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Helsinki Metro's Cellular Network Pilot – Results and Observations

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Glossary and terms

4G	4th Generation Cellular Network
5G	5th Generation Cellular Network
APC	Automatic Passenger Counting
APN	Access Point Name
ATC	Automatic Train Control
ATS	Automatic Train Supervision
BIC	Bearer Independence Concept
BBU	Base-Band Unit
CBTC	Communication-Based Train Control
CCTV	Closed Circuit Television
DL	Down-Link
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FRMCS	Future Railway Mobile Communication System
GoA4	Grade of Automation 4
GSM-R	Global System for Mobile Communications-Railway
GUI	Graphical User Interface
iPerf	Widely used network testing tool
LTE	Long Term Evolution
MetroLAN	Helsinki Metro Wide Area Network
MNO	Mobile Network Operator
NR	New Radio
NSA	Non-Stand Alone
RAN	Radio Access Network
RFID	Radio Frequency Identification
RRU	Remote Radio Unit

RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
SA	Stand Alone
SNR	Signal-to-Noise Ratio
TCP	Transmission Control Protocol
TDD	Time Division Duplex
UDP	User Datagram Protocol
TCS	Train Control System
UIC	The International Union of Railways
UL	Up-Link
VoIP	Voice over Internet Protocol

1. Introduction

1.1 Radio Technologies for train control systems

Communications-Based Train Control (CBTC) and European Train Control System (ETCS) are recognised in the railway sector as train control systems.

A typical ETCS architecture comprises a radio cellular communication subsystem, the Global System for Mobile Communications-Railway (GSM-R) which will be replaced in the near future by the Future Railway Mobile Communication System (FRMCS) currently standardised by the International Union of Railways (UIC) and based on cellular technologies.

CBTC has been widely adopted in recent years on metros and other urban railway services and is the recognized concept for mass transit state-of-the-art technology. Although the performance and functional requirements for a CBTC system are established within an IEEE standard, there are currently no independent CBTC standardisation defining functional requirements for interoperability between different suppliers' CBTC systems or with ETCS standards.

From a radio communications point of view, a typical CBTC architecture comprises a train to wayside communication subsystem, currently based on Wi-Fi, with some early deployments of cellular based communication subsystems.

There are also several studies which tackle the Bearer Independence Concept (BIC) for rail where the train application selects the appropriate bearer depending on the use case and performance requirements.

It is also widely recognised across the rail and telecommunications communities that a new generation of railway radio telecommunication system is required to address the demand for new digital services across a wide range of railway users and application use cases.

1.2 Helsinki's Metro Capacity Upgrade

Helsinki City Transport is in the process of implementing a programme to increase the metro's capacity and reliability.

There are also several systems in use in the metro, including the existing trip stop system, that are approaching or are already at the end of their lifecycle.

As part of the capacity upgrade programme of works the existing trip stop system will be re-placed with a new continuous Train Control System (TCS) that will enable shorter headways and increase the safety level of metro operations.

This new Train Control System is expected to use packet-based data transmission of train control information, and it requires the building of a new radio network for this data transmission between the train and wayside equipment. It is also the intention of Helsinki City Transport to use the radio network in the future to fulfil the business, performance, and critical requirements of a diverse range of users and systems.

This paper is aiming to share the results of a cellular pilot that was deployed by Helsinki City Transport, with the technical assurance support of WSP's Communications and 5G Connectivity experts, to inform on the suitability of cellular based communication subsystems for train control and other metro systems applications.

2. Cellular pilot description

City Transport deployed a new cellular communication network to test 4G and 5G network performance and its suitability against ATC and other metro systems requirements.

This pilot deployment delivered 4G and 5G coverage to one of the Helsinki metro's depot test-track and its associated tunnel.

The chosen location offered a good combination of open-track section and tunnel section replicating the Helsinki Metro network environment.

There were two independent networks present, one on private spectrum (single frequency band) and another on the Mobile Network Operator's public bands.

