5G Programmable Infrastructure Converging disaggregated network and compUte REsources

D6.3 Final Demo and Testbed experimentation results

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v1.0	Final revision and submission to the EC	Paris Flegkas (**UTH**) Ioanna Mesogiti (**COS**) Anna Tzanakaki (**UNIVBRIS-HPN**) Jesús Gutiérrez (**IHP**)	31/05/2020

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Executive Summary

5G-PICTURE's Work Package 6 (**WP6**) focused on the demonstration and evaluation of the main architectural functionalities and solutions developed in the technical WPs. The demonstration activities were carried out following a set of planned use cases (UCs) that took place in the different project demo sites including: a Rail deployment in Barcelona in the railway lines of FGC, the smart city 5GUK testbed in Bristol, and a Stadium in Bristol.

This deliverable reports on the details of the integration and demonstration results stemming from the three UCs under consideration. Details on the available commercial components installed at the sites, together with the 5G-PICTURE components leveraged in the demonstration activities are included. Finally, this deliverable presents the results collected from validation experiments performed using the setups of the demo sites.

In addition to the three main 5G-PICTURE demonstration activities, this document reports on some specific lab demonstrations including the Massive MIMO demonstration and a demo on precise synchronisation through a multi-technology transport network.

Railway

5G-PICTURE focused on the demonstration of an optional multitenant 5G network model for FRMCS (Future Railway Mobile Communication System), focusing on performance and business services. A high performance network model based on moving Wireless Access nodes located inside trains connected to track via different vehicle to infrastructure (V2I) technology options has been trialled (see Section 3 for more details). More concretely, the 5G-PICTURE railway trial leverages millimetre wave (mmWave) technology developed and integrated in the 5G-PICTURE project to provide V2I connectivity. A network inside the train is connected to the track via electronic self-directed beams (from track and train antennas). Selected trackside stanchions are fitted with forward and rearward-facing antennas. The train head and train tail are also fitted with forward and rearward-facing antennas. The wireless session continuity of this solution is controlled by a Mobility Server, also designed, developed and integrated during the 5G-PICTURE Project. The wireless infrastructure at the track is connected to the core railways or operator network via a low-cost optical G.metro network, designed, developed and integrated during the project. The mmWave RAN combined with the G.metro / 100GE infrastructure constitute a low-cost solution to provide 1Gb connectivity to a moving train, with less than 2 ms end-to-end (E2E) latency and precision timing synch support. All in all, 5G-PICTURE has demonstrated a low cost high performing multiservice network to facilitate 5G deployment in railways.

Smart City

The 5G-PICTURE data plane considers a set of highly configurable wired/wireless infrastructures and interfaces, integrated in a single transport solution for smart city UC demonstration at the Millennium Square in city of Bristol (see Section 4 for more details). At the wired transport segment, 5G-PICTURE adopts a hybrid network solution deploying passive and high capacity elastic optical networks. At the wireless transport segments, 5G-PICTURE combines mmWave technologies operating at 60 GHz unlicensed frequency along with other unlicensed and licensed Sub-6 GHz bands. The transport network technologies considered for this 5G-PICTURE demonstration have different characteristics, including rates of operation spanning from few kbit/s up to several Gbit/s, and adopt a wide range of protocols and technology solutions. The smart city demonstration also deployed a high-speed programmable multi-Protocol/PHY interfaces to enable mapping of traffic across infrastructure domains, using state-of-the-art Field Programmable Gate Arrays (FPGAs) hardware to perform a wide range of functionalities including traffic adaptation, protocol mapping and other functions to aggregate and disperse different transport and transmission protocols. At the access network segment, massive MIMO (mMIMO) components were deployed along with 5G NR network nodes (eNB/gNBs) and high-speed Wi-Fi Access Points – all connected to their associated core network parts located at the University of Bristol (UNIVBRIS) –

showcasing the multi-tenancy capabilities (among others) of the 5G-PICTURE transport network deployment

Stadium

The Stadium demonstration section (Section 5) focuses on augmenting the production network of an existing infrastructure deployed at the Ashton Gate Stadium, Bristol UK. This stadium features already an internal high speed, Software Defined Network (SDN) provided by Zeetta Networks. The network supports a number of services for the Stadium's internal IT requirements plus public Wi-Fi for match days and events. The goal of 5G-PICTURE is to turn this network into a 5G network comprising multiple infrastructure and network domains, with the implementation of the 5G OS architecture developed in 5G-PICTURE's WP5 in a complex production network environment. Together with this, a set of network components and functionalities developed by and delivered from 5G-PICTURE partners (access nodes, transport nodes and compute nodes) have been deployed for running the UC.

The demonstration focuses on addressing the following 5G themes for the mega-event/stadium vertical:

- Application aware, programmable network over heterogeneous hardware.
- Differentiated treatment of the application traffic using slices.
- Service resilience using slices in a multi-connectivity link scenario for Wi-Fi and high capacity wireless access technologies, such as Massive MIMO.

A real-time, crowd-sourced video production application called Watchity was used for testing the UC. Watchity comprises an application for capturing and uploading video/audio from an end user device and a cloud hosted video production platform, which in our case, ran on Amazon Web Services. The demonstration successfully showed that how the 5G-PICTURE intelligent network autonomously detected and prioritised video traffic in order to maintain QoE.

1. Introduction

The 5G-PICTURE Work Package 6 (**WP6**) focuses on the demonstration and performance evaluation of the main architectural functionalities and features described in detail in the technical WPs. It also reports on the demonstration activities of the project with the aim to assess the implementation of the 5G-PICTURE solutions in support of use cases (UCs) that rely on 5G networks.

The three main 5G-PICTURE UCs, reported in deliverables D6.1 [1] and D6.2 [3], have been implemented in the following demonstration sites:

- a 5G railway experimental testbed showcasing seamless service provisioning and mobility management in high-speed moving environments,
- a stadium with ultra-high user density, supporting media services, and
- a smart city environment available in the 5GUK testbed in Bristol, UK.

The first deliverable of WP6 (D6.1) reported on the definition and planning of the UCs to be demonstrated in the three demonstration sites mentioned above. The UCs were specified in terms of new equipment to be deployed in the current infrastructures, test scenarios and services to be executed, and a detailed time plan until the end of the project when the final demonstrations take place.

Deliverable D6.2 reported the initial demo site setup and validation tests of the demonstration activities of 5G-PICTURE. More specifically, results from testbed experiments and initial deployment of equipment in the project demo sites are described, including also updates on the planning and test scenarios for all major demos. The deployment and results from testbed validation and integration tests of the Railway use case were reported with all the technologies involved in the demo. For the Stadium demo, updates on the implementation of the control plane components were described and initial validation from the Watchity crowdsource media application and wireless access technologies were reported. In the context of the smart city related demos to take place in the 5GUK testbed in Bristol, updates on the infrastructure and the deployment of 5G-PICTURE technologies were presented with a detailed description of the scenarios and end-user applications to be used. Initial validation results are also included from the Massive MIMO antenna to be deployed.

This deliverable (deliverable D6.3) delves into the final details of the integration activities at the different demo sites, and presents the demonstration results obtained before, during and after the 5G-PICTURE final demonstration week held in March 2020. Details on the available commercial components installed at the sites, together with the 5G-PICTURE components leveraged in the demonstration activities are also included. Finally, a detailed set of results associated to the Key Performance Indicators (KPIs) of interest per site are included. Moreover, additional results of individual demonstration activities are reported.

1.1 Organization of the document

This deliverable is structured in six (6) main sections.

Following the introduction section, Section 2 provides an overview of the 5G networks and services and the relation between the 5G target KPIs and the 5G-PICTURE KPI evaluation framework and results.

Section 3 focuses on the Rail UC that was trialled in Barcelona in November 2019, providing in full detail the deployment and the obtained results and a thorough analysis of the outcomes of the demo.

Section 4 presents the demonstration activities that were carried out in the context of the smart city demos that took place in the 5GUK testbed in Bristol in March 2020. A detailed description of the infrastructure and the analysis of the achieved results are included. Initial validation results are also included from the Massive MIMO system deployed at the University of Bristol (CSN Group) lab.

Section 5 focuses on the stadium UC in Bristol. The 5G-PICTURE implementation leveraging Zeetta's existing SDN infrastructure, and accommodating a number of additional network components / functions

/ domains to be orchestrated by the 5G OS, is presented in detail. In addition, the final demonstration and validation results from the Watchity crowdsource media application are reported.

Section 6 provides details on the individual demonstration activities captured in this document.

A summary and the main conclusions of the deliverable are captured in Section 7. Finally, additional details that complement the text included in the body of the document are reported in the Annexes (Section 10).

2. Evaluation Framework and KPIs Overview

The initial 5G-PICTURE experimentation plan comprising the tests to be executed and the KPIs to be assessed for the evaluation of the 5G-PICTURE solutions for the three main vertical UCs has been provided in deliverable D6.1 [1].

The complete evaluation framework of 5G-PICTURE includes, on one hand, the architectural and deployment options analysis for the assessment of specific aspects/factors of the 5G-PICTURE solutions (included in [2]). On the other hand, it includes the experimentation at the demonstration sites of the project that are directly linked with the three main vertical UCs, namely: 1) the Railway UC, 2) the Smart City UC and 3) the Stadium UC. The vertical demonstrators' testbed setup and initial validation results have been reported in deliverable D6.2 [3].

