5G SubConnect

Project Report

Executive Summary

The 5G SubConnect project ran from 1st November 2021 until 31st March 2022, investigating the potential for 5G connectivity to add value to maintenance activities in the tunnels of the Glasgow Subway and underground railway systems in general. The project was supported by DCMS and was carried out by the University of Strathclyde and Strathclyde Partnership for Transport (SPT).

Subway maintenance in the Glasgow Subway comprises essentially two main activities:

1) Periodic inspection of the subway stations, tunnels, traction power supply equipment, and the fleet of rolling stock to assess the current state of assets and infrastructure as part of an ongoing monitoring process to identify areas in need of repair or replacement;
2) Carrying out the repair or replacement of assets that have been identified as problematic or potentially problematic.

Inspection involves track-walking outside of operational hours (i.e. during the night), and is conducted twice a week by the maintenance team. This involves two people per circle (four people in total) walking the full length of the tunnels (10.5 km) equipped with notepad and pen to record any defects which have arisen since the previous inspection and/or to update the status of previously known defects or issues. At the end of the track walk, a report is entered into the Maintenance Management System, which may, if appropriate, lead to a work order being generated in order to address the identified defects or problems.

Discussions with relevant SPT staff have revealed that a network capable of supporting certain use cases would be highly desirable. These include:

- Use of real-time, high-definition video to support multiple activities including tele-conferencing between personnel in the tunnels and a central office.
- Ability to upload and download pictures and recorded videos to/from a centralised data repository from within the tunnels.
- The ability to acquire accurate positioning of assets and personnel in the tunnel system to enhance efficiency and safety of maintenance activities.
- The use of sensors for conditioning monitoring of assets and infrastructure in the tunnels and platforms.

This requires a network that is capable of achieving high uplink throughput rates to support multiple static and mobile HD video cameras at each subway station, and there must also be the ability to determine the position of assets and infrastructure in the subway without relying on any Global Navigation Satellite Systems (GNSS) such as GPS, as GNSS signals generally don’t propagate into tunnels. The network must also be capable of supporting a wide range of sensors for condition monitoring at various locations.

Various network design considerations were contemplated and a small 5G test network was built in order to test and demonstrate the use cases identified as being potentially useful or desirable for a 5G network to support. Due to the short duration of the project, it was not possible to deploy the test network in the Glasgow Subway tunnels; instead, a representative network deployment was set up at one end of a corridor in the Royal College Building at the University of Strathclyde, to simulate the tunnel environment.

Key learnings from the project include:

- Real-time video upload, video-conferencing, positioning, and sensor-based condition monitoring have the potential to realize tangible benefits for underground train operators. The technology solution requires some further development, but many of the key technology building blocks already exist. Integration into business operations systems and processes needs to be considered and planned for, however.
- 5G positioning technology has good promise, but it isn't quite here yet. 3GPP standards support new positioning techniques, but certain functions require implementation, and UE support will rely on next-generation chipsets. Development effort needs to be planned and implemented. UE support is another issue, and this will come in time.
- In a more general context, getting consumer UE devices to connect to a Private 5G network is often a challenge, due to carrier-based feature locking being implemented by UE manufacturers. Many, perhaps most, consumer handsets will not connect to a Private 5G network without firmware modification. They will connect only to registered, known PLMNs. It will be difficult to realize the benefits of deploying Private 5G networks which are intended to be used with consumer UE devices, unless steps are taken to ensure that UE devices will connect to any network ID, whether it's a mainstream public network or a small, private one. The may require a change in policy and regulation by governments, regulators, and the GSMA.

The learnings from 5G SubConnect have been valuable in helping us to develop our understanding of the potential for digital connectivity to contribute to maintenance activities in subway tunnels and the current limitations that need to be addressed in order to make it viable. The project team has identified a number of potential benefits associated with deploying a private 5G network in the Subway to help with maintenance activities, and a set of high-level technical requirements has been created.

The project's activities and outputs have been derived from high-level estimates and discussions with relevant SPT personnel, and various technical tests have been carried out on a test network that was developed and implemented in the University of Strathclyde. A key next step would be to develop a prototype network solution in the tunnel environment itself, and to implement a pilot in the tunnels with the maintenance teams making use of the connectivity, in earnest, on a trial basis. In parallel, further investigation and development of suitable positioning technology will be required.

With this in mind, we will be seeking to explore opportunities for developing and implementing such a pilot, which would allow us to test and confirm the expected benefits and refine the assumptions that lie behind the envisaged high-level network technical requirements and architecture design. This would also lead to suitable CAPEX and OPEX estimates.

Contents

List of Acronyms

3GPP	3rd Generation Partnership Project
5G SA	5G Standalone
5G NSA	5G Non-Standalone
5GPC	5G Packet Core
AMF	Authentication and Mobility Function
AoA	Angle of Arrival
AR	Augmented Reality
BBU	Baseband Unit
bps	bits per second
BS	Basestation
CAPEX	Capital Expenditure
CP	1) Control Plane 2) Communications Provider
CPF	Control Plane Function
DCMS	Department for Digital, Culture, Media, and Sport
DL	Downlink
EIRP	Effective Isotropic Radiated Power
eMBB	Enhanced Mobile Broadband
eNB	Enhanced Node B – essentially, a basestation (4G)
ESMLC	Evolved Server Mobile Location Centre
FPGA	Field-Programmable Gate Array
fps	frames per second
gNB	5G Node B – essentially, a basestation (5G)
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HD	High Definition
IoT	Internet of Things
LAL	Local Access Licence
LDPC	Low Density Parity Check
LMF	Location Management Function
LPP	LTE Positioning Protocol
LPWAN	Low Power, Wide Area Network
LTE	Long-Term Evolution
MCS	Modulation & Coding Scheme
MEC	Mobile Edge Computing
MHN	Mobile Hotspot Network
MIMO	Multiple Input, Multiple Output
MME	Mobility Management Entity
mMTC	Massive Machine Type Communications
MNO	Mobile Network Operator
NB-IoT	Narrowband-IoT
NDI	Network Device Interface
NRPP	New Radio Positioning Protocol
OPEX	Operational Expenditure
OTDOA	Observed Time Difference of Arrival
PBCH	Physical Broadcast Channel

PCI	1) Peripheral Component Interconnect 2) Physical Cell ID
PLMN	Public Land Mobile Network
PRS	Position Reference Signals
PZT	Pan-Zoom-Tilt
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RAT	Radio Access Technology
RRH	Remote Radio Head
RSTD	Reference Signal Time Difference Measurements
RTT	Round Trip Time
SAL	Shared Access Licence
SD	Standard Definition
SDR	Software Defined Radio
SIM	Subscriber Identity Module
SISO	Single Input, Single Output
SNR	Signal to Noise Ratio
SPT	Strathclyde Partnership for Transport
SRS	Sounding Reference Signal
TDD	Time Division Duplex
UE	User Equipment
UL	Uplink
UP	User Plane
UPF	User Plane Function
URLLC	Ultra Reliable Low Latency Communications
USB	Universal Serial Bus
VR	Virtual Reality

1 INTRODUCTION

Following completion of the 5G RailNext project in March 2021, discussions were held with the Department for Digital, Culture, Media, and Sport (DCMS), the University of Strathclyde's Software Defined Radio Lab (StrathSDR), and Strathclyde Partnership for Transport (SPT) regarding potential follow-on work within the 5G Testbeds & Trials Programme.