2.1 Trackside infrastructure

The trackside radio infrastructure incorporated:

- Two overlapping networks (one private in 2300MHz and one public in 3500MHz) covering the metro depot test tracks and its associated tunnel.
- Various antenna deployments:
    - Radiating cable deployment for private network
    - Rooftop sites providing additional redundancy and ability to test additional handover scenarios (when communication from the radiating cable must be handed over to a macro site)
    - In-tunnel directional antennas as infill solution for the public network
    - Existing Mobile Network Operator's macro sites in the area
- Various radiating cable topologies and connection methods (e.g. different sides of the track, or tunnel wall fixing locations), as well as various radiating cable transition scenarios (e.g. height change or track side change)
- Various dedicated Base Band Units (BBU) and Remote Radio Units (RRU) feeding respectively the radiating cables for the private network and the antennas for the public network.

Table 1: Bands deployed per radio position

Technology and Band	1	2	3	4	5	6	7	8	9
5G NR 3500 MHz (5G NSA)	X	X	X	X	X				
4G LTE Anchor	X	X	X	X	X				
4G LTE 2300 MHz	X			X		X	X	X	X
5G NR 2300 MHz (5G SA)	X			X		X	X	X	X

The test track consisted of 800 m of open track and 600 m of tunnel.

This deployment provided additional benefits when evaluating suitability of the technology as it enabled the testing of high availability arrangements, the density of the deployment, the performance of several installation methods, as well as the evaluation of potential fault scenarios.

2.1 Train equipment

The train installations included two dedicated routers for the private network each connected to two undercarriage antennas and a third independent router for the public network connected to four rooftop antennas. The routers presented and ethernet interface for connection to the on-board train systems and the test system.

Due to technical limitations of the routers, it was not possible to setup those in an active/hot standby configuration which would be more reflective of the actual intended end-system. Regardless, this deployment enabled the testing of high availability train arrangements (via individual router test result correlation) and a basis for ongoing evaluation of the train antenna positions. Finally, the ethernet interface provided a standard IP interface that was used as an input for the various test streams.

2.2 Integration with mobile core and end-to-end connectivity

The core architecture implemented a resilient backhaul into the Mobile Network Operator's core. The end connection was presented for resilience via two private Access Point Name (APN) servers providing the gateway between the mobile network and the metro's Local Area Network (Metro-LAN). This architecture enabled the testing of a private interface into the testing system as well as testing the capability of the network to carry existing metro systems' traffic.

The end-to-end connectivity implementation is illustrated in figure. In this diagram the green components represent the radio network, and the purple components represent any application/system that uses standardised interfaces, showcasing the flexibility of the deployment.

This architecture provided standardised interfaces for connection into external systems and is representative of the architecture of modern and standardised radio communication networks that can be used for track-to-train communications. In this concept the radio communication network is seen as a bearer independent "black box" by the application responsible for sending and receiving the packets.

In this pilot, the purple components were the testing equipment which was generating and capturing the data streams for further evaluation. This is discussed in more detail in Section 3.

3 Testing

3.1 Testing objective and key performance indicators

The objectives of the testing were:

1. To measure all desirable performance indicators that can inform on the suitability of the cellular networks to support existing and future applications.
2. To measure the performance of the radio environment in normal and failure (degraded service) modes and confirm suitability of the antenna and radiating cable specification and location.
3. To confirm functionality of existing on-board systems over the cellular network.

The performance tests were executed against the performance indicators specified in below. These performance indicators were agreed with City Transport and derived from:

- Metro/urban rail user and system requirements documentation developed by collaboration programmes such as Shift2Rail,
- via engagement with the industry/system suppliers and
- WSP's previous experience with similar systems/use cases.

Table 2: Data communication requirements per application stream.

