 5G networks were capable of sending the "stop" command sufficiently quickly to avoid damage to the spindle. ● Release 16 of the 3GPP 5G standards was, at the time of testing (Q1 2019),

machine and prevent damage to the spindle?		expected to deliver Ultra Reliable Low Latency Communications (URLLC) – it is possible that this would meet the requirements of this use case. Release 16 is not expected to be available until later in 2020.
Visual monitoring (UC3) *(Proof of Concept)* – Could 5G support the use of ultra-high resolution of live streaming to enable remote monitoring of real-time conditions of working facilities in the factory environment?	Worcester Bosch	• 4G was insufficient to support the throughput levels required with more than a single 4K/UHD camera. Even with a single camera, the 4G network was operating close to its limit. 4G was sufficient, however, to support 3 cameras with HD rather than UHD. • 5G was required to support the visual monitoring test. The increased throughput supported three 4K/UHD cameras.
Condition monitoring (UC4) – Is 5G required to enable automated remote monitoring of the status of production machines using multiple sensors?	Worcester Bosch	• 4G was found to be sufficient to support the use case in isolation in Worcester Bosch. However, when considered as part of a broader "Factory of the Future" strategy, in which this kind of use case might co-exist with other use cases, such as UC3, 5G may be required. • Whole factory deployments requiring an especially high density of devices - for example, 1 million per sq km – and/or which generate high volumes of

		frequently-polled data may require 5G in their own right.

Cost of 5G Implementation and Benefits Achieved

While the project was not specifically tasked to look at the costs of 5G implementation to a factory environment, our work over period 1 and period 1.5 has given an insight to potential costs and the potential payback that might be achieved. It must be remembered that the period 1 network was pre-release equipment and even into period 1.5 the availability of some required elements, specifically edge user connection devices remained limited. As the project ends, we are already starting to see more competition and a downward trend in costs as manufactures increase their 5G offerings to the market. We expect the release of 5G SA standards to further accelerate the availability of equipment and a further reduction in implementation costs.

In summary our work showed that while we could not yet identify a "killer application" for 5G in a factory, by the implementation of only 2 or 3 5G applications would lead to an acceptable payback of less than 4 years, in some cases as quickly as 1 year. We provide further information on our findings at Appendix C.

Security by Design

Built around its work on W5G QinetiQ has developed and launched four new services covering Network Security Testing and a Test and Assurance Service for 5G applications.[1] These services form part of a coherent market offering within QinetiQ's Cyber and Digital Resilience portfolio, specifically aimed at providing a complete security offering for 5G IoT Device and Platform testing.

The 'security by design' testing flagged a growing need for an industry-wide authentication "kitemark" standard for IoT devices to be enabled in manufacturing settings.

Skills

The W5G-led cross industry skills report[2], Gearing Up Our People to Drive the Power of 5G, sets out a blueprint for addressing this at national and local level, and is presented alongside this report. It is clear that while the telecommunications sector has challenges in bringing new engineers through, it is also important that wider industry sectors, including manufacturing, should be developing their internal capacity to better understand the latest digital and mobile network capabilities and their potential applications to ensure opportunities to improve are maximised.

Primary research from thought leaders across industry, academia, government departments and mobile operators identified a number of insights which, were they not addressed, would limit the UK's ability to maximise the potential returns from 5G and a long list of possible recommendations to resolve them. This long list was then prioritised based on the level of impact and ease of implementation, resulting in the following short list:

1. Developing a national high-profile team of role models to inspire our next generation workforce, to get them excited about working in a 5G world

[1] https://www.qinetiq.com/Sectors/Telecomms/5G-Security
[2] https://www.wlep.co.uk/current-projects/worcestershire-5g/report-library/

2. Creating a digital coaching programme for business leaders, to give them the knowledge and skills needed to see how 5G can deliver a step change in productivity;
3. Soft skills training for our existing telecoms engineering workforce to enable them to function successfully in the new 5G environment;
4. Support for businesses trying to identify and quantify how 5G will resolve business challenges and create new opportunities; and
5. Detailed statistical analysis to drill down into the telecoms engineering gaps, by region, to ensure that any essential technical skills voids can be plugged.

Within Worcestershire, the W5G project helped the Heart of Worcestershire College, and the University of Worcester, to develop 5G-specific course materials, tailored to the practical business and engineering operations of a 5G world. In addition, HOWC has established itself as a 5G Academy as a response to the shortfall of ICT Engineering roles key to the success of future 5G opportunities for Worcestershire and the wider ecosystem.

Wider Ecosystem

If the potential economic returns that we observed with Mazak (just over 2%) were extrapolated at a local, regional, and national, the potential economic benefits would be significant.

However, we are at the beginning of the journey, so success requires all players within the ecosystem to collaborate like never before to drive the development and adoption of 5G and Industry 4.0 applications, this includes;

- Productisation and packaging of the 5G / industry 4.0 “in a box” solutions for the wider SME sector to buy and adopt, delivering on the plug and play opportunity;
- Development of low power, low data rate, low cost sensors will support much wider deployment in commercial environments.
- A new commercial model for operators to offer the enterprise sector, making 5G progressively more economically attractive;
- A clear opportunity for the System Integrator (SI) community to help drive this collaboration and adoption;
- A big role for manufacturing industry representative bodies to help bring awareness of how 5G can drive productivity improvements.

This report aims to provide a further catalyst for progress.

Contents

1 The Worcestershire 5G Testbed and Consortium

In March 2018 DCMS chose the Worcestershire 5G (W5G) consortium as one of six early stage 5G testbeds and trials (5GTT) projects. W5G was selected to work with manufacturing industry to understand the opportunities and challenges of deploying new technologies based on the developing international standards for future 5G networks. The 5G Testbeds and Trials (5GTT) Programme was designed to bring together the best of UK innovation, resources and expertise to explore the benefits and challenges of deploying 5G technologies, against a backdrop of significant global attention on 5G network development in a research and design environment.

Building on Worcestershire's Connected County strategy and world-leading manufacturing sector, a W5G consortium was developed to work with the DCMS to test the real-life deployment of a 5G network and assess the impact on selected Industry 4.0 use cases.

W5G's primary aims were to:

1. Assess and quantify how 5G can facilitate Industry 4.0 – the enablement of cyber-physical systems within an industrial setting – to deliver increased productivity. W5G set out with a hypothesis of testing if 5G can deliver a 1% improvement in productivity and operational efficiency.
2. Develop new cyber-security services to be applied to both 5G New Radio and the critical Industry 4.0 applications which use the network. The goal was 'security by design'.
3. Collaborate with and contribute to the wider 5G ecosystem including the creation of new course content at Heart of Worcestershire College and the University of Worcester to help produce the next generation of engineers.

W5G created a powerful and sustainable partner and supplier ecosystem to underpin the establishment of the testbed network and the credibility of its results. The W5G partner consortium has comprised the following organisations over the course of an initial 15-month period (Period 1) plus a further 9-month extension period (Period 2), also engaging a supply chain comprising over 30 companies of all sizes:

Leaders for innovation across Worcestershire and the Midlands	**Worcestershire Local Enterprise Partnership**, **Worcestershire County Council**, **and Malvern Hills Science Park (MHSP**
Leaders in the development, deployment, and operation of 5G networks in the UK and Internationally	**AWTG, Ltd (AWTG),Telefonica UK (O2) and BT** **5G Innovation Centre (5GIC)** at The University of Surrey **Huawei** (Period 1)**, Ericsson** (Period 2)
Leaders in Industry 4.0 applications	**Worcester Bosch Group** **Yamazaki Mazak Corporation (Mazak)** (Period 1) (Deployment of use cases across major manufacturing facilities in Worcester)
Leaders in cybersecurity and 'security by design'	**QinetiQ** providing service assurance and security testing
Local leaders in the delivery of the new 5G skills and education	**Heart of Worcestershire College (HoWC),** and **University of Worcester (UW)** as associate members of the consortium.

Table 2: Consortium Partners

The W5G programme has established and delivered the following key activities:

- **Development of two instances of both a 4G and 5G Network** (Non-Stand Alone—NSA—architecture) and enhanced mobile broadband testing undertaken, upgradable to full stand-alone architecture through software updates.
- **Definition, deployment and testing of four Industry 4.0 use cases with Mazak and Worcester Bosch** – with testing conducted in both 4G and 5G environments to establish if 5G was required to enable each use case.
- **Cyber-security, spectrum resilience capabilities, and test/assurance services** for 5G networks to ensure 'security by design' undertaken by QinetiQ on the networks deployed and on one of the Industry 4.0 applications.
- **Evaluation of the national skills agenda** and development of a set of industry generated insights and recommendations to address any opportunities and threats, as well as delivering local further education and higher education course material.

W5G has also disseminated knowledge through collaboration and active engagement with UK5G the 5G Innovation Network, and with DCMS both within and outside of the UK, collaborating and contributing to reports on Spectrum[2] and Security[3], and provided 5G leadership across the Midlands.

Project Evolution and Phasing

The project implementation plan was to evolve the network through a series of iterations described more fully in the Network Summary of this report (Section 2). Use case design was considered at an early stage to incorporate "Security by Design" at the earliest practicable point, and to identify the vulnerabilities that would be subject to security testing at both network and application level.

The progression from Period 1 to Period 2, summarised in Figure 1 involved a decision to uplift the testbed platform from a research and development-based solution to a platform that more closely mimics a commercially available platform, subject to continued evolution of standards and interoperability.

[2] https://uk5g.org/media/uploads/resource_files/Spectrum_NH_discussion_paper_20Feb19.pdf
[3] https://uk5g.org/media/uploads/resource_files/5G_Architecture_and_Security_technical_report_-_04Dec18.pdf

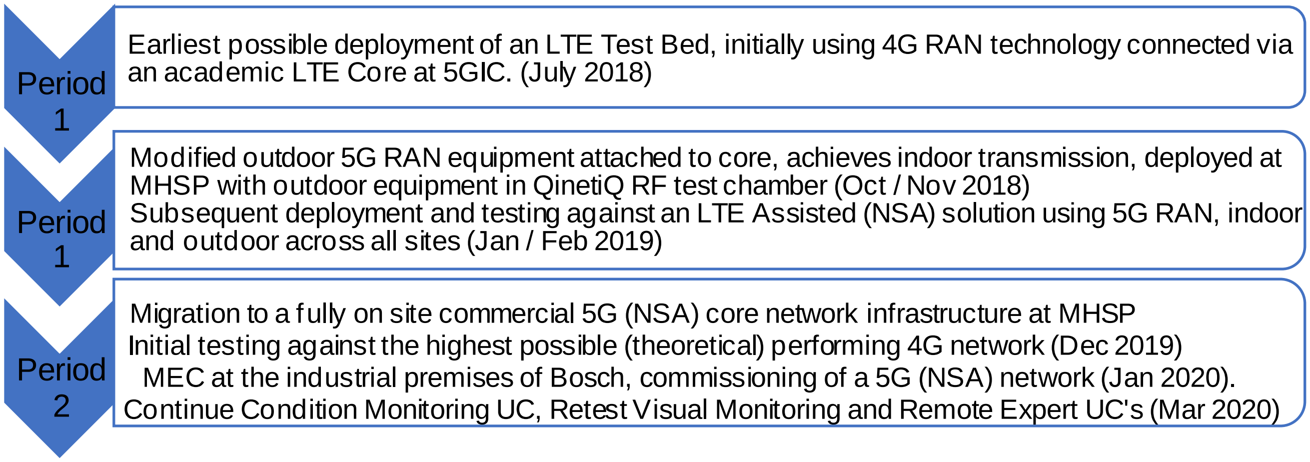


Figure 1: Project Phasing

The progressive approach has enabled the project and its industrial partners to benefit from a sustained period of testing as well as overcoming a range of practical engineering and resource constraints.

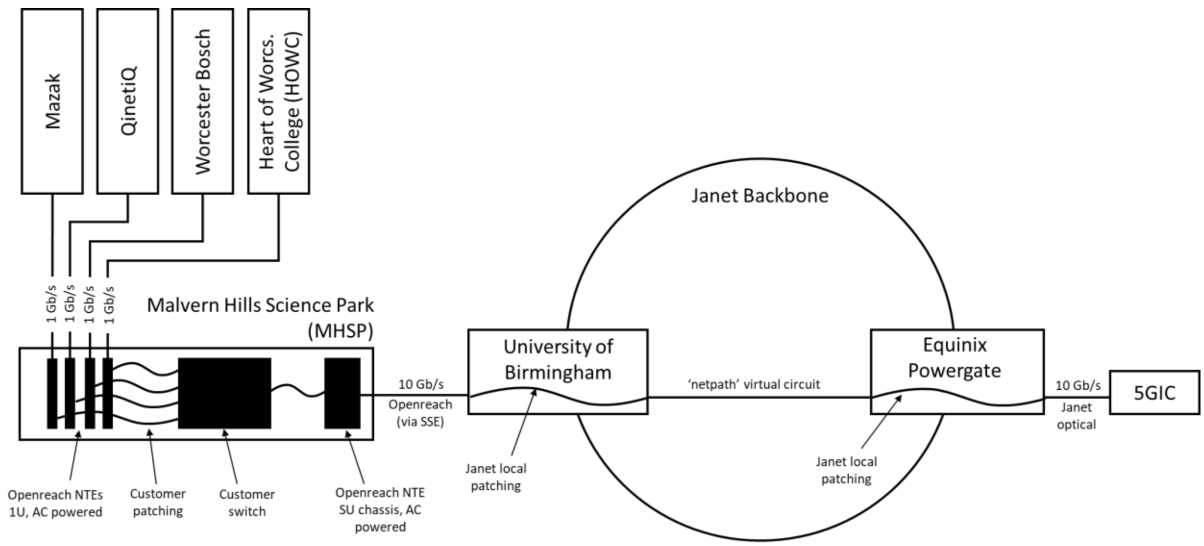
Moreover, the W5G platform is now better prepared to support subsequent commercial exploitation opportunities, has benefitted from the contribution of in depth telco and security expertise from multiple equipment vendors and operators over a period of two years, and provides a pathway to achieving a full 5G Standardised Architecture when the opportunity supports this further evolution.

2 The W5G Network

The W5G Network has been designed and configured to provide for the wide range of use cases envisioned under the project as a key means of verifying of the potentials for 5G in Industry 4.0 scenarios. In line with the project implementation plan, the network has evolved through a series of iterations broadly as introduced and summarised in Section 1 ("The W5G Testbed and Consortium") of this report.

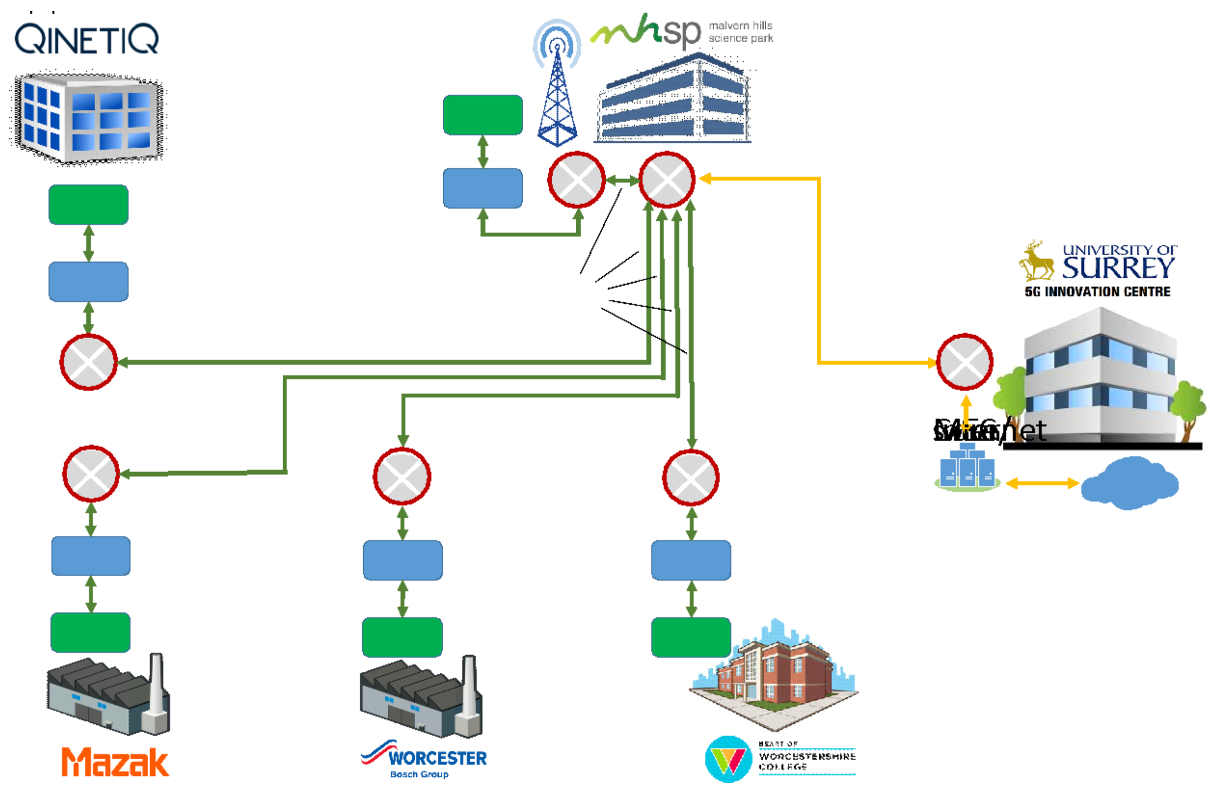
The W5G network is compliant with 3GPP 5G standards.[4] The key elements of the architecture are as follows:

1. Core network (Evolved Packet Core—EPC).
2. Radio Access Network (RAN).
3. Fibre backhaul and interconnectivity.
4. Enterprise Operations Support System (E-OSS).
5. Consumer Premises Equipment (CPEs).
6. End-user devices.
7. Mobile Edge Computing (MEC) capabilities.
8. Hardware and application(s) for each specific use case.



W5G Period 1 Network Schematic Figure 2 "(a)"

[4] 3GPP Release 15 and 16 standards, https://www.3gpp.org/release-15 and https://www.3gpp.org/release-16, accessed March 2020.



(b)

Figure 2: The W5G network at partners' sites for Period 1: (a) Network connectivity perspective, (b) mobile networks perspective. BBU = BaseBand Unit, RRU = Radio Resource Unit.[5]

Figure 2 depicts views of the network in Period 1 of the project. Figure 2(a) is from the perspective of the lower-layer wired connectivity provided to the various partners, and Figure 2(b) is a higher-level viewpoint from a mobile networks perspective including some detail on the network elements therein. Additionally, Figure 3 presents the mobile network perspective for Period 2 of the project, this time mapped on to actual locations and noting that the underlying connectivity solutions remained broadly the same as in Period 1. This is with the exception that in Period 1 the Core, MEC capabilities and Internet breakout were hosted at 5GIC, whereas in Period 2 these key components were hosted in Worcestershire.

Radio access provisioning in Period 1—hence associated RAN elements—has been at MHSP, Worcester Bosch, Mazak, QinetiQ and HOWC sites; in Period 2 such provisioning has been at MHSP, Worcester Bosch, and QinetiQ. Backhaul and Internet service provisioning, and interconnection of the sites, has been provided by leased Janet network connections in both Phases. The path back to MHSP from other sites has been through IPSec tunnels. This is one feature compliant with the overall principle of "security by design" that W5G and its network has adhered to.

[5] Note: The QinetiQ, MHSP, Mazak, Worcester Bosch and Heart of Worcestershire College sites all had indoor RAN; QinetiQ operated both outdoor and indoor RAN within an RF chamber. MHSP had outdoor RAN on a 25m Mast.

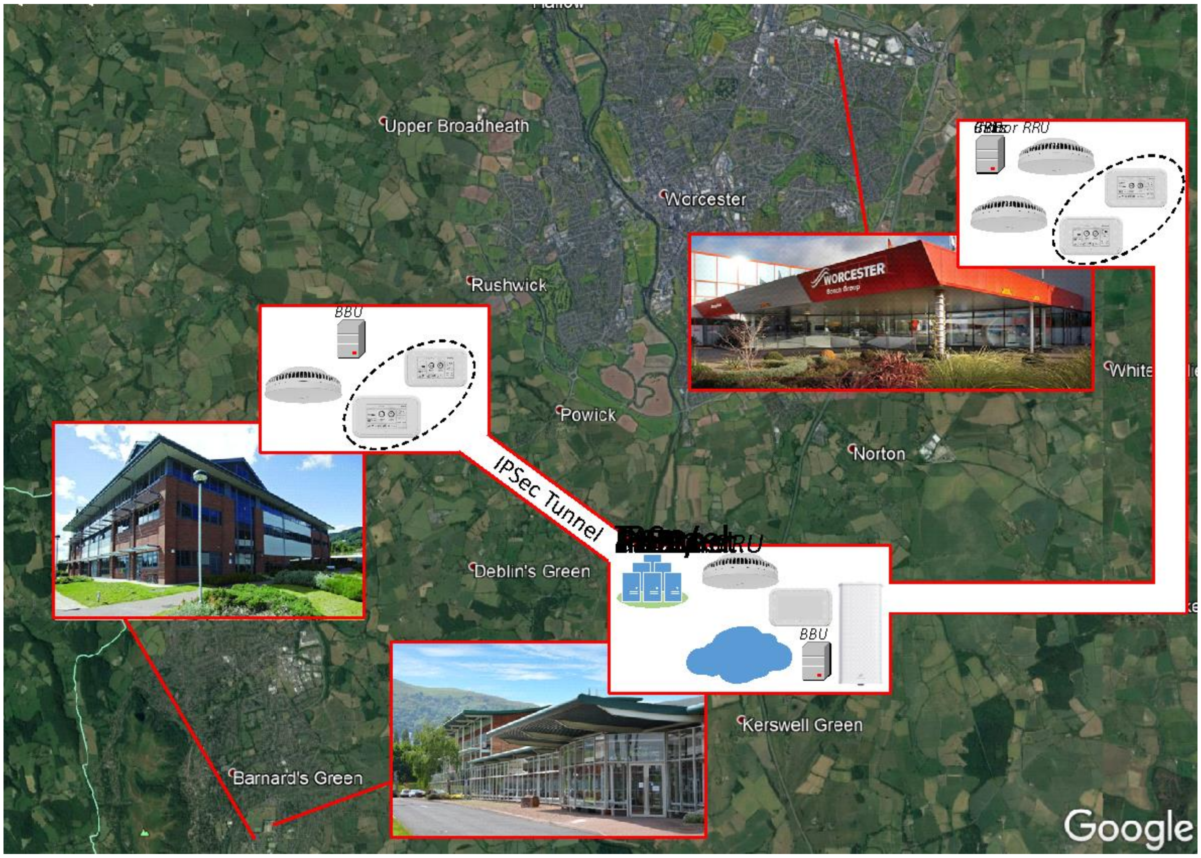


Figure 3: The W5G network at partners' sites for Period 2 from the mobile network perspective mapped on to actual locations. Note: For clarity of this depiction, the full numbers of RRUs and CPEs at each location are significantly reduced.