Although 5G RailNext focused primarily on the benefits of on-train connectivity for passengers, SPT conveyed that they were also interested in exploring the potential benefits of 5G connectivity for other activities. In particular, they identified subway maintenance as a key area where 5G connectivity could potentially play a role in improving the efficiency and effectiveness of maintenance tasks.

These discussions resulted in the 5G SubConnect project, which ran from 1st November 2021 to 31st March 2022, with the aim of investigating the potential for 5G connectivity to add value to maintenance activities in the tunnels of underground railway systems.

This report captures the key outputs of the project.

2 PROJECT BACKGROUND

5G SubConnect was borne out of the successful completion of the international collaborative project 5G RailNext, which was completed in March 2021.

5G RailNext aimed to demonstrate the potential of 5G-enabled internet connectivity for passengers travelling on trains in the subway. In addition, the project explored innovative methods of delivering advertising content and infotainment using 5G connectivity and Augmented/Mixed Reality (AR/MR) applications. The project also involved collaboration with an engineering research team from South Korea who developed a complementary connectivity solution for the Seoul Metro.

Within 5G RailNext, the StrathSDR team was responsible for the design, installation, testing and trial of a 5G-enabled end-to-end connectivity solution in the Glasgow subway. The network was a private Mobile Hotspot Network (MHN) comprising a private 5G link connecting track to train, offloading to an on-board Wi-Fi network for end-user connectivity. The overall network topology is illustrated in Figure 2.1.

The 5G network was deployed at Buchanan St station and during the trial was able to provide coverage to a test train travelling on the outer circle between Buchanan St and St Enoch's stations. During the trial, participants on the train were able to connect to the internet and interact with the infotainment and AR/MR applications.

The 5G network was one of the first deployments of a 5G Standalone (SA) in the UK and was comprised of three components – a 5G Packet core (5GPC), a 5G Basestation (BS) or gNodeB (gNB), and a 5G SA modem or User Equipment (UE). Unlike Non-Standalone (NSA) networks, a 5G SA network consists of only 5G components and does not rely on a 4G anchor.

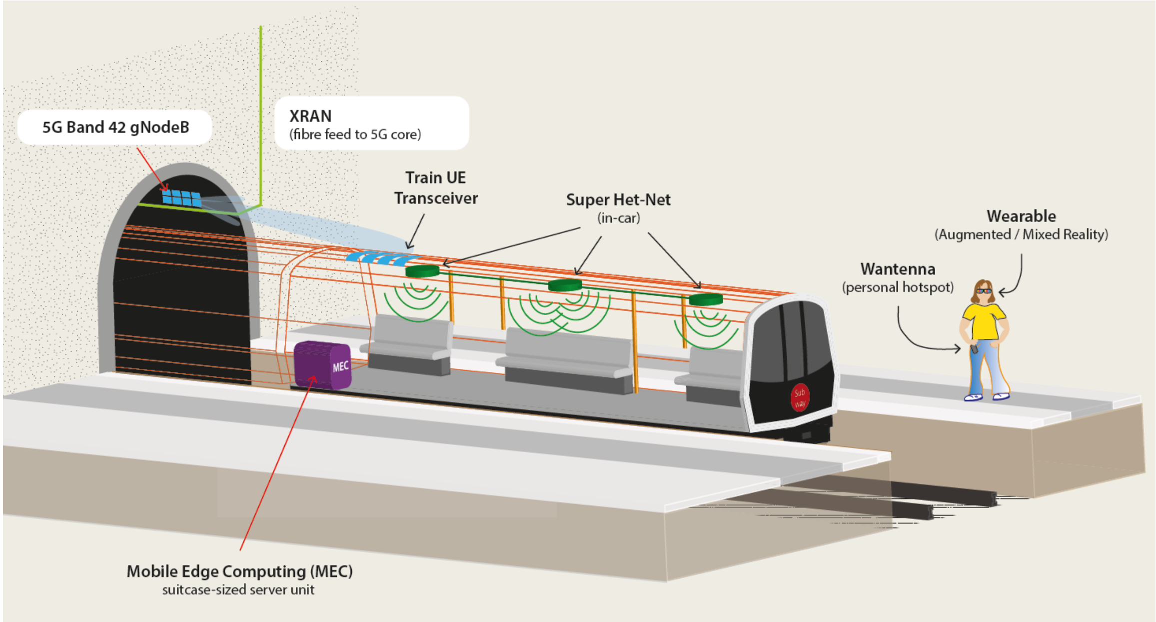

Figure 2.1: Illustration of MHN deployed in Glasgow Subway for 5G RailNext.

Figure 2.2 shows the Remote Radio Head (RRH) deployed above the station platform and the antenna mounted above the traveller information sign.

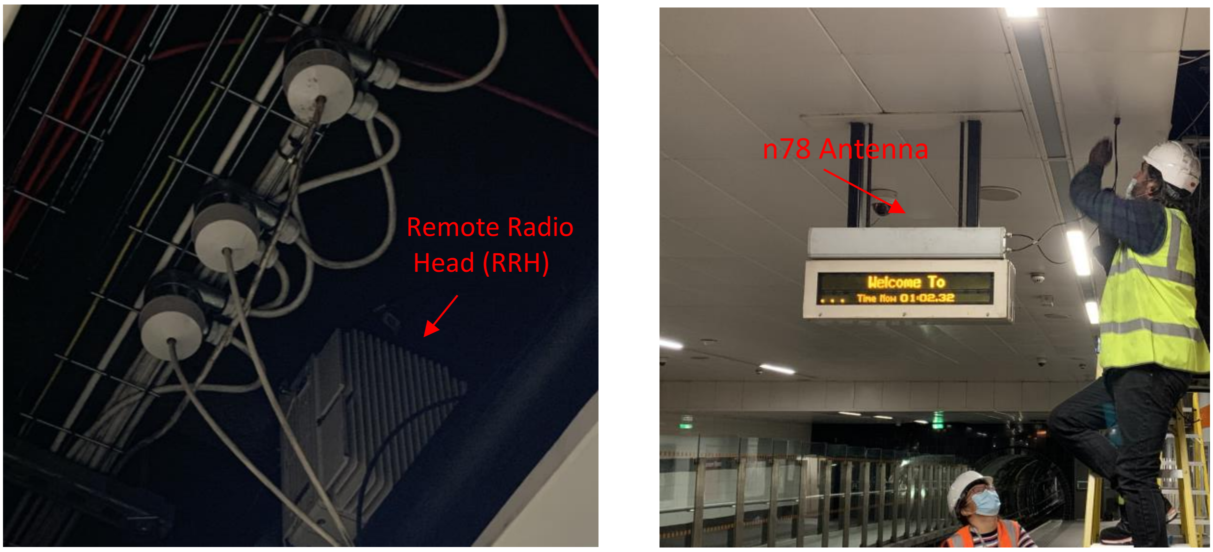

Figure 2.2: Deployment of Remote Radio Head (RRH) and n78 antenna at Buchanan St Station.

In the final configuration, the radio was tuned to a centre frequency of 3.52 GHz and a bandwidth of 20MHz, and 2x2 MIMO transmission was configured for the downlink. The spectrum is licensed to public Mobile Network Operators (MNOs) but an Innovation & Trial licence was obtained from Ofcom after it was determined that the 5G RailNext network would not interfere with MNO networks. In order to minimise the likelihood of any interference, the transmitter power level was set to the lowest possible value that guaranteed acceptable coverage in the tunnels and at both stations.