It should be noted that the individual test sites correspond to different vertical UCs, with varying requirements, operational environments, deployment capabilities, services to be delivered, etc. Therefore, the deployed 5G-PICTURE solution at each of these sites comprised different components / features / capabilities under the generic umbrella of the 5G-PICTURE architecture focusing on the specific technology aspects relevant to the solution under consideration and the associated KPIs. These KPIs have been defined based on relevant work published by Standardisation bodies, 5G-PPP and the 5G-PICTURE project and verticals' specificities.

2.1 Overview of 5G Network and Services KPIs

During the last years, standardization bodies such as 3GPP, ETSI and ITU, as well as industry alliances and regulatory bodies have focused on the definition of the application and networks services [12] and the required Quality of Service (QoS) to be delivered by 5G network deployments [13]. The work of these bodies has also led to the definition of the various KPIs and target values to assess the 5G infrastructure (user and network equipment capabilities) and network deployments ([6],[7],[8],[9],[10],[11]). An overview of this work has been provided in 5G-PICTURE deliverable D2.3 [2], and has been used as a basis for the identification of specific, measurable, KPIs that can be used for the evaluation of the 5G-PICTURE solutions. A discussion focusing on the alignment of 5G PICTURE performance analysis and standard defined KPIs follows.

In particular, ITU initially defined the general capabilities and targets (KPIs) of future IMT-2020 deployments [12] as follows: Peak Data Rate of 20 Gbit/s, User Data Rate of 100 Mbit/s, Mobility of up to 500 km/h, Area Traffic Capacity of 10 Mbit/s/m^2, Connection Density of 10^8 devices/km^2, Latency of <1 ms, Network energy Efficiency 100x and Spectrum Efficiency 3x that of IMT-Advanced.

Further Vertical applications to be served by 5G networks have been identified by various bodies (e.g. NGMN, 3GPP) along with a number of Service Classes (by 3GPP and ITU-T), including: enhanced Mobile BroadBand (eMBB), massive/enhanced Machine Type Communications (m/eMTC) and Ultra Reliability Low Latency Communications (URLLC). For these service classes the critical network service-related KPIs and the target values to be achieved by 5G equipment and network deployments have been identified by 3GPP ([6],[7],[8],[9],[10],[11]). Indicatively the eMBB Service Class is associated with data rate -critical services like video streaming, video conferencing and virtual reality, requiring user data rates of even 100Mbit/s, as well as high traffic density of even 3.75 Mbit/s DL/m^2 and 7.5 Mbit/s/m^2 UL (e.g. for Crowdsourced video the requirement is >10,000 users/km^2), and high mobility in case of services provided on-board vehicles. The m/eMTC Service Class is associated with device density-critical services like *massive IoT* deployments (e.g. metering sensors) and *enhanced MTC* deployments (e.g. automotive sensors). Finally, URLLC Service Class is associated with reliability and latency-critical services like "mission critical" communications in industry automation, medical application, etc., requiring latencies of even below 1ms in control plane and below 10 ms in data plane.

At the same time, in the context of 5G-PPP activities, the infrastructure and services' KPIs defined by standardization bodies and industry alliances have been compiled, resulting in high-level, operational 5G network deployment KPIs [14], [16].

Combining ITU and 3GPPs targets/KPIs it is obvious that there are KPIs depending highly on network equipment capabilities such as: aggregate and per user data rates (on UE and Access Network nodes' supported data rates), high mobility (on network equipment capability to mitigate Doppler and high bit error rate (BER) effects), and there are KPIs that are related to the network architecture and deployment options such as broad coverage, service availability, etc., or other KPIs that are both equipment and deployment dependent such as Packet/Frame Loss, Traffic Density, Jitter, OPEX minimisation, Energy Efficiency etc.

At the same time, the initially defined KPIs became gradually overloaded with definitions tailored to specific services, deployments, test purposes, etc. thus with no correspondence to the defined target values. For the purposes of assessing 5G network equipment/architectural solutions/deployments based on common/harmonised KPIs a parallel 5G-PPP WG exercise led to further decomposition and definition of the Latency and Service Deployment Time performance KPIs [15]. This work has also been used as reference for the definition and evaluation of the associated 5G-PICTURE KPIs.

Latency

In particular, as already mentioned in [2] towards having a common reference for assessing the generic latency KPI, given the fact that latency depends on equipment as well as application and network deployment specificities, the E2E latency has been decomposed into the following network segment-specific latency contributions (see Figure 2-1).

Service Deployment Time

Similarly, as already mentioned in [2], the generic "Service Deployment Time" KPI has been decomposed into sub-KPIs referring to the following phases ([15]): Platform Provisioning, Service/Application Onboarding, Service Instantiation/Configuration and Activation, Service Modification and Service Termination, as detailed in [15] and reported in [2]. This was performed in order to have a common reference for assessing the generic "Service Deployment Time" KPI, given that service deployment involves a number of different processes that depend on the nature of the service and the network deployment setup.

It should be noted that besides the service-related KPIs, 5G network technologies/ architecture/ deployments will also address a number of requirements and KPIs identified in the context of 5G-PPP projects. These include multitenancy, interoperability with various technologies, resilience, security, scalability and so on, as already presented in [17].

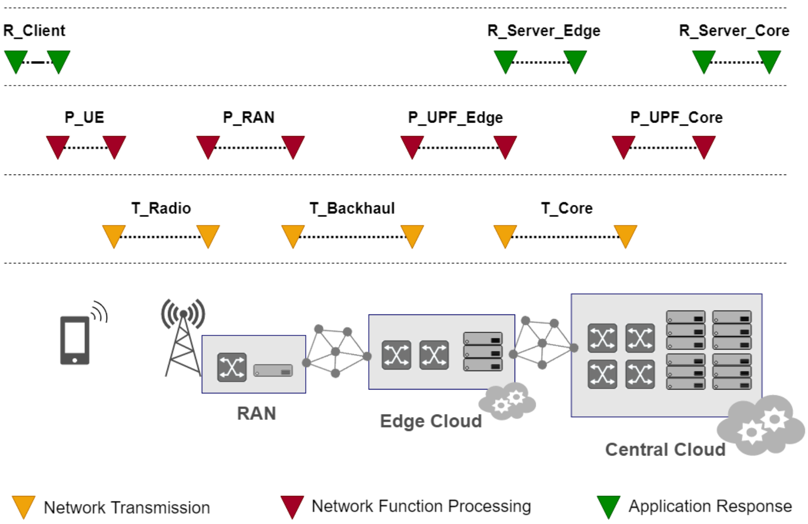


Figure 2-1: Reference framework of delay contributions of an E2E latency ([15])

Table 2-1: KPIs Evaluation through Architecture and Deployment Options' Analysis

KPI	Means of Evaluation
Multitenancy support	Architecture Analysis (D2.3) & Demo
Scalability	Architecture Analysis (D2.3)
Resilience	Architecture Analysis (D2.3)
CAPEX/OPEX efficiency	Techno-economic Analysis (D2.3)
Energy Efficiency	Energy Efficiency Analysis (D2.3)
Reliability	Architecture Analysis (D2.3) – but usually evaluated at operational state
Availability	Architecture Analysis (D2.3) – but usually evaluated at operational state
Co-existence of heterogeneous processing capabilities	(GPPs, GPUs, FPGAs, HW accelerators) through the disaggregated 5G-PICTURE approach – addressed in Architecture Analysis (D2.3)

As mentioned above, this work has been used as basis for the identification of specific, measurable, understandable KPIs for the evaluation of 5G-PICTURE solutions.

2.2 Overview of KPIs Evaluation in 5G PICTURE

2.2.1 KPIs Evaluation through Architecture and Deployment Options' Analysis

Given the versatility of the 5G network and service requirements and KPIs, various evaluation methods have been used for the assessment of different KPIs in the context of 5G-PICTURE. To this end, the KPIs included in ***Table 2-1*** have been evaluated by means of architectural and deployment options analysis, and the results have been reported in detail in [2].

2.3 KPIs Evaluation through 5G-PICTURE Demonstrators

Equipment capabilities and short scale network deployment options have been evaluated in the 5G-PICTURE demonstrators. This was performed on the basis of specific and measurable KPIs as defined by relevant standardisation bodies, 5G-PPP and the specificities of the 5G-PICTURE technology deployed. However, it should be highlighted that the different 5G-PICTURE demonstration activities focused on different vertical industries and associated services having very different requirements, customers/users/stakeholders' profiles and operational environments. As a result, in each demonstrator testing and evaluation activities focused on different KPIs.

In particular, the **Railway demonstrator** focused on the evaluation of the 5G-PICTURE with respect to the he following aspects:

1. Multitenancy and slicing capabilities in terms of transmitting critical, performance and business services -addressing different tenants/service consumers as elaborated in section 3 – over the converged optical – wireless deployment.
2. Capability to achieve the required 5G data rates on board the train.
3. Capability to achieve the required latency for critical communications.
4. Capability to achieve seamless operation at high speeds.

The demonstrator proved the deployment capability to:

- Achieve max. 1 Gbit/s and average 500 Mbit/s (for each direction UL/DL) data rates on train (access network node level rates – depending on distance and geography).
- Achieve average one-way, E2E latency of ~2 ms (4 ms average Round Trip Time (RTT)); with maximum one-way, E2E latency of 4 ms on static train, and of 17 ms on a moving train.
- Allow for seamless service provisioning over high speeds – even speeds of 90 km/h (tested).