2.1 Non-Stand Alone (NSA) Capability

The 5G network deployment is based on 3GPP Non-Stand Alone (NSA) Option 3X architecture. This involves using a 4G/LTE network to provide the "control plane" (i.e., control) for the 5G radio network equipment.

There are good reasons behind the network still being based on 5G NSA. At various stages in the W5G project it has been anticipated that 5G SA would be available in equipment far earlier. Indeed, this has generally been the expectation of the industry, including of the most prominent chipset manufacturer for mobile equipment Qualcomm.[6] However, challenges and market demand have led to the case for the development of such equipment becoming viable far more slowly. Operators and other stakeholders have seen the need to build out 5G capabilities more gradually and economically on top of the underlying support of pre-existing 4G/LTE infrastructures, utilising the wide-area coverage provided by those for signalling/control and other purposes in a NSA mode of operation. Standards that are truly building on 5G SA capabilities—are also being completed later than anticipated. Indeed, the specifications freeze for 3GPP Release 16 did not occur until July 2020[7]

[6] Qualcomm, "The first 5G standard is complete — so what's next?", https://www.qualcomm.com/news/onq/2018/03/21/first-5g-standard-complete-so-whats-next, March 2018.
[7] 3GPP Releases included timeline, https://www.3gpp.org/release-16, accessed July 2020.

2.2 Utilised Spectrum

The 4G/LTE and 5G RAN equipment as used in the context of W5G falls entirely under the Ofcom "Innovation and Research" licensing environment. For Period 2, Ofcom has granted a license allowing access to a range of centre frequencies and bandwidths. The subset of centre frequencies and bandwidths actually used in Period 2 are:

- For the 4G/LTE equipment, in Frequency Division Duplex (FDD) mode of operation:
  - 2,517 MHz centre frequency for the uplink, 20 MHz bandwidth.
  - 2,637 MHz centre frequency for the downlink, 20 MHz bandwidth.
- For the 5G equipment, in Time-Division Duplex (TDD) mode of operation:
  - 3.54 GHz centre frequency, 80 MHz bandwidth.

The context was significantly different in the prior Period 1 work given that operator 5G deployments had not yet taken place. This meant that almost the entire 3.4-3.8 GHz range was available at that time, and the project was able to use the maximum carrier bandwidth of 100 MHz in Period 1 with the exception of the last two months of its duration in which it was also limited to 80 MHz. This limitation since then has been due to operator testing and deployments taking place, and the need to avoid interfering with those.

As alluded to elsewhere in this section, 5G equipment is still at a stage of development where its true capabilities and flexibilities are gradually being implemented by manufacturers. This is also the case for the radio interface and its flexibility. Although many of the use cases considered in W5G were strongly uplink-heavy in terms of traffic requirement, the network equipment was limited to a small number of downlink-heavy choices in terms of symbol mappings within timeslots—far less than the range of options defined in 5G/3GPP standards. [8] The mode of operation of the equipment in Period 2 was with 25% of the time resource allocated to the uplink. There was the option to push this to 30%, however, it was decided to not be worth the risk of moving to that less-standard mode of operation given the limited gain involved.

2.3 Transitions to the Current Design and Deployment

The network has undergone three key phases of development, as outlined in Figure 1 of Section 1. These have been:

1. An initial 4G/LTE-only deployment (Period 1a), with the network based on Huawei RAN equipment and a Core network developed (in conjunction with AWTG) and hosted at the University of Surrey 5G Innovation Centre (5GIC). The MEC was ultimately also hosted there.
2. Upgrading that to 5G Non-Stand Alone (NSA) capability (Period 1b).
3. After May 2019, the provisioning of the network with Ericsson equipment and an on-site Commercial Core capability and moving that to the Malvern Hills Science Park (MHSP) in Worcestershire. This also included moving MEC to the MHSP (Period 2).

2.3.1 Commercial Core and Legacy Equipment

In Period 1 the project used the University of Surrey's 5GIC academic core with early-release Huawei RAN equipment. This solution underpinned the use case testing undertaken in Period 1a and 1b (see Section

[8] 3GPP TS 38.213 v16.1, "NR;
Physical layer procedures for control
(Release 16)" Table 1.1.1-1, http://www.3gpp.org/ftp//Specs/archive/38_series/38.213/38213-g10.zip, accessed May 2020.

3), including a plan to move to a 5GSA solution with software upgrades required to meet the next release of 3GPP standards.

For Period 2, the decision was taken to uplift the testbed platform to a solution that more closely mimics a commercially available platform. Ericsson "network in a box" solution, comprising both a core and RAN, was already commercially available was used.

This progressive approach has enabled the project and its industrial partners to benefit from a sustained period of testing as reflected in the Network and Use Case learnings described in this report, as well as overcoming a range of practical engineering and resource constraints in the network deployment process.

Moreover, with a local core the W5G platform is now better prepared to support subsequent commercial exploitation opportunities, and has benefitted from the contribution of in depth telco and security expertise from multiple equipment vendors and operators over a period of two years and still provides a pathway to achieving a full 5GSA Architecture when the opportunity supports this further evolution.

2.3.2 MEC Integration and Location

Mobile Edge Computing (MEC) is the provision of computational capability close to the edge of the mobile network, i.e., close to the radio base stations communicating with users. This is in order to support the network and its use cases. MEC becomes important in the context of 5G where constraints such as on latency—eventually being as low as 1 ms in the 3GPP Release 16 URLLC mode of operation—are such that even propagation delay of traffic back to the Core could have a serious effect. Additionally, given the immense data capacities possible in 5G, MEC might help the network and its performance in general through keeping data closer to the edge. MEC can also yield security benefits through information not being shared outside of a given physical location/domain. It is further noted that capabilities higher up in the network—and particularly the Internet—are not developed to be able to handle the exacting requirements of 5G around aspects such as reliability and latency.

MEC can assist distributing the network functions—such as the Core—closer to the users, thereby reducing aspects such as latency by reducing the distance over which the network traffic must travel. MEC can also assist end-user applications, providing a store of information, caching capability, and mimicking the remote environment at the other end of the link among various other capabilities. This is in conjunction with the user application, through the deployment of a user application counterpart on the MEC. W5G has aimed to take advantage of such capabilities for a number of its use cases, for example, allowing the caching/storage of information from sensors in the context of the Worcester Bosch Condition Monitoring use case, thereby greatly assisting timely access to the information in critical scenarios and reducing unnecessary backhaul traffic for the network.

There are extensive security considerations in hosting MEC, or indeed any server-related equipment, within industrial networks and environments. Extensive work was undertaken up until May 2019 on the integration and hosting of MEC capabilities with networks at Bosch and Mazak, but this presented some significant challenges due to security and other specific configuration aspects of the host networks. These factors limited Period 1 learning to early demonstration of application concepts in relation to MEC working over 5G.

A decision was made to host MEC capabilities at MHSP after May 2019, addressing the challenges around issues such as security and local network configuration constraints. MHSP is a well serviced, neutral and flexible site, physically close to the application endpoints in the manufacturer's facility; therefore would be suitable to demonstrate many of the benefits of MEC—notably from the perspective of MEC assisting Industry 4.0 applications rather than Core functions. This colocation of the MEC was facilitated by the strong relationship and participation of MHSP in the project. The development of a commercial core at MHSP also greatly enhanced the case for the moving of MEC capabilities to that location, given the additional level of infrastructure capability therefore being deployed at MHSP and the routing of the traffic to that location as the mobile network domain gateway point given the presence of the Core there.

2.4 Specifications of the Networks

Here we summarise the specifications of the networks. In Period 1, the Core and MEC were at 5GIC. A 10 Gbps pipe was provided to MHSP, and from there 1 Gbps was provided to each of the other locations within W5G. The outdoor 5G base station at MHSP supported 64T64R MIMO, and the outdoor base station at QinetiQ supported 8T8R. Outdoor 4G base stations both supported 2T2R. The indoor 5G base stations all supported 4T4R MIMO, and the 4G ones supported 2T2R. The frequency supported was up to 100 MHz although only 80 MHz was used towards the end of Period 1.

The theoretical throughput can be calculated per section 4.1.2 of 3GPP TS 38.306 v16.0.0.[9] In this case, the sub-carrier spacing was set to 30 kHz, and we assume the bandwidth of 100 MHz. Using the maximum modulation bits per symbol of 6 (64 QAM) as was used by the Period 1 network, a scaling factor of 1, slot format 32 as was used by the Period 1 network, and assuming only 4T4R per single device (as an example, the Samsung Galaxy S10 5G phone supports 4x4 MIMO), the maximum theoretical 5G throughput would be 1,502 Mbps on the downlink and 536 Mbps on the uplink for the outdoor deployment. For the indoor deployment, these results should be the same. For the outdoor deployment, however, it is noted that through MU-MIMO 16 users could theoretically be supported in parallel on the downlink or uplink with this rate.

For the Network in Period 2, most specifications were broadly similar. However, the bandwidth was dropped to 80 MHz, and the downlink/uplink ratio was different as follows. Where “D”, “U” and “S” respectively refer to downlink, uplink and a special slot, the alternative network provider implemented a TDD slot structure of DDSU. Moreover, the S slot was of a special slot format of 11, 0, 3 (downlink, uplink, flexible symbols), where the flexible symbols were used merely as spacing (not implemented as variable downlink/uplink). For the uplink ratio, this configuration gives 14/(14*4) = 25% allocated to the uplink, and for the downlink it gives (14+14+11)/(14*4) = 69.64% allocated to the downlink, with the remainder of the duration not being used. Again, using the Samsung Galaxy S10 5G phone example, the theoretical maximum for Period 2 given all of these factors was therefore 970 Mbps on the downlink, and 372 Mbps on the uplink. Further, in Period 2 the sole outdoor antenna supported 8T8R—meaning that 2 S10 5G devices could theoretically be supported at this rate in parallel. Moreover, in Period 2 with Ericsson, this downlink/uplink structure could add up to 2 ms latency in waiting for a uplink transmission slot, up to 1 ms on the downlink, and up to 3 ms round-trip. In Period 1 with Huawei, where each slot carries both downlink and uplink symbols, such latency could only be up to 0.5 ms both on downlink and uplink, and up to 1 ms round-trip.

As another key difference in Period 2, the network was served by an Internet capacity/gateway of 100 Mbps—50 Mbps guaranteed, and 50 Mbps contended with other users in the MHSP. Moreover, whereas the Core Network for Period 1 was hosted around 150 km away as-the-bird-flies (300 km away round-trip) at 5GIC, the Core Network for Period 2 was directly at MHSP. Assuming optical fibre carrying the signal—in which the speed of light is approximately 2/3 of that in air—this automatically added at least 1.5 ms latency to the round-trip for Period 1 compared with Period 2. Of course, in reality, far more would be added than that, due to the indirect routing of the fibre and other aspects involved in such latency, such as processing delay, transmission delay awaiting for a slot to transmit downlink/uplink, and the actual transmission. The extra propagation distance and delay would also cause some reduction to TCP

[9] http://www.3gpp.org/ftp//Specs/archive/38_series/38.306/38306-g00.zip

throughout due to effects of the bandwidth-delay product ("bandwidth" in this context meaning the end-to-end data capacity supported).

Finally, it must be noted that the actual real-world throughput can be significantly different from theoretical maxima. Different throughput target values have therefore often been used at various stages in the project, based on interactions with providers of Period 1 and 1.5—also expressed in terms of TCP vs. UDP performance. One indicative set of values is 300 Mbps on the downlink for TCP, and 855 Mbps on the downlink for UDP2

Observed Network Performance

Representative values of network performance from Period 1 and 1.5 are given in Tables 3 and 4. These values are broadly achieved by averaging a range of results, except where we feel anomalies are present. We have chosen Transmission Control Protocol (TCP) traffic specifically here, as this it is the transport cornerstone for the vast majority of applications over the Internet and mobile networks.

	4G/LTE (2x20MHz)	5G (100MHz)
Downlink TCP throughput (Mbps)	66	235
Uplink TCP throughput (Mbps)	31	35
End-to-end latency DL (ms)	13	11

Table 3: Network performance representative values achieved in Period 1.

The results in Table 3 indicate significant gains over 4G/LTE in Period 1, and Table 4 indicates even further significant gains in Period 2 despite the utilised 5G spectrum being reduced by 20% from 100 MHz bandwidth to 80 MHz. It is noted that specific challenges with TCP were experienced in Period 1—likely due to TCP's conservative congestion control approach—and the resolution of those in Period 2 is one significant reason for the leap in performance that is seen. The repositioning of both the Core and the MEC, moving closer to the applications, have influenced the performance between Period 1 and Period 2. We acknowledge that both the Period 1 and the Period 2 networks would have benefited from further optimisation.

	4G/LTE (2x20MHz)	5G (80MHz)
Downlink TCP throughput (Mbps)	114	605
Uplink TCP throughput (Mbps)	32	53
End-to-end latency DL (ms)	15	12

Table 4: Network performance representative values achieved in Period 2.

2.5 Lessons Learned in the Network Deployment, and Future Suggestions

Our systems integrator has identified a number of lessons learned in the deployment process. Future suggestions have also been made. These are shared below.

The W5G consortium delivered a testbed at the very cutting edge of 5G and the first true such 5G network in a factory environment in the UK. In order to get to this point, a considerable number of challenges were overcome. Not least of which, there was a lack of standards when we started out in early 2018. In effect, we were working well in advance of the technology standards being defined, which itself gave rise to a number of related challenges such as the lack of chipset availability, feeding into the unavailability of development modules and manufacturer equipment in general.

The live commercial 24/7 manufacturing environment was also extremely challenging. Issues around the specific configurations for the networks in such locations given aspects such as local network management norms have been challenging here. These have been accentuated by issues around the development and deployment of the MEC and Core, and hosting and configuration solutions that have had to be worked through to address those.

As usual in network deployments, radio transmission and backhaul are the bottlenecks requiring considerable optimisation/effort. 5G is no different, being highly challenging for existing host networks backhaul and Internet breakout capabilities, given the extremely high capacities it introduces. Aspects such as low latency and high reliability in 5G lead to the need to reconsider how conventional IP networks are designed—and to some extent managed—in order to realise such capabilities end-to-end. Further, the mapping to challenging applications taking advantage of the new dimensions introduced around areas such as latency and reliability in 5G have led to the need to operate across a number of different spheres of interest, beyond the usual telecommunications areas. Novel technologies that are introduced in 5G in general—such as Software Defined Networks (SDN) and Network Function Virtualisation (NFV)—have led to the need to expand into other areas accordingly. It has also been observed in W5G that applications can add a very significant latency, requiring careful optimisation such that the latency added by the 5G networks, however low, does not take the user-experienced latency to a level that can be observed.

Further on the topic of application-layer performance, work in W5G has led to a number of important observations being derived in the use case testing of Appendix B3. One key observation is that the capabilities of 5G are opening realms of video quality that are beginning to push outside of the comfort zones of current video codec designs. Section B3.4 draws key recommendations on the need for cross-layer optimisation, and perhaps solutions such as error correction within codecs to be able to cope with the real-time streaming of large, high-quality video frames over wireless networks. Top-down optimisation, based on the challenging requirements of such applications addressing the characteristics of the network accordingly, might also be undertaken. Of course, 5G should eventually be prime for such capabilities through technologies such as network slicing and the radio flexibility offered by 5G NR.

A key lesson in terms of technologies has been the observed need for very high quality in-building design, coverage estimation and optimisation. W5G has been fortunate to have had access to indoor and outdoor 5G equipment from two different high-profile manufacturers. An overriding observation in both indoor and outdoor cases has been that performance for 5G has been far more variable than 4G/LTE. Our investigations have implied that this is likely to have been due to greater propagation uncertainty at 5G frequencies compared with, e.g., 4G/LTE and earlier. Other radio environmental aspects such as electrical interference in an industrial context might also play a part. There would be value in further research and development around wireless communications in Industry 4.0 being undertaken to explore such issues further. In any case, propagation and coverage differences are to a large extent a natural consequence of the higher frequencies at which 5G operates. Moreover, the extent to which 5G pushes the boundaries of what is possible in terms of higher-order modulation and coding schemes, in the context of aspects such as propagation variations and likely electrical interference in such Industry 4.0 scenarios, might explain significant performance variations.

Installation within live manufacturing environments has resulted in compromise to the design, not only to accommodate the needs of the manufacturing partner but also to enable the systems integrator to easily maintain the solution going forward. This leads to the observation that partnership landscapes of the traditional operators/vendors/suppliers and the interaction with customers will need to be optimised and re-templated in order to deliver such network deployments at scale—noting the vast new performance dimensions introduced by 5G around aspects such as latency and reliability, and the associated new customers and stakeholders that are therefore brought into the fold.

Several observations have been made through this work and more general analysis of 5G, leading to thoughts on technical developments and enhancements that would facilitate 5G thereby maximising beneficial impacts socially and for the economy. Many such items are related to challenges around in-building coverage, including the need for better in-building design, changes in building practices/standards to facilitate communications provisioning and propagation, spectrum sharing to increase lower frequency spectrum available, and observations around the density of deployments necessary and the need for indoor deployments—which in turn have implications around, for example, sharing of equipment and slicing. The overriding challenge here is that 5G uses significantly higher frequencies than prior generations of mobile communications systems. This leads to the key gains such as greater bandwidths/capacities at such frequencies the facilitation of far more-advanced MIMO technical configurations, those higher frequencies propagate poorly.

A clear further issue for 5G is the proper consideration of security. The presence of vastly more of the communication capabilities in software, and the mixing of different services on common physical infrastructure through slicing, accentuate the need to mitigate possibilities for hacking or other malicious acts. The novel mission-critical services through 5G given its capabilities, such as emergency communications, military and indeed Industry 4.0 and associated risks involved, further accentuate the need for security structures and accreditation processes to be well developed.

Highlights

The W5G Network—using equipment from two world-leading mobile network equipment manufacturers and expertise of the team in deploying that and configuring it for challenging use cases—has been the most advanced 5G network solution deployed in an advanced manufacturing setting in the UK. It has therefore realised a number of major achievements and firsts. Some of these are listed as follows:

- First deployment of 5G NSA in a manufacturing environment in the UK.
- First instance of an enterprise-led implementation of a private 5G NSA network in the UK.
- First in-depth 'security by design' review and development of a 5G manufacturing network.
- Profound performance achievements through 5G. Performance characteristics and achievements of the network in general are covered in Appendix A, and in the contexts of the specific use cases are in Appendix B. Some key take-aways are:
    - Downlink throughputs of around 600 Mbps, or higher in some cases—despite being limited to 80 MHz carrier bandwidths for many of the tests in which such performances were achieved. Throughputs of 600 Mbps have been achieved even when congestion-controlled TCP is used, the transmission rate of which—due to the characteristics of its congestion control algorithms—can be challenged to match the high capacity of 5G wireless links. Achieved UDP throughputs have been up to around 800 Mbps.
    - Uplink throughputs approaching of up to around 70 Mbps for UDP and 55 Mbps for TCP in the best cases.
    - End-to-end latencies over the network as low as around 10 ms. This is despite being based thus-far on 5G NSA, which is not tailored to low-latency scenarios. 5G SA is tailored to such scenarios.
    - Good reliability even while being deployed in a trial environment and in Period 1 used early-access equipment.

From experience of the W5G network to date we believe the deployment of 5G NR can provide a platform for potential transformation in manufacturing by supporting new use cases that deliver greater production efficiency, flexibility and scalability, and open-up new ways to deliver services and products. The opportunity is significant; 5G represents a step change in connectivity for advanced manufacturing settings achieving requirements for multiple new use cases through the dimensions of low latency, ultra-high reliability, and vast numbers of connected devices that it introduces. Moreover, since W5G began there have been a number of subsequent developments, notably in 5G standard setting and access to end-user-devices to name but two.

It should also be noted that there is also an increasing amount of fibre to the premises being built, making transmission links more affordable for businesses than ever before. Ofcom have also released their spectrum sharing framework, allowing the likes of small businesses the ability to apply for Shared Spectrum Licenses that open up parts of the radio spectrum between 1.8 GHz and 26 GHz, at very accessible prices. These developments are undoubtedly going to enable industry to build small private 5G networks, with the support of a systems integrator where required; providing the vendor equipment can operate within the available frequency bands and the vendors appetite to engage outside of their traditional MNO markets.

3 Industry 4.0 – Use Cases and Key Findings

W5G developed and tested next-generation technologies across four Industry 4.0 use cases, designated UC1 through to UC4 for further reference in this report, as summarised in Figure 4 below, working with the 2 manufacturing members of the consortium, Mazak and Worcester Bosch, both of which are based in Worcester.

In addition, a number of security-related themes use cases were investigated at QinetiQ, through the network deployment there. This is important in Industry 4.0 scenarios, as security violations can lead to loss of commercially sensitive data and/or cause damaging outages/failures of equipment, potentially at significant expense or even risk to life. These are covered in Section 4.

Figure 4 illustrates where the four use cases sit relative to International Telecommunications Union generic use case typology for 5G.

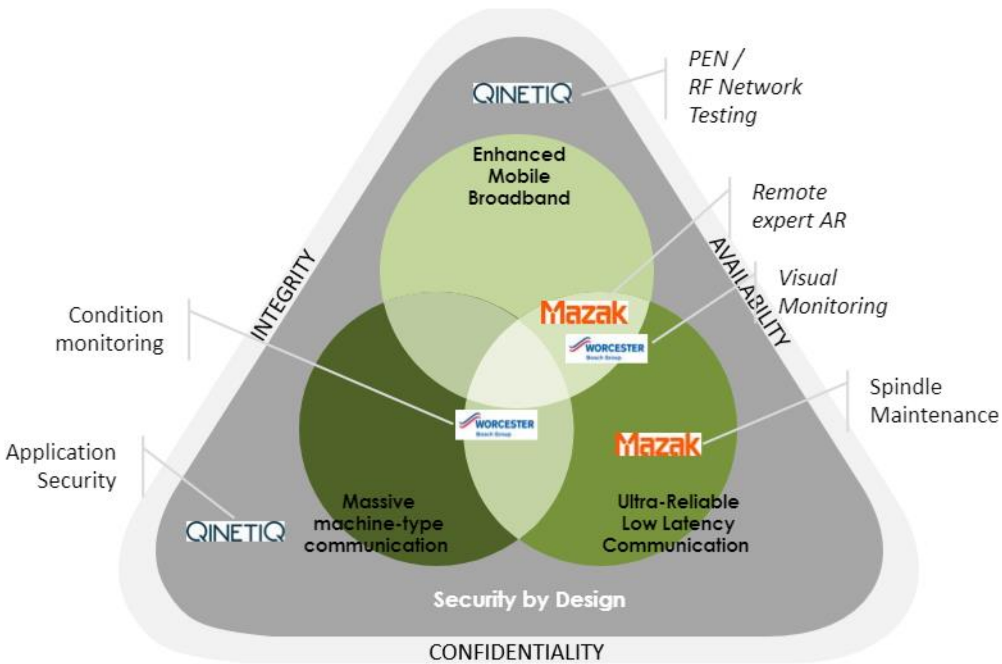


Figure 4 – Industry 4.0 Use Case types

Mazak Use Cases

Yamazaki Mazak design, build, sell and support large scale milling and CNC machines used in a wide range of industries, including Formula 1 and other hi-tech industries. The European Manufacturing Plant in Worcester is not just a machine tool assembly plant; they machine their own castings, make their own spindles, their own turrets, their own tool magazines and their own sheet metal covers.