The average throughput achieved was 90.3 Mbps on the downlink (i.e. from platform to train) and 16.2 Mbps on the uplink (from train to platform). In TDD networks, the downlink rate is typically higher than the uplink rate due to significant biasing towards the downlink. The achieved rates were deemed acceptable for 5G RailNext, but through further development in the laboratory and procurement of more advanced radio hardware, the StrathSDR team has been able to significantly improve these data rates. This is particularly relevant for 5G SubConnect and is one of the main advantages offered by 5G networks over 4G networks.

The UE used in the 5G RailNext project was a 5G SA-capable SIM8200-EA modem based on the Qualcomm x55 chipset, as shown in Figure 2.3.

Figure 2.3: SIM8200-EA 5G SA Modem

The modem has an M.2 form factor and can interface with any Linux based computing device such as a Raspberry Pi or Intel NUC through an M.2 to USB 3.0 daughterboard. It is capable of receiving up to four MIMO streams on the downlink and supports channel bandwidths of up to 100MHz in the relevant frequency bands.

3 MAINTENANCE ACTIVITIES IN THE SUBWAY

Maintenance is a key aspect of subway operations and is necessary to ensure that trains run in a safe and timely manner on a daily basis. Subway maintenance in the Glasgow Subway comprises essentially two main activities:

1) Periodic inspection of the subway stations, tunnels, traction power supply equipment, and the fleet of rolling stock to assess the current state of assets and infrastructure as part of an ongoing monitoring process to identify areas in need of repair or replacement;
2) Carrying out the repair or replacement of assets that have been identified as requiring attention.

Inspection involves track walking outside operational hours (i.e. during the night), and is conducted twice a week by the maintenance team. This involves two people per circle (four people in total) walking the full length of the tunnels (10.5km) equipped with notepad and pen to record any defects which have arisen since the previous inspection and/or to update the status of previously known defects or issues. At the end of the track walk, a report is entered into the Maintenance Management System, which may, as appropriate, lead to a work order being generated in order to address the identified defects or problems.

From discussion with the SPT maintenance team and other SPT staff, several key challenges with the current maintenance approach have been identified:

- Specifying the location of tunnel-located assets and infrastructure is often approximate and it can be difficult to relocate the asset/infrastructure when it comes to carrying out a repair or replacement. Unfortunately, due to being underground, positioning using Global Navigation Satellite Systems (GNSS) is not possible.
- In order to improve communication, it would be beneficial to have real-time video conferencing between team members carrying out inspections in the tunnels and staff in the office.
- It would be useful to have the ability to take pictures/videos of assets and infrastructure from within the tunnels and upload these to a centralised database[1] for future reference.
- It would be useful for staff in the tunnels to be able to download and access technical drawings and other relevant information related to assets, such as maintenance records or details of cable runs, for example.
- Within the context of the modernisation programme that SPT is currently undertaking, worker safety is likely to become more challenging as electrical power will be energised in sections of the system, which is a change from the current practice of fully isolating the whole system during maintenance hours. Therefore, work zones and geo-fencing will become important options to consider, requiring accurate location of workers to be known and communicable. Again, using a GNSS is not possible for this.

The key elements required for addressing these challenges are: 1) The ability to upload and download data (pictures, video, etc.) from inside the tunnels to/from a centralised location; 2) The ability to carry out real-time video conferencing between team members in the tunnels and colleagues in the office or depot; and 3) The ability to provide accurate positioning in the absence of GNSS.

Further discussions subsequently revealed that it would also be beneficial and desirable to have real-time measurement and logging of sensor data for monitoring the condition of assets and infrastructure in the tunnels and platforms. (Data to be measured would include power consumption, temperature, and air quality, among other things.)

4 USE CASES TO BE SUPPORTED

From the discussions described in the preceding sections, the following use cases have been identified for a 5G network that supports maintenance activities in the Glasgow subway:

- Use of real-time, high-definition video to support multiple activities including tele-conferencing between personnel in the tunnels and a central office, determining the location of personnel throughout the tunnel system and platforms with the ability to generate alarm notifications when people enter risk areas or unauthorised areas, and high-quality monitoring of assets and infrastructure to enhance inspection and maintenance activities.
- Ability to upload and download pictures and recorded videos to/from a centralised data repository (e.g. an Asset Management System) from within the tunnels. This capability would be useful for monitoring the condition of specific assets/infrastructure and would help with reporting and the generation of work orders when a defect is identified. This

---

[1] SPT envisages that their Maintenance Management System would be the central data repository, so that pictures and videos could be linked to Work Orders and also used in recording the history of assets in this system.

would also enhance general defect and condition capture to support analytics around wear profiles and deterioration rates.

- The ability to acquire accurate positioning of assets and personnel in the tunnel system to enhance efficiency and safety of maintenance activities. At present, obtaining the position of assets is difficult due to the absence of GNSS reception in the tunnels.
- The use of sensors for conditioning monitoring of assets and infrastructure in the tunnels and platforms including, but not limited to, power consumption and logging, temperature monitoring, and air quality monitoring. It would be beneficial to have real-time monitoring and logging of sensor data from a centralised location to enhance efficiency and the decision-making process.

In essence, the network must be capable of achieving high uplink throughput to support multiple static and mobile HD video cameras at each station. (Some of the mobile cameras might simply be ruggedised handsets or tablets). These cameras would be used for video inspection of assets to enhance maintenance activities and for monitoring of risk areas in the Subway. The resulting video streams must be transported to a central location, such as the SPT depot.

There must also be the ability to determine the position of assets and infrastructure in the subway in the absence of GNSS. In 3GPP Release 16, a new positioning framework has been developed which promises far improved performance than was possible with previous generations of the standard. At present, however, there is little or no availability of chipsets supporting Release 16 positioning for 5G SA, although it has been identified that modules based on upcoming chipsets will, with the correct firmware version, support positioning. In addition to this an implementation of the Location Management Function (LMF) entity is needed to support positioning. This would have to be either developed and implemented in-house or purchased from a 3rd party supplier. A rough approximation of position could be derived based on the use of prior knowledge of the UEs assigned to particular personnel and the Physical Cell IDs (PCI) of radios located at different stations. This could be used to give very approximate locations of personnel win the tunnel system.

Finally, the network must be capable of supporting a wide range of sensors for condition monitoring at various locations. This use case could be satisfied by a Narrowband Internet of Things (NB-IoT) network, which would have the benefit of consuming relatively low power.

5 NETWORK DESIGN CONSIDERATIONS

5G has been defined to support three different use case types: Enhanced Mobile Broadband (eMBB), Ultra Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (mMTC).

In the broadest terms, eMBB use cases aim to maximize the data rates available to the user in both downlink and uplink directions. The URLLC use cases aim to reduce the end-to-end latency of the network when compared to 4G, and new features have been added to support this, including a flexible numerology or sub-carrier spacing. The mMTC use cases are designed to enhance connectivity for devices and to further support the so-called Internet of Things (IoT).