	Min. Data rate (DL-Mbps)	Min. Data rate (UL-Mbps)	Max. latency (oneway-ms)	Jitter (ms)	Packet loss ratio (lost/ delivered %)	Max. msg/comms timeout (s)	Max. connec-tion setup time (s)
ATC	0.2	0.2	100	N/A	0.1	3	5
Critical CCTV[1]	0.2	10	100	30	0.1	1	1
Train diagnostics	0.5	0.5	150	N/A	0.5	1	3
Location Tracking[2]	<0.1	<0.1	100	N/A	0.1	1	5
Passenger counting system	<0.1	<0.1	500	N/A	0.5	3	5
Train network management	0.2	0.2	300	N/A	1	5	5
Train commercial displays	2	0.2	500	N/A	0.5	3	3
Public Wi-Fi[3]	250	25	300	30	1	1	3
VoIP[4]	0.15	0.15	100	20	0.1	1	1

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[1] Per camera. Assumed to be used as operationally critical video for GoA4 in the future.
[2] Assumed to be used for accurate positioning tracking.
[3] Per train.
[4] Assumed to be used as operationally critical voice in the future.

3.2 Testing architecture and strategy

A measurement test server was providing the endpoint for the UDP and TCP data streams that were simulating the various applications. The iPerf tool was used to generate and measure this network traffic to and from the test server. In addition to those streams, capacity tests were also executed using TCP. During capacity testing the test stream was configured to use all available bandwidth. In addition, network flows were measured at both ends with passive network monitoring probes which provided the network performance indicators for uplink and downlink directions. It is noted that traffic prioritisation was not implemented during the tests.

Each test was executed across one test run package, where a test run package is defined as a combination of four different test runs over the entire length of the test track (approximately 1400 m). The test run package included the following sequence of train runs:

1. One westbound run reaching full speed (up to 80 km/h) between the test-track endpoints (G to A).
2. One eastbound run reaching full speed (up to 80 km/h) between the test-track endpoints (A to G).
3. One westbound run between the two track end points, stopping at strategically selected locations (F, D and B) which were marked on the track.
4. One eastbound run at slow speed (20 km/h) between the two track endpoints (A to G).

Overall, there were more than 140 testing scenarios executed over 60 test run packages. The tests were rationalised in thirteen groups which were based upon operational and failure scenarios, and they included:

- RF-scanning (RSRP, RSRQ, SINR, PCI etc)
- Single train and two trains runs
- Capacity testing
- Data stream testing
- Overload testing
- Degraded mode testing (Different radio positions off)
- Handover testing - radiating cable to macro
- Different train speeds
- Network and train reboot

3.2 Test results

3.2.1 Private network (LTE)

3.2.1.1 Normal mode

Normal mode was the instance where all the radio units which were connected to the radiating cable were online.

Quality of coverage

Table 3 shows the average values recorded along the test track and across one test run package for each router individually as well as their combined results. It is noted that due to router limitations it was not possible to test them in active/hot standby mode and as such the combined view provides a worst-case scenario.

Overall signal levels and quality were excellent along the track. The south router experienced slightly worse signal levels due to its antenna’s location with respect to the radiating cable.

Table 3: Radio coverage average values (Private band).

North Router		
RSRP (average)	-77,3 dBm	Excellent
RSRQ (average)	-9,2 dB	Excellent
South Router		
RSRP (average)	-81,7 dBm	Good
RSRQ (average)	-9,5 dB	Excellent
Both Routers		
RSRP (average)	-79,5 dBm	Excellent
RSRQ (average)	-9,4 dB	Excellent

The ranges for the radio coverage parameters are defined in 4 and Table 5.

Table 4: RSRP metrics

RSRP	Signal strength
>= -80 dBm	Excellent
-80 dBm to -90 dBm	Good
-90 dBm to -100 dBm	Fair to poor
<= -100 dBm	Cell edge/No coverage

Table 5: RSRQ metrics

RSRQ	Signal quality
>= -10 dB	Excellent
-10 dB to -15 dB	Good
-15 dB to -20 dB	Fair to poor
<= -20 dB	Very poor/No coverage

Performance metrics

Table 6 below shows the average and maximum capacity as well as the latency in both Downlink and Uplink across one test run package. Results are presented for each router individually but also when the results from both are combined. It is noted that due to router limitations it was not possible to test them in active/hot standby mode and as such the combined view provides a worst-case scenario.

Table 6: UL/DL capacity and latency of the private bands.