The **Smart City demonstrator** focused on the evaluation of 5G-PICTURE solution with regards to the he following aspects:

1. Integration and coexistence of 5G NR and LTE-A network deployed by **UNIVBRIS-HPN**, mmWave transport network deployed by **IHP**, as well as fronthauled/backhauled active mMIMO radio units by Xilinx Dresden (**XDE**), over a single 100 Gbit/s transport network based on **UNIVBRIS-HPN**'s Time-Shared Optical Network (TSON) transport network solution.
2. mMIMO capabilities using **XDE** Active Sub-6 GHz mMIMO radio unit.
3. mmWave mesh backhaul/fronthaul network capabilities.
4. Multitenancy both at radio access and at transport network parts.
5. Using Smart City Safety and Virtual Reality applications deployed at **UNIVBRIS-HPN**'s MEC resources/facilities.

The demonstrator also proved the deployment capability to:

- Achieve 100 Gbit/s over a single optical link using TSON.
- Achieve ~1 Gbit/s over IHPs' mmWave mesh backhaul network.
- Achieve ~180 Mbit/s UL and DL per user data rate, and max.100 Mbit/s with the virtual reality application.
- Achieve average latency between Device and the Cloud Serving node of 26 ms, which is close to the theoretical target of 20 ms for 5G newtroks, and significantly lower than the expected latency of <50 ms for the Smart City Safety application and <35 ms for the Virtual Reality one.
- Below 1 ms average RTT between IHP's mmWave hops – Access Points (APs).
- Fronthaul latency (from Xilinx Dresden Active Sub-6 GHz mMIMO radio unit over TSON to the associated Baseband Unit (BBU)) of ~ 70 μs (200 μs for the first packet).

The **Stadium demonstrator** focused on the evaluation of the following 5G-PICTURE solution aspects:

1. Slicing capabilities, in particular slice instantiation, slice configuration and slice handover (otherwise known as slice re-configuration) over **I2CAT**s' Slicing enabled Wi-Fi controller and nodes and Zeetta Networks (**ZN**)'s Layer 2 Network Slicing for Transport Networks.
2. Co-existence of multiple processing capabilities across multiple technological domains all aggregated by the MDO (Multi-Domain-Orchestrator).
3. SDN capabilities through the ZN's SDN solution for Layer 2 Network Slicing for Transport Networks.
4. Multi Domain Orchestration capabilities through the University of Thessaly (**UTH**)'s multi domain orchestration platform.
5. Multi version VNF instantiation and termination over the University of Paderborn (**UPB**)'s solution on compute sources, as well as UPBs' slice reconfiguration VNF.
6. MEC capabilities (for instance through UPB's VNFs deployment and domain controllers' execution on MEC servers).
7. Using **I2CAT**'s Watchity application for demonstrating application instantiation, auto scaling and termination.

The demonstrator also proved the deployment capability to:

- Achieve 20-25 Mbit/s per user.
- Slice provisioning time below 40 seconds (37.8 s).
- Slice instantiation and reconfiguration (HO) in the order of some seconds – less than 40 s (compared to hours required currently, as they require manual interaction).
- RTT of 40 ms even during the slice reconfiguration (HO) phase.

- Achieve low network service deployment and termination times – below 5-6 seconds for services consisting of 4 VNFs.
    - Service Termination time below 5-6 seconds.
    - Service Deployment time in Compute domain below 5-6 seconds.

Besides these three integrated demos, a number of lab demonstrations was performed for the evaluation of the following:

1. mMIMO capabilities using **UNIVBRIS-CSN** mMIMO equipment, achieving Spectral Efficiency (SE) of max. 15.5 b/s/Hz, and average 8.2 b/s/Hz in UL, which significantly enhances LTE/LTE-A's UL SE of 3.75 b/s/Hz, by a factor of 2x to 4x.
2. **IHP**'s demonstration on the synchronization harmonizer.

The evaluation of the 5G-PICTURE solution on the basis of KPIs through the 5G-PICTURE demonstrator is summarized in ***Table 2-2*** and the results are provided in detail in the following sections of this deliverable.

Table 2-2: Overview of KPIs and Means of Evaluation in 5G-PICTURE

Category	KPIs		Means of Evaluation	Railway Demo	Stadium Demo	Smart City Demo
Telecom Operator - specific	Multitenancy support		Architecture Analysis (D2.3) & Demo	√	√	√
	Co-existence with heterogeneous processing capabilities		Demo		√	
	Scalability		Architecture Analysis (D2.3) & Demo	√	√	√
Network Level - specific	Number of connected devices		Not Demonstrated – Requires large scale deployment			
	Radio Network node capacity		Demo	√		√
	Transport Network capacity		Demo	√		√
	Spectral Efficiency		Demo		√ (mMIMO demo)	
	E2E Latency		Demo	√		√
	Latency	T_RAN Latency	Demo	√ various decomposed results retrieved including various latency contributions over the different backhaul network segments		
		T_Backhaul				√ (over a number of segments)
		T_Core				
		P_UE				
		P_RAN				
		P_UPF_Edge				
		P_UPF_Core				
		R_Client				
		R_Server_Edge				
		R_Server_Core				
Service Level - specific	User data rate		Demo	√	√	√
	Reliability		Architecture Analysis (D2.3) & Demo	√		√
	Availability		Architecture Analysis (D2.3) – but usually evaluated at operational state			

Category	KPIs		Means of Evaluation	Railway Demo	Stadium Demo	Smart City Demo
	Ubiquitous access		Not demonstrated – Requires large scale deployment			
	Mobility		Demo	√		
	Positioning Accuracy		Out of scope of the Project			
	Service Deployment Time					
	Phase 0. Platform Provision	Platform configuration	Out of scope of the Project			
		Platform deployment	Out of scope of the Project			
	Phase 1. Onboarding	Network Slice Template (NEST)	Services and VNFs onboarding has been performed prior to demonstrators but these aspects are out of scope of the Project			
		Network Service Descriptor (NSD)				
		VNF package (VNFD)				
		MEC Application Descriptor (MEC AppD)				
		Other applications				
	Phase 2. Instantiate, Configure & Activate	Instantiate Network Slice (NSI)	Demo		√	
		Instantiate & Activate Network Service (NS)	Demo		√	
		Instantiate & Configure VNFs in service chain (VNF)	Demo		√	
		Instantiate & Configure MEC Application (MEC App)	Demo		√ (VNFs on MEC)	
		Instantiate & Configure other applications	Demo		√	
		Configure other NFVI elements	Out of the scope of the project			
		Configure SDN infrastructure	Demo		√ (meaning service provisioning at Transport domain)	
		Configure Optical WAN	Has been performed prior to demonstrators but these aspects are out of scope of the Project.			

Category	KPIs		Means of Evaluation	Railway Demo	Stadium Demo	Smart City Demo
	Phase 3. Modify	Modify Network Slice configuration	Demo		√	
		Modify Network Service configuration	Out of the scope of the Project			
		Detect scale out/in decision	Demo		√	
		Implement manual scale out/in	Autoscaling has been demonstrated			
		Implement autoscale out/in	Demo		√	
		Modify VNF configuration in service chain	Demo			
		Modify MEC App configuration	Out of the scope of the Project			
		Modify configuration of other applications	Out of the scope of the Project			
		Modify configuration of other NFVI elements	Out of the scope of the Project			
		Modify configuration of SDN infrastructure	Demo		√	
		Modify Optical WAN circuit	Out of the scope of the Project			
	Phase 4. Terminate	Terminate Network Slice (NSI)	Demo		√	
		Terminate Network Service (NS)	Demo		√	
		Terminate VNFs in service chain (VNF)	Demo		√	
		Terminate MEC Application (MEC App)	Demo		√ (VNFs deployed on MEC)	
		Terminate other applications	Demo		√	
		Remove configuration of other NFVI elements	Out of the scope of the Project			
		Remove configuration from SDN infrastructure	Demo		√	
		Terminate Optical WAN circuit	Out of the scope of the Project			

In general terms, the Railway Demonstrator focused on KPIs' related to E2E services and mobility over integrated wireless-optical infrastructure for the support of FRMCS, the stadium demonstrator focused on KPIs' evaluation related to the network softwarisation capabilities focusing on NVF and network services lifecycle across multiple technological domains and MEC, while the smart city demo focused on KPIs' evaluation related with 5G backhaul and fronthaul services, through a real 5G NR network deployment. The detailed results of these demonstrators' along with the evaluation are presented in the following chapters of the deliverable.

3. Railway Demonstration

3.1 Introduction

FRMCS defines three service categories: i) critical, ii) performance and iii) business services. Critical are essential for safety like communication between the operation centre and the cabin, or due to a legal obligation. Critical services are expected to run over critical spectrum and dedicated network. Performance services are those that improve the railway operation like telemetry. Business services are related to services to passenger, like wireless internet. In terms of 5G evolution, performance and business services may run either over dedicated infrastructure from the railways or over a 5G slice leased from a Mobile Network Operator (MNO).

3.1.1 Rail use case. Evolution to 5G

It is unclear that the traditional cellular network model based on cells along the track can efficiently support the evolution towards 5G along main railway paths, since:

- There is low or no traffic from other demands to share the network.
- The traffic demand from the train is instantly high but moving fast between cells, creating many inefficient handovers.
- The higher 5G frequency requires more sites due to higher operational frequency.

5G-PICTURE demonstrated an optional multitenant 5G network model for railways, for performance and business services.

3.1.2 Optional multitenant Network Model

5G-PICTURE demonstrated in the form of a field trial an optional high performance network model based on moving Wireless Access nodes inside trains connected to the track via different vehicle to infrastructure (V2I) technology options (see ***Figure 3-1***). Wireless nodes inside the train can be owned by the train or telco operators. V2I networks can be owned by railway infrastructure administrators or telcos.