The use cases outlined in Section 4 for the subway network fall within the scope of eMBB and mMTC. On the one hand, there is a requirement for real-time, high-resolution video (HD or better) which would benefit from features introduced as part of the eMBB use case type. In particular, there is a need for high-resolution video on the uplink, e.g. from cameras in the tunnels back to a centralised location. In 5G Standalone (SA), new features, such as a flexible Time Division Duplexing (TDD) frame structure and 2x2 Uplink MIMO, are supported, which can lead to significantly increased uplink throughput when compared to other technologies.

Conversely, a sensor network to support condition monitoring activities in the tunnels would be best served by an Enhanced Machine Type Communication (eMTC / LTE Cat M1) or Narrowband Internet of Things (NB-IoT) radio network. Both eMTC and NB-IoT are examples of Low Power, Wide Area Network (LPWAN) radio technologies. These networks are designed to support connectivity of devices (such as sensors/appliances) or "things" rather than people. The relative benefits of eMTC over NB-IoT are higher data rates and support for voice calling and mobility. Due to the static nature of many of the sensors in the tunnels, an NB-IoT network is likely to be sufficient.

Positioning functionality can be supported by 5G SA radios, although there are specific challenges associated with this, as alluded to in Section 4 and described more fully in Section 6.2.

In order to simultaneously support both types of use case (i.e. eMBB and eMTC), a multi-Radio Access Technology (Multi-RAT) network is likely to be required. In a Multi-RAT architecture, two or more radio technologies are supported at a single base station site. In this case, the Multi-RAT network would consist of a 5G SA radio (to support video, upload/download applications, and positioning) and an NB-IoT radio (to support sensor applications).

Depending on the spectrum band employed, it may be possible to support both radio technologies with a single physical radio. For example, Band n28 (700MHz) is supported in 5G networks and in NB-IoT networks. A 5G carrier in Band n28 could therefore be transmitted along with an NB-IoT sideband carrier from the same radio. However, Band n28 (700MHz) is not a band covered by the Ofcom Shared Access Licence (SAL) framework, so it would be difficult to support a private network with this spectrum. (A Local Access Licence (LAL) could potentially be obtained, but it is by no means certain that the MNOs would be comfortable with such an approach.) In any case, the use of 700 MHz spectrum also places limits on the bandwidth and number of MIMO streams of the 5G network; such limits are not as prevalent in the mid-frequency bands, i.e. spectrum at around 3.5 GHz.

The 5G network could instead, therefore, be deployed in the Band n77 SAL range (3.8GHz–4.2GHz), and the NB-IoT network could be deployed in the Band n3 SAL range (1876.7MHz–1880MHz). For reference, an NB-IoT carrier is 200kHz wide, so it would fit well within the limits imposed by the SAL. The resulting high-level architecture for a single base station site is illustrated in Figure 5.1.

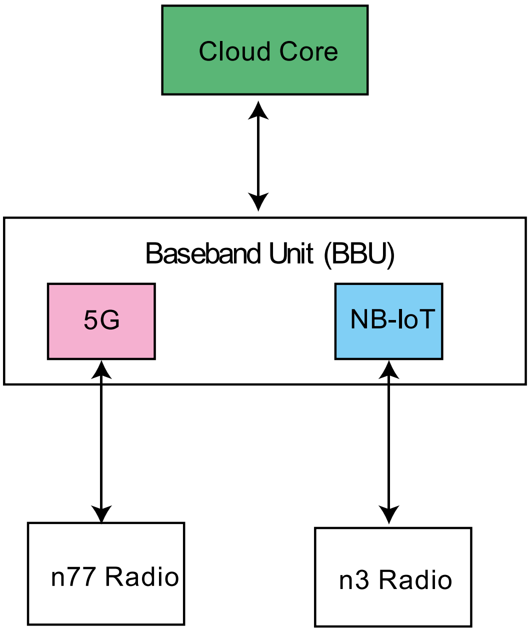

Figure 5.1: Illustration of a single-site base station employing 5G eMBB and NB-IoT.

As can be observed in Figure 5.1, both the 5G SA and NB-IoT radio stacks are implemented on a single Baseband Unit (BBU). A Software Defined Radio (SDR) implementation of the radio stack enables agile and flexible configuration of the network parameters, allowing a custom network configuration to be developed more easily. In addition, the network can be updated with new features through remote software upgrades.

The radio stacks are then connected via a backhaul network to a Cloud core running on a cloud services platform. This core would be used for all base station deployments in the subway. This would require internet access for the BBUs via the SPT network, but it would lead to a more streamlined deployment. In addition, a local User Plane Function (UPF) could be deployed in the Subway to ensure that network traffic is transported to the local network as quickly as possible. This would probably be implemented on a server connected to the Subway network.

From the User Equipment (UE) perspective, the network will very probably consist of a mixture of handsets and tablets and M2 5G/NB-IoT modules. The tablets and handsets would be used by personnel in the tunnels for video streaming and tele-conferencing for inspection activities and uploading/downloading documentation and information to/from the central database. An example of a suitable tablet device is the Samsung S7 5G shown in Figure 5.2.

Figure 5.2: Samsung S7 5G Tablet.

The Samsung S7 5G tablet can be ruggedised to make it suitable for use by personnel in the tunnel system. This particular device supports both n77 and 5G SA, but at present it cannot connect to a private Public Land Mobile Network (PLMN) without a specially acquired firmware update. The situation is similar with the Samsung S21+ 5G handset. This appears to be due to carrier-locking to commercial operators by the manufacturer, which makes the use of private 5G networks more difficult. This is a problem that will affect most, if not all, private 5G network deployments, and it will need to be addressed at an international level if widespread implementation of private 5G networks is to become possible.

The 5G SA modem modules would be used for fixed camera deployments, i.e. those used for monitoring particular areas of the station and tunnel system. A suitable video delivery protocol for the cameras is Network Device Interface (NDI). This protocol allows high resolution streaming (up to 4K @ 25 fps) between two endpoints on a network. The protocol also allows for talkback and tally and pan-zoom-tilt (PZT) functionality for remote communication and camera control. The protocol can also run directly on a suitable handset or tablet, although this uses software encoding rather than Field Programmable Gate Array (FPGA) accelerated encoding, and as such, it therefore has lower overall performance. However, for fixed camera deployments, an FPGA-based encoder could be used for enhanced performance. The n77 network can also support standard teleconferencing tools, subject to appropriate backhaul network connections.

A suitable NB-IoT modem would be required to connect the sensors to the n3 NB-IoT network. These typically come in either PCIe or M2 form factors and can be interfaced to a Raspberry Pi or other low power computing platform via a suitable USB daughterboard. The NB-IoT modems are suitable for sensor deployments as they are small form factor and have low power requirements, meaning that they can be deployed in confined/awkward spaces and powered by battery for long periods of time.

6 TEST NETWORK

After a high-level understanding of the maintenance activities was established, a small 5G test network was built in order to test and demonstrate the use cases identified as being potentially useful or desirable for a 5G network to support. Due to the short duration of the project, it was not possible to deploy the test network in the Glasgow Subway tunnels; instead, a representative network deployment was set up at one end of a corridor in the Royal College Building (RCB) at the University of Strathclyde, to simulate the tunnel environment to a certain extent. The test network was built using 5G SA operating in the n77 band.