Two use cases were developed with Mazak, as summarised in the following table:

Use case	Description
Augmented Reality-enabled remote training ('Remote Expert', UC1)	Mazak provide support to customers who have purchased their machines. This may require a visit to the customer site by a Mazak engineer, and due to the wide range of machines sold by Mazak and the extent of customization available, there is no guarantee that a single visit will result in a fix. Mazak wanted to test whether an Augmented Reality solution providing interactive live streaming and communication between centrally located experts and remote engineering staff operating in the field to improve their ability to fix issues first time, thereby reducing the need for follow-up visits, minimizing machine downtime for Mazak's customers, thus reducing the cost to serve individual customers and improving service quality.
Preventative maintenance – spindle (UC2) *(Proof of Concept)*	Mazak's machines contain a number of expensive parts. UC2 was a machine-oriented mission-critical application to enable automated remote monitoring and control of the spindle in operation. Critically it supports processing power to move away from individual machines onto machine edge computing, which Mazak might then be able to make available to its customers on a commercial basis (subject to further development, assessment of demand etc). The Spindle on a Mazak CNC machine tool is a critical component which has high cost and high impact replacement implications. As CNC machine tools have got faster and more complex, associated costs have increased: a spindle can cost between [£15,000 and £30,000] to replace. Loss of production and additional parts, combined with the need to re-work irretrievably damaged high-end pieces, could result in the costs of spindle failure being considerably higher than the cost of the spindle itself. Mazak Spindles are usually only removed for corrective maintenance *after* an issue or failure occurs. A solution which could actively monitor the condition of the spindle in real time and provide early warning of imminent failure would considerably reduce repair costs, and downtime. This was a proof of concept developed to test how quickly a "stop" message could be sent to a machine, using a machine in Mazak's research centre.

Table 5

Further details on these use cases are contained in Appendix B.

Worcester Bosch Use Cases

Worcester Bosch are the UK market leader in domestic boilers. Their current product range includes gas and oil boilers, hot water cylinders, renewable technologies such as heat pumps and solar water heating systems, as well as controls and accessories.

Two use cases were developed with Bosch, as summarised in the following table:

Use case	Description
Visual monitoring (UC3) ***(Proof of Concept)***	The purpose of this Use Case was to implement ultra-high resolution of live streaming to enable remote monitoring of real-time conditions of working facilities in the factory environment. It was recognized that video monitoring of machines carrying out repetitive tasks is not in its own right sufficient to change the way companies may operate; however, as technology progresses, the addition of Artificial Intelligence to this kind of application, might be of benefit to industry, by enhancing maintenance programmes or by reducing the costs of maintenance, or a combination of the two; hence, the positioning of this Use Case as a Proof of Concept.
Condition monitoring (UC4)	The purpose of this Use Case was to develop alternative maintenance strategies for individual machines based on condition and observed performance, instead of routine scheduled or periodical maintenance which doesn't necessarily reflect underlying machine performance or condition. Multiple sensors were deployed to monitor the status of machines, tracking a range of data including vibration and temperature.

Table 6: N.B. Further details on these use cases are contained in Appendix B.

Approach to Use Case testing

All four Use Cases were tested on the private 4G networks deployed into the Mazak and Bosch facilities in Worcester before being tested on the private 5G networks deployed into the same locations. The aim of this testing was to identify for each Use Case whether 4G was sufficient to achieve the aim of the Use Case, or whether 5G was required.

For UC1 – Mazak's "Remote Expert" – testing was also conducted using a commercial 4G network. Given the aim of this use case, and given that the performance of the private 4G networks deployed was close to the theoretical maximum for 4G, it was important to determine whether an engineer at a customer site with access only to busier commercial available 4G networks would be able to utilise the capabilities of the Remote Expert solution.

During the W5G project all use case testing – other than testing of UC1 on a public 4G network - was conducted in Mazak's and Bosch's premises. [After the swap of equipment supplier and the newly configured network, testing of UC1 was planned to move to Malvern Hills Science Park; however, as of 31st March this testing has been delayed due to the outbreak of COVID-19 which meant that the Mazak staff who were scheduled to support the testing in the Science Park with both their time and equipment, were not available to do so at the scheduled time. These tests will be completed during the extension period which has been requested from DCMS.]

The detailed findings from Use Case Testing are set out in Appendix B, however in summary:

- UC1 – Commercial 4G network access was found to be suitable for relatively short sessions only, as it was subject to multiple interruptions which was detrimental to the user experience. Testing in both Phases of the project identified that many scenarios were manageable with the high quality private 4G networks installed; however, testing in Period 2 (at MHSP, whereas Period 1 testing was conducted at Mazak's Worcester premises) found that image quality was significantly improved in 5G compared to 4G, with 5G achieving image resolution between HD and UHD, which 4G was unable to achieve.
- UC2 – Preventative Maintenance: Spindle was not supported by 4G as latency in 4G (more than 40ms RTT at the application level) was greater than the target (no more than 20 ms RTT), which resulted in a long gap between the stop signal being sent and the machine stopping, and ultimately in damage to the spindle. While the use of the private 5G network improved performance (to 23ms RTT at the application level) it was not assessed to have done so to the degree required by Mazak to make the solution viable. No testing was conducted of UC2 in Period 2 because there were no anticipated enhancements during Period 2 expected to address the specific requirement for very low latency; this was not due until a later release of the 3GPP standards for 5G (Period 1 testing only)
- UC3 – Visual Monitoring[10]: In Period 1 testing at Bosch, 4G was found to be insufficient to support the throughput levels required for more than a single 4K camera. During Period 2, testing at MHSP confirmed the same, with the private 4G network operating close to its limit with just one camera. With the private 5G network, however, it was possible to support three 4K cameras, and image quality was significantly improved compared to 4G, with 5G achieving image resolution between HD and UHD, which 4G was unable to achieve.
- UC4 – Condition Monitoring was supported on the private 4G networks deployed in Period 1 and 1.5; 5G was not required.

These are the findings for individual Use Cases. In reality, manufacturers will need to consider their connectivity requirements for multiple use cases running simultaneously. This would suggest that any manufacturer considering the deployment of video streaming capabilities as part of their plans to deploy Industry 4.0 capabilities would need 5G coverage.

Table 7 below presents key conclusions which confirm the need for 5G to support factory wide automation.

Use case	Test results	Overall conclusions
Augmented Reality-enabled remote training ('Remote Expert', UC1)	Commercial 4G was found to be suitable only for relatively short sessions, with the user experience precluding lengthy interaction driven by higher than expected dropouts, which required users to	**5G REQUIRED.** The throughput and latency capabilities of 5G broadly increase productivity by addressing the need to

[10] Some challenges were experienced with streaming over 5G in both Period 1 and 1.5 which were traced to the codec used in the RedZinc application. In short, it was found that if a high frame quality is used at high resolution, codecs such as mjpeg and H.264 could be vulnerable to low level packet loss. Annex C provides more details on the potential issues, and on possible solutions, which manufacturers and other users of such technology should consider when deploying this kind of use case.

	reconnect each time, significantly impacting on usability. Testing in both Phases of the project identified that many scenarios were manageable with the high quality private 4G networks installed. However, testing in Period 2 found that image quality was significantly improved in 5G compared to 4G, with 5G achieving image resolution between HD and UHD, which 4G was unable to achieve. The higher image resolution in 5G is likely to provide a better platform for AI capabilities. The greater throughput and multi-user MIMO capability of 5G would also make it easier for manufacturers to deploy this kind of use case alongside other use cases. Performance on the 4G private network was, in isolation, very good; however, co-existent use cases could lead to the 4G network reaching the bounds of its capabilities when trying to run use cases such as this (as evidenced by the experience on a commercial 4G network, where this use case was effectively contending for bandwidth with multiple other users).	leverage a limited pool of highly skilled expert engineers across their client base in the most efficient way possible and improve service responsiveness (UC1). 5G allows fully mobile remote working across all settings. Although UC1 in isolation performed very well on the high quality 4G networks on which it was tested, the image quality on 5G was significantly better than in 4G. When combined with other use cases, the performance observed in 4G could be compromised by competing throughput demands.
Preventative maintenance – spindle (UC2) ***(Proof of Concept)***	**5G was required** for preventative maintenance as it requires low latency and high reliability. The ultra-reliable low latency communications to achieve latency of less than 10ms is not expected to be available until the advent of Standalone 5G networks as part of Release 16 of the 3GPP standards. The private 4G network was incapable of meeting these exacting requirements and even if the latency could be further reduced there was no mechanism to ensure consistent and reliable performance.	When 5G SA is available, we would also expect 5G to help address the need to assist clients to avoid costly spindle damage, which affects productivity and also has a reputational impact on Mazak (UC2).
Visual monitoring (UC3) ***(Proof of Concept)***	4G was insufficient to support the throughput levels required with more than a single 4K/UHD camera. With a single camera, the 4G network was operating close to its limit. 5G was required to support the visual monitoring test. The increased throughput comfortably supported three 4K/UHD cameras.	UC4 INDIVIDUALLY REQUIRES 4G, HOWEVER WHEN COMBINED WITH OTHER APPLICATIONS SUCH AS UC3, 5G WOULD BE REQUIRED. Although initial testing found that a very high quality private 4G network was enough to support UC4 in isolation and

		low sensor densities, Worcester Bosch would look towards 5G as a solution when looking to deploy additional applications which require 5G in order to avoid having to run 4G and 5G networks alongside each other.
Condition monitoring (UC4)	**4G was sufficient** to support the use case in isolation at low sensor densities. **Note**: Whole factory deployments requiring an especially high density of devices – for example, 1 million per sq. km – and which generate high volumes of frequently polled data ***may*** require 5G in their own right.	The capabilities of 5G broadly increase productivity through: (i) addressing the inability to flexibly reconfigure production line with any preventative monitoring solution that is hard wired. i.e., presenting an appropriate alternative wireless solution (UC3), and (ii) addressing the need to have real time machine condition data to enable preventative maintenance, as any breakdown however infrequent is hugely disruptive to the production line (UC4).

Table 7 – Industry 4.0 Key Use Case Conclusions

5G and the "Factory of the Future"

In order for 5G to enable the "Factory of the Future", 5G technology needs to continue to evolve and enable new use cases and applications. However, adoption will be driven not just by the availability of 5G capability; it has to be cost effective. The adapted sensors that W5G deployed in the Worcester Bosch factory would not be cost-effective for solutions requiring hundreds or thousands of sensors. Established IoT applications exploit very low-cost sensor technology and 5G needs to support similar low-cost devices, otherwise cost may become a barrier to adoption of 5G.

Unless 5G is able to cost-effectively support applications like W5G's UC4 – which didn't need 5G in its own right – alongside the more demanding applications with higher data rates and/or low latency requirements which can only be met by 5G, manufacturers may be faced with an unwelcome financial penalty if they opt for 5G over 4G, with the benefits from the more demanding use cases being offset by the higher costs of supporting use cases that would otherwise only require 4G (or indeed other technologies).

W5G therefore recommends that the 5G ecosystem focuses on all aspects of 5G deployment, and in particular on the availability of cost-effective sensors and other customer premises equipment, alongside the evolution of the 5G radio standards which have rightly been a major focus of attention in recent times.

What business benefits does 5G bring?

For UC1 – Remote Expert, having proven that the solution developed was technically feasible, Mazak set about answering the question "How often might the Remote Expert system have prevented follow-up customer visits by a customer engineer if 5G were available to the engineer on their first visit?". Based on an assessment of nearly 240 follow up diagnostic visits over a 2-month period in early 2019, Mazak estimated that 15% could have been avoided had the system been available. With each follow up visit taking a further day on average, the effort Mazak estimated might have been avoidable was estimated to be 216 man days over a full year, equivalent to just over 2% of available engineering resource effort. This was effort that Mazak believed it would be able to refocus onto other customer issues or investing in enhanced customer satisfaction *if 5G was widely available*.

Testing for UC4 - Condition Monitoring in Worcester Bosch Manufacturing Operations was supported with the use of modified Bosch XDK sensors to measure equipment condition in real time, this focused on vibrational analysis, cycle count and gravitational force on machines and monitored via dash boards in real time. The use of XDK sensor technology to support Condition Based Monitoring was technically proven on production equipment during the project, with subsequent testing focused on fine-tuning the Use Case and operational improvements. Key learnings from this period of operation included:

- The unit cost of the adapted sensors used in the Condition Monitoring trial (UC4) would be too high to justify widespread deployment, especially in circumstances where the sensors aren't expected to provide significant amounts of business-critical data - smaller more cost-effective sensor technologies e.g NBIoT, LTE- M, may be utilised in such circumstances. There are not currently any cost-effective, energy-efficient 5G enabled sensors available on the market.
- The need for robust sensors, designed to withstand harsh factory environments – manufacturers need access to sensors that are small enough to avoid damage from the moving parts of the equipment they are intended to monitor.

In terms of business benefits, Worcester Bosch had targeted potential productivity gains of 1% through this use case. As at 31st March 2020, Bosch have not been able to underpin this level of improvement based on UC4 as implemented. Notwithstanding this, they had identified and initiated plans on three further 5G-enabled use cases planned for 2020 / 2021 (Copper Pipe Bending, Storage Racking Detection, and Automated Guided Vehicles) which, when combined with further enhancements to sensor technology to better support UC4, they believed would underpin productivity improvements of up to 1%.

None of the use cases assessed by the W5G consortium, and none of the further use cases identified by Bosch, were sufficient on their own to justify investing in a private 5G network. Based on the costs of deploying the 5G network and the various applications considered to date, it is likely that larger manufacturers will need to implement multiple use cases over time in order to justify the investment in 5G. Indicative modelling by W5G suggests possible payback periods of between 1 and 4 years from such investment. However, the anticipated evolution of 5G - such as the advent of 5G SA, the move towards URLLC and the introduction of network slicing which may allow companies to run their corporate networks on a network slice - could have a significant positive impact on the economics of 5G by extending the scope of activities underpinned by 5G and delivering benefits not addressed by Industry 4.0. For further information see Appendix C.

Highlights

- W5G trialled four Industry 4.0 use cases during Period 1 and 1.5;
- A high performing 5G network is required to support factory wide automation compared to the best performing alternative networks. Optimised 4G networks may be sufficient to support isolated use cases but whole factory implementations require the speed, latency and device density that can only be delivered and supported by 5G networks;
- Significant potential productivity returns of just over 2% were identified as part of the work carried out in Mazak. Although Bosch had not underpinned the 1% productivity benefits that they believed might be achievable from UC4, they nevertheless had identified a number of other use cases that they believed would do so;
- Productivity returns could be utilised in a number of ways including the creation of additional capacity, and to help deliver improvements in the customer experience;
- None of the use cases considered by W5G would justify 5G investment in isolation. Multiple use cases, each delivering some commercial benefit, will likely be required to justify the move to 5G;
- Manufacturers should consider whether they are likely to wish to deploy any use cases likely to require high data rates and throughput before deploying a private network in their environment – where such use cases may be required, even in the future, a private 5G network would likely be required;
- Modem availability for 5G is still an issue, with very few devices on the market. It appears that many manufacturers are awaiting the release of 3GPP (Release 16) standards before they commit to large scale manufacturing;
- For use cases dependent on sensors, it is important that sensor technology progresses to provide cost-effective 5G-ready sensors capable of being deployed in potentially hostile factory environments;
- For small business to adopt 5G services, improvements in 5G CPE and more of a "plug and play" experience will be required. In time we expect the price to install, commission and operate a 5G network to reduce.

4 Security Testing

QinetiQ's role within the project was to support the W5G goal to deliver "Security by design" by developing dedicated 5G security services whilst undertaking a practical evaluation of security in the W5G environment:

- Test and Assurance Service for 5G Applications.
- Network Security and Resilience of the 5G Radio Access Network (RAN).

QinetiQ conducted their work on a fully operational implementation of the 5G Non- Standalone (NSA) network architecture which was physically installed at their site in Malvern.

5G Customer Premise Equipment (CPE) devices, as well as Internet of Things (IoT) sensors with dedicated integrated 4G modems, were used to connect to the 5G testbed network.

Application Testing

On application testing QinetiQ has worked with Worcester Bosch to evaluate the availability, integrity and confidentiality considerations of the sensor-based conditional monitoring use case (UC4 – see Section 3) across the factory.

Security application testing on the first version of the Bosch XDK sensor identified that it was vulnerable to externally induced network drop-offs. Testing found that the XDK rarely resumed transmission after network availability was restored and needed user interaction (i.e. a full power cycle) to reconnect.

It was also observed that the memory used by the application almost doubled over a 75-minute observation period which was indicative of a memory leak - when an application wrongly holds on to memory even though it no longer has a use for it - within the application. These two issues were directly affecting functional performance and impacted the availability aspect of security, something that would not have come to light quickly in the absence of testing.

Bosch subsequently reconfigured the sensor, and a second round of testing by QinetiQ verified that the fixes applied by Bosch addressed the issues identified previously, adding significant digital resilience to the network connectivity of the XDK sensors.

The 'security by design' testing flagged a growing need for an industry-wide authentication standard for IoT devices to be enabled in manufacturing settings. Future considerations on manufacturing spectrum (see 5G-ACIA) and security considerations for manufacturing network slicing are uppermost in consortium partners minds.

Network Testing

The W5G network is, uniquely, the only indoor and outdoor NSA 5G network that has been security tested.

QinetiQ's security testing of the W5G network identified factors that impacted the availability and performance of the network and highlighted the security complexity for manufacturers in the roll-out of new networks into facilities.

Results of testing clearly identified additional security controls that could be applied to the core network to increase resilience and availability, improve confidentiality and performance, and reduce overall risk to the integrity of the network.

Period 1 results were consistent with an early stage R&D based testbed – rather than a commercially hardened network.

In Period 2 the W5G network was rebuilt to a well architected and documented level following good security practices and standards, consistent with its current experimentational nature. The testbed phase has been completed and further performance and security optimisation work would be required to support a full commercial deployment, having regard for the partners, use cases and data sensitivities. The QinetiQ test reports detail these measures more specifically.

The W5G security use cases have demonstrated that security assessment techniques can be applied to a 5G network. Further key learning could be achieved by undertaking a security by design approach to a 5G standalone (SA) network, including improved security features and a full complement of 5G network features, e.g. Network Slicing, Distributed Core and Mobile Edge Compute configuration as well as 5G New Radio SA waveform.

Device design, including CPE and base stations, should be cognisant of security and assurance requirements. 5G, IoT and Industry 4.0, offer huge potential to introduce security by design approaches with devices being designed for specific job and therefore to specific design and security requirements. IoT application testing is crucial to understanding the risks associated with the implications of these design decisions.

Lessons Learned and Future Opportunities

QinetiQ have developed a portfolio of 5G Security and Resilience services as a result of the Worcestershire 5G project. These provide security and assurance of the 5G network, smartphone apps and IoT through a suite of integrated consultancy and testing services:

- 5G Network Design Security Consultancy – a bespoke security consultancy service, specifically focussed on 5G, enabling delivery of secure 5G network designs.
- 5G Network Security Testing – a comprehensive suite of security assurance testing services for 5G networks. These can be used to test and assure the security of the deployment of a 5G network design.
- 5G App Testing – a 5G Smart Phone app security testing service with one-off and subscription models, with standard and enhanced security reports options available.
- 5G IoT Device and Platform Testing – a bespoke IoT security testing service.

Highlights

- QinetiQ observations confirm that "security by design" should be considered an essential feature of 5G network deployment, bringing the opportunity to identify and mitigate unexpected behaviours that may subsequently be discovered by network security testing.
- Built around its work on W5G QinetiQ has now developed and launched new services covering Network Security Testing and a Test and Assurance Service for 5G applications. These services form part of a coherent market offering within QinetiQ's Cyber and Digital Resilience portfolio, specifically targeted at providing a complete security offering for 5G IoT Device and Platform testing.
- 5G incorporates many improved security features and offers a highly flexible network capable of delivering many new business critical services. By undertaking security design and testing that spans the end to end service (e.g. Sensors, MEC, network, applications) businesses can take full advantage of this revolution in mobile communications with confidence.

5. Skills and Education Ecosystem

5.1 Skills Overview

The 5GTT projects have been leveraged to create education, training and skills opportunities and learnings that are applicable both locally, across the UK and internationally. This is in recognition of the risk that by not linking the supply of digital skills to the future demands of industry, the UK's investment attractiveness as a place to do business is diminished. As much as the future successful returns from Industry 4.0 and 5G will be about technological and use case applications, its ultimate success, and UK PLC's relative success internationally, will be profoundly about human capabilities.

The W5G skills workstream covered two main objectives:

- Through collaboration with industry thought leaders, create a report which describes 5G skills readiness, including any risks, issues and opportunities to support future demand, along with recommendations for delivering a 5G ready workforce in the UK.
- To work with its academic partners to include 5G content into relevant courses.

In 2018 /19 W5G undertook primary and secondary research in the form of a comprehensive literature review and a substantial workshop attended by thought leaders from across the industry, including the other 5G testbeds including Smart Tourism 5G, AutoAir, and 5GRIT testbeds, representation from Industry, Academia, Government and Network Operators. The overall aim was to better understand the skills requirements to deliver 5G and identify key insights and recommendations.

5.2 Insights and Recommendations

The output from this work is a separate report entitled Gearing Up Our People to Drive the Power of 5G[11]. This report concluded that to increase adoption of Industry 4.0, the IoT revolution and associated economic benefits offered by 5G, the UK requires a national digital movement of significant scale.

Five key recommendations were prioritised alongside strategies for action via a centrally co-ordinated government team, working through an agile approach with regional organisations such as Local Enterprise Partnerships (LEPs) and locally based Digital Skills Partnership networks. The five key recommendations are:

- National high-profile team of role models to inspire young people early on.
- Digital mentoring programme for business leaders.
- Softer skills training for existing engineers.
- Benefits case and scale up support for industry.
- Statistical analysis through gov agencies on what telecoms engineers are needed, by region.

[11] https://www.wlep.co.uk/current-projects/worcestershire-5g/report-library/

Whilst the existing workforce, despite a lack of age and gender diversity will manage the upgrade to 5G, this in and of itself will not deliver the benefits of 5G. The UK needs to increase the size of its entire digital workforce and evolve their skills in order to deliver a next-generation human digital backbone.