North Router	
DL Capacity (average)	30,2 Mbps
UL Capacity (average)	4,1 Mbps
TCP delay (average)	42 ms
South Router	
DL Capacity (average)	28,3 Mbps
UL Capacity (average)	4,0 Mbps
TCP delay (average)	46 ms
Both Routers	
DL Capacity (aggregate)	55.9 Mbps
UL Capacity (aggregate)	8,4 Mbps
TCP delay (average)	44 ms

The private network can comfortably and consistently fulfil the requirements for ATC and critical voice communication. Due to Uplink capacity limitations the critical CCTV stream failed its performance criteria.

1. The VoIP stream fail its performance criteria only in one specific location and only for one of the two routers, namely between remote positions 6 and 7 where the radiating cable changes track sides and there is a long coaxial cable run under the track connecting each side. This was an expected result that should be considered when deploying the complete radiating cable system. It also must be noted that if the routers were supporting active/hot stand-by configuration then this fail would not materialise as it is indicated in the combined view row.
2. The CCTV stream fails all its performance criteria with the exception of bandwidth during these tests. The reason for these failures was that the Uplink capacity of the system had been reached due to the use of duplicated CCTV streams for each of the routers during the test run package. It is noted that the CCTV stream was using very stringent performance

criteria most suited for GoA4 operation.

Two-train tests

Dual train runs were also conducted to test the perturbation of the radio environment under different operational scenarios where two trains run in parallel (either the same or different directions).

It was observed that in all scenarios there was no difference to the radio communications when compared to a single train run package, so compliance was the same as the one presented before. There was only one exception in the open track where there was some abnormal handover behaviour that caused a brief spike in latency to around 500 ms for the routers closest to the radiating cable. This issue could be attributed to the multipath environment being created by the second train running in parallel and towards the same direction while the radiating cable lies between the trains. This is a typical scenario where system optimisation during system acceptance would be expected to resolve.

It is also noted that that radio communication handover between the radiating cable system and the rooftop macro sites also performed as expected during the dual train running.

3.2.1.2 Degraded mode

The degraded mode tests were perturbating radio conditions that simulated the failure of radio locations within the tunnel and open track areas. The aim was to get an understanding of the radio design principles and to test the density of the pilot's cell deployment. These observations could inform a future system deployment.

The main observations were:

1. There was degradation of latency in the coverage area of radio positions 1, 6 and 7 when these were off.
2. Most of the service degradation was observed in areas were changes in radiating cable topology (changing positions/heights etc.) were occurring.
3. Uplink was affected in areas were changes in radiating cable topology (changing positions/heights etc) were occurring but there was limited effect on the downlink performance.
4. Due to the private nature of the network, lack of external interference caused the system to perform better than expected in low signal situations.
5. The two rooftop sites were able to provide good coverage and good handovers to the open track area when the radiating cable radio units in the same area were off.
6. For maximum redundancy the radio design should avoid designing private network cell edge areas at the same location as public network cell edge areas. By overlapping the network design, the reliability of the dual layer network could be maximised.

It is noted that the public network could fulfil the role of the back-up network for the ATC traffic in all areas where private network degradation was observed.

There was just one instance of a delay spike (124 ms roundtrip delay) and long connection establishment time (4,7 % higher than tolerance) within the tunnel at the handover area of radio positions 3 and 4. However, in the dual layer view, this specific position does not represent a problem as the private band can adequately provide a service during the degraded mode.

3.2.2 Public Network (5G NSA)

3.2.2.1 Normal mode

Normal mode is the instance where all the public network radio units within the tunnel (positions 1, 2, 3, 4 and 5) and the Mobile Network Operator’s macro layer around the depot area were online.

Quality of coverage

The radio signal coverage tests showed that the signal level and signal quality was at an overall excellent level in the public bands. Table 7 shows the average values recorded along the test track and across one test run package.

Table 7: Radio coverage average values (Public band).

Public Router		
RSRP (average)	-60,8 dBm	Excellent
RSRQ (average)	-8,7 dB	Excellent

For the criteria of signal/quality classification please refer Table 4 and Table 5.

Regardless of these excellent results there were two locations which have experienced worse signal conditions compared to the rest.

The first location was within the tunnel and within the handover area between radio positions 3 and 4. Handover optimisation in this area could resolve the issue.