6.1 Testing of n77 5G SA Network

The test network deployed in the corridor consisted of a G2 i9 server blade running 3GPP Release 15 compliant 5GPC and gNodeB software stacks. The n77 radio head was capable of 4x4 MIMO operation within a 100 MHz bandwidth in the range 3.8-4.1 GHz. The actual deployment was 2x2 100 MHz on the downlink and SISO 100 MHz on the uplink. Figure 6.1 shows the network as deployed in the corridor.

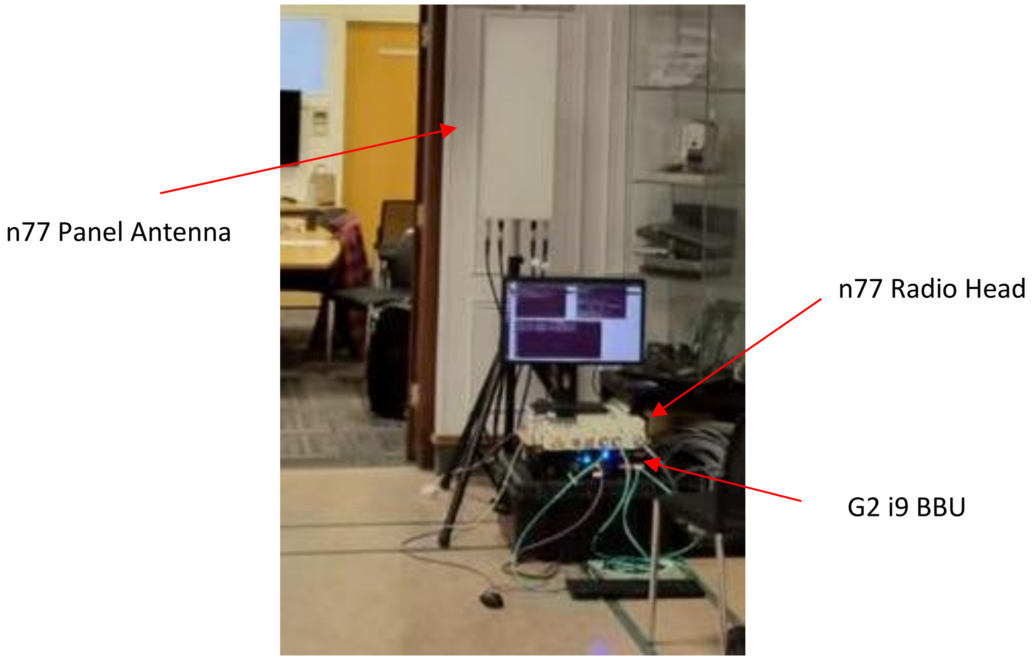

Figure 6.1: 5G SA n77 Network deployed in RCB corridor.

Since n77 is a TDD band, a suitable TDD frame structure had to be defined for the gNB. The TDD configuration that was used is shown in Figure 6.2. The TDD pattern has 5ms periodicity and there are

10 slots in each 5ms period. There are 4 downlink slots (i.e. slots where all symbols are dedicated to downlink transmission) and 5 uplink slots (i.e. slots where all symbols are dedicated to uplink transmission). The flexible slot consists of 10 downlink symbols, 2 uplink symbols, and 2 null symbol periods used for downlink to uplink switching. Therefore, the TDD configuration is uplink biased in order to enable higher uplink throughputs.

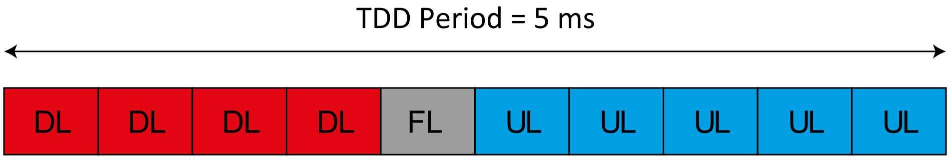

Figure 6.2: TDD Configuration for n77 5G SA network.

A video call was conducted over the network between two Samsung S21 handsets at various points in the corridor, as shown in Figure 6.3. The network was more than capable of satisfying the use case requirements, with several simultaneous calls possible. In addition, two 1080p 50fps NDI streams were simultaneously transmitted over the 5G network to a laptop connected directly to the BBU when demonstrating the network for representatives of SPT and DCMS. An HD 1080p 50 fps stream would be more than sufficient for supporting high-quality video monitoring and inspection of assets and infrastructure in the tunnel.

The first stream was generated using an HD Camera connected to an FPGA-based H.264 encoder box which was interfaced to the 5G network through a Raspberry Pi-based router and SIM8300-G M2 modem. The second stream was generated from the Samsung S21 handset connected directly to the 5G network. This employed a software-based H.264 encoder.

Each 1080p 50 fps stream requires 12.5 Mbps, after H.264 video encoding, within the NDI protocol. Therefore, an uplink data rate of 25 Mbps was required to support both streams. The network was able to handle these, showing that it is capable of supporting multiple cameras simultaneously.

A network speed test was also run with a handset near to the antenna to give an indication of the peak throughput that this network configuration can achieve under good signal conditions. The results, shown in Figure 6.4, indicate that the network is capable of achieving downlink and uplink rates of up to almost 450 Mbps and 300 Mbps, respectively. However, this requires ideal SNR conditions (above 30dB) and a Modulation & Coding Scheme (MCS) of ~27, which uses 256-QAM and the highest possible Low-Density Parity Check (LDPC) code rate.

In poorer SNR conditions, the MCS may drop to around 8, where 16-QAM modulation and a code rate of ~0.5 is employed for improved robustness. In this case, the maximum uplink throughput will drop to ~ 90 Mbps, which would still allow support for approximately 6 simultaneous HD streams (allowing for sufficient headroom). However, not all camera units are likely to experience poor SNR simultaneously, allowing the gNB to schedule higher MCS for cameras with better SNR and ensure that more cameras can be supported within the bandwidth.

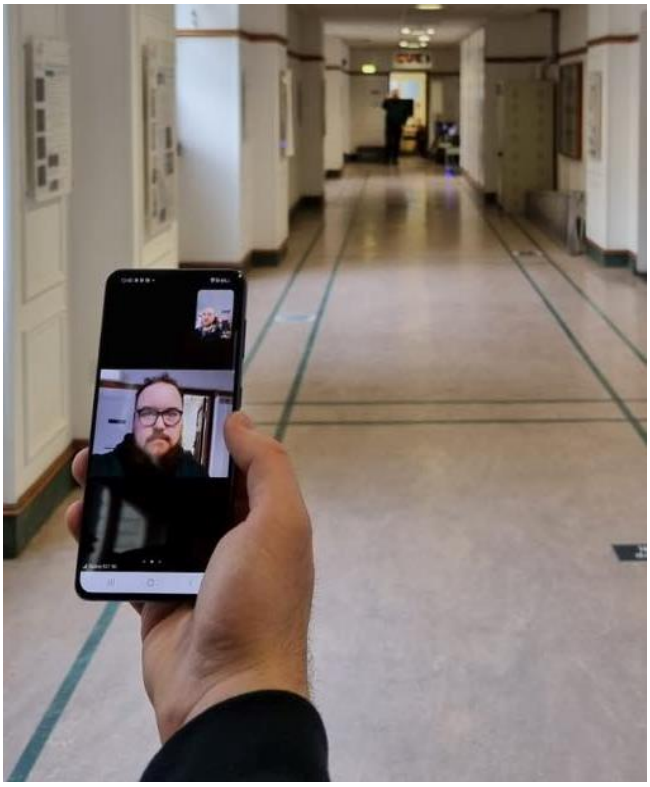

Figure 6.3: Video call conducted over n77 5G SA network in corridor.