This optional network model is a high performance, low cost, multitenant, multi-technology approach to facilitate 5G deployment for railways.

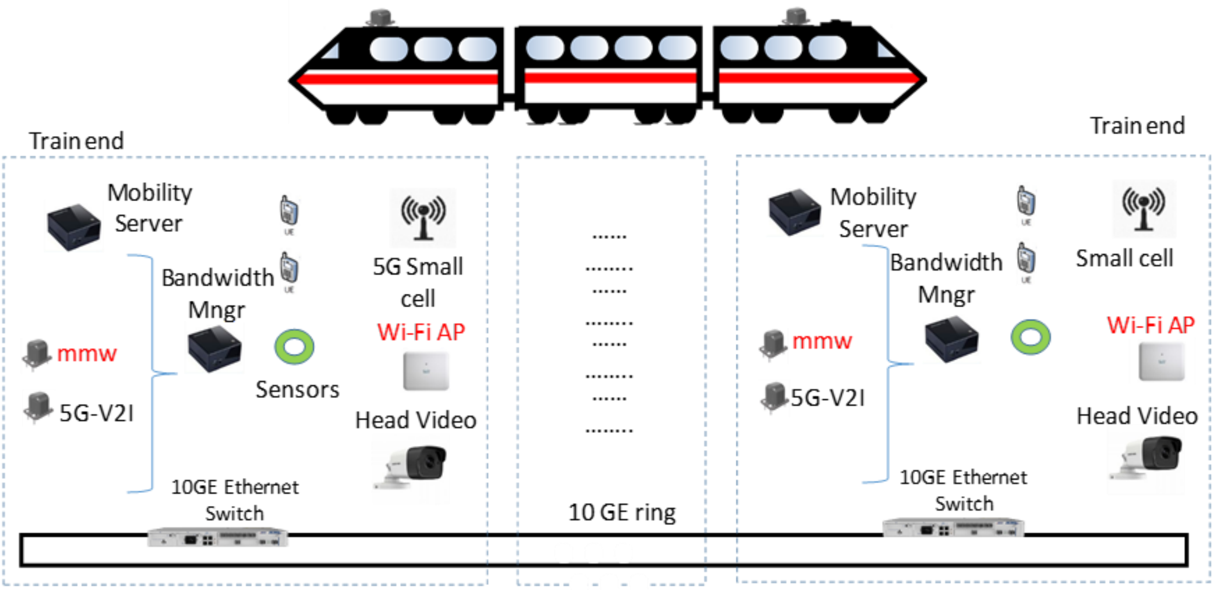


Figure 3-1: Optional Network Model.

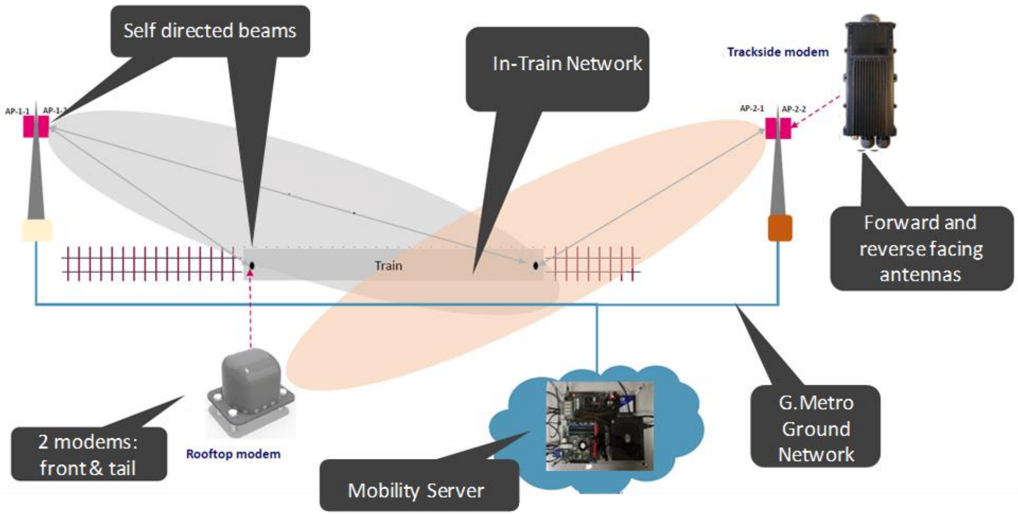


Figure 3-2: High Performance Solution Architecture. MmWave RAN

3.1.3 High Performance Solution Architecture. MmWave RAN

The 5G-PICTURE trial is based on mmWave technology developed and integrated in the 5G-PICTURE project to provide V2I connectivity (see ***Figure 3-2***). A network inside the train is connected to the track via electronic self-directed beams (from track and train antennas). Selected trackside stanchions are fitted with forward and rearward-facing antennas. The train head and train tail are also fitted with forward and rearward-facing antennas.

The wireless session continuity of this solution is controlled by a Mobility Server, also designed, developed and integrated in the framework of the 5G-PICTURE Project.

3.1.4 High Performance Solution Architecture. G.metro and 100G aggregation

The wireless infrastructure on the track described in the previous section is connected to the core railways or operator network via a low-cost optical G.metro network, designed, developed and integrated during the project (see ***Figure 3-3***). This network that can be implemented with full redundancy to support railways stringent safety requirements. Its main characteristics are:

- A network with automatic provisioning of multiple 10 Gbit/s services.
- Based on remote passive nodes, since pluggable lasers are integrated inside the mmWave equipment.
- An outdoor cabinet designed and developed during the project for all non-mmWave components at mmWave trackside sites: G.metro/WDM filters, power switch, patch panel,
- And a 100GE aggregation network to protect and aggregate traffic between mmWave poles and the core network.

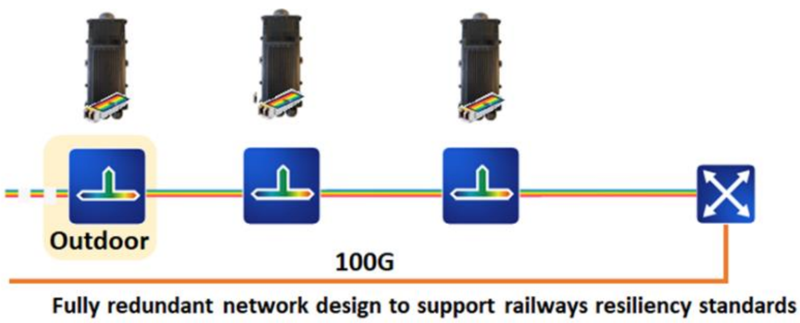


Figure 3-3: High Performance Solution Architecture. G.metro and 100G aggregation

The mmWave RAN combined with the G.metro / 100GE infrastructure provide a low-cost solution to offer 1Gb to a moving train, with less than 1ms end to end latency and precision timing synch support. It represents a low cost high performing multiservice network to facilitate 5G deployment in railways.

3.2 Existing Infrastructures in FGC

Ferrocarrils de la Generalitat de Catalunya (**FGC**) is a public railway undertaking (operator and railway administrator). FGC was established in 1979 to operate and maintain historical railway lines with their origins in middle of XIX century. During past years new lines have been added to FGC and historical ones have been improved in terms of operation and infrastructure in line with current operative mode.

FGC operates and maintains different lines: for passengers, with mixed traffic freight and passengers, and tourist lines with rack railways and funiculars. Each of these systems has their own requirements in terms of communication and supporting services. The details provided in this deliverable refer to Barcelona – Vallès passengers' line. This line has 66.3 million passengers annually (2019 figure) with regional, commuter and metro services for Barcelona and surrounding areas. This line has 50 km of double track with 37 stations, the newest were opened in 2017 and the eldest with their origins in the middle of XIX century. It is operated with 46 train units, with a minimum frequency of 112' and a maximum speed of 90 km/h.

Regarding the communications and supporting services to the operation that currently are in FGC they are divided in two main groups as depicted in ***Figure 3-4***, critical communications coloured in orange and non-critical communications coloured in green. Following the FRMCS classification related to the use of the communication and supporting services, critical communications are those that are essential for train movements and safety or are a legal obligation, non-critical communications are divided into ones related to the improvement of the operation performance and into other businesses to passengers.

FRMCS is a UIC project to work towards the development of the successor of GSM-R (predicted to be obsolete by 2030). FRMCS User Requirements Specification document from January 2019 is one of the first steps in this process, where the railways' needs are identified and defined in a consistent and technology independent way.

In this deliverable the definitions and characteristics of the different communication and supporting services that define FRMCS are used in the introduction to each communication, subsequently the general definitions are contextualized by the systems used in FGC to cover the communications needs.

FGC classification of the current communications and supporting services is schematically depicted in ***Figure 3-4*** and summarized in ***Table 3-1***.