The UK needs to develop a flexible skills strategy, which will increase the size of its digital workforce and evolve skills in order to deliver a next-generation human digital backbone and associated products and services, such as IoT. Only then can the potential benefits of 5G be realised.

10 key insights, summarised in Table 8 below, were prioritised for action against three key WHAT?

- The state of the existing telecommunications engineering workforce
- What this means for the deployment and adoption of 5G
- How out future workforce needs to change to realise the benefits

The state of the existing telecoms engineering workforce:	What this means for the deployment and adoption of 5G:	How our future workforce needs to change to realise benefits:
There is a shortage of suitable qualified engineers available in the UK. Our engineering workforce lacks age diversity. Our engineering workforce lacks gender diversity. The gap in skills is being managed with international resources.	The existing workforce will manage the technical upgrade to 5G. There will be a surge in demand for ICT skills when industry proves the case for 5G. There is the need for a flexible skills strategy, which can adapt as 5G matures.	Telecoms engineers of the future need to evolve both their technical and soft skills. Change agents within industry, service provision, and government need to become more digitally literate and more closely aligned. There is the opportunity to strengthen our STEM workforce with resources from disciplines less relevant in the 5G age.

Table 8 – Skills Report insights

These insights and recommendations have since been shared with Policy makers at DCMS and DfE to inform the future skills agenda at national level that we suggest might potentially form the basis of a small central programme. These findings have also formed the basis of knowledge dissemination via the report's wider contributing group.

5.3 Further and Higher Education in Worcestershire

The University of Worcester (UW) and Heart of Worcestershire College (HOWC) and have been leading the local agenda on understanding the skills that will be required in the future in order to install and maintain 5G networks.

Specifically, they are continuously reviewing the role further and higher education settings will need to play to support 5G and new labour markets through two skills work packages:

- Design of academic and vocational course materials - incorporating a broader array of topics that are relevant to 5G including Internet of Things (IoT), Distributed Systems and Cyber Security – to prepare future network engineers to gain a hybrid skill set to leverage the benefits of 5G by UW or alternatively introduce engineers, managers and skilled professionals across different disciplines and sectors to 5G networks and their properties.

- Design and deliver vocational course materials – including IoT, RF Engineering, Cyber Security, and Wireless Networking – up to Higher National Diploma level that will prepare future network engineers to leverage the benefits of 5G.

5.3.1 University of Worcester Course Development

The University of Worcester (UW) is a leading public teaching and research university, based in Worcester, serving Worcestershire, Herefordshire and a UK / international body of students. It has one of the best records of graduate employment in the country placed in the top 10 for sustained employment after graduation. UW focused on two key areas:

- Designing course materials that provide students with a fundamental understanding and underpinning skills of 5G technologies and the benefits they enable. Pending market demand, course material will be developed for two courses, Digital Technology Solutions Professional Degree Apprenticeship and Optional Modules for Undergraduate Computing course.

- Providing course materials which supplies wider businesses with students that have the right mix of skills to commission, manage and leverage benefits from 5G networks. This is based on scoped out industry requirements for Future Network Engineer, setting out the skills that it is thought businesses will need from their network engineers in order to commission, manage and leverage benefits from 5G networks.

The key activities for this work have been:

- Working with industry partners to identify gaps in course content and develop new course material.
- New course commenced in September 2019 with updated Optional Modules for Undergraduate Computing.
- Developed an academia and industry skills working group, supported by WLEP; working across all 5G pilots, sharing learning and promoting 5G potential to business.

The W5G project provided academic teams with access to key learnings, subsequently applied to course development and roll out as launched in September 2019:

- Focused feedback on partners understanding of the skills and jobs gaps in the industry, and therefore a direction of travel for graduate or work placements to those areas.
- Greater consideration of broader employability 'soft skills' considered in curriculum planning.
- Shone the spotlight on the challenge of raising interest in STEM choice for young people with a need to map out career path potential. Moving forward UW will strengthen its partnership work with Worcestershire County Council’s Employment & Skills team, WLEP, and Chamber of

Commerce to promote and support grassroots promotion in schools and colleges about 5G and STEM career choices.

5.3.2 Heart of Worcestershire College Course Development

Heart of Worcestershire College (HoWC) provides vocational, technical and professional courses, access programmes, apprenticeships, degrees, foundation degrees, HNDs, HNCs, NVQs and business training. Unlike other Academic institutions, students at the HoWC not only benefit from industry driven learning materials but the unique opportunity to familiarise themselves with the technology in tandem.

The key activities for this work have been:

- Engagement with 5G industry around vocational course requirements and development up to Higher National Diploma (HND) level, culminating in a Future industry skills requirement specification.
- Gap analysis relative to previous HoWC course content and what is required for a future network engineer.
- Planned schemes of Work for 5G related modules: Transport Network Design, Internet of Things, Cloud Computing, and Virtual Reality and AR Development.

The first cohort of students started the new courses in September 2019, the courses intend to train approximately 50 students per annum.

The W5G project has provided HoWC unique access to companies working within the telecoms industry, for example, Huawei Carrier division, Telefonica/O2, and BT which has been invaluable in helping shape the content of the course materials. Key learnings that have been incorporated into course material include:

- That 5G will bring together skills from existing radio engineers and IP Network engineers, with both sets having to develop a common set of skills, for example network or packet design. This means that future Network Engineering courses will need to have content/modules covering radio/spectrum. HoWC have embedded this content into the existing Higher National Diploma Network engineering modules.

- Further course content development has been supported though hands-on experiences of delivering a large-scale multi-discipline project – the testbed and trials. Key lessons incorporated into course material includes examples such as effectively sharing intellectual property and collaboration between private and public sector bodies. HoWC have found this useful, and used this for case study development, for use in Project Management modules.

- Addressing the skills gap in Industry 4.0 and how industry/business can best utilise technology (using 5G as the enabler) to increase productivity.

- HoWC's engagement with Huawei has led to its selection as one of only 9 Huawei 5G Academies in the country. This operates alongside its existing Networking Academy and has given staff and students access to a greater range of network devices across multiple vendors, broadening experiences and enhancing future employment opportunities.

5.4 Building a Worcestershire Skills Legacy

Alongside the new course development across UW and HOWC, a skills legacy has been developed across the Worcestershire and Midlands Ecosystem. This has been delivered through:

- The delivery of skills events, such as the Skills Roadshow that has demonstrated the returns from 5G in manufacturing to children and young people.

- The development of an immersive virtual reality (VR) Worcestershire Museum, illustrating the depth of manufacturing and industry innovation that has begun and been delivered in Worcestershire.

- The hardware for this alpha VR educational tool was financed by W5G. This tool is not only a demonstration of a VR use case in education and cultural industries, but also a key marketing platform to attract children and young people towards the 5G agenda in Worcestershire.

- The launch of a new Huawei Academy at HoWC in March 2019 to educate the next generation of 5G multi-skilled engineers, acting as a key bridge to the skills gap in the manufacturing industry.

<u>Highlights</u>

- To increase adoption of Industry 4.0, the IoT revolution and associated economic benefits offered by 5G, the UK requires a national digital movement of significant scale. The W5G led cross industry skills report, Gearing Up Our People to Drive the Power of 5G, sets out a blueprint for addressing this at national and local level.
- 5G specific course materials have been developed by the Heart of Worcestershire College, and the University of Worcester, tailored to the practical business and engineering operations of a 5G world. HOWC has established itself as a 5G Academy as a response to the shortfall of ICT Engineering roles key to the success of future 5G opportunities for Worcestershire and the wider eco-system.

"*The 5G Academy will train the next generation of 5G Engineers for the country. It will also be made available for our existing students as well as new entrants to the industry. We are delighted to be recognised for the hard work we have done supporting 5G skills growth within Worcestershire and we look forward to training the next generation of engineers."*

(Heart of Worcestershire College's Principal and Chief Executive, Stuart Laverick)

6 W5G So What?

Worcestershire's vision is to "build a connected, creative, dynamic economy that delivers increased prosperity for all those who choose to live, work, visit and invest in Worcestershire." Specifically, the 5G Testbed and Trails programme has afforded Worcestershire a once-in a lifetime opportunity to take early-mover advantage within the 5G ecosystem. This report and the activity delivered is part of a much wider programme in Worcestershire aiming to achieve that vision. W5G provided local and regional companies the opportunity to be amongst the first to trial and implement the collection of use cases enabled by 5G, with a focus on manufacturing, industry 4.0 and 'security by design'.

The collaboration of the W5G consortium involving world-class industry leading manufacturers, vendors, mobile network operators, systems integrators, cyber security experts, academia and local government; has been key to the success of W5G.

Summary of achievements

Over the last 2 years, a number of significant achievements have been made by W5G, including:

- The establishment of two efficient 4G networks, the first deployment of a 5G network (NSA) in the UK, deployed across two factories in Worcestershire; the deployment of a second private 5G network with localised MEC and Core. (Detailed in Section 2)
- The trialling of Industry 4.0 use cases, identifying significant productivity improvements of 1-2%. (Detailed in Section 3)
- Leading on work on 'security by design' identifying the business imperative for effectively building in security and risk considerations in any future deployments, raising clear skill and capability requirements in the manufacturing and security sectors. (Detailed in Section 4)
- Development of clear insights and outcomes from the skills agenda and education sector. (Detailed in Section 5)
- Learning of lessons for MNOs and future deployments of 5G in manufacturing
- Establishment of a vibrant consortium and Worcestershire ecosystem, that are acting to attract further interest in 5G and Industry 4.0.

Whilst the W5G project has been operating and investigating amongst our other aims, the potential productivity benefits 5G could have for UKPLC. British manufacturers, along with most sectors and the wider population, have faced a multitude of challenges over the past 18 months, including a lack of skilled employees, prolonged uncertainty over Brexit and at the time of writing the challenge of COVID-19 restrictions. These challenges have manifested in a prolonged period of low productivity for the sector. As we look ahead beyond 2020 and consider how best to overcome these challenges, it's clear that new technologies, especially 5G, present an opportunity to enable enhanced digital connectivity and drive performance improvements right across the manufacturing value chain and beyond. The legacy of W5G locally through the work and relationships established will continue beyond the end of the project, it is hoped the findings in this report can be spread across the 5G ecosystem for all to consider.

Appendix A: Network Testing

This appendix provides some detail and results from the overall network testing conducted at the partner sites. The testing has been performed at various stages in the development, at the last instance in Period 2 of the project in June 2020 when premises reopened, and resources were available after the COVID lockdown.

The testing and results described in Sections A1 and A2 relate primarily to that last instance of investigation up to June 2020, Period 2, for completeness- provide some brief insights into the case for the prior Period 1.

A1 Test Methodology

As regards the Period 2, general testing has been done with the objective of measuring and validating the performances of the installed 4G/LTE and 5G networks, as per design specifications. This Appendix merely covers some key aspects; further detail on the test methodology and performance measurements for Period 2 can be obtained in more detailed reports prepared by AWTG.[12] [13] [14] [15]

A1.1 4G/LTE

The 4G/LTE network testing was conducted using a Nemo Walker Air solution connected to one LTE-A capable Samsung Galaxy S8 smartphone and a Master tablet unit that controlled and monitored the operation of the test units. The test UE was configured to connect and operate over LTE Band 7 with the provisioned 20 MHz bandwidth. The tests were performed using a server provisioned in the MHSP MEC.

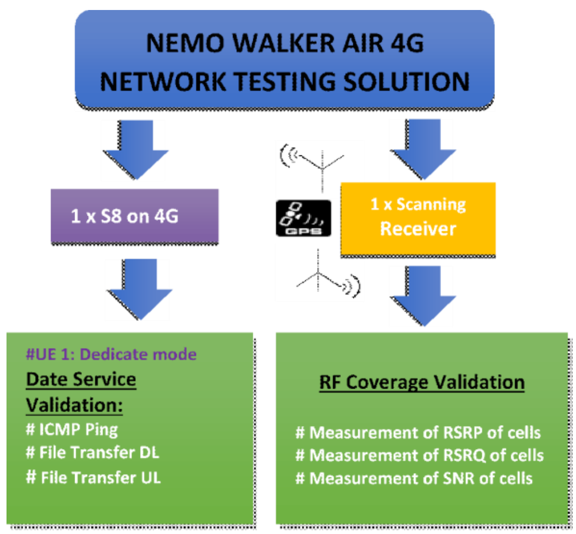


Figure 5: 4G Testing configuration

In addition to the above, the PCTEL scanner was used to scan, measure, and log the RSRP, RSRQ and the signal to noise plus interference ratio of the cells.

[12] AWTG, “M21 MHSP 5G Network Acceptance Test Report,” June 2020.
[13] AWTG, “M21 Bosch 5G Network Acceptance Test Report,” June 2020.
[14] AWTG, “M21 Bosch 5G Uplink Throughput Optimisation Report,” June 2020.
[15] AWTG, “Radio Access Network (RAN) Site Integration & Operational Acceptance Report – Stage 2,” 12 February 2020, March 2020.

A1.2 5G

The 5G network test methodology consisted of using a Samsung galaxy S10 5G conducting UDP speed tests to an MPS provided by Ericsson on the MEC at MHSP, and TCP speed tests to an iperf server set up on the same machine. 5G Stationary tests were conducted at multiple locations on site. Figure 6 depicts the testing configuration.

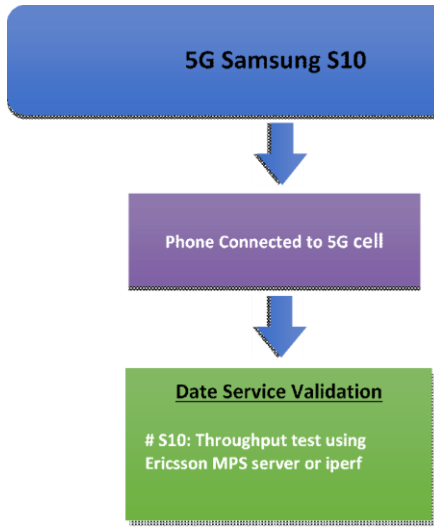
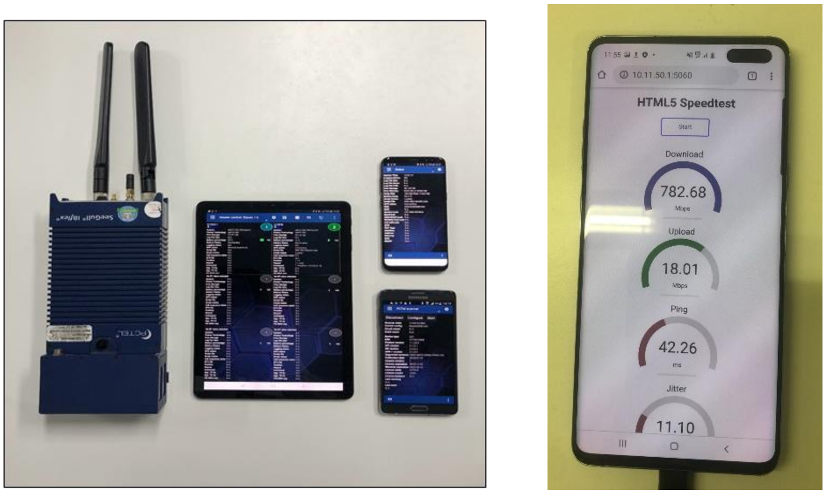


Figure 6: 5G testing configuration.

In totality, considering both the 4G/LTE and 5G testing, the hardware and software resources used were as follows. Further, the 4G PCTEL scanning hardware and the 5G Samsung Galaxy S10 5G phone are depicted in Figure 7. The PCTEL specifications are given in Table 9.

- Hardware resources:
  - Dell laptop,
  - 5G-enabled SIM card,
  - Samsung S10 5G mobile phone,
  - PCTEL Scanner,
  - Samsung S8 mobile phone,
  - Samsung Note 4 mobile phone,
  - Ericsson speed test server,
  - Samsung SM-T835 tablet.
- Software Resources:
  - Windows 10 Professional Operating System,
  - Nemo Analyser.



4G *5G*

Figure 7: Key parts of the 4G and 5G testing hardware, with associated software running on it.

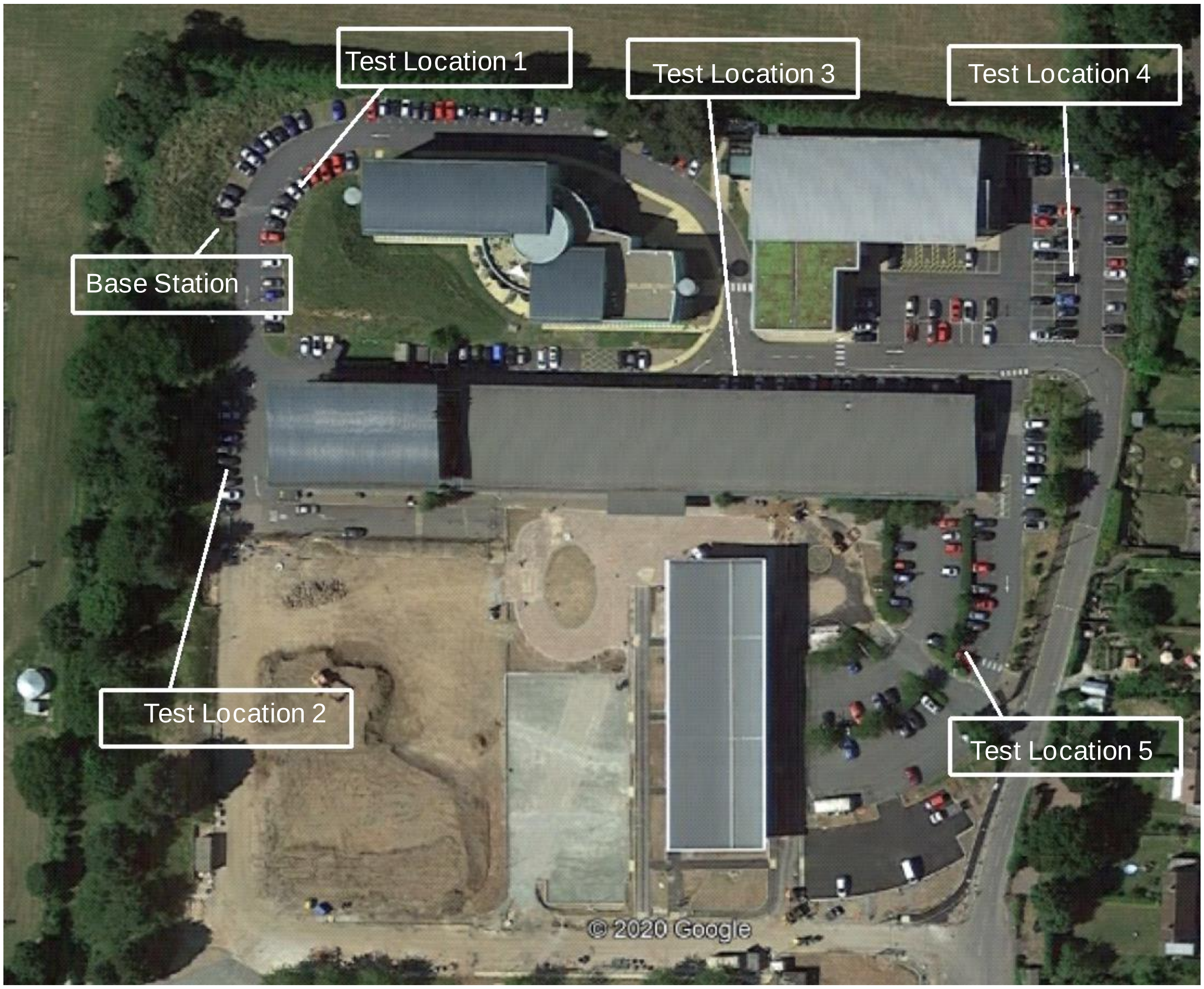
RF Scanning Receiver Details			
Receiver Model	SeeGull 08900-E	**Serial Number**	MY45091702
Manufacturer	PCTEL		
Frequency Range	10 MHz to 6 GHz		
Dynamic Range	-120 to -20 dBm		
Channel Bandwidths	5 KHz to 20 MHz		
Accuracy	+/- 1 dB		
Independent Receive Paths	2		

Table 9: PCTEL 4G mobile network scanner specifications.

o A2 Test Locations

The locations of tests were as follows. QinetiQ testing locations cannot be disclosed for security reasons.

Walk testing was done outdoors in MHSP, stopping to take measurements of the performance achieved by the macro-cell in static locations. These locations are as in Figure 8.



Test Location 1 Test Location 2 Test Location 3 Test Location 4 Test Location 5

Figure 8: MHSP outdoor macro-cell walk testing locations.

Drive testing was also done to assess the outdoor macro-cell performance at MHSP, again stopping to take measurements at static locations. These locations are as in Figure 9.

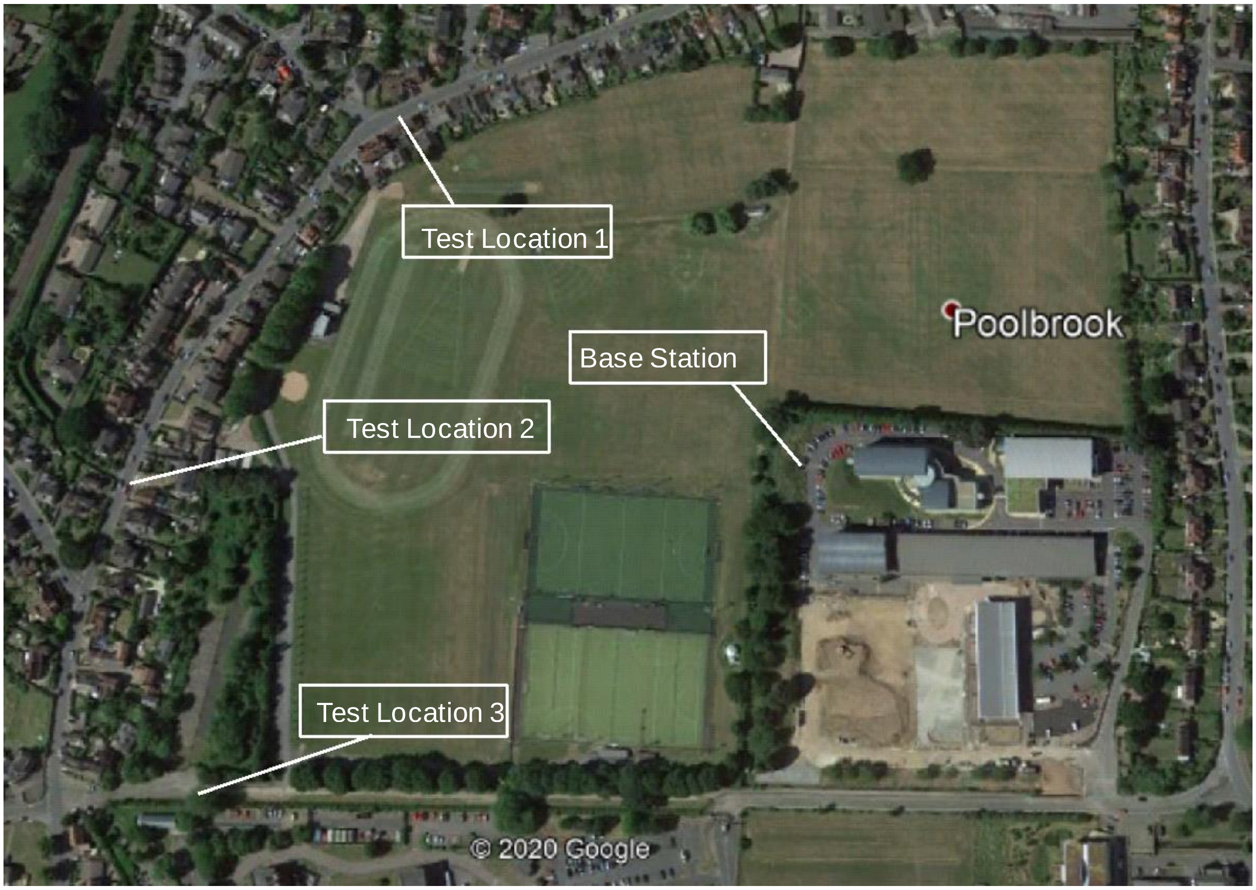


Figure 9: MHSP outdoor drive testing static locations.