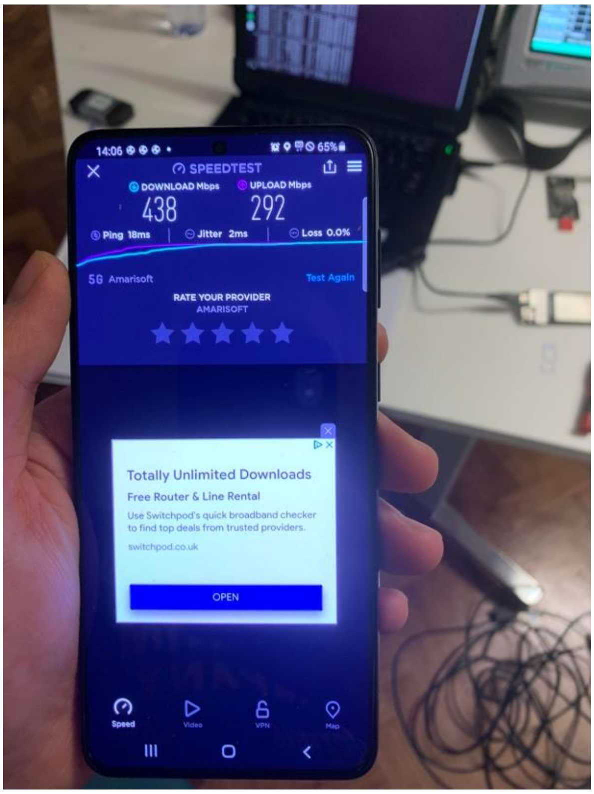

Figure 6.4: Speedtest for n77 5G SA network using Samsung S21 Handset.

In a typical station/tunnel deployment, it can be assumed that there would be up to two static HD cameras and as many as three mobile cameras carried by personnel. (The mobile cameras could be ruggedised handsets or tablets). Therefore, each base station radio would have to support up to five HD streams.

This equates to a total of 62.5 Mbps if all streams are running simultaneously. This could easily be supported by the network configuration described above, even in low SNR conditions, with all devices using an MCS of around 8. Therefore, the network allows a significant variation in MCS (27 to 8) and therefore SNR, while still being able to support five HD streams. As mentioned though, it would be unlikely that all units would experience low SNR simultaneously, allowing the gNB to schedule more spectral resources for lower SNR cameras and thus adequately support all five cameras.

6.2 Evaluation of Positioning in 5G SA Networks

As described in Section 4, a key use case identified for 5G networks in the subway environment is determining accurate location of personnel and assets/infrastructure in the tunnel system.

At present, determining the position of assets within the Glasgow Subway tunnels is typically approximate and it is often difficult to relocate the asset/infrastructure when it comes to carrying out a repair or replacement. In addition, there is currently no method of locating and tracking personnel when they are working in tunnels. Having such a capability would be desirable for safety reasons, especially if certain parts of the track are to be energised during maintenance hours.

In a typical outdoor environment, positioning could be carried out using a Global Navigation Satellite System (GNSS) such as the Global Positioning System (GPS). However, GPS is not suitable for underground environment as the signals transmitted by the satellites are not available below ground.

Other 3GPP-based positioning methods are available though, the most prominent being Observed Time Difference of Arrival (OTDOA), which was first introduced in 3GPP Release 9 of the 4G Long Term Evolution (LTE) standard.

OTDOA uses a technique known as multi-lateration to calculate a position using a set of Reference Signal Time Difference Measurements (RSTD) made by the UE from one or more eNBs (4G) or gNBs (5G). The position is calculated in a special sever unit known as the Evolved Server Mobile Location Centre (ESMLC) in 4G or the Location Management Function (LMF) in 5G [1].

The ESMLC/LMF communicates directly with the UE using the LTE Positioning Protocol (LPP) / New Radio Positioning Protocol (NRPP) through the Mobility Management Entity (MME) / Authentication and Mobility Function (AMF) which are the main components of the core network. Figure 6.5 shows a high-level architecture for the positioning calculation.

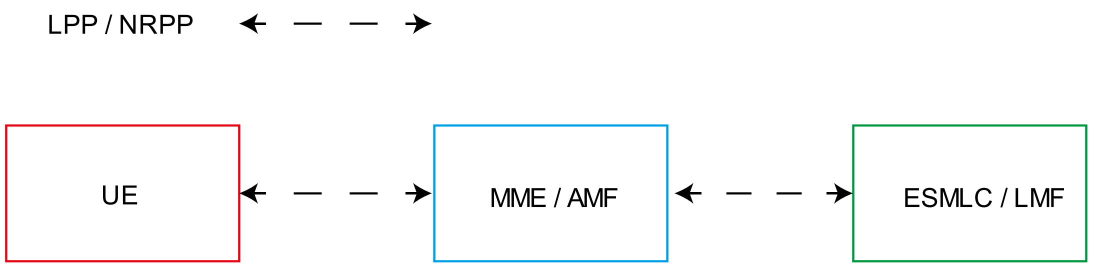

Figure 6.5: High-Level 4G/5G Positioning Architecture.

The RSTD measurements are made using special Position Reference Signals (PRS) which are transmitted simultaneously from each participating eNB/gNB. Through the LPP/NRPP protocols, the

UE communicates the RSTD measurements but also receives assistance data such as a list of available eNB/gNBs and the relevant parameters of the PRS needed by the UE.

OTDOA requires visibility of at least 4 eNBs/gNBs to calculate a 3D position (lat/long/elevation). In the Subway environment, it would be difficult or impossible for a UE to see 4 radios simultaneously. It is more likely that only 2 radios would be visible, meaning that a 1D position calculation would be the best possible outcome, i.e. the relative distance of a UE along the tunnel.

As part of 3GPP Release 16, new PRS signals have been introduced along with several new positioning methods such as Downlink-OTDOA (DL-OTDOA) (this is an updated version of the OTDOA method first introduced in 3GPP Release 9), Uplink-OTDOA (UL-OTDOA) which uses time difference measurements made by the gNBs via Sounding Reference Signals (SRS), Multi-Cell Round Trip Time (RTT) and Downlink/Uplink Angle of Arrival (AoA) which exploit beamforming capabilities inherent in 5G networks.

The positioning requirements for commercial applications have been set out in the standards documents. They state that for commercial applications the horizontal positioning accuracy should be better than 3 metres (indoor) and 10m (outdoors) for 80% of UEs. Vertical positioning accuracy must be better than 3 metres (both indoors and outdoors) for 80% of UEs. For regulatory use cases, the requirements are less strict, requiring horizontal positioning to be better than 50 metres for 80% of UEs and vertical positioning to be better than 5 metres for 80% of UEs [2]. These requirements outline the level of accuracy that will be possible with 5G SA positioning methods based on 3GPP Release 16.

Another important problem is finding UEs that currently support the 3GPP based positioning methods. Most mobile broadband modems based on the Qualcomm x55 architecture do not currently support positioning. However, discussions have indicated that positioning will be supported by several UE modems, albeit some of them may require a suitable firmware upgrade. Therefore, in the relatively near future, it should be possible to develop and test 5G-based positioning using an n77 5G SA network.