The second location is at the open track at the front of the metro depot where the track was bending, and which was covered by the Operator’s macro sites. There could be a number of reasons for this including surrounding buildings shadowing the location and the terrain topography around the depot.

Performance metrics

Table 8 below shows the average and peak capacity in both Downlink and Uplink across one test run package.

Table 8: UL/DL capacity of the public bands

Public Router	
DL Capacity (average)	65,8 Mbps
DL Capacity (peak)	153,1 Mbps
UL Capacity (average)	69,8 Mbps
UL Capacity (peak)	143,8 Mbps

The network’s capacity was sufficient to serve all data streams being tested with the exception of the Public Wi-Fi data stream which was not able to achieve its maximum set capacity with an average DL throughput of 86.4 Mbps against a target of 250 Mbps. It is noted that maximum capacity results have been affected by the number of hops between depot’s local area network and the Mobile Network Operator’s core. Troubleshooting during the tests revealed that by optimising the end-to-end connectivity a 300 % increase in capacity could be achieved.

The maximum connection setup time for the CCTV stream fails by approximately 7 % at the handover areas mentioned before only when the Wi-Fi stream (which was consuming the entire bandwidth) is also present. It is noted that there was no priority setting for the data streams. It is also noted that the CCTV stream was using very stringent performance criteria most suited for GoA4 operation. Taking these into consideration it was concluded that the public network can meet the current CCTV requirements. If the CCTV stream is to be used for safety critical applications, then priority needs to be implemented into the network or careful consideration given to the radio design.

The Wi-Fi service is a best effort service for metro passengers and failing its maximum throughput target was not considered a critical failure. It is noted that the Wi-Fi stream can potentially achieve its target if the end-to-end connectivity is optimised.

Taking all the above into consideration it was concluded that the public band was sufficient to serve all data streams that were simulating the different metro applications. Results could be further improved if radio parameters such as handover thresholds and overlap zones are properly fine-tuned.

Two-train tests
Dual train runs were also conducted to test the perturbation of the radio environment under different operational scenarios where two train run in parallel (either the same or different directions). It was observed that in all scenarios there was no difference to the radio communications when compared to a single train run package, so compliance was the same as the one presented above.

There was only one exception in the open track when the second train was physically obstructing the Line-of-Sight from radio position 5 at the start of the tunnel causing a brief interruption to the radio communication. This can be attributed to the low antenna height at the end of the tunnel, as was highlighted within the pilot’s assurance team iBwave simulations of the tunnel environment. Optimisation of the antenna position needs to be taken into consideration during the design stage of similar systems.

3.2.2.2 Degraded mode

The degraded mode tests were perturbating radio conditions that simulated the failure of radio locations within the tunnel only. The aim was to get an understanding of the radio design principles and to test the density of the pilot’s cell deployment. These observations can inform a future system deployment.

1. Due to the cell density, there were no issues experienced in the tunnel other than the longer than normal delay around the handover area between positions 3 and 4. This area was also showing longer than average delays during the normal mode tests. These was more noticeable when either positions 3 or 4 were off. This could be attributed to the geometry of the track, the size of the tunnel and the relevant positions of the directional antennas providing the coverage in this area which are lower than antennas on the roof of the train. This is a clear example of a location where proper pre-installation radio design could avoid this issue.
2. Signal quality and signal levels were good to excellent throughout the tunnel during all degraded mode scenarios which reveals that the radio design could be rationalised (less density but better located cells).
3. There was degraded signal quality in the open track area when the last tunnel radio (position 5) was off. This resulted in one occurrence of longer than average packet delay. This is

a clear indication that radio design should consider sufficient coverage is provided for handover between tunnel and macro layers.

4. For maximum redundancy the radio design should avoid designing public network cell edge areas at the same location as private network cell edge areas. By overlapping the network design, the reliability of the dual layer network could be maximised.

It is noted that the private network could fulfil the role of the back-up network for the low bandwidth train services such as train diagnostics, commercial displays, location tracking etc in all areas where public network degradation was observed. This is assuming prioritisation of traffic and QoS is implemented.