Performance was measured at three static indoor locations at the MHSP, as served by the indoor 4G/5G networks. These locations are as in Figure 10.

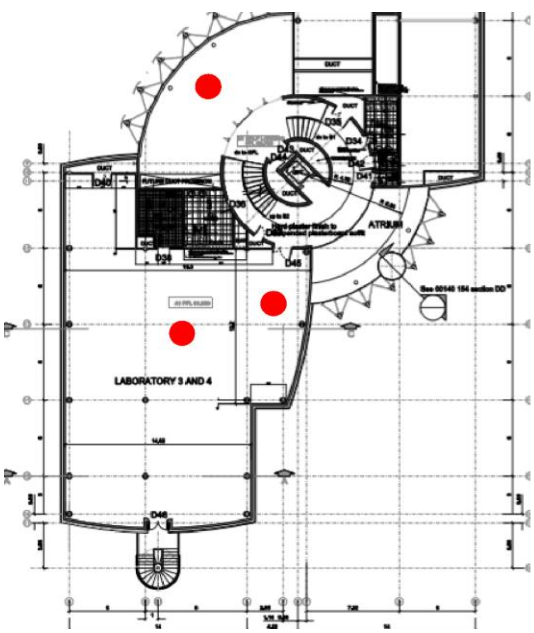


Figure 10: MHSP indoor testing locations.

Finally, performance was measured in several locations on the Bosch factory floor, both at the busy time of the factory and in shift change in which production lines were quiet. These locations are as in Figure 11.

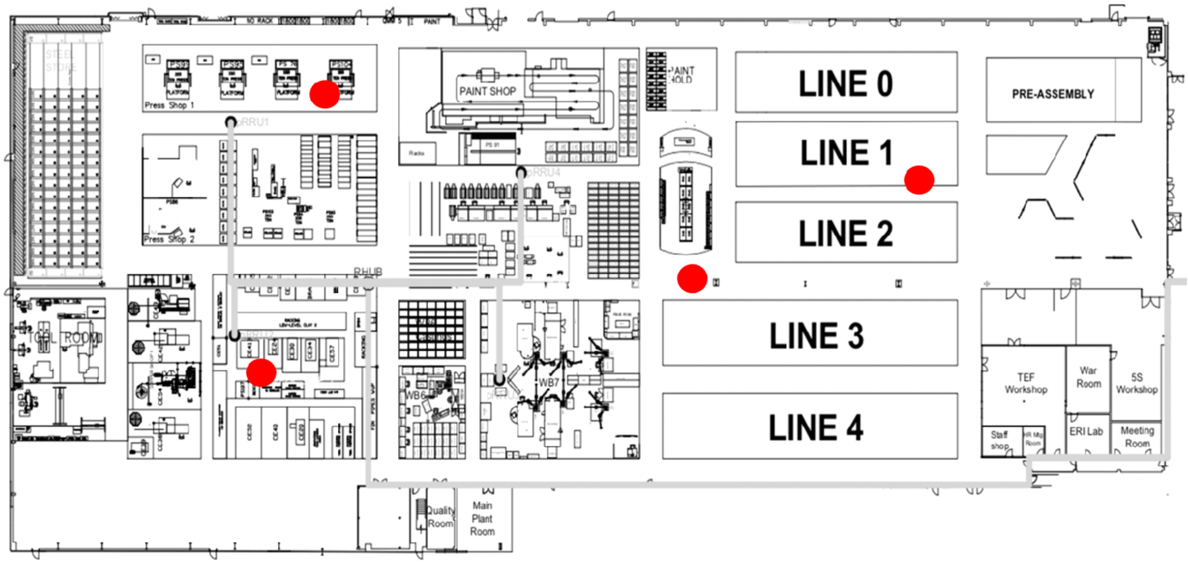


Figure 11: Bosch factory floor testing locations.

A2 Summary Results

The results in terms of average performance among all the tests for each of the given locations are provided in Table 10. More detailed results are provided in dedicated reports. It is noted that the end-to-end latency has been obtained by halving the measured round-trip time in all cases.

Based on this, for 4G/LTE the following observations can be derived:

a. The service was available for all cells. The average end-to-end latency was reasonably-consistent at around 14-17 ms.

b. Throughputs were high both on the downlink and uplink, although of course the downlink was much higher than the uplink. The indoor small cells achieved better performance than the outdoor macrocell. A possible explanation for this is the greater radio path diversity present through reflections indoors, noting that the 2x2 MIMO capability is the same for both indoor and outdoor provisioning given that this was the limitation of the Samsung Galaxy S10 5G phone.

    a. Throughput was around 10-30% lower for TCP compared with UDP measurements. This is broadly as expected.

c. The results of the network tests indicated good RAN performance in terms of both radio coverage and data service performance. From an RF perspective, coverage with an average Reference Signal Receive Power (RSRP) of -83.52 dBm, -95.64 dBm, -82.67 dBm and -58 dBm at Bosch, MHSP outdoor drive test, MHSP outdoor walk test, and QinetiQ respectively.

	DL (Mbps)	UL (Mbps)	Protocol	Latency (ms)	Test tool	Location	Comments
Bosch quiet period indoor small cell 5G	645	59	UDP	11.5	Ericsson MPS Server	Factory shop floor	
	525	54	TCP	10	iperf	Factory shop floor	Windows cmd used for ping test
Bosch busy period indoor small cell 5G	620	56	UDP	12.5	Ericsson MPS Server	Factory shop floor	Static test
	515	47	TCP	11	iperf magic app	Factory shop floor	Static test
MHSP indoor small cell 5G	790	57	UDP	10.5	Ericsson MPS Server	Indoor	Static test
	620	44	TCP	9.5	iperf magic app	Indoor	Static test
MHSP outdoor macrocell 5G	620	52	UDP	20.1	Ericsson MPS Server	Outdoor	Static test
	534	45	TCP	NA	iperf magic app	Outdoor	Static test
MHSP outdoor-to-indoor 5G	464	50	UDP	21	Ericsson Speed Test Server	Indoor	UE located indoors but connected to the outdoor macro site
QinetiQ indoor small cell 5G	574.4	65.9	UDP	14.9	Ericsson MPS Server	Indoor	Static test
Bosch indoor small cell 4G	122	43.5	TCP	15.5	Nemo (FTP)	Factory shop floor	Walk test
MHSP outdoor macrocell 4G	92.7	33.8	UDP	17.65	Ericsson MPS Server	Outdoor	Static test
	83.3	23.33	TCP	14.4	Nemo (FTP)	Outdoor	Walk test
MHSP outdoor macrocell 4G	74.6	37.5	TCP	14.7	Nemo (FTP)	Outdoor	Drive test
QinetiQ indoor small cell 4G	199	23	TCP	13.6	Nemo (FTP)	Indoor	Walk test

Table 10: Average performances for each location tested in Period 2. Experimental observations and scenario classifications are also provided.

For 5G, the following observations can be derived:

a. Full-service availability was achieved for all cells. End-to-end latencies were reasonably consistent at around 10-12ms, marginally better than 4G/LTE. However, for the 5G macrocell the end-to-end latency was much higher at around 20.1 ms.

b. Throughputs were very high, ranging up to the high hundreds of Mbps on the downlink and never dropping below 500 Mbps. On the uplink throughputs were less, as expected, but never below 44 Mbps and reaching as high as 57 Mbps in some cases. Throughput of the macrocell was again usually lower than the indoor small cells. Reduced outdoor diversity could again be an explanation for this, noting that indoor and outdoor were both constrained to the same 4x4 MIMO given the (nevertheless, field-leading) capabilities of the Samsung Galaxy S10 5G phone.

    a. These throughputs were again around 10-30% lower for TCP compared with UDP. This is broadly as expected.

    b. These throughputs were very significantly below the theoretical maxima calculated in Section 2.1. This is to be expected in real-world scenarios.

    c. The throughputs were nevertheless always high enough to easily address possible use cases that are currently envisaged including those in W5G. However, whereas the downlink could cover all scenarios in terms of video, for example, including even uncompressed video in some cases in order to minimise latency and maximise quality, the uplink would need further tuning to the case. Further, software flexibility is needed and should be implemented to better tune the downlink/uplink ratio for the specific collection of use cases required.

o A3 Comparison with Earlier Period 1 Results

A number of tests were performed in Period 1. A key difference in Period 1 was that a 100 MHz 5G carrier was able to be used, however, towards the end of Period 1 that bandwidth had to be dropped to 80 MHz—as it remained in Period 2. As follows some brief observations from a comparison of Period 2 results with results that were obtained when the 100 MHz bandwidth was used in Period 1:

- 4G/LTE testing results were broadly similar. This was despite the Core being hosted at 5GIC in Period 1 and at MHSP in Period 2.
- 5G latency results were marginally better in Period 1, typically by around 1-3 ms in one direction. This might be explained by the differences in slot formats between the networks of the different phases as discussed in Section 2.1.
- In terms of UDP traffic similar downlink throughput performances of 500 Mbps+ were achieved in both phases. TCP performance, however, was considerably lower in Period 1, peaking at 235 Mbps. The larger bandwidth-delay product in Period 1 due to the Core being hosted at 5GIC is one potential—at least partial—explanation for this.
- The maximum uplink performance achieved in Period 1 in one case was 65 Mbps—very similar to that achieved in Period 2.
- Low or zero packet error rate was experienced in both phases. However, in some contexts an error rate of around 1% as measured in Period 1, and if such packet errors were occurring that would be one likely explanation—in conjunction with the high bandwidth-delay product—for the TCP performance being lower in Period 1. However, it has also been noted that packet losses are experienced in Period 2, likely affecting the performances of the most challenging UDP streaming cases as observed in Appendix C3.

● Appendix B: Detailed Use Case Stories

W5G have supported 4 manufacturing-related use cases:

- UC1 – Augmented Reality Remote Expert Support (MHSP, run by AWTG), covered in Section B1.
- UC2 – Spindle Preventative Maintenance (Mazak), covered in Section B2.
- UC3 – Visual Monitoring (MHSP, run by AWTG), covered in Section B3.
- UC4 – Condition Monitoring (Worcester Bosch), covered in Section B4.

The use cases are constructed to show the benefits of 5G telecommunication networks to industrial scenarios, as well as to investigate aspects of their security.

There are also a number of security-related test cases that were investigated at QinetiQ, through the network deployment there. This is important in Industry 4.0 scenarios, as security violations can cause damaging outages/failures of equipment, potentially at significant expense or risk to life.

B1 Augmented Reality Remote Expert Support

Call outs for field engineers to repair customers' critical equipment are a daily occurrence for many manufacturers. Through the field engineer wearing an Augmented Reality (AR) headset connected to a Remote Expert or other resource such as AI, it is possible for the field engineer to receive instructions from a remote expert in real-time and discuss potential fixes, access information in real time, point out potential concerns, and provide commentary on his/her findings for quality control, audit and logging.

B1.1 Description

This use case demonstrates the concept of such a remote expert interacting with a field engineer through an AR headset worn by the field engineer. It allows the remote expert to point out objects with real-time written overlay on the field engineer's AR headset view, and to talk to the field engineer among other forms of input. Such capabilities allow the field engineer to:

- Follow complex instructions without having to refer to tablets, rugged computers, or smartphones.
- Receive support from remote subject matter experts who can guide them on unfamiliar, highly specialist equipment or configurations.
- Access large amounts of related data (e.g., on product lifecycle information, up-to-date, accurate service and parts information, inventory, part numbers, etc.).

Two key AR system elements in particular have been utilised:

- The Ubimax xAssist solution[16], which provides remote expert assistance to significantly reduce machine downtime and mitigate the costs of further field engineer visits and associated travel costs. Since the remote expert sees exactly what the person can see on-site, very detailed feedback and instructions are possible.
- The intuitive xAssist user interface, via which the remote expert can control what the person on-site sees and hears on his/her headset, providing overlays with markers, video, audio, pictures, screenshots, access to documents, and more. Sessions can be recorded for documentation

[16] Ubimax xAssist, https://www.ubimax.com/en/solutions/xassist.html, accessed March 2020.

purposes. Image quality and frame rate can be automatically adapted depending on connection speed.

The intention was for the Ubimax xAssist solution to be trialled over 5G both at Mazak and in the MHSP, however, trialling at MHSP wasn't possible due to the unexpected coronavirus lockdown of the facility two days before the delivery of equipment and trialling.

The aim of this use case has been to incorporate the use of AR technologies with advantages that future ubiquitous 5G networks can offer across customer sites, increasing the efficiency and productivity of the field force. 5G is a key enabler for delivering remote support solutions because of the following characteristics of the technology:

Latency –The application can work at high latencies, but the user experience is not acceptable for working hands free in an engineering context. Every millisecond saved in network latency has the potential to improve user experience. 5G will ultimately offer much better end-to-end latency than 4G. It might be noted that the 3GPP service performance requirements for AR in human-machine interfaces is only 10 ms.

Availability and Reliability – Any disconnect between the remote expert and an inexperienced field engineer working on industrial machines will severely limit the use of this application, as users will not risk complex activities if they fear a loss or lack of availability of connection. 5G's ultimate improvements in availability and reliability will give a level of credibility required for such applications to be adopted. 3GPP service performance requirements for AR in the case of human-machine interfaces include a mean time between failures of ~1 month.

B1.2 Test Methodology

The technical solution hence inherently also the test methodology for this use case are described as follows:

- A Ubimax xAssist client application is run on a Toshiba DynaEdge DE-100 Windows 10 mobile PC, connected via a USB-C port to a Toshiba AR100 HD headset with camera and a small screen in the field of view. The Ubimax xAssist software is initiated to give access to the user view when wearing the headset.
- The Dynaedge is connected via a USB-C port and adaptor to an Ethernet port on a 4G/LTE and 5G portable CPE. The Toshiba Dynaedge / AR100 comprise the AR Headset used for testing.
- The video traffic from the camera is uploaded in real-time to the Ubimax xAssist application on the MEC.
- An expert user can interact with the application via a web browser connecting to a web server run on the MEC, this connection is also enabled over the mobile network via an Ethernet connection to a 4G/5G modem.
- The expert can add content to the image displayed and this augmented view is then displayed on to the AR100 small screen in real time.

In the context of the end-to-end connection over the 5G network between the field engineer's and remote expert's equipment, this set-up is depicted in Figure 12.

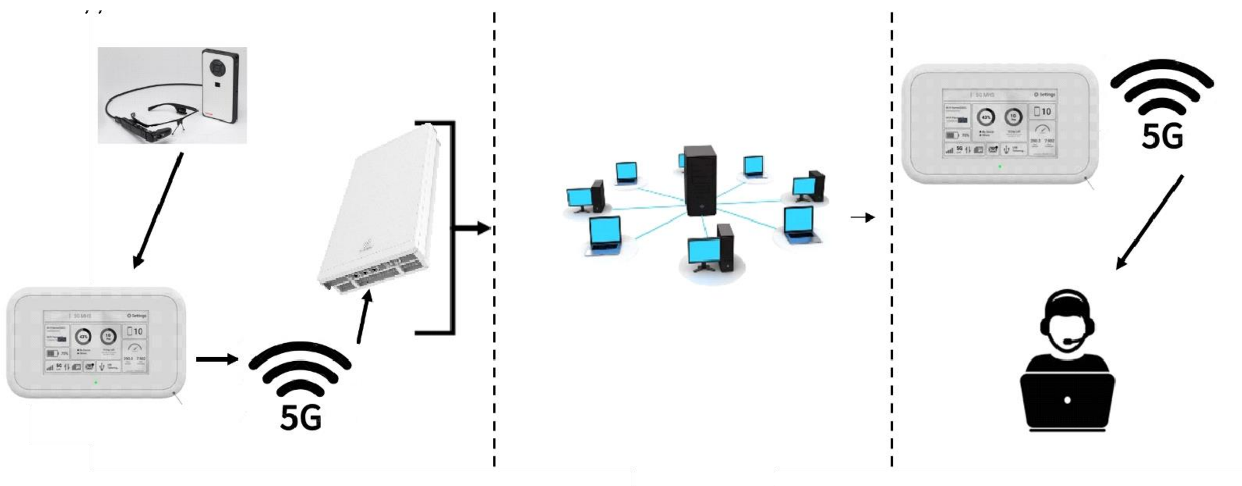


Figure 12: End-to-end remote expert connectivity over the 5G network

A command centre operating over a web server is provided to give visibility of the AR Headset view, allowing the remote expert to assist field engineers or customers via the AR Headset. This is depicted in Figure 13.

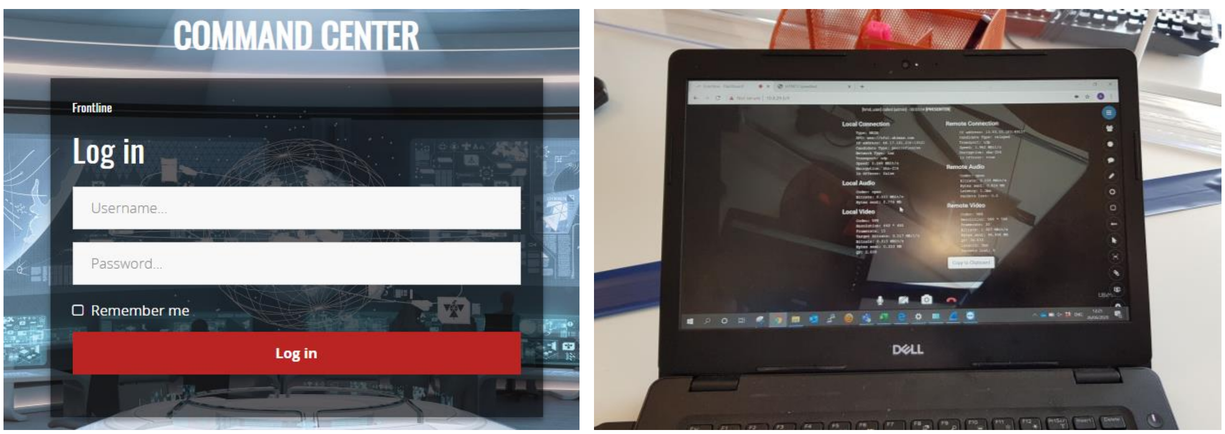


Figure 13: Remote expert command centre.

The testing followed a six-step process—as detailed in Figure 14. This testing process in Period 1 and 1.5 of the project remained broadly the same, although covered somewhat different scenarios. One key difference between these phases was that in Period 1 the tests were done at Mazak using the 4G/5G network that was provided at that time, and in Period 2 the tests were done in MHSP using the different 4G/5G network as swapped out and provided by an entirely new network manufacturer/provider.

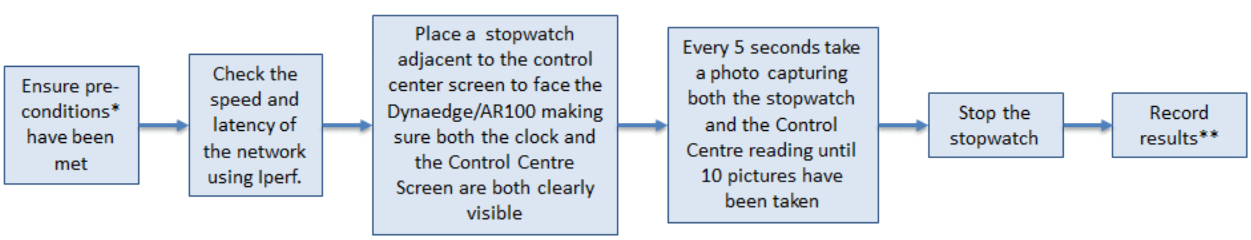


Figure 14: Remote expert use case testing process.

This approach to calculating latency at the application level using a photograph of the remote expert view of a timer along with the actual timer itself, is shown in Figure 15. The example here demonstrates 210ms latency in the field engineer's view being seen by the remote expect. iperf is a widely used tool for network performance measurement. The iperf measurements referred to in Figure 15 were taken before each day's tests.

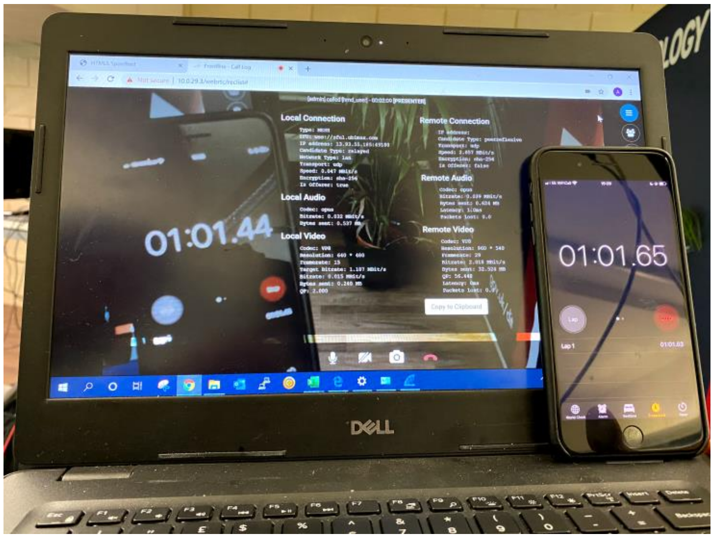


Figure 15: Methodology to assess network latency.

Figure 16 depicts the technical field engineer as equipped for the use case testing, including the components that are involved on the field engineer side.