In the meantime, an ad-hoc positioning method would be possible using Cell IDs. Each individual gNB deployed in the Subway would be configured to transmit a different Physical Cell ID (PCI). This information is contained in the Physical Broadcast Channel (PBCH), which is the first channel the UE looks for when it is activated. With knowledge of the PCI assigned to each gNB, and the PCI of the gNB to which a particular UE of interest is attached, it would be possible to determine a rough position. An example of this positioning method is illustrated in Figure 6.6.

For example, if it was known that the Buchanan St gNB had a PCI of 500 and the St Enoch gNB had a PCI of 501, then it could easily be determined that a UE attached to PCI 500 was between Buchanan St and St Enoch but probably closer to Buchanan St since it is attached to the Buchanan St gNB. If the PCI changed to 501, then handover would have occurred, implying that the UE would then be closer to St Enoch station. This method would be especially useful for personnel tracking as each UE would be assigned to a particular person beforehand, and with this information and the PCI, it would be possible to determine their approximate locations within the tunnels.

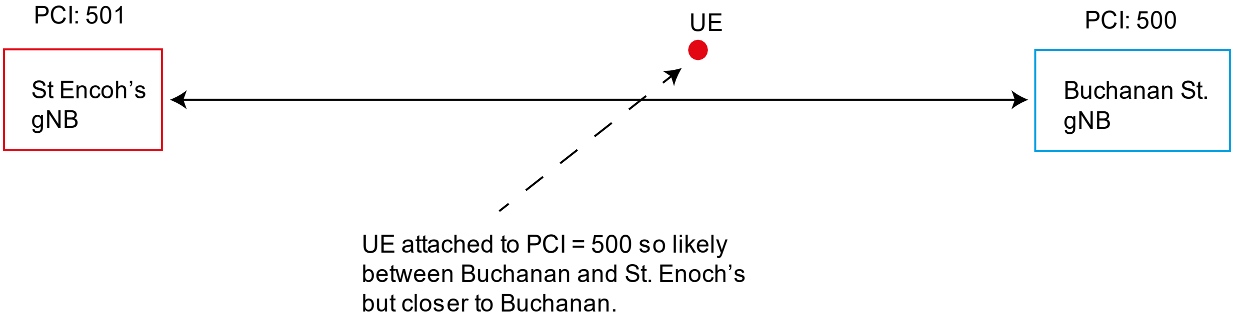

Figure 6.6: Illustration of Cell ID Based Positioning Method.

7 HIGH-LEVEL NETWORK REQUIREMENTS

This section describes the high-level requirements of a Private 5G network that supports maintenance activities in the tunnels of SPT's Glasgow Subway. The use cases to be supported have been identified and defined through discussion with relevant SPT staff, and the network requirements described in this section are defined with this in mind.

7.1 High-Level Technical Requirements

Based on the use cases described in Section 4, the following is a list of high-level technical requirements that the network would need to meet:

- **The network will operate in a band covered by the Ofcom Shared Access Licence (SAL) so that it is suitable for private use.** As mentioned, the 5G SA portion of the network should be implemented in n77 spectrum (3.8 – 4.2 GHz) and the NB-IoT network should be implemented in n3 spectrum (1876.7 – 1880 MHz).
- The n77 5G SA radio will be used to support HD video and general data transfer as well as positioning, and the n3 radio will be used to support the NB-IoT sensor network. The n77 network would require **200MHz of bandwidth between 3.8-4.2GHz**. This would ensure that adjacent cells could operate on different frequencies and still use a 100MHz carrier. Conversely, **the NB-IoT network would require a maximum of 400kHz in n3 between 1876.7 and 1880MHz**.
- It is assumed that any given base station radio in the subway would have to be able to support up to five simultaneous HD video streams. Of these, two cameras would be static in the station area and three would be mobile and carried by SPT personnel. Assuming 1080p/50fps and H.264 encoding, each stream would require 12.5 Mbps, meaning that **the radio would have to support a total uplink throughput of 62.5 Mbps**. This needs to be satisfied even in low SNR conditions. Therefore, it is recommended that a **100 MHz SISO configuration is deployed with an uplink-biased TDD configuration**.
- An **RTT latency of 25ms or less** between the end user devices and the SPT network is required to support the HD video streaming applications. This may be achieved by deploying a local User Plane Function (UPF) to transfer user data to the SPT network as quickly as possible. There are also several possible optimisations of the gNB stack that can be performed to reduce RTT if necessary.

- Without proper RF coverage simulations and field testing, it is not possible to precisely determine the number of base stations or the optimum transmit power that would be required to provide coverage to the entire Subway. However, based on work carried out during 5G RailNext, **the Effective Isotropic Radiated Power (EIRP) required to provide adequate coverage to each subway station and the tunnels between them would not exceed 37dBm (i.e. 5W) for the n77 network**. In fact, it is likely that the EIRP would be far lower in the majority of cases. **The NB-IoT network would also transmit at a power level lower than 5W EIRP**.
- During a discussion with SPT, it was decided that ***any* form of positioning accuracy would be deemed useful**. The 'ad hoc' positioning method described in Section 6.2 and illustrated in Figure 6.6 would allow approximate tracking of personnel in the tunnels and stations. As mentioned, with 3GPP Release 16 features and maturation of technology, it may be possible to demonstrate positioning accuracy in the order of metres without assistance from a GNSS.
- **It is assumed that a single base station will be required for each subway station.** Therefore, a total of 15x base stations (30x radios) would be required in order to provide suitable coverage to the entire subway network. Note: it may be that the actual design would require fewer than 15x base stations, e.g. if a single base station was able to provide coverage between Buchanan St and St Enoch. This cannot be determined at this stage without access to proper RF field measurement data taken in the Subway.
- A **common synchronisation clock will be required** to ensure TDD synchronisation between base stations to prevent interference and to enable handover. (This common clock may have to be derived from a source other than a GNSS.)
- Suitable **firewalls and other security measures** will be placed on all units to prevent unwarranted or malicious access to the SPT network.

7.2 Other (Non-Technical) High-Level Requirements

The network solution must be as convenient as possible to deploy in the Subway environment. As was demonstrated in 5G RailNext, a full n77 base station including Baseband Unit (BBU), Radio Head and antenna can be deployed over 2 or 3 nights by a small team. This would avoid a lengthy network installation process, which would save time and money.

The network solution should be easy to configure and update as requirements evolve, e.g. change of spectrum licence or bandwidth requirements. The ability to configure and upgrade the network with ease is one of the key benefits of a Software Defined network solution. Out of band network access to the equipment is therefore required.

The network should also be easy to operate so that with adequate training from a 3rd party, SPT would be able to run the network themselves and have only minimal reliance on outside support.

Although it is envisaged that the network would be designed for private use, it should be possible to run commercial applications and use cases if desired. For example, the network should allow neutral hosting, i.e. allow the radio network to connect to multiple MNO core networks. With this model, SPT could potentially generate income from the network, subject to suitable agreements being negotiated with the mainstream MNOs.

8 BUSINESS CASE

This section outlines the high-level business case for the deployment of a private 5G network that supports maintenance activities in the tunnels of SPT's Glasgow Subway. It starts with an outline of the expected benefits and then proceeds to consider the key components that would make up the CAPEX and OPEX costs.