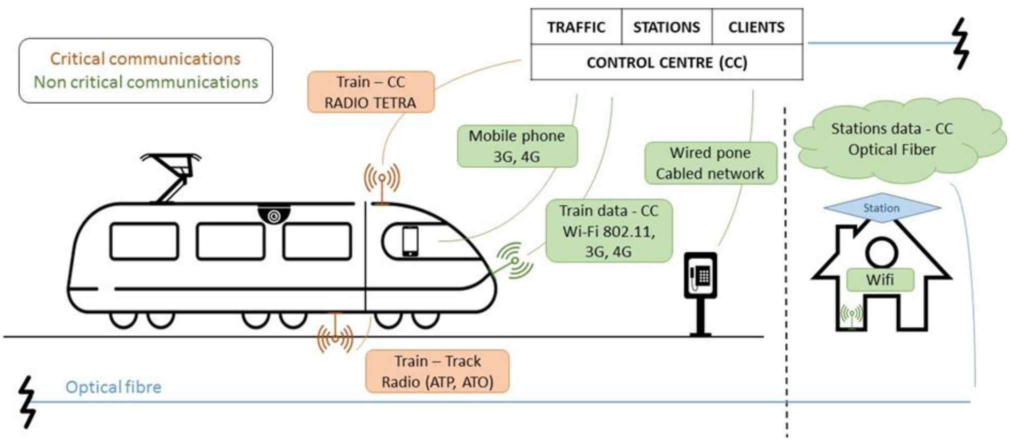


Figure 3-4: FGC communication and supporting services current operative mode

Table 3-1: FGC communication and supporting services current operative mode

CLASSIFICATION	APPLICATION	COMMUNICATION NETWORK
CRITICAL	Train - Control Centre	Radio TETRA
	Train - Track	Radio (ATP - ATO)
NON – CRITICAL PERFORMANCE	Mobile phone	3G, 4G
	Wired phones	Cabled Network
	Train data	Wi-Fi 802.11 and 3G, 4G
	Stations data	Optical Fiber

Table 3-2: FRMS Attributes for Train – Track communication

TYPE OF COMMUNICATION	SYMETRY UP/DOWN RATIO	DISTRIBUTION	LATENCY	BANDWITH DATA TRANSFER.	RELIABILITY	SETUP. TIME FOR STABLISH	SPEED OF THE USER
Bi-Directional voice. User to user.	50/50. Bi-directional.	User to User. Between to users human or system.	Normal. No explicit requirement.	High.	High.	Normal.	Low. Les 40 km/h.
Uni-Directional voice. “Broadcast” communication.	100/0. Uni-directional.	Multi-user. Between group of users human or system.	Low. Immediate.	Medium.	Normal.	Immediate.	Normal. Between 40 and 250 km/h.
Bi-directional data. Sending and receiving data.	80/20. Internet use.	N/A.	N/A.	Low.			High between 250 and 500 km/h.
Uni-directional data. Sending or receiving data.	N/A. air interface do not used.			N/A.			

The ***Table 3-2*** above summarizes the FRMCS definitions for communication between the train and the Control Centre in both directions, this is that the driver shall be able to initiate a communication to any controller that was, is or will be responsible for the movement of the train. And from the other side, an authorized controller shall be able to set up a voice communication to a driver.

The communication attributes the FRMCS defines for Train to Control Centre communication are highlighted in black in ***Table 3-2***.

This communication is provided using Trans European Trunked Radio (TETRA) system, which includes the necessary infrastructure and equipment to stablish voice and data communication between FGC Operation Control Centre (OCC) and the on-board equipment of FGC trains.

This technology is a standard defined by the European Telecommunications Standards Institute (ETSI) in the 90 s aimed at critical communications, related to the public security and air and railway sectors as it provides robust and safe communications.

Standards that define the TETRA system are listed below:

- ETSI EN-300-392, part 1 – 18, Terrestrial Trunked Radio (TETRA); Voice plus Data (V+D).
- ETSI EN-300-394, Terrestrial Trunked Radio (TETRA); Conformance Testing.
- ETSI EN-300-395, Terrestrial Trunked Radio (TETRA); Speech codec.

- ETSI EN-300-396, part 1 – 10, Terrestrial Trunked Radio (TETRA); Direct Mode Operation (DMO).
- ETSI EN-101-021, part 1 – 8, Terrestrial Trunked Radio (TETRA), User requirements specifications.

TETRA system provides mobile communications of digital radio in the band of 150 to 90 MHz with different sub bands reserved for the different type of users. The architecture of the system is composed by:

- Network equipment composed by the Base Stations (BS) and equipment in charge of amplifying the coverage.
- Control system and network switching.
- Network management with control panel.
- Mobile Stations (MS) composed by the mobile terminals.
- Line Terminal Units (LTU) composed by the radiant system.

○ **Train – Track: Radio (ATP, ATO)**

Table 3-3 summarizes the FRMCS definitions for communication between the train and the track for Automatic Train Control (ATC) and Automatic Train Operation (ATO). These systems require a reliable communication bearer in order to ensure efficient data transfer between the on-board system and the ground system, or between a train and other trains or between a train and other trackside elements.

The communication attributes the FRMCS establishes for Train-to-Track communication highlighted in black in **Table 3-3**.

The different equipment that compose the ATP and ATO systems use codes based on radio transmissions with information on velocity and position of the trains.

Specifically, the radio signals through which the codes are transmitted are composed by an audio frequency carrier current and a low frequency modulation FSK. The signals are transmitted to the rails by Transmitters (Tx) placed in the interlocking.

***Table 3-3:* FRMCS Attributes for Train – Track communication**

TYPE OF COMMUNICATION	SYMETRY UP/DOWN RATIO	DISTRIBUTION	LATENCY	BANDWITH DATA TRANSFER.	RELIABILITY	SETUP. TIME FOR STABLISH	SPEED OF THE USER
Bi-Directional voice. User to user.	50/50. Bi-directional.	User to User. Between to users human or system	Normal. No explicit requirement.	High.	High.	Normal.	Low. Les 40 km/h.
Uni-Directional voice. “Broadcast” communication.	100/0. Uni-directional.	Multi-user. Between group of users human or system.	Low. Immediate.	Medium.	Normal.	Immediate.	Normal. Between 40 and 250 km/h.
Bi-directional data. Sending and receiving data.	80/20. Internet use.	N/A.	N/A.	Low.			High between 250 and 500 km/h.
Uni-directional data. Sending or receiving data.	N/A. air interface do not used.			N/A.			

Table 3-4: FRMCS Attributes for Train – Track communication.

TYPE OF COMMUNICATION	SYMETRY UP/DOWN RATIO	DISTRIBUTION	LATENCY	BANDWITH DATA TRANSFER.	RELIABILITY	SETUP. TIME FOR STABLISH	SPEED OF THE USER
Bi-Directional voice. User to user.	50/50. Bi-directional.	User to User. Between to users human or system.	Normal. No explicit requirement.	High.	High.	Normal.	Low. Les 40 km/h.
Uni-Directional voice. “Broadcast” communication.	100/0. Uni-directional.	Multi-user. Between group of users human or system.	Low. Immediate.	Medium.	Normal.	Immediate.	Normal. Between 40 and 250 km/h.
Bi-directional data. Sending and receiving data.	80/20. Internet use.	N/A.	N/A.	Low.			High between 250 and 500 km/h.
Uni-directional data. Sending or receiving data.	N/A. air interface do not used.			N/A.			

The ATP system has eight different types of transmitters, each of them with a different nominal carrier frequency. The different frequencies are applied in sequences such as one ATP loop never has the same carrier frequency than the collaterals ones and the opposite track ones. The nominal carrier frequencies are: f1 4080 Hz, f2 4320 Hz, f3 4560 Hz, f4 4800 Hz, f5 5040 Hz, f6 5280 Hz, f7 5520 Hz, and one for reserve f9 6000 Hz. The carrier frequencies are modulated FSK through 1 and 14 modulation frequencies between 20 Hz and 80 Hz in 4 Hz steps.

The codes are transmitted using the Audio Frequency Track Circuits (AFTC), systems that are not specifically installed for the ATP. The exception is in switches zones where the own functionalities of Audio Frequency Track Circuits (AFTC) are separated from ATP functionalities. In these zones the codes are transmitted through loops installed in the rail web specifically for the ATP system.

The codes are read by an antenna installed in the underside of the train units exclusively for the reading of this codes and its transmission to the rest of the equipment involved in the ATP and ATO systems.

- **Mobile phone: 3G, 4G**

Following the FRMCS purpose and use definitions of this communication need between company personnel, a ground user shall be able to set up voice communication to another ground user. Voice communication is needed between each agent involved in the railway sector.

The attributes that FRMCS establishes for this communication are the following highlighted in black in ***Table 3-4*** above.

This communication between agents (including passengers) placed in stations, control centre, tracks, etc. is provided by mobile phone coverage 3G, 4G provided by all the mobile operators along the whole FGC line including tunnels. To ensure the coverage specific installations from each Mobile Network Operator in Spain are required. The installation required by each MNO require the installation of base stations in FGC stations with their corresponding network of boosters. And there is also necessary the installation of a Radiant Cable along the tunnels of FGC.

- **Wired phone**

Table 3-5 summarizes the FRMCS definitions for communication needed for line side telephony. An agent shall be able to set up a voice communication at certain points along the line, in case that 4G and 3G does not work. The communication attributes the FRMCS defines for this communication are highlighted in black.

Table 3-5: Wired Network attributes

TYPE OF COMMUNICATION	SYMETRY UP/DOWN RATIO	DISTRIBUTION	LATENCY	BANDWITH DATA TRANSFER.	RELIABILITY	SETUP. TIME FOR STABLISH	SPEED OF THE USER
Bi-Directional voice. User to user.	50/50. Bi-directional.	User to User. Between to users human or system.	Normal. No explicit requirement.	High.	High.	Normal.	Stationary
Uni-Directional voice. “Broadcast” communication.	100/0. Uni-directional.	Multi-user. Between group of users human or system.	Low. Immediate.	Medium.	Normal.	Immediate.	Normal. Between 40 and 250 km/h.
Bi-directional data. Sending and receiving data.	80/20. Internet use.	N/A.	N/A.	Low.			High between 250 and 500 km/h.
Uni-directional data. Sending or receiving data.	N/A. air interface do not used.			N/A.			