3.2.3 Private Network (5G SA)

The 5G SA network implementation was one of the first 5G SA 2300 MHz TDD commercial networks in Finland not yet accessible by the general public. It should be noted that the routers used in this pilot were not specifically specified to be fully compliant with 5G SA.

Quality of coverage

Table 9 shows the average values recorded along the test track and across one test run package for each router individually as well as their combined results. It is noted that due to router limitations it was not possible to test them in active/hot standby mode and as such the combined view provides a worst-case scenario. Signal levels are broadly the same while signal quality was shown to be worse for both routers when compared to LTE.

Table 9: Radio coverage mean values for 5G SA and comparison with 4G LTE (Private band).

North Router		
RSRP (average)	-78,0 dBm (-1% vs LTE)	Excellent
RSRQ (average)	-11,3 dB (-23% vs LTE)	Good
South Router		
RSRP (average)	-83,0 dBm (-2% vs LTE)	Good
RSRQ (average)	-11,4 dB (-20% vs LTE)	Good
Both Routers		
RSRP (average)	-80,5 dBm (-1% vs LTE)	Good
RSRQ (average)	-11,4 dB (-21% vs LTE)	Good

For the criteria of signal/quality classification please refer to Table 4 and Table 5.

Performance metrics

Table 10 below shows the average and aggregate capacity as well as the latency in both Downlink and Uplink across one test run package. Results are presented for each router individually but also when the results from both are combined. It is noted that due to router limitations it was not possible to test them in active/hot standby mode and as such the combined view provides a worst-case scenario. It is also noted that during the 5G SA tests the measurement server was located closer to the Mobile Network Operator’s core when compared to the test server within the depot’s Local Area network utilised in the 4G LTE tests. This has probably resulted in better performance as it is illustrated in the Table 10 below.

Table 10: UL/DL capacity and latency of the 5G SA and percent comparison vs 4G LTE (Private Band).

North Router	
DL Capacity (average)	32,6 Mbps (+8% vs LTE)
UL Capacity (average)	4,5 Mbps (+10% vs LTE)
TCP delay (average)	30 ms (-29% vs LTE)
South Router	
DL Capacity (average)	38,2 Mbps (+35% vs LTE)
UL Capacity (average)	4,6 Mbps (+15% vs LTE)
TCP delay (average)	27 ms (-41% vs LTE)
Both Routers	
DL Capacity (aggregate)	70,8 Mbps (+27% vs LTE)
UL Capacity (aggregate)	9,1 Mbps (+8% vs LTE)
TCP delay (average)	29 ms (-34% vs LTE)

The private network can comfortably and consistently fulfil the requirements for ATC and critical Voice communication when the results from both routers are correlated. The ability of individual routers to maintain a stable communication path was observed to be worse in 5G SA than in 4G LTE in areas where the radiating cable was on the other side of the train compared to the respective router's antennas.

Due to Uplink capacity limitations the critical CCTV stream failed its performance criteria.

1. All failures noted for the individual routers occur in areas where the radiating cable is on the opposite side of the respective router's antennas. This happens in the tunnel for the south side router and at the level crossing area between radio positions 6 and 7 for the north side router. This was an expected result that should be considered when deploying the complete radiating cable system. These results can potentially be improved with the improving maturity of the 5G SA technology and the 5G SA routers. It must also be noted that if the routers were supporting active/hot stand-by configuration then this failure should not materialise as it is indicated in the combined view row.
2. The CCTV stream again fails all its performance criteria with the exception of bandwidth during these tests. The reason for these failures was again that the Uplink capacity of the system had been reached due to the use of duplicated CCTV streams for each of the routers during the test run package. This was expected as the 5G SA implementation did not provide additional capacity over the same channel bandwidth and the same MIMO configuration. It is also noted that the CCTV stream was using very stringent performance criteria most suited for GoA4 operation.

3.2.4 Reboot tests

The last set of tests that were performed were aiming to test the ability of the ATC stream to be re-established simulating a reboot of the train in one instance and a reboot of the radio network in another instance. The elapsed time between loss and re-establishment of the connection was measured during the test and this is reported in the table below.