8.1 Expected Benefits from a 5G Network

A key benefit of a private 5G network for SPT would be to improve the overall efficiency of the maintenance activities. The private 5G connectivity would be used to support HD video streaming for video calling, visual inspection of assets/infrastructure in the tunnels, and monitoring of risk areas. This capability would be beneficial in improving communication between personnel in the tunnels and staff in the central office. It would be expected to improve the efficiency of identification and reporting of issues found during maintenance activities and help to improve the condition monitoring process.

The connectivity would also allow personnel to take pictures/videos and upload these directly to an asset management system or maintenance management system. This would facilitate improved condition monitoring and would enable quicker identification and repair of problems associated with assets/infrastructure, which would ultimately lead to cost savings. Monitoring of risk areas in the stations and tunnels would be beneficial in terms of health and safety, and data derived from this could also be used to improve Subway operations more generally.

At present, determining the position of assets/infrastructure in the tunnels is often approximate, which increases the difficulty of locating assets when a repair or replacement is required. Having more accurate knowledge of position would reduce the time spent by maintenance personnel attempting to determine the location of an asset when a repair is required. This could lead to improved on-shift productivity which would have obvious benefits for overall maintenance efficiency. In addition, being able to roughly locate personnel when working in the tunnels would improve safety. (More specifically, the ability to determine the position of a particular staff member would give the opportunity to simultaneously carry out certain activities such as maintenance and train testing without adversely affecting safety.)

Having a low-power sensor network would allow conditions to be monitored in real-time from a central location. Candidate metrics highlighted by SPT include air quality in the tunnels, temperature, vibration monitoring, etc. This type of condition monitoring would enable a much broader view and understanding of the state of the subway through time, and would help to improve overall efficiency of maintenance and general subway operations.

Finally, if a suitable agreement could be negotiated with Mobile Network Operators (MNOs), SPT could potentially also run a commercial service on the 5G network through Neutral Hosting. This could allow SPT to charge MNOs to enable connectivity for their customers in the tunnels. In effect, this would allow SPT to generate revenue from the network. (It should be acknowledged, however, that agreeing such an arrangement is by no means straightforward.)

8.2 Costs

The high-level architecture design for a single base station site was described in Section 5. Table 8.1 lists the main components required for a single base station.

Table 8.1: List of basestation main components.

n77 5G Radio Head (2x1 100MHz capable)
n3 NBIoT Radio Head (Low power)
Basestation compute platform, CPRI and backhaul network interfaces
Antennae (x2), RF cable
Licensed 5G/NBIoT vBBU Software
Fibre Optic Cable, Transceivers, Power cable, bracketry etc

The Capital Expenditure (CAPEX) required for each base station depends significantly on the choice of vendor/supplier and on the precise specification of each component. We are therefore unable to provide hard numerical values, but we can consider the general upper and lower limiting points, as follows:

At the upper end of the scale, given that a private 5G network is being considered here, there is considerable freedom of choice in terms of network supplier, and the cost need not necessarily be as high as would be the case for a national MNO base station. At the lower end of the scale, a 5G network is likely to cost more than, say, a typical Wi-Fi network as can often be found in train stations and other public spaces. In other words, the CAPEX for a private 5G network is very likely to fall somewhere between these upper and lower limits.

In addition to the CAPEX costs, there will be an ongoing annual Operating Expenditure (OPEX) associated with running the network. Here, too, the costs may vary considerably depending on the choice of vendor/supplier, but the main OPEX cost categories are likely to be as listed in Table 8.2.

Table 8.2: List of base station main components.

Spectrum Licences (Annual)
1G Internet Capacity (Annual)
Electricity Costs (Annual)
Annual failure costs & Repairs
Software Licensing

8.3 Summary

In summary, there are numerous potential benefits associated with deploying a private 5G network in the Subway to help with maintenance activities. The various use cases outlined by SPT can be met using a combination of a mobile broadband 5G network and an NB-IoT network to support various sensors. Even if the network doesn’t end up being used to generate direct revenue itself, it could potentially reduce operating costs and improve revenue generated by the Subway service. There is also scope in future to generate revenue indirectly through neutral hosting.

Further work is required to investigate and confirm these benefits and to derive some more detailed and more precise cost estimates, but it this stage, it does appear that there could be a viable business case for 5G in tunnels generally.

9 KEY LEARNINGS

The 5G SubConnect project has investigated the potential for 5G connectivity to add value to maintenance activities in the tunnels of underground railway systems. Key learnings from the project include:

- Real-time video upload, video-conferencing, positioning, and sensor-based condition monitoring have the potential to realize tangible benefits for underground train operators. The technology solution requires some development, but many of the key technology building blocks already exist or will do so in the near future. Integration into business operations systems and processes needs to be considered and planned for, however.
- 5G positioning technology has good promise, but it isn't quite here yet. 3GPP standards support new positioning techniques, but certain functions require implementation, and UE support will rely on next-generation chipsets. Development effort needs to be planned and implemented. UE support is another issue, and this will come in time.
- In a more general context, getting consumer UE devices to connect to a Private 5G network is often a challenge, due to carrier-based feature locking being implemented by UE manufacturers. Many, perhaps even most, consumer handsets will not connect to a Private 5G network without firmware modification. They will connect only to registered, known PLMNs. It will be difficult to realize the benefits of deploying Private 5G networks which are intended to be used with consumer UE devices, unless steps are taken to ensure that UE devices will connect to any network ID, whether it's a mainstream public network or a small, private one. This may require a change in policy and regulation by governments, regulators, and the GSMA.

These learnings have been valuable in helping us to develop our understanding of the potential for digital connectivity to contribute to maintenance activities in subway tunnels and the current limitations that need to be addressed in order to make it viable.

10 CONCLUSION AND NEXT STEPS

The learnings from 5G SubConnect have been valuable in helping us to develop our understanding of the potential for digital connectivity to contribute to maintenance activities in subway tunnels and the current limitations that need to be addressed in order to make it viable. Our investigations have resulted in us acquiring good understanding of maintenance-related use cases, evaluating the current state of 5G technology, and working out the high-level system requirements of connectivity in the tunnels for supporting such activities. The project team has identified a number of potential benefits associated with deploying a private 5G network in the Subway to help with maintenance activities, and a set of high-level technical requirements has been created.

The project's activities and outputs have been derived from high-level estimates and discussions with relevant SPT personnel, and various technical tests have been carried out on a small test network that was developed and implemented in the University of Strathclyde. A key next step would be to develop a prototype network solution in the tunnel environment itself, and to implement a pilot in the tunnels with the maintenance teams making use of the connectivity, in earnest, on a trial basis. In parallel, further investigation and development of suitable positioning technology will be required.

With this in mind, we will be seeking to explore opportunities for developing and implementing such a pilot, which would allow us to test and confirm the expected benefits and refine the assumptions that lie behind the envisaged high-level network technical requirements and architecture design. This would also lead to suitable CAPEX and OPEX estimates.

11 REFERENCES

[1] Reiner Stuhlfauth, “Positioning in 5G NR: A Look at the Technology and Related Test Aspects”, Rhode & Schwarz White Paper (Version 02.00), PD 3683.5151.52, January 2022.

[2] https://blog.3g4g.co.uk/2020/10/positioning-techniques-for-5g-nr-in.html

StrathSDR

SPT

Department for
Digital, Culture,
Media & Sport

Document Version: 1.0
July 2022