Table 3-6: FRMCS Attributes for Train data communication

TYPE OF COMMUNICATION	SYMETRY UP/DOWN RATIO	DISTRIBUTION	LATENCY	BANDWITH DATA TRANSFER.	RELIABILITY	SETUP. TIME FOR STABLISH	SPEED OF THE USER
Bi-Directional voice. User to user.	50/50. Bi-directional.	User to User. Between to users human or system.	Normal. No explicit requirement.	High.	High.	Normal.	Low. Les 40 km/h.
Uni-Directional voice. “Broadcast” communication.	100/0. Uni-directional.	Multi-user. Between group of users human or system.	Low. Immediate.	Medium.	Normal.	Immediate.	Normal. Between 40 and 250 km/h.
Bi-directional data. Sending and receiving data.	80/20. Internet use.	N/A.	N/A.	Low.			High between 250 and 500 km/h.
Uni-directional data. Sending or receiving data.	N/A. air interface do not used.			N/A.			

FGC has a legal obligation to provide this communication. The equipment and the installation are composed by a phone copper cable installed alongside the track and at some specific points on the line, specifically where there are switches, a physical phone is connected to this cable. This phone can connect only directly to the control centre.

- **Train data**

Table 3-6 summarizes the FRMCS definitions for train data used to enhance operational performance of the railway system, for example the most common data transmitted from the train to the control centre are video images from the CCTV system installed inside the train. The communication attributes the FRMCS defines for this communication are highlighted in black.

In the FGC train data are transmitted through a specific and dedicated network comprising two different architectures: one for sections of the line in tunnel and the other one for outside sections.

Table 3-7: FRMCS Attributes for Stations data communication

TYPE OF COMMUNICATION	SYMETRY UP/DOWN RATIO	DISTRIBUTION	LATENCY	BANDWITH DATA TRANSFER.	RELIABILITY	SETUP. TIME FOR STABLISH	SPEED OF THE USER
Bi-Directional voice. User to user.	50/50. Bi-directional.	User to User. Between to users human or system.	Normal. No explicit requirement.	High.	High.	Normal.	Low. Les 40 km/h.
Uni-Directional voice. "Broadcast" communication.	100/0. Uni-directional.	Multi-user. Between group of users human or system.	Low. Immediate.	Medium.	Normal.	Immediate.	Normal. Between 40 and 250 km/h.
Bi-directional data. Sending and receiving data.	80/20. Internet use.	N/A.	N/A.	Low.			High between 250 and 500 km/h.
Uni-directional data. Sending or receiving data.	N/A. air interface do not used.			N/A.			

For the sections of the line in tunnel there is a Broadband Radio Communications System, the purpose of which is to provide a local broadband network of for high speed wireless data transmission from the train to the control centre. This network allows to transmit images from the CCTV systems, alarms, failures, diagnosis from the train unit equipment and train unit records, among others.

The communications system consists of the Data Radio Communication System (DRCS), a core Fibre redundant system, a CCTV system and a centralized maintenance system.

The DRCS uses Wi-Fi 802.11a standard for the transmission. The installed equipment includes the Access Points, one installed in each train and several along the track, and the Wi-Fi antennas that are working in the 5.8 GHz frequency.

- **Stations data**

Table 3-7 above summarizes the FRMCS definitions for communication between infrastructure systems and a ground-based system for monitoring and remote controlling of stations, lifts, escalators, etc. In FGC all stations are remotely controlled from the control centre the communication network that supports this is a Scada system and optical fibre.

The communication attributes the FRMCS defines for this communication are highlighted in black.

3.2.1 Existing infrastructures KPIs

3.2.2 Selected KPIs

In this section we report a list of KPIs selected from the complete list of KPIs included in 5G-PICTURE deliverable D2.1 (see ***Table 3-8***). The KPIs have been selected to quantitatively asses the performances of the current railways' communication infrastructure and the performance gain achievable by using the 5G-PICTURE proposed solution.

Table 3-8: KPIs definition

Requirement	Definition	Type of value, unit of measure
latency	**E2E latency**: the time it takes to transfer a given packet from a source to a destination, measured at the network interface, from the moment it is transmitted by the source to the moment it is successfully received at the destination.	ms

BER	The **bit error ratio** (BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval. BER is a unitless performance measure, often expressed as a percentage	Ratio, no units
Data rate (DL/UL data rate)	**Peak** and **average values of data rates** should be provided. The data rate is a time-variable function. It might be important to define some parameters (e.g. peak, burst, average) in order to better describe the data rate	bit/s
Packet delay variation	**Variation in latency** as measured in the variability over time of the packet latency across a network. Packet delay variation is expressed as an **average of the deviation from the network mean latency**	ms
Availability	**Connection availability**: the percentage of available time (w.r.t. total time) in a generic observation period of the connection across the transport network. A bidirectional path or connection is in the unavailable state if either one or both directions are in the unavailable state. **Communication service availability**: percentage value of the amount of time the E2E communication service is delivered according to an agreed QoS, divided by the amount of time the system is expected to deliver the E2E service according to the specification in a specific area.	
Mobility	fixed (no mobility: office, home) or **max speed in movement** (pedestrian or on a transportation mean: train, road vehicle, airplane, drone, …)	km/h
Clock sync accuracy	Accuracy to carry timing signals	ms
Power	The average energy power consumed per km	W / km

3.2.3 Typical KPIs for existing wireless networks in FGC

Table 3-9 includes the typical KPIs for the existing wireless networks in FGC.

Table 3-9: Existing FGC wireless networks KPIs

Subsystem	Data Rate DL/UL Kbit/s	Latency ms	Packet delay variation ms	Packet loss rate	Availability %	Clock synch accuracy ms	Mobility Km/h	Power W/km
TETRA	500[1]	1000[2]	400[2]	5%[2]	99.9999%	N/A	250	N/A
Radio ATP-ATO [4]	100 Kbit/s to 4 Mbit/s	5	1	10^{-3}	99.9999%	N/A	500	N/A
3G-4G	100 Mbit/s	50[3]	10[3]	0.4%	99,99%	N/A	250	N/A
Wi-Fi 802.11a [5,6]	54 Mbit/s	13	2	N/A	99%	N/A	90	N/A

[1] https://www.bakom.admin.ch/dam/bakom/en/dokumente/faktenblatt_tetra.pdf.download.pdf/factsheet.pdf

[2] https://doi.org/10.1007/s11276-009-0196-8

[3] M. Kassim, R. A. Rahman, M. A. A. Aziz, A. Idris and M. I. Yusof, "Performance analysis of VoIP over 3G and 4G LTE network," 2017 International Conference on Electrical, Electronics and System Engineering (ICEESE), Kanazawa, 2017, pp. 37-41.

[4] As indicated in deliverable D2.1

[5] Throughput and latency performance of IEEE 802.11x physical layers. Authors Shah, Vishal; Cooklev, Todor.

[6] Pilot Study Report of Multiple Wi-Fi Vendors' Performance. Wi-Fi alliance.

3.3 5G-PICTURE Demonstrator. Introduction

The system architecture for the railway use case was developed as per 5G-PICTURE deliverable D6.1 “Specification of Vertical Use cases and Experimentation plan” section 4 (Rail Use Case). The demo deployment was carried out in different phases and the final use case scenario was successfully executed in the rail environment in Barcelona. The general network architecture, the deployment of technologies, and demo results are detailed in the following sections. The Track Access Network (TAN) and Train Communication Network (TCN) components and a time plan with the different phases are also described.

A general scheme of all the demo components is shown in ***Figure 3-5***. The figure reflects a track segment East of Olesa de Monserrat station. Four stanchions equipped with mmWave AP’s interconnected with fibre forms a telecommunications infrastructure. This connects to a set of on-board devices mounted on a specific train that passes by this section. Martorell station at the other end of the section (to Olesa de Monserrat) is used to simulate a very simplified OCC (Operations Control Centre).

The remainder of the Railway demonstration section is organized as follows:

- The railway line used in the demo, near Olesa de Monserrat station will be described on section 3.5*, Demo Location*.
- The infrastructure mounted on the train used in the demo is described on section 3.6, *Train Equipment Description*.
- Section 3.7, *Track Equipment description*, describes all the elements that were installed on the track section near Olesa Station.
- Section 3.8 *Stations Equipment Description,* describes the elements to be installed inside Olesa and Martorell stations.
- Successive sections contain some additional information needed to conform the detailed installation project; a low-level design document that was also elaborated from the information contained in this document.