Table 11: Reconnection time of the ATC stream under different reboot scenarios

Test type	Elapsed time for reconnection
Train reboot	7 min 13 s
Radio network reboot	4 min 8 s

In both tests the ATC stream was re-established successfully at its set bit rate after the elapsed time mentioned above.

3.2.5 Secondary tests

The secondary testing only involved standard visual functionality tests of the existing on-board train systems utilising existing City Transport Graphical User Interfaces (GUIs) and monitoring screens.

During these tests the existing on-board Cisco router, acting as a gateway, routed any onboard data to/from the depot's local area network via the cellular routers under both private (4G) and public networks (5G NSA) during dedicated test run packages.

The purpose of the tests was to confirm capability of both network and router to carry existing train systems' traffic.

The test results confirmed that the data communication of all existing onboard systems worked normally via all cellular routers (private north, private south, and public) and for both networks.

4. Final observations

In this section we present our observations for the ability of the networks implemented during this pilot to fulfil City Transport's current and future business, performance, and critical requirements of a diverse range of users and systems. We also summarise our deployment observations.

1.1 Performance

Ability to support signalling

The pilot test results showed that both the private network (4G or 5G) and the public network are suitable to support ATC performance requirements. In high public network load scenarios, it is advised that QoS is implemented to ensure the reliability of any safety critical streams.

Ability to support current systems

The pilot tests showed that the public network is suitable to support metro's onboard existing systems. It was observed that when the public network was capacity stressed, with all applications present, the Wi-Fi stream could not reach its maximum intended capacity of 250Mbps. This was due to bandwidth limitations experienced during the Pilot tests and is related to end-to-end connectivity restrictions and by the number of hops between end devices and the Mobile Network Operator's core. Troubleshooting during the tests revealed that a considerable increase in capacity could be realistically achieved by addressing these limitations.

Ability to support future systems

The pilot tests showed that the private network could not reliably service the critical CCTV stream due to the bandwidth limit of that network and the fact that the CCTV stream was duplicated over the two private routers. At the same time the VoIP stream could be reliably serviced indicating that if there was more capacity the issue with CCTV could be resolved.

1.2 Deployment

Private network deployment observations

In normal operation mode, the band used (2300 MHz) and the density of the radio units was demonstrated to fulfil the requirements for ATC and critical voice communication.

For the private network, there was degradation of latency in the coverage area of three out of the four radio positions when these were offline. Most of the service degradation was affecting the Uplink and it was observed in areas were changes in radiating cable topology (changing positions/heights etc.) were occurring.

Due to the private nature of the network, lack of external interference caused the system to perform better than expected in low signal situations.

The two rooftop macro sites were able to provide good coverage and good handovers to the open track area when the radiating cable radio units in the same area were off.

In the 5G SA mode all failures noted for the individual routers occur in areas where the radiating cable is on the opposite side of the respective router’s antennas.

Public network deployment observations

Signal quality and signal levels were good to excellent throughout the tunnel during all degraded mode scenarios. At the same time there were a few occurrences of longer than average delays in a certain handover area within the tunnel. This could be attributed to the geometry of the track, the size of the tunnel and the relevant positions of the directional antennas providing the coverage in this area which are lower than antennas on the roof of the train. These observations reveal that the radio design within the tunnel could be rationalised (less density but better located cells)
Other results showed that the radio design needs to also consider that sufficient coverage is provided to allow handovers between tunnel and macro layers.

An overarching observation was that for maximum redundancy the radio design should avoid designing private network cell edge areas at the same location as public network cell edge areas. By overlapping the network design, the reliability of the dual layer network can be maximised.
A final observation is that routers/mobile gateways working in high availability mode and/or application devices that can manage packet duplication via multiple routers are recommended in order to increase data communication reliability.

1.3 Conclusions

This innovative pilot demonstrated that a cellular based communication subsystem is suitable for train control as well as other metro systems applications.

The pilot outcomes provided insights into the deployment of such systems and also confirmed the expectation that in order to meet the strict radio communication availability requirements necessary to support safety critical applications, at least two radio network layers should be present. These layers can be presented via implementation combinations of private and public networks including 5G SA slicing, depending on the current and future user requirements.