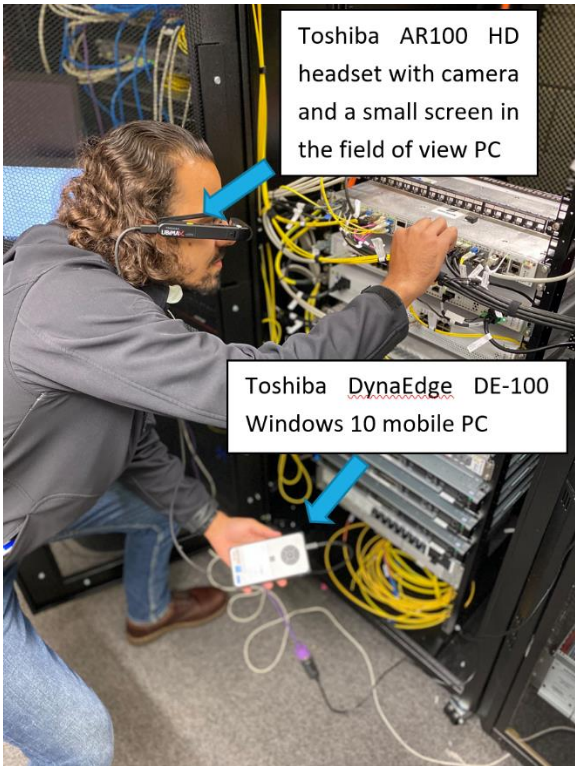


Figure 16: Technical Field Engineer equipped for the use case.

In Period 1 and Period 2, there were minor differences in the tested scenarios. In Period 2 of the project, nine tests were conducted at the MHSP. These were as follows:

- Test 1: Dynaedge/AR100 using 5G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 1 - DOT1.
- Test 2: Dynaedge/AR100 using 5G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 2 - DOT2.
- Test 3: Dynaedge/AR100 using 5G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 3 - ~60 meters from the 4G/5G Mast.
- Test 4: Dynaedge/AR100 using 4G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 1 - DOT1.
- Test 5: Dynaedge/AR100 using 4G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 2 - DOT2.
- Test 6: Dynaedge/AR100 using 4G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 3 - ~60 meters from the 4G/5G Mast.
- Test 7: Dynaedge/AR100 using 5G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 1 - DOT1.
- Test 8: Dynaedge/AR100 using 5G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 2 - DOT2.
- Test 9: Dynaedge/AR100 using 5G coverage connected to UbiMax Frontline calling Laptop logged in UbiMax Frontline installed on server on premises (MHSP) – Test Location 3 - ~60 meters from the 4G/5G Mast.

The precise testing locations within the MHSP in Period 2, and with respect to the outdoor antenna for the context of outdoor-to-indoor provisioning testing are depicted respectively in Figures 17 and 18.

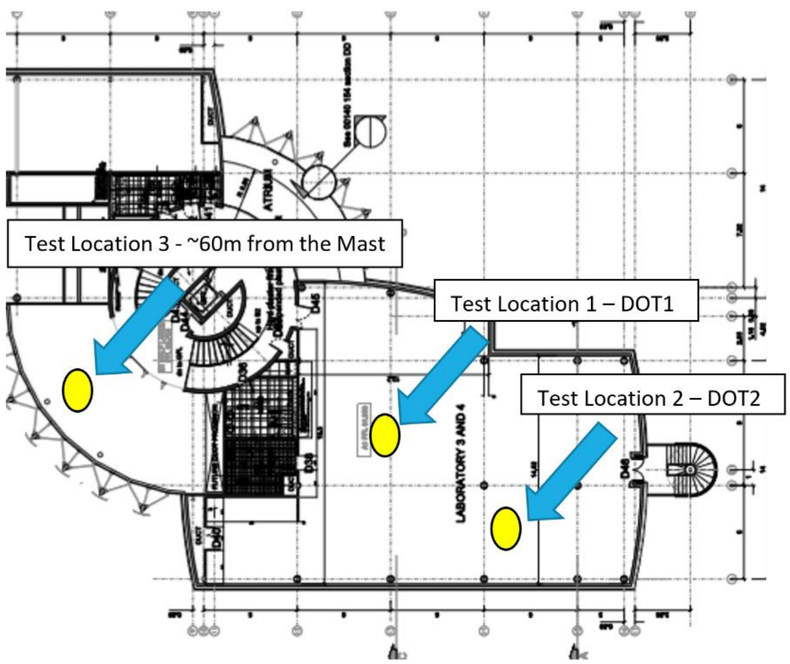


Figure 17: Testing sites within the MHSP.

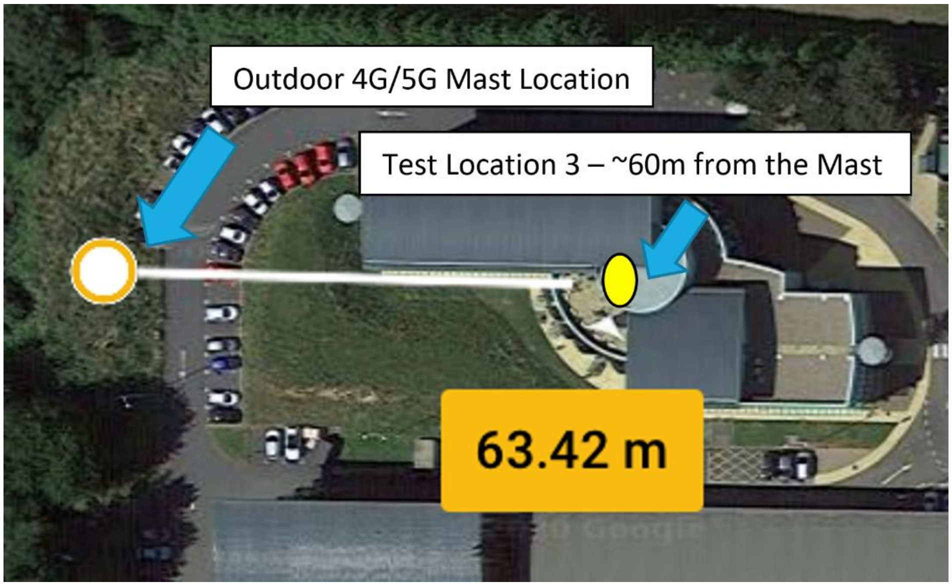


Figure 18: Outdoor-to-indoor coverage testing site within the MHSP.

B1.3 Use Case Validation Outputs

Period 1

In Period 1 of the project, the testing results yielded the following observations. First regarding the number of service drop outs:

- When tested on a commercial, public 4G network within the factory environment, 10 disconnects were observed over the 60-minute test duration (one every 6 minutes).
- When tested on the project's private 4G network performance improved, but still proved challenging for the engineers with 4 disconnects over the test duration (one every 15 minutes).
- When tested on the 5G network, the AR headset operated reliably, providing uninterrupted functionality over the test duration, with no disconnects observed over the 60 minutes test duration.

Performance optimisation around service dropouts continues within the scope of Mazak, with areas of improvement potentially including updating the neighbour lists, reducing interference and improving absolute signal level. As defined in 3GPP standards[17], the target mean time between failures for 5G is ~ 1 month.

Regarding Latency and throughput, a baseline hardwired test has shown high software latency of around 200 ms, which means that any network latency might be visible impact for the end user, taking the overall latency over the 250 ms value observable to the human eye. Test results showed that, additionally to the 200 ms software-related baseline:

- Wi-Fi LAN tests led to an end-to-end latency level of 140 ms.
- Private 4G network tests yielded an end-to-end latency of 23 ms.

[17] 3GPP TS 22.104 V17.2.0, "Service requirements for cyber-physical control applications in vertical domains; Stage 1", December 2018. Available at http://www.3gpp.org/ftp//Specs/archive/22_series/22.104/22104-h20.zip, accessed March 2020.

- 5G tests yielded an end-to-end latency of 21 ms.

No issues were identified with throughput, being sufficient to cover the use case in all scenarios noting that the element of greatest demand on throughput, the 720p video uploaded in real-time from the headset, was still far below the throughput capabilities of even Wi-Fi and 4G.

Given the testing performed, it was clear that public 4G would not work for this use case, whereas 5G does support the communication service reliability and end-to-end latency requirements. Private 4G does not provide the reliability requirements needed for the use case.

Period 2

For testing in Period 2 of the project, a baseline hardwired test has shown high software latency at 200 ms, which means that all network latency has a visible impact for the end user, affecting the potential use case for AR in a manufacturing setting.

Test results showed that:

- 4G network tests yielded an end-to-end latency of 21 ms (on top of the 200 ms baseline).
- 4G network tests yielded an end-to-end UDP throughput of 39 Mbps, with no loss.
- 5G tests yielded an end-to-end latency of 23 ms average (on top of the 200 ms baseline).
- 5G network tests yielded an end-to-end throughput of 77.65 Mbps average, with less than 1% loss.

Regarding image resolution and bitrate, test results showed that:

- 4G tests yielded an end-to-end Image Resolution of 480 * 270 to 640 * 480 pixels.
- 4G network tests yielded an end-to-end UDP Bitrate of 1,823.33 Mbit/s on the Dynaedge.
- 5G tests yielded an end-to-end Image Resolution of 640 * 480 to 1440 * 810 pixels.
- 5G network tests yielded an end-to-end UDP Bitrate of 2,011.66 Mbit/s on the Dynaedge.

5G stands out on both tested parameters reaching an image resolution between HD and Full HD, and bitrate significantly higher than 4G.

B1.4 Analysis in Terms of Company Benefits

The remote expert use case was intended to test the overall potential business returns from the application of 5G in a manufacturing context. The quality benefits of 5G have been clearly shown.

Having functionally tested the use case, the business benefits of a deployment of this service delivery model has been internally assessed at Mazak.

A key business benefit question reviewed was: "How often might the AR system have prevented follow-up customer visits by a Mazak engineer if 5G were available to the engineer on their first visit?"

In answering this, it is noted that in early 2019 Mazak engineers completed 236 follow-up diagnostic call-outs. Of these:

- 15% (36) could have been avoided if the AR system had been available during the first call-out.
    - Of this 15%, 8% would have been addressed by remote expert technical support on a specific machine issue.
    - Again of this 15%, 7% would have been addressed by effective quality assurance of the solution where the Field Engineer's work would have been reviewed by another expert engineer.

The results are depicted in Figure 19.

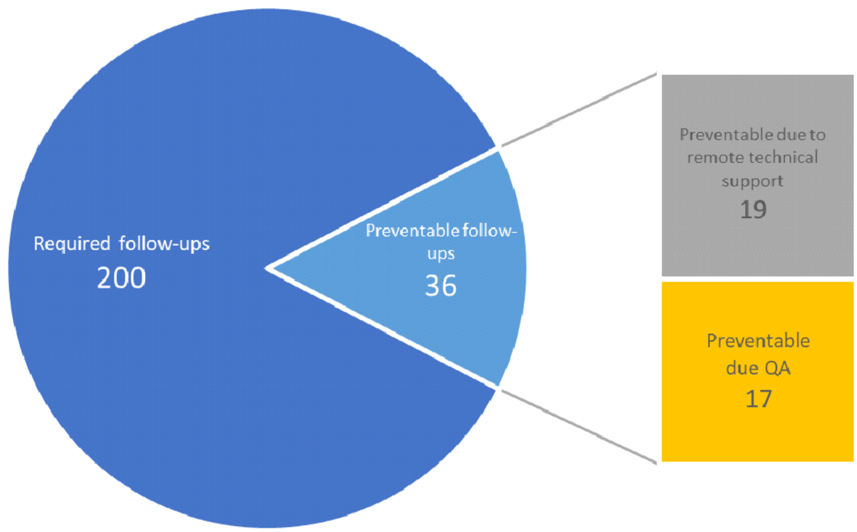


Figure 19: Analysis of number of preventable engineer follow-ups if supported by the Remote Expert use case through access to 5G technologies

On average, an engineer uses one working day per customer visit. Assuming an additional 18 jobs a month (36/2) are resolved during first visits, this would mean that over twelve months the organisation could free up 216 days (12*18) per year of engineer time. This additional capacity could be used to respond to 18 additional jobs per month, addressing the existing backlog at a faster rate and increasing customer satisfaction.

Assume 48 field engineers working 200 days each results in 9,600 total days worked. 216 days freed up divided by 9,600 engineer days = 0.0225. 1/(1-0.0225)=1.023, or 2.3% productivity gain assuming those engineers could instead be working on something else instead.[18]

o B2 Spindle Preventative Maintenance

The Spindle Preventative Maintenance use case was carried out at Mazak until May 2019. Given its close linkage with the precise industrial equipment at the Mazak location, it has not continued through since Mazak no longer being involved in the project after May 2019. The reporting and detailing on this case therefore is up to that time.

Numerical Control (NC) or Computer Numerical Control (CNC) machines provide large improvements over non-computer type machining. Modern CNC machines allow for the creation of complex machine parts requiring a variety of tools, all of which are controlled by a single NC.

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[18] This productivity gain requires the 5G network; testing shows that 4G networks do not support this use case sufficiently. For example, when the AR headset was tested on commercial, public 4G, it proved difficult within the factory environment, with 10 disconnects over the 60-minute test period (once every 6 minutes). When tested on the private 4G network, performance improved, but still provided difficulties for the engineers with 4 disconnects over the test period (once every 15 minutes). On the 5G network, the AR headset operated reliably, providing uninterrupted functionality over the test period (zero drop outs over 60 minutes). 5G also showed a 2ms lower latency.

The Spindle on a Mazak CNC machine tool is a critical component which has high cost and high impact replacement implications. As CNC machine tools have got faster and more complex, associated costs have increased: Each Spindle costs between £15,000 and £30,000 to replace. In addition, loss in production, materials, and additional parts may cost in excess of £60,000 for a single spindle replacement.

Mazak Spindles are usually only removed for corrective maintenance after an issue or failure occurs. A solution which could actively monitor the condition of the spindle in real time and provide early warning of imminent failure would considerably reduce repair costs and downtime.

▪ B2.1 Description

This trial sought to develop a 5G solution that:

- Reduces the total cost of ownership to Mazak customers.
- Increases efficiency and scalability of the service by porting the solution to the cloud.
- Increases revenue and uptake of the service by lowering the initial service/product capital cost.

5G was necessary because it is able to reduce end-to-end latency—without compromising reliability—to below the (approximate) 10 ms value required for reactivity to be sufficient to take action and avoid damage being caused. 4G cannot achieve either latency or reliability requirements.

The current on-machine Data Processing Unit (DPU) preventative maintenance solution costs £40,000 and has a customer uptake of less than 2%. The trial involves moving the spindle preventative maintenance application away from the machine's physical location, replacing it with a remote hosted solution. This would create potential cost savings and maintenance benefits for Mazak clients, providing early warnings of failure and emergency stop control, and more information for operation and maintenance status to clients, including MTTF and Mean Time To Repair (MTTR) analysis.

The trial also tested a second application where the DPU could be moved away from the machine into a cloud-based platform to reduce costs and increase adoption. This DPU provides adaptive programming to the machine where an object being cut has surface and shape variations that need to be scanned and then the DPU generates an adapted program to machine the variable surface. For the trial the object being engraved was an egg. The machine scans the egg, sends data to the remote computing capability, which then sends back a cutting programme based on the unique shape of the egg. The latency of the network is less important in this use case, but the network has to be extremely reliable in sending the scanned data and then receiving the adaptive program.

5G is an enabler of preventative maintenance solutions for the following reasons:

- Security: Clients are reluctant to allow the non-5G Spindle Application to traverse their IT networks due to security concerns.
- Latency: The preventative maintenance use case will require round trip latency of less than 20 ms for most common cutting speeds and materials. Obviously the slower the cutting speed the less impact a stop signal delay will have on the spindle and material being cut.
- Reliability: The Block Error Rate of current networks - 2% to 10% - is too high
- Processing considerations: Mobile edge processing will be required to effectively deploy the solution in order to achieve the latency levels necessary.

- High availability: Most networks provide availability around 99.1%. This would amount to approximately 15 minutes of downtime per day on average – far too high for Mazak's client base where the DPU functions in the trial would be hosted over such a network.

B2.2 Test Methodology

To test this use case, sensors on the Machine Spindle were linked to an acquisition unit that combined data on the status of the machine's cutting programme and sent the combined data through to an application hosted on the MEC. The application evaluated the sensor data, and if the data was outside the previously defined baseline parameters it would send a stop signal to the machine.

Testing of this use case was configured as follows:

- Each of the 12 Marposs sensors were connected to a separate Marposs communications unit VM-03 which is also connected to the Machine Tool Numerical Control (NC) system. This unit combined data from the NC I/O about the current cutting program being run with the sensor data.
- The data was sent directly to a Huawei E5885 CAT6/4G+ Mifi modem (for 4G testing) and the Huawei 5G CPE unit (for 5G testing) via Ethernet over copper. These devices made the radio connection to the Huawei LampSite receivers for both the 4G/LTE and 5G testing.
- At the MEC hosted by 5GIC the Marposs Measurement Transducer application passed the sampled data to the Marposs GEM application hosted on the same virtual environment. The data was analysed against parametric baseline data matching the exact stage of cutting.
- If the data were outside of these parameters a stop signal was sent to the machine NC via the Marposs VM-03 Communications unit, and then the IO interface with the Machine NC.
- The stop signal was received by Mazak's NC system which then stopped the spindle drives.
- Office staff were able to see visualisations of the system at work. Data was stored and a web interface required.

B2.3 Use Case Validation Outputs

Two test subsets were undertaken: Egg Engraving and MARPOSS Study. Both applications have been made to work to a proof-of-concept level.

The engraving use case tested:

- Egg scan ETC—the scanning of a standard non-uniform surface, an egg in this case.
- Remote processing—surface requirement mapping at 5GIC.
- Egg engraving ETC—machine engraving of the egg.

5G-connected remote processing supported a less than 9 second processing time which is more than acceptable for Customer requirements. Critical was the continuous availability of the network when transferring data, as achieved through 5G.

The MARPOSS study tested the ability to effectively send a 'stop signal' to a spindle from a MEC platform as the spindle cut through aluminium. Machining thresholds indicate that spindle head damage would be incurred if a cut were greater than 3 mm into the aluminium.

Testing results indicated:

- The wired LAN baseline configuration meets the latency requirement.

- Latency over the 4G network was greater than 40 ms at the application level, which would result in spindle damage.
- While tests of the 5G network indicated ~23 ms RTT, results at the application level were above the levels needed for this use case.
- Further testing was required to isolate where the additional latency was being introduced for the use case to be optimised over 5G. Optimisations including network protocols and/or channels being used, and further testing on polling intervals.

B2.4 Analysis in Terms of Company Benefits

The use case on preventative maintenance and adaptive programming provided a number of key learnings leading to company benefits, including:

- Preventative Maintenance requires a low end-to-end latency and high reliability. The private 4G network was incapable of meeting these exacting requirements and even if the latency could be further optimised there is no mechanism to ensure consistent and reliable performance. If industry is going to provide a business grade solution, then clients will require (and demand) guaranteed performance that can underpin contractual Service Performance Levels (SLAs).
- The network would be required to achieve less than 10 ms end-to-end latency, and this would only be possible if the MECs were located in Worcestershire rather than in the 5GIC as had to be done for compatibility reasons before the close of this use case.
- The Adaptive Programming “Post Processing” test was less dependent on latency, only dependent on required “high-availability”. This was better on 5G than 4G in the Mazak test environment.
- Third party peripheral hardware (Data Processing Units) could be moved away from the Machine Cabinet.
- Remote “Post Processing” applications could be highly transformative for Machine Tool and Computer Aided Design (CAD) / Computer Aided Machining (CAM) Systems, even at higher latencies.
- Machine Tool data rate is minimal and does not challenge data capacity capabilities.
- There were technical challenges to enable these applications for peer-to-peer communication in terms of Network Address Translation (NAT) / Firewall Traversal.
- MEC Server configuration proved challenging, and the MEC concept for local peer-to-peer communication needed a standardised platform on which Industrial suppliers could deliver applications.

B3 Visual Monitoring

Worcester Bosch’s Visual Monitoring Use Case aims to achieve anomaly detection through video image real-time capture and analysis. It leverages cutting-edge technologies including the reduced size and cost of camera equipment, availability of MEC and virtualisation capabilities, advancement in image recognition including AI, and the increased communications capabilities of 5G. The end result is the creation of a visual process and quality monitoring solution that does not require huge capital investment.

- ### B3.1 Description

This use case assesses technology capabilities to enable video-based process and quality monitoring to become a harness in the maintenance and reliability industry toolkit. It aims to develop a system that allows for productivity increases by:

- Identifying bad quality parts before they are used in the production process. This is achieved by capturing an image of the part being checked and referencing this image against a baseline image to understand deviations.
- Increasing the production capability of the overall factory by increasing equipment effectiveness.

For example, an imbalanced machine can be detected through its rocking back and forth. Motion amplification can make subtle motions visible to the user; displacement measurements can be made with around 100 times better sensitivity that traditional imagery-based measurements. High-speed video can also be captured when triggered by a fault condition, giving the maintenance engineer an undistorted, slow-motion video of the events.

5G is an enabler of visual monitoring solutions for the following reasons:

- **Bandwidth:** As image quality and frame rate increase, so do bandwidth requirements. The Worcester Bosch target throughput is 60 Mbps on the uplink, shared among three video streams.
- **Latency:** The solution requires low latency to provide real-time information sufficiently fast to act on decisions—for example, to pick the faulty part off a the production line before it has passed, or conversely speed up the production line. It might be desirable to perform video analytics at the edge of the network to achieve required latency. This underlines the importance of MEC in order to reduce transmission propagation latency.
- **Storage considerations:** The amount of data generated requires large storage devices which need the network to have the ability to transfer, store and retrieve the information easily.
- **Processing considerations:** Appropriately placed MEC can benefit the use case by removing the processing from the machine and reducing deployment costs.
- **High availability and reliability:** For a production grade solution, the network needs to be available and reliable. Extremely low error rates can be achieved in 5G—depending on configuration. A packet error rate of around 0.1% or lower at a packet size of around 1,472 B (i.e., a typical UDP/IP packet size with an Ethernet MTU of 1,500 B) can be important as a key learning through this use case—especially when certain high-quality codecs and video frames are used in Industry 4.0 scenarios. Such a low packet error rate is equivalent to a bit error rate of below 10^{-6}.

- ### B3.2 Test Methodology

Testing for this use case focuses on 5G enablement in utilising modern video technologies to simplify anomaly detection and analysis. This use case draws on the BlueEye[19] video cloud platform application provided by RedZinc, displaying three 4K/UHD cameras monitoring various parts of a manufacturing process.

Testing done in Period 1 of the project concentrated solely on RedZinc Ubuntu Linux boxes each connected to a camera streaming to the BlueEye remote application in the cloud. In Period 2 of the project, in addition to repeating such testing, this use case was extended to a more thorough analysis of

[19] RedZinc BlueEye, https://www.redzinc.net/blueeye-operators, accessed March 2020.

the 4G and 5G network performance as might benefit various other such video platforms. This was done by iperf testing of the uplink, from the RedZinc Ubuntu Linux boxes to which the cameras were connected to an iperf server running on the MEC collocated with the Core. Such an approach ruled out possible external effects interfering with the observed end-to-end performance—such as the MHSP gateway, competing traffic on the Internet itself, or the characteristics and loads of cloud servers that might alternatively be used.