Figure 3-5: Demo Introduction

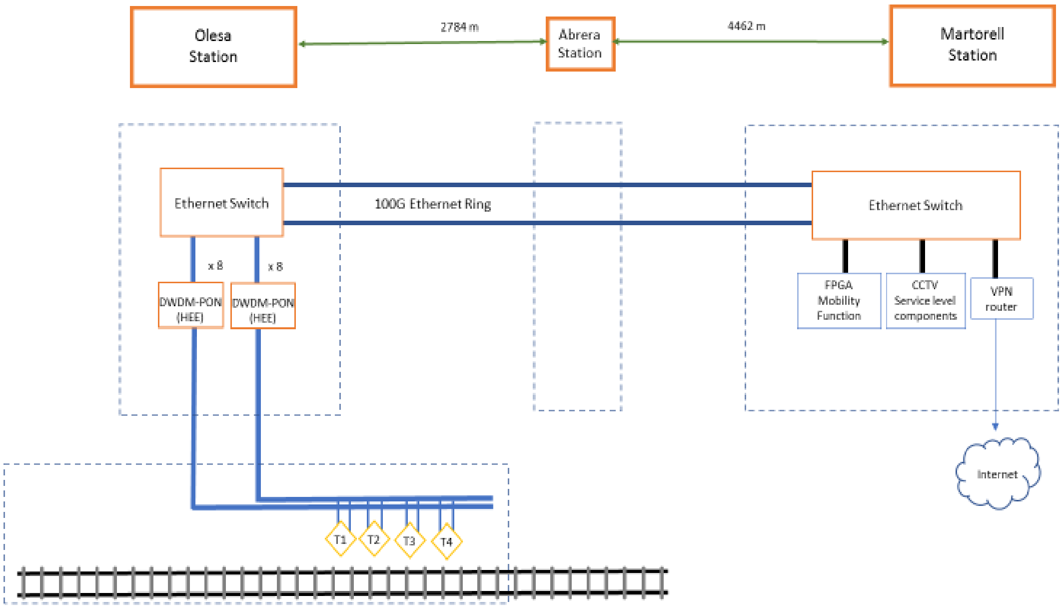


Figure 3-6: Complete demo description

Installation on track had to be executed out of trains' service timetable, from 12:10 to 4:40 AM, this schedule could be modified depending on the day and any eventuallity. Installation on train was done only when the train was out of service.

The demo site comprises approximately 1.5 km of track. The commercial trains speed is over 60 km/h, up to 90 km/h, if the antenna connection is instantaneous this provides two minutes of demo in movement and one-minute static due to the connection in Olesa station. The commercial train including the 5G equipment passes through the section twice per hour. It should be mentioned that there was the option to perform some specific running's during nights through the section when no commercial trains are running.

3.4 Demo objectives

3.4.1 Key objectives

The following objectives were on target for the Railway demonstration:

- To demonstrate the performance of mmWave links (throughput, latency, jitter) based on project KPI's.
- To check the links' behaviour in adverse weather conditions.
- To build the new TAN architecture: mmWave + passive WDM + Ethernet aggregation.
- To demonstrate the TAN can be shared to provide public services for passengers and railway operational services.

TAN components:

- mmWave APs along the track.
- A passive WDM interconnecting the APs with fibre.
- A 100G Ethernet Aggregation Ring to collect the data along a complete track.

TCN components:

- mmWave antennas and modems (duel antenna units front and rear of train).
- ADVA Ethernet Switch.
- Flow Blade.
- A 10G fibre ring along all train.
- Service level equipment (Wi-Fi AP's/CCTV cameras).

3.4.2 Performance tests general description

The railway demo demonstrates the feasibility of having a common telecommunications infrastructure in a railway moving environment to support different services (both critical for operations, and non-critical for the clients/passengers).

The KPIs were measured in two ways:

- Parameters related to TCP transfers between devices connected to the on-board network and a server located at Martorell station.
- Parameters related to the live-recording of CCTV files produced by the images captured by the on-board high definition cameras. Optionally, these images can be displayed in a screen located at Martorell station.

The measured parameters were collected and automatically sent to the Martorell station, where they were automatically stored. In particular, the following parameters were collected for each executed test:

- Min/max/average throughput.
- Min/max/average packet delay and jitter.
- Min/max/average data BER.
- Min/max/average packet loss rate.
- Start time/End time and date.
- Train Direction (Olesa-> Abrera-> Olesa).

Additionally, each TCN/TAN element had the possibility to store additional information about these transfers. The demo plans to use this information for cross-analysis in case there was weather information (collected by the Micro Rain Radar or equivalent information described in Annex D in section 10) to investigate possible correlations with the data.

3.5 Demo Location

3.5.1 Line information

Testing was done in Llobregat – Anoia Line, this Line has a freight historical origin, it was constructed to transport mining products from Súria mines and textile products from the Llobregat and Anoia basins. The first section of this line was constructed in 1893. Due to this origin, it has metric track gauge 1000 mm. Over the years, different passenger and goods lines have been opened In Barcelona and the surrounding areas. Nowadays the line has mixed traffic, passengers and different freight such as cars, car parts or salt. Along the line there are different train services, some metro for Barcelona, some suburban services connecting Barcelona and surrounding areas and some commuter trains which connect more remote areas of Catalonia.

Figure 3-7: Llobregat – Anoia rail line

3.5.2 Martorell Enllaç – Olesa Track Section

The section selected to develop and carry out the 5G-PICTURE railway demonstration is placed between Olesa and Abrera stations. The information sent by the 5G network was sent to Martorell station where the control centre was simulated. The track section characteristics are shown in ***Table 3-10*** and the following figures show parts of the track and the line route.

Table 3-10: Track section characteristics

Characteristics	Open air	
	Curves with big radius	
	Without surrounding obstacles	
Stations	Martorell Enllaç	Pk. 28.696
	Abrera	Pk. 33.158
	Olesa de Montserrat	Pk. 35.942

Figure 3-8: Images from ME-OL.

Figure 3-9: Line route ME-AB.

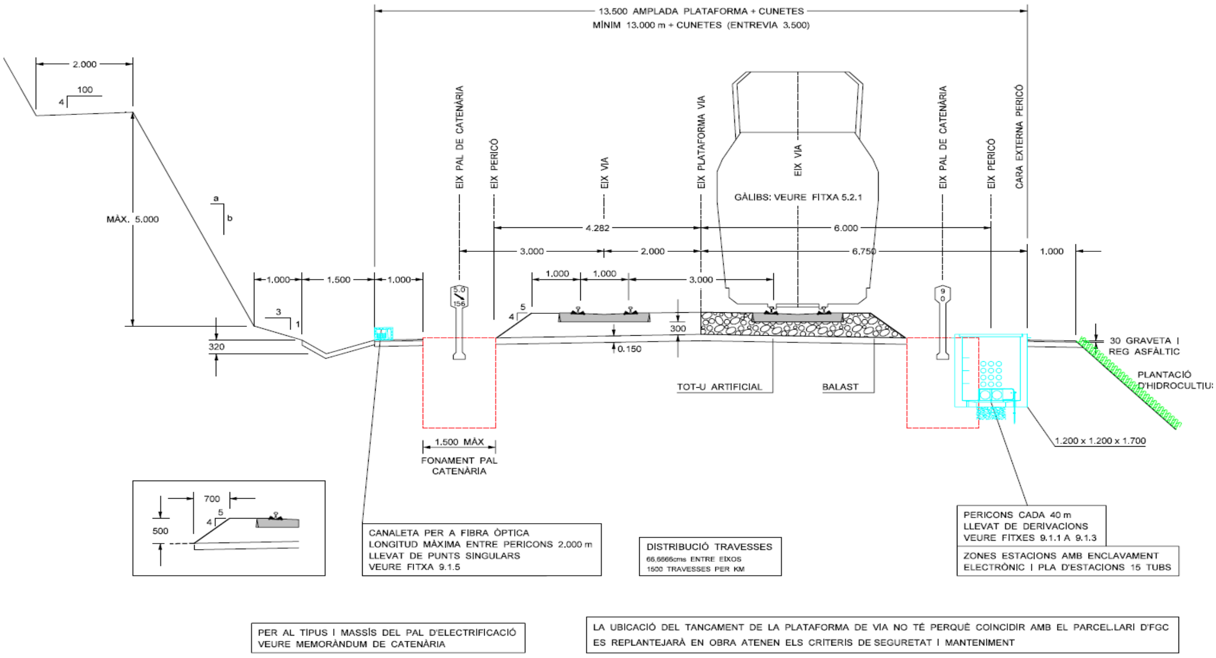


Figure 3-10: Nominal section in open air Llobregat – Anoia line

3.6 Train equipment description

3.6.1 TCN scheme

One FGC train was equipped with a TCN (see ***Figure 3-11***):

- Two on-board dual antenna mmWave units, mounted at the front and rear of the train, with their Host Processor Modules connected to both ends of a 10G Ethernet ring.
- A 10G ring that consists of two Ethernet switches interconnected with fibre; each of them in a different wagon.
- A FlowBlaze node to manage the traffic behaviour inside the train connected to to the 10G ring
- One Wi-Fi AP will be connected to each switch to provide Internet Access
- CCTV cameras will be connected at some points of the TCN (driver point of view).