This additional Period 2 iperf testing was both from a single RedZinc box, and the three boxes communicating concurrently—each connected to a different CPE running over the 4G/5G network. Through such testing, it is therefore possible to infer performance as would be the case if any other type of camera were connected with its own 4G/5G interface. Such testing might also be used to also infer how good the performance would be with other codecs, noting that the BlueEye application operated in a very specific scenario using the mjpeg or H.264 codec and with a fixed user-definable bitrate, thereby limiting what would otherwise be inferable from the testing done only with the BlueEye application. As well as investigating the performance for a range of UDP link rates on the uplink through iperf, such testing was extended to the use of TCP transport—therefore being comparable to progressive TCP video streaming as many current video stream methods rely on—if latency is less of a concern.

In both Period 1 and Period 2 of the project, the test configuration was broadly as in Figure 20. The two key differences between Period 1 and Period 2 were of course that the network provider/equipment was entirely changed between the phases, and the testing was additionally done at Bosch in Period 1 and at MHSP in Period 2.

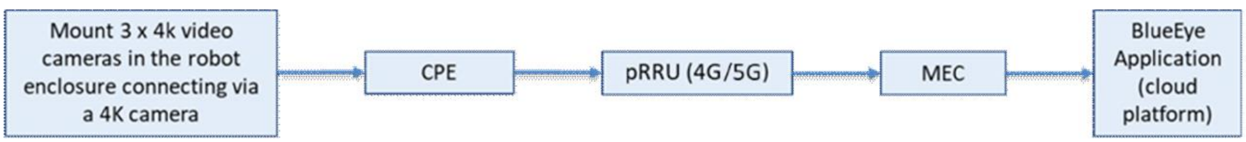


Figure 20: Visual monitoring testing configuration

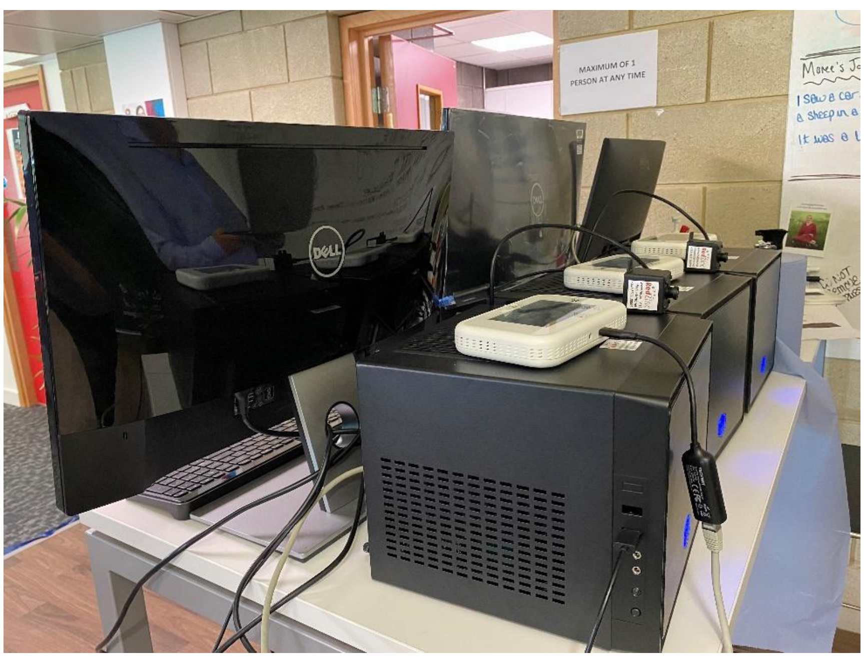


Figure 21: Photo of visual monitoring tests setup.

Figure 21 is a photo of one example of the setup of the system during testing. It is noted that in order to avoid any potential risk of interference (e.g., intermodulation) among the three depicted WNC routers, they were physically separated from each other in the process of the actual testing.

In a number of tests in Period 2—and also to a somewhat lesser extent in Period 1—the remote application was not able to receive the stream, even though it was proven through the iperf test that the data rate (typically far more than 20 Mbps per camera/box) and packet loss rate (far less than 1%) were always easily sufficient for even 3 concurrent 4K/UHD streams to be conveyed. This only seemed to happen over the 5G network. Many investigations were undertaken to try to ascertain why this was, over several experimental sessions at MHSP. The project later performed analysis which likely explains why RedZinc had this issue in the presence of such (even low level) packet loss—especially if the fixed data rate of the video were high and the frame rate of the video were low. Significant learnings can be taken from this. This analysis and its learnings are covered in Section B3.4.

▪ B3.3 Use Case Validation Outputs

First addressing the work that was done with the BlueEye remote application, results comparing 4G and 5G performances for both Period 1 and 1.5 of the project are as in Table 11.

Results in Period 1 showed that the 4G network could support all three cameras, but at below HD resolution—therefore not meeting the use case requirements. These results confirmed that 4G technology was insufficient to deliver the performance needs of the use case. Equivalent 4G results in Period 2 showed a significant improvement, and the ability of the 4G network to not only carry the 4K/UHD video, but also stream from the 3 cameras concurrently with HD resolution—although this aspect of enhancement is derived using the later iperf performance testing.

The 5G results from Period 1 significantly bettered those of the 4G network, achieving all scenarios. In Period 2—given testing after the COVID-19 lockdown return—broadly similar results were shown.

The additional iperf testing done in Period 2 has allowed performance to be derived for a far-more challenging scenario: streaming 4K/UHD from all 3 cameras concurrently on the uplink. This is shown as achievable outright over the 5G network, and with high compression (low bitrate) over 4G.

	1 camera, HD, 60 FPS, ~10 Mbps	3 cameras, HD, 60 FPS, 3 x ~10 Mbps	1 camera, UHD/4K, 15 FPS, ~15 Mbps	3 cameras, UHD/4K, 15 FPS, 3 x ~15 Mbps
4G Testing – Phase 1	Yes	Yes, but below HD resolution	No	Not tested, but "No" per implications of 1 camera test
4G Testing – Phase 1.5	Yes	Yes – per iperf performance testing	Yes	No
5G Testing – Phase 1	Yes	Yes	Yes	Not tested
5G Testing – Phase 1.5	Yes	Yes – per iperf performance testing	Yes	Yes – per iperf performance testing

Table 11: One and three-camera visual monitoring testing for the 4G and 5G networks.

The uplink, as is the key consideration of this use case, is typically more challenged given the asymmetric dimensioning of resources in radio networks. Indeed, for the networks in Period 1 and 1.5 respectively, the ratio of resources allocated to the uplink was 28.6% and 25%—and there was little scope to change that. This means that the network in Period 1 should have been very slightly better for the uplink than that in Period 2, and vice-versa for the downlink. Nevertheless, the performances experienced for the Period 1 and Period 2 networks were broadly similar noting that other aspects such as MIMO configuration for the indoor networks were also the same.

Figure 22 gives an example of the 4K/UHD video received over the network, as streamed from one of the 4K cameras during the testing.

Figure 22 Example camera output for the 4K/UHD visual monitoring configuration.

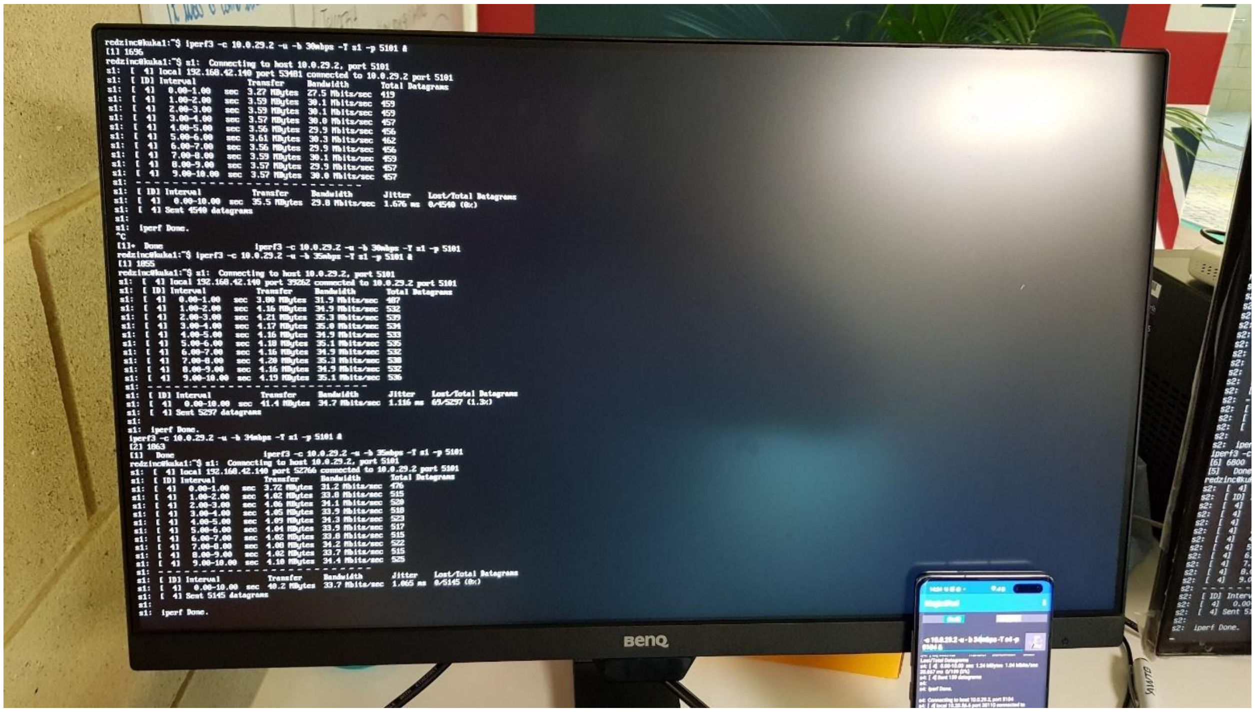
Iperf performance testing results obtained in Period 2 of the project covering the range of scenarios on the uplink are shown in Table 12. In addition to these results, 4 concurrent TCP flows on the uplink were also tested from 3 WNC routers plus 1 Samsung Galaxy S10 5G phone. The performances achieved for this additional case were, for the WNCs, 33.0 Mbps, 27.2 Mbps, 26.8 Mbps, and for the S10 5G, 16.7 Mbps. The total TCP uplink rate achieved for these 4 concurrent devices was therefore 103.7 Mbps.

	1 stream/CPE	3 concurrent streams/CPEs
4G UDP	30 Mbps, 0% packet loss	10 Mbps, 0% packet loss for all streams
4G TCP	31.2 Mbps	Not tested
5G UDP	40 Mbps, 0.13% packet loss	34 Mbps; 0%, 0.78%, 0.06% packet loss
5G TCP	42.0 Mbps	33.8 Mbps, 29.1 Mbps, 33.5 Mbps

Table 12: One and three-stream iperf testing for the 4G and 5G networks.

This results comfortably show that the Period 2 network can achieve far in excess of what is required for 4K/UHD streaming from the 3 separate devices concurrently—such a requirement being around 15-20 Mbps maximum data rate, and less than 1% packet loss—although UDP over the 5G network almost always experiences some small level of packet loss. UDP over the 4G network experiences no packet loss, or a loss that is so low that it was not detected in the durations that the range of tests were performed.

Figure 23 depicts the results of the iperf UDP uplink performance testing (34 Mbps case, as mentioned above) concurrently from the three RedZinc Linux boxes/WNCs.



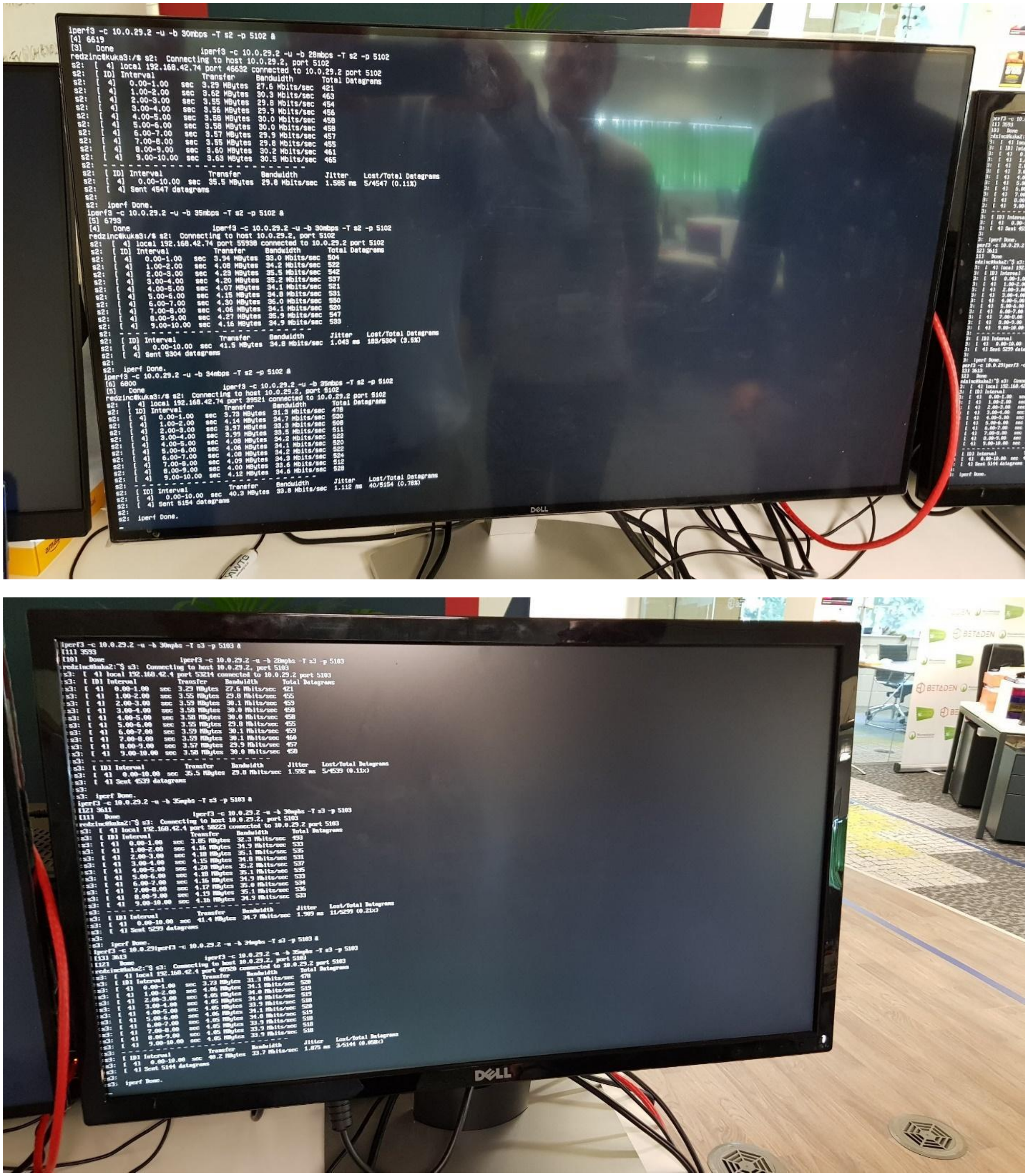


Figure 23: Iperf performance testing showing all three RedZinc boxes/streams/WNCs achieving 34 Mbps uplink concurrently over the 5G network, with less than 1% packet loss.

- ## B3.4 Codecs Issue and Learnings

There were challenges with the streaming operating over the 5G network, especially in Period 2 but also to a somewhat lesser extent in Period 1. Noting that the application uses fixed bitrate streaming, these issues were particularly noticeable if the amount of data used to construct each frame was high. This might occur if the frame rate of the video was low in order to achieve superior quality images, or in cases of very high-resolution video such as 4K/UHD.

As shown in Section B3.3, the 5G network can achieve rates of at least 34 Mbps UDP uplink per RedZinc box/link, with all three links streaming concurrently each using a different WNC router. However, there is always some UDP packet loss over the 5G network—an extremely low amount and definitely always less than 1%. Packet losses for the boxes/links in the aforementioned 34 Mbps example were respectively 0% (such no packet loss is rare for the 5G), 0.78%, 0.06%. Packet size here was left at the default for UDP in iperf3 of 1,470 B—so for smaller packet sizes (which should be the case for your application) the experienced packet loss will be far lower than that, as packet loss is binomial.

After several experimental efforts to understand why this is happening, the optimisation team has analysed the issue mathematically and broadly identified current video codecs as the issue. The RedZinc system is using Motion JPEG (mjpeg) or H.264 codecs. First considering mjpeg, given loss to any part of a frame, that whole frame is lost. The probability of a frame failing is one minus the probability of all packets in the frame succeeding. Therefore, given a packet error rate p (say, 0.5 %), a frame rate of f fps (say, 15 fps), a bitrate of b (say, 20 Mbps, which is realistic for high quality 4K/UHD), and packet size s (in bytes), the probability of each frame being lost is

$$1-(1-p)^{\left(\frac{b}{8\cdot f\cdot s}\right)}.$$

For the aforementioned 4K/UHD values, this gives

$$1-(1-0.005)^{\left(\frac{20000000}{8\cdot 15\cdot 1{,}470}\right)}=0.43,$$

i.e., the frame loss rate is 43% even if the packet loss is only 0.5% (1/200 packets). For just 1% packet loss, this increases to 68% frame loss. These values are derived noting that less than 1% packet loss should be “good” for video[20], and 34 Mbps with less than 1% packet loss should easily be sufficient to provide 4K/UHD video at a quality far in excess of that achieved by consumer video streaming—which might typically stream at 24 fps with a maximum bitrate of around 15-20 Mbps.

For the case of H.264 the situation would be very marginally worse, as if one “I” frame (i.e., actual image in the video sequence) was lost (again, with 43% probability for 0.5% packet loss rate), then both the “P” (predicted from the last frame) and “B” (bidirectionally-predicted both from the last a following frame) frames would be lost. So, a longer drop-out would be observed. Moreover, even if the “I”-frame were successful, the “errors” would have another (much smaller) bite of the cherry with the “P” frame (which if lost, would cause the “B” frame to also be lost) and then the “B” frame. Because the amount of data sent for the “P” and “B” frames is vastly lower than that for the “I” frames, the error rate for H.264 would be only very marginally worse than mjpeg. This is unless there were a lot of motion, e.g., an action movie (i.e., much bigger “P” and “B” frames being sent, as the differences between frames would be greater). If so, then H.264 would be very significantly worse than mjpeg.

Important learnings can be derived from this experience and analysis. Codecs like mjpeg and H.264 have their benefits and should not be ruled out. However, if a high frame quality is used at high resolution (i.e., the amount of data per frame is high), such codecs are particularly vulnerable to even a very low level of packet loss. The network might to be very carefully tuned to use such a codec—incorporating extra error correction to address data errors, at a small loss to achieved throughput. The coding method used by the network might also be further investigated. Alternatively, the video codec itself might incorporate some level of error correction to address packet loss on a per-frame basis. This might be preferable in order to

[20] https://en.wikipedia.org/wiki/Packet_loss#Acceptable_packet_loss

maximise the effectiveness of the codec when deployed among a range of communication systems—not requiring bespoke optimisation of the communication system for each deployment. In fact, the codec or video container might itself measure the UDP packet loss rate as experienced over the network, calculate impact on frame loss rate such as done above, and accordingly introduce the appropriate coding rate to achieve a desired frame loss rate target. Without top-down cross-layer optimisation, i.e., the ability to change or optimise the network based on the application requirements, such an approach would be necessary.

- B3.5 Analysis in Terms of Company Benefits

At the outset of this work back in Period 1 of the project, questions were posed for the visual monitoring use case which if answered affirmatively would verify the potential company benefits of it. Those questions and their answers—based on the work done and the experimental evidence obtained both in Period 1 and 1.5 of the project—are in Table 13.

Question	Answer
Is it possible to deploy multiple wireless high-resolution cameras and visual monitoring equipment and get back images and video of high enough quality for a human or a machine learning platform to use?	The testing suggests that this is possible.
Is the technology base, such as the use of cameras and telecommunications network capable of providing the infrastructure required to build such a system?	The testing indicates that all resolutions and quality thresholds are possible, such as might be used by AI—although the 5G network is more challenged in cases of high resolution and frame quality due to the implied larger frame sizes and greater loss probability. However, this might be improved with codec optimisation on the application side as well as coding enhancements and developments such as better slicing on the network side.

Table 13: Worcester Bosch questions for the Visual Monitoring use case.

Commercially, Worcester Bosch—as the target for this use case—would be testing both use cases by estimating how many person-hours they would have saved where a potential fault or issue identified by the visual monitoring application supported by 5G. These hours would show as a reduction in the unavailability hours figure which are tracked as a KPI in the Worcester Bosch factory.

Unplanned unavailability hours can be attributed to one of three reasons at Worcester Bosch:

- Unplanned outages: Considers unplanned stops of the production line. These will be caused by breakdown of machinery and are therefore highly impacted by the implementation of preventative maintenance.
- Performance: considers slow cycles, which are usually due to human error or differences in individual performance.
- Quality: considers defects (including parts that need rework). In most cases at Worcester Bosch, this is due to issues with the raw materials, rather than the production line.

Therefore, the key target KPI is unplanned outages.

Based off a sample of machine availability data (average monthly data for 2018) Worcester Bosch has calculated that they would need to reduce the hours lost due to unplanned outages by approximately 114 hours (19%) to increase efficiency by 1% across the factory. This would increase total monthly average productive hours from 75.5% to 76.5%. Worcester Bosch forecast that this increased efficiency will be observed.

B4 Condition Monitoring

Worcester Bosch's Condition Monitoring use case draws on Machine Condition Monitoring, a technique for sensing equipment health and other operating information and analysing this to quantify the condition and correct operation of the equipment. This is done so that potential problems can be detected and diagnosed early in their performance and corrected by suitable recovery measures before they become severe enough to cause production line breakdown or other serious knock-on consequences.

Automated Machine Condition Monitoring is necessary because the increasing volume of data being collected about machine condition is becoming too large for engineers to deal with, and can be hard to analyse. This has led to the introduction of mathematical models for predictive analysis, as well as in some cases machine learning tools.

B4.1 Description

Worcester Bosch's condition monitoring solution is designed to enable Worcester Bosch maintenance engineers to remotely monitor the condition of any machine in the plant—using Bosch XDK sensors[21] connected to the 5G network—and to receive real-time data flow and early warnings of problems. Instead of enforcing routine planned maintenance outages, this will enable Worcester Bosch to potentially use the sensor data to determine when intervention is actually necessary.

The use case has assessed the technology enablement capability to allow sensor-based monitoring to become a harness in the maintenance and reliability industry toolkit, focusing on the ability to create a preventative maintenance solution based on anomaly detection.

5G is an enabler of condition monitoring solutions for the following reasons:

- **Wireless:** Infrastructure costs are high for wired solutions and reduce flexibility around relocation of machinery and devices.
- **Latency:** This solution requires low end-to-end latency, between 10 and 50 ms,[22] to provide real-time information. With decreasing latency, event response times might be better.

[21] Bosch XDK, https://xdk.bosch-connectivity.com, accessed March 2020.
[22] See lower target interval in Table A.2.3.2-1: Service performance requirements for process monitoring, of 3rd Generation Partnership Project; 2019, Technical Specification Group Services and System

- **Reliability:** The Block Error Rate of current networks of 2% – 10%, is too high for condition monitoring solutions.
- **High density of devices:** The anticipated growth and deployment of IoT devices and sensors will supersede the capability of less advanced networks.
- **Processing considerations:** Mobile edge processing is required to effectively deploy a real-time data solution.
- **High availability:** For a production grade solution, the network needs to be available and reliable. There is a need to have real time machine condition data to enable preventative maintenance as any breakdown, however infrequent, is hugely disruptive to the production line.

The condition monitoring case was originally hardwire tested to set baseline values for data throughput and end-to-end latency.

B4.2 Test Methodology

Again testing different phases of deployment both for 4G alone working up to 5G NSA and its benefits, condition monitoring tests first involved the creation of a 'standard state profile' of the machines on the factory floor, through the monitoring of each machine during a stabilisation period by an analysis application. The analysis application then was able to compare the standard state profile with the incoming live data and inform users of any deviations or irregularities.

Ultimately in the 5G configuration, the testing configuration was as in Figure 24. 4G testing involved the 5G components referred to in this figure being interchanged with equivalent 4G ones.

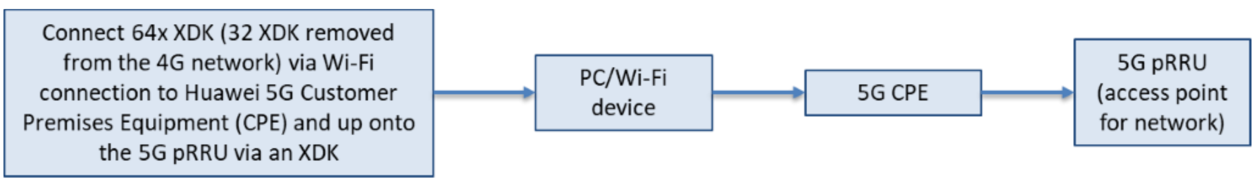


Figure 24: Typical Condition monitoring testing process

The sensors were mounted on 36 machines across the Worcester Bosch plant, all within coverage of the 4G and 5G network deployments. These machines were selected as they are critical pieces of machinery that cause assembly line stoppages or high cost/time repairs when not operational.

The Mean Time Between Failure (MTBF) is a key parameter intended to be analysed as part of this work. MTBF describes the expected time between two failures for a repairable system. Heavy duty machinery at Worcester Bosch does have a relatively long MTBF, often spanning months or even years. The sensors are also each monitoring a very specific element of the equipment, so for accurate tracking, a failure would need to occur on a piece of machinery being monitored and for the causal component to be being monitored on the piece of machinery as well. To get a statistically sufficient amount of such rare-event data, this trial continued for a full 20-month duration. Obtained failure data over the extended period has proven not to be sufficient to underpin a direct measurable improvement for this use case.

As part of this work, Worcester Bosch have also iterated the dashboards which give engineers information about machinery performance, as shown in Figure 25. Temperature, humidity, pressure, motion and acceleration have been tracked, with motion and acceleration showing the most useful results. Because of

Aspects; Service requirements for cyber-physical control applications in vertical domains; Stage 1 (Release 16) the position of the XDKs on 3D printed mounts, temperature has been the most difficult unit to accurately measure.

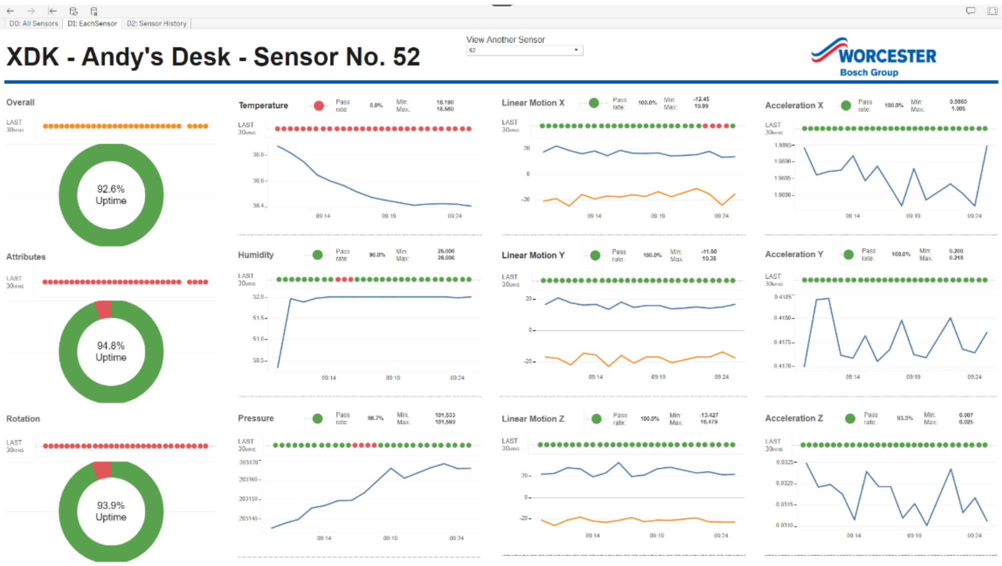


Figure 25: XDK dashboard highlighting changes in temperature, humidity, pressure, motion and acceleration, as well as any durations for which these parameters are outside of expected ranges for the system.

In terms of assessing the network performance, this solution had been tested on both the 4G and 5G network, where Worcester Bosch had been specifically looking at density of devices on the network that are supported, as well as latency figures.

- ### B4.3 Use Case Validation Outputs

For the 4G network the results were baselined with a single hardwired sensor to a local PC, hosting the application to give a control measure. This was then followed by testing scalability of both the network and the application by increasing the number of sensors on the network up to a maximum of 100 XDK's. Further details of this can be found in the LLD document.

In terms of results, Worcester Bosch observed that with the 4G network deployment and configuration, the 100 XDK's were being handled by the network with no impact to the data being sent. Although density of devices was a target test, Worcester Bosch have been unable to carry out an accurate test because of the shortage of available 5G modems. It was clear, however, that both 4G and 5G could supported the required density.

Requirements for this use case set a 10-50 ms end-to-end latency target. XDK's add an application/processing delay of 12 ms. The project observed end-to-end latency (XDK client PC to MEC, i.e., excluding XDK processing delay) over the 4G and 5G networks. These results indicate improved latency on 5G compared with 4G, with a latency of 10-12 ms depending on the number of connected XDK sensors for 5G, compared with 20-34 ms for 4G. Although none of the messages were lost in this testing, a likely explanation for the increasing latency for the 4G case is that the network was becoming overloaded leading to a delay in forwarding traffic. This is in addition to the observation that the baseline latency as reported in the 1 XDK case was significantly higher for 4G vs. 5G, showing that 5G significantly outperforms 4G in terms of latency irrespective of traffic loading effects. This makes 5G far more amenable to time-sensitive actions, e.g., shutting down the system or returning it to a safe state in minimal time based on a sudden impulse detected—as might be caused by a mechanical failure.

▪ B4.4 Analysis in Terms of Company Benefits

At the outset of the work, questions were posed to the visual monitoring use case in terms of understanding potential company benefits. Those questions and their answers based on the work done and experimental evidence obtained are given in Table 14.

Question	Answer
Is it possible to recognise anomalies, faults and abnormal operation with the use of a real-time condition monitoring solution?	The 5G testing suggests that this will be possible with the increased communication capabilities addressing a far-increased number of sensors, data load per sensor, and latency sensitive requirements.
Is the technology base, such as the sensors and telecommunications network capable of providing the infrastructure required to build such a system including the possibility of mobile or modular production lines?	The features of the 5G telecommunication network are shown to outclass the 4G telecommunication network to a level that a wide range of monitoring possibilities might be realised. The wireless characteristic and good measured coverage performance indicate production mobility/modularity being possible while not sacrificing such sensing systems.

Table 14: Worcester Bosch questions for the Condition Monitoring use case.

Commercially, Worcester Bosch would test its use cases by estimating how many hours they would have saved if a potential fault or issue were identified by the monitoring application supported by 5G. These hours would show as a reduction in the unavailability hours value, which are tracked as a KPI in the Worcester Bosch factory.

Unplanned unavailability hours can be attributed to one of three reasons at Worcester Bosch:

- Unplanned outages: Considers unplanned stops of the production line. These will be caused by breakdown of machinery and are therefore highly impacted by the implementation of preventative maintenance.
- Performance: Considers slow cycles, which are usually due to human error or differences in individual performance.
- Quality: Considers defects (including parts that need rework). In most cases at Worcester Bosch, this is due to issues with the raw materials, rather than the production line.

Therefore, the key target KPI to reduce using preventative maintenance is unplanned outages.

Based on a sample of machine availability data, Worcester Bosch have calculated that they would need to reduce the hours lost due to unplanned outages by approximately 114 hours (19%) to increase efficiency by 1% across the factory. This would increase total monthly average productive hours from 75.5% to 76.5%. The sample size for such rare-event data in the project is still too small, so testing is still underway with a deadline for the completion of all trialling and evidence collation by the end of 2020. Worcester Bosch are forecasting that this target increased efficiency will be observed.

Worcester Bosch noted that there may be some displacement of unplanned stops into planned losses, as issues with machinery are detected and pre-emptively fixed. Though, as the hourly cost of planned losses is far lower than unplanned outages, this would still cause an increase in profit margin for Worcester Bosch overall.

Appendix C: Indicative Cost Benefit analysis

W5G has undertaken some high-level modelling to establish whether the potential savings that might derive from 5G and Industry 4.0 are sufficient to justify the likely investment required to provide 5G coverage in factory environments. We had been asked by a number of observers "how much does it cost to deploy 5G in a factory?" However, each deployment will be specific to the requirements of the factory in question, so the model that we undertook is intended to provide a highly indicative view of the potential cost of deploying 5G to underpin a range of theoretical scenarios.

Each scenario considers:

- The capital cost of the 5G network to support the scale of the use case(s) to be deployed
- The costs of deployment
- The costs of network optimisation
- The number of applications to be deployed
- The cost per application
- The costs of user equipment (UE)
- The cost of any sensors (where required).

The costs are indicative but based on observed costs in Periods 1 and 2, adjusted for assumed developments in prices as 5G technology becomes more readily available, and to reflect the number of factories supported by a single network core.

We have looked at the full costs of the 5G network and associated UE and excluded any financial assistance/support that an operator or other third party might wish to offer.

Six scenarios were considered for modelling purposes, with each scenario characterised by:

- The number of organisations supported by the core
- The assumed scale of the factory
- The number of use cases (visual monitoring and/or proactive monitoring)
- The number of processes addressed by each use case
- Assumed benefits per process

A simple cost-benefit analysis based on a 10% cost of capital was estimated for each scenario.

The outputs from these scenarios are provided below.

Example 1

Requirement

Item	Description	Option	Qty	Unit
Type of 5G network		Private		
Number of user organisations			3	user organisations
Size of factory (single customer)			4,500	m^2
Proactive Monitoring (single customer only)				
Processes that require proactive monitoring			2	processes
Benefit per process p.a.			£75,000	
Number of machines				
Small	1 sensors per machine		5	machines
Medium	3 sensors per machine		3	machines
Large	5 sensors per machine		2	machines
Visual Monitoring (single customer only)				
Processes that require visual monitoring			0	processes
Benefit per process p.a.			£0	
Number of machines				
Small	1 cameras per machine		0	machines
Medium	2 cameras per machine		0	machines
Large	3 cameras per machine		0	machines

Total Cost of 5G and Applications

One-off	£306k
Recurring p.a.	£16k

Investment Appraisal

	One-off	Yr1	Yr2	Yr3	Yr4	Yr5
Benefit		£150k	£150k	£150k	£150k	£150k
Cost	-£306k	-£16k	£0k	£0k	£0k	£0k
Net Benefit	-£306k	£134k	£150k	£150k	£150k	£150k
Cumulative		-£172k	-£22k	£128k	£278k	£428k

Cost of Capital	10%	
NPV	£248k	
IRR	38%	
Payback	34	months

Disclaimer

This model provides a highly indicative view of the potential cost of provisioning 5G enabled Industry 4.0 applications.
Actual costs will depend on market developments, radio surveys and more detailed assessment of the application requirements.
Excludes any financing/financial engineering provided by the operator.

Example 2

Requirement

Item	Description	Option	Qty	Unit
Type of 5G network		Private		
Number of user organisations			1	user organisations
Size of factory (single customer)			4,500	m^2
Proactive Monitoring (single customer only)				
Processes that require proactive monitoring			3	processes
Benefit per process p.a.			£75,000	
Number of machines				
Small	1 sensors per machine		5	machines
Medium	3 sensors per machine		3	machines
Large	5 sensors per machine		2	machines
Visual Monitoring (single customer only)				
Processes that require visual monitoring			2	processes
Benefit per process p.a.			£100,000	
Number of machines				
Small	1 cameras per machine		3	machines
Medium	2 cameras per machine		1	machines
Large	3 cameras per machine		1	machines

Total Cost of 5G and Applications

One-off	£584k
Recurring p.a.	£35k

Investment Appraisal

	One-off	Yr1	Yr2	Yr3	Yr4	Yr5
Benefit		£425k	£425k	£425k	£425k	£425k
Cost	-£584k	-£35k	£0k	£0k	£0k	£0k
Net Benefit	-£584k	£390k	£425k	£425k	£425k	£425k
Cumulative		-£194k	£231k	£656k	£1,081k	£1,506k

Cost of Capital	10%	
NPV	£995k	
IRR	64%	
Payback	19	months

Disclaimer

This model provides a highly indicative view of the potential cost of provisioning 5G enabled Industry 4.0 applications.
Actual costs will depend on market developments, radio surveys and more detailed assessment of the application requirements.
Excludes any financing/financial engineering provided by the operator.

Example 3

Requirement

Item	Description	Option	Qty	Unit
Type of 5G network		Private		
Number of user organisations			1	user organisations
Size of factory (single customer)			15,000	m^2
Proactive Monitoring (single customer only)				
Processes that require proactive monitoring			5	processes
Benefit per process p.a.			£50,000	
Number of machines				
Small	1 sensors per machine		12	machines
Medium	3 sensors per machine		8	machines
Large	5 sensors per machine		5	machines
Visual Monitoring (single customer only)				
Processes that require visual monitoring			0	processes
Benefit per process p.a.			£0	
Number of machines				
Small	1 cameras per machine		0	machines
Medium	2 cameras per machine		0	machines
Large	3 cameras per machine		0	machines

Total Cost of 5G and Applications

One-off	£776k
Recurring p.a.	£43k

Investment Appraisal

	One-off	Yr1	Yr2	Yr3	Yr4	Yr5
Benefit		£250k	£250k	£250k	£250k	£250k
Cost	-£776k	-£43k	£0k	£0k	£0k	£0k
Net Benefit	-£776k	£207k	£250k	£250k	£250k	£250k
Cumulative		-£569k	-£319k	-£69k	£181k	£431k
Cost of Capital	10%					
NPV	£133k					
IRR	16%					
Payback	45	months				

Disclaimer

This model provides a highly indicative view of the potential cost of provisioning 5G enabled Industry 4.0 applications.
Actual costs will depend on market developments, radio surveys and more detailed assessment of the application requirements.
Excludes any financing/financial engineering provided by the operator.

Example 4

Requirement

Item	Description	Option	Qty	Unit
Type of 5G network		Private		
Number of user organisations			1	user organisations
Size of factory (single customer)			15,000	m^2
Proactive Monitoring (single customer only)				
Processes that require proactive monitoring			5	processes
Benefit per process p.a.			£100,000	
Number of machines				
Small	1 sensors per machine		12	machines
Medium	3 sensors per machine		8	machines
Large	5 sensors per machine		5	machines
Visual Monitoring (single customer only)				
Processes that require visual monitoring			3	processes
Benefit per process p.a.			£15,000	
Number of machines				
Small	1 cameras per machine		5	machines
Medium	2 cameras per machine		3	machines
Large	3 cameras per machine		2	machines

Total Cost of 5G and Applications

One-off	£1,027k
Recurring p.a.	£58k

Investment Appraisal

	One-off	Yr1	Yr2	Yr3	Yr4	Yr5
Benefit		£545k	£545k	£545k	£545k	£545k
Cost	-£1,027k	-£58k	£0k	£0k	£0k	£0k
Net Benefit	-£1,027k	£487k	£545k	£545k	£545k	£545k
Cumulative		-£540k	£5k	£550k	£1,095k	£1,640k
Cost of Capital	10%					
NPV	£986k					
IRR	42%					
Payback	12	months				

Disclaimer

This model provides a highly indicative view of the potential cost of provisioning 5G enabled Industry 4.0 applications.
Actual costs will depend on market developments, radio surveys and more detailed assessment of the application requirements.
Excludes any financing/financial engineering provided by the operator.

Example 5

Requirement

Item	Description	Option	Qty	Unit
Type of 5G network		Private		
Number of user organisations			3	user organisations
Size of factory (single customer)			4,500	m^2
Proactive Monitoring (single customer only)				
Processes that require proactive monitoring			3	processes
Benefit per process p.a.			£75,000	
Number of machines				
Small	1 sensors per machine		5	machines
Medium	3 sensors per machine		3	machines
Large	5 sensors per machine		2	machines
Visual Monitoring (single customer only)				
Processes that require visual monitoring			0	processes
Benefit per process p.a.			£0	
Number of machines				
Small	1 cameras per machine		0	machines
Medium	2 cameras per machine		0	machines
Large	3 cameras per machine		0	machines

Total Cost of 5G and Applications

One-off	£356k
Recurring p.a.	£18k

Investment Appraisal

	One-off	Yr1	Yr2	Yr3	Yr4	Yr5
Benefit		£225k	£225k	£225k	£225k	£225k
Cost	-£356k	-£18k	£0k	£0k	£0k	£0k
Net Benefit	-£356k	£207k	£225k	£225k	£225k	£225k
Cumulative		-£149k	£76k	£301k	£526k	£751k

Cost of Capital	10%	
NPV	£481k	
IRR	54%	
Payback	16	months

Disclaimer

This model provides a highly indicative view of the potential cost of provisioning 5G enabled Industry 4.0 applications.
Actual costs will depend on market developments, radio surveys and more detailed assessment of the application requirements.
Excludes any financing/financial engineering provided by the operator.

Example 6

Requirement

Item	Description	Option	Qty	Unit
Type of 5G network		Private		
Number of user organisations			5	user organisations
Size of factory (single customer)			1,500	m^2
Proactive Monitoring (single customer only)				
Processes that require proactive monitoring			2	processes
Benefit per process p.a.			£50,000	
Number of machines				
Small	1 sensors per machine		3	machines
Medium	3 sensors per machine		1	machines
Large	5 sensors per machine		0	machines
Visual Monitoring (single customer only)				
Processes that require visual monitoring			0	processes
Benefit per process p.a.			£0	
Number of machines				
Small	1 cameras per machine		0	machines
Medium	2 cameras per machine		0	machines
Large	3 cameras per machine		0	machines

Total Cost of 5G and Applications

One-off	£243k
Recurring p.a.	£13k

Investment Appraisal

	One-off	Yr1	Yr2	Yr3	Yr4	Yr5
Benefit		£100k	£100k	£100k	£100k	£100k
Cost	-£243k	-£13k	£0k	£0k	£0k	£0k
Net Benefit	-£243k	£87k	£100k	£100k	£100k	£100k
Cumulative		-£156k	-£56k	£44k	£144k	£244k

Cost of Capital	10%	
NPV	£124k	
IRR	28%	
Payback	29	months

Disclaimer

This model provides a highly indicative view of the potential cost of provisioning 5G enabled Industry 4.0 applications.
Actual costs will depend on market developments, radio surveys and more detailed assessment of the application requirements.
Excludes any financing/financial engineering provided by the operator.

Appendix D: Glossary of Terms

Abbreviation	Full Terminology
3GPP	3rd Generation Partnership Project
5GIC	5G Innovation Centre
5GRIT	5G Rural Integrated Testbed
5GTT	5G Trials and Testbed
AAU	Active Antenna Unit
AR	Augmented Reality
AWGN	Additive White Gaussian Noise
AWTG	Advanced Wireless Technology Group
BBU	Baseband Unit
CAD	Computer Aided Design
CAM	Computer Aided Modelling
CESG	Computer Engineering Security Group
CPE	Customer-premises equipment
DCLG	Department for Communities and Local Government
DCMS	Department for Culture Media and Sport
eMBB	Enhanced mobile broadband
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplex
GTP Tunnel	GPRS Tunnelling Protocol
HNC	Higher National Certificate
HND	Higher National Diploma
HoWC	Heart of Worcestershire College
IL	Impact Level
IMSI	International Mobile Subscriber Identity

IMT	International Mobile Telecommunications
IoT	Internet of Things
IRAD	Internally-funded Research and Development
ITU	International Telecommunications Union's
LTE	Long Term Evolution
MAST	Mobile Application to Secure Tenure
MEC	Mobile Edge Computing
MHSP	Malvern Hills Science Park
MIMO	Multi-Input Multi-Output
mMTC	Massive machine-type communication
MNO	Mobile Network Operator
NAT	Network Address Translation
NFV	Network Function Virtualisation
NSA	Non-Standalone Architecture
NVQ	National Vocational Qualification
OMC	Operations and Management Centre
OSS	Operational Support System
R&D	Research and Development
RAN	Radio Access Network
RAND	Random Number
RF	Radio Frequency
RHUB	RRU HUB
SA	Standalone Architecture
SDN	Software Defined Network
SDS	Software Defined Security
SME Businesses	Small and medium sized enterprises
STEM	Science, technology, engineering, and mathematics
TCP	Transmission Control Protocol

TDD	Time Division Duplex
TDD Technology	Time Division Duplex Technology
TMSI	Temporary Mobile Subscriber Identity
UC	Use Case
UCC	Urban Connected Communities
UED	User End Devices
UMTS	Universal Mobile Telecommunications Service
URLLC	Ultra-reliable low latency communication
USIM	UMTS Subscriber Identify Module
UW	University of Worcester
VLAN	Virtual Local Area Network
VR	Virtual Reality
WAN	Wide Area Network
WAN Connection	Wide Area Network Connection
WLEP	Worcester Local Enterprise Partnership
XDK Sensor	Cross-Domain Development Kit Sensor