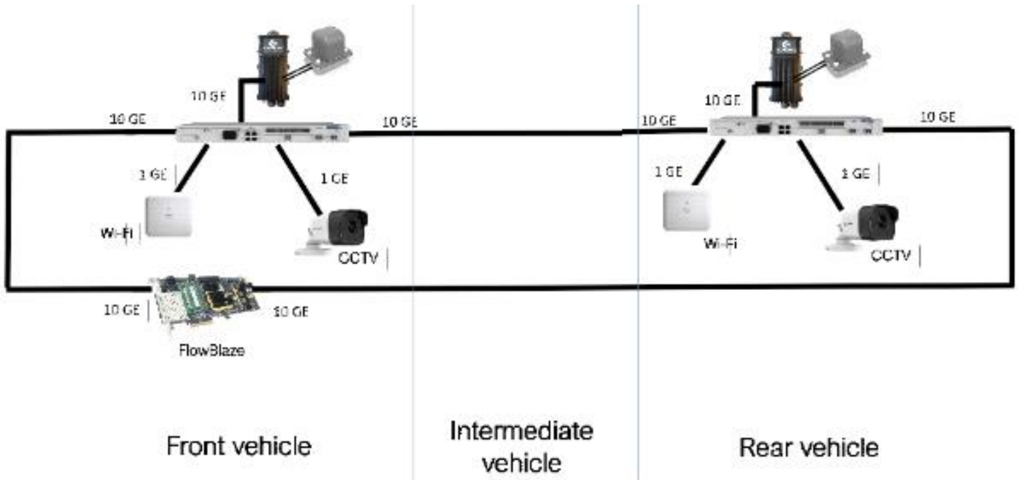


Figure 3-11: Train equipment

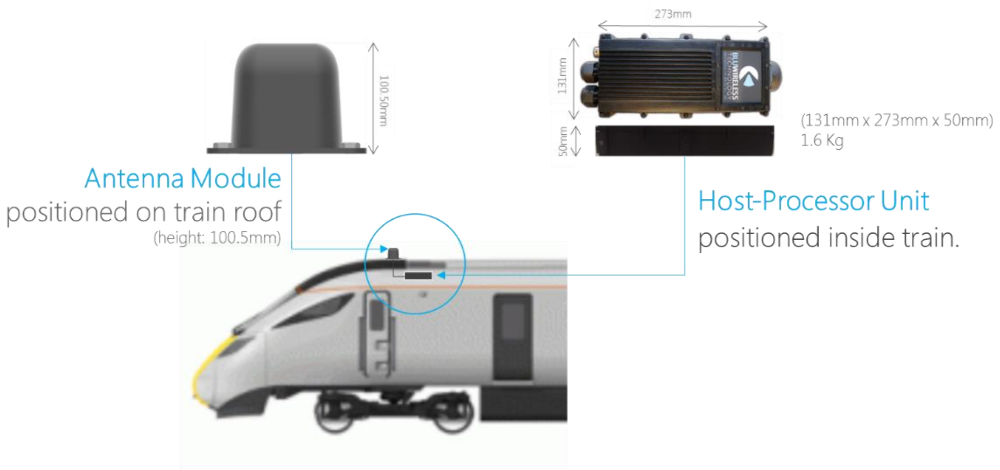


Figure 3-12: Train Unit (TN-201LC) Components

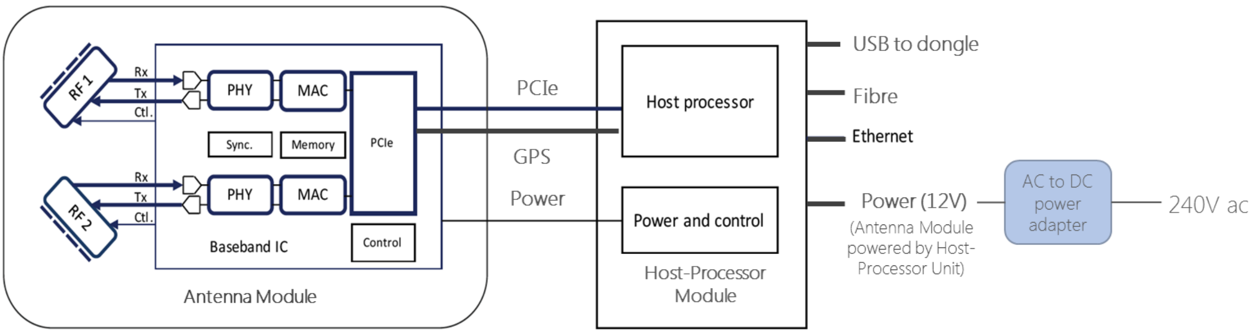


Figure 3-13: Train Unit (TN-201LC) Schematic

The description of additional components of the TCN is included in Annex A.

3.6.2 On-board mmWave Units

One FGC train was equipped with two Blu Wireless train units, one at each end of the train (see ***Figure 3-12***), to maximize mmWave and coverage. For a maximum Line of sight, the train units should sit proud of any other equipment on the train roof.

The Blu Wireless train unit TN-201 LC consists of two components: the Antenna Module fixed to the train roof and the Host Processor Module fixed inside the train (see ***Figure 3-13***). A separate Host Processor Module is required for each Antenna Module. Max distance between the Antenna Module and the Host-Processor Module: 1.75 m (the PCIe cable is 2 m long).

Three separate cables connect the train roof antenna module and the Host Processor module inside the train: PCIe (Control -Plane and User-Plane data), GPS for train position and speed, and power.

In the system it is not necessary to add a GPS antenna. The GPS antenna is integrated in the same Antenna Module and the GPS receiver is integrated in the HPU. Between both there is a coaxial cable with male SMB connector.

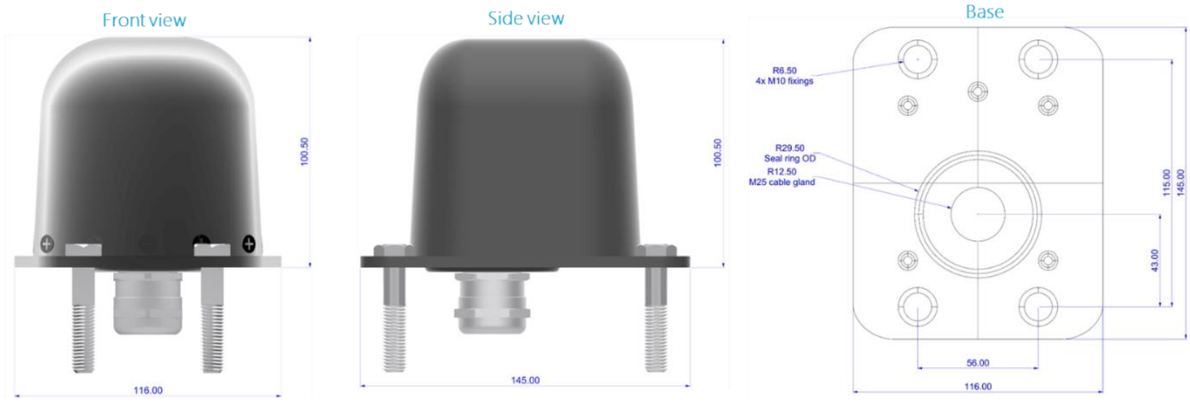


Figure 3-14: Antenna Module (train roof)

Figure 3-15: Host Processor Module (inside train)

3.6.2.1Antenna Module (train roof)

Dual antenna, dual baseband unit for IEEE 802.11-2012 DMG / WiGig at 60GHz.

Connection to Host-processor Module via iPass HD, Power and GPS.

Plastic Radome enclosure with aluminium housing.

Overall height 100.50mm. Weight 530g.

Train mounting screw holes same as Kathrein 741009 train antenna unit.

Powered by Host processor Module.

3.6.2.2Host Processor Module (inside train)

Cavium CN8130 Network Processor.

Supports RJ45, SFP+ for 10Gb copper/fibre, USB 3.0

Aluminium enclosure with adaptor for standard VESA mounting.

Power: 12V DC (Antenna Module powered by Host Processor Module).

3.6.2.3Train Unit (TN-20a1LC) Monitoring

There are three options for monitoring Train Unit (TN-201LC) performance. Initial testing required the tester to access the train and connect to the train units via a network cable (options 1 or 2). Later testing was completed remotely via cellular dongle (option 3).

Option 1: On-board monitoring via network cable to train unit.

Network cable from Host Processor Module to the laptop PC on the train.

Laptop PC only required when tester is on-board the train.

Laptop PC monitors a single train unit at a time.

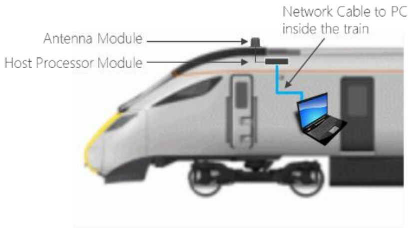


Figure 3-16: On-board monitoring via network cable to train unit.

Option 2: On-board monitoring via train network.

Network cable or fibre from each train unit to single point at the centre of the train.

Laptop PC only required when tester is on-board the train.

Laptop PC monitors both train units simultaneously.

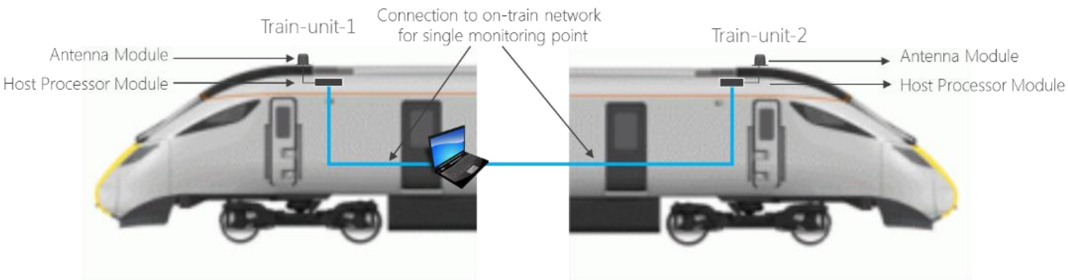


Figure 3-17: On-board monitoring via train network.

Option 3: Remote monitoring via cellular dongle.

Each Host Processor Module connected to a cellular dongle.

Dongle fixed inside the train close to the Host Processor Module.

Dongle position needs to ensure reasonable cellular coverage – preferably close to a window.

Tester does not need to board the train to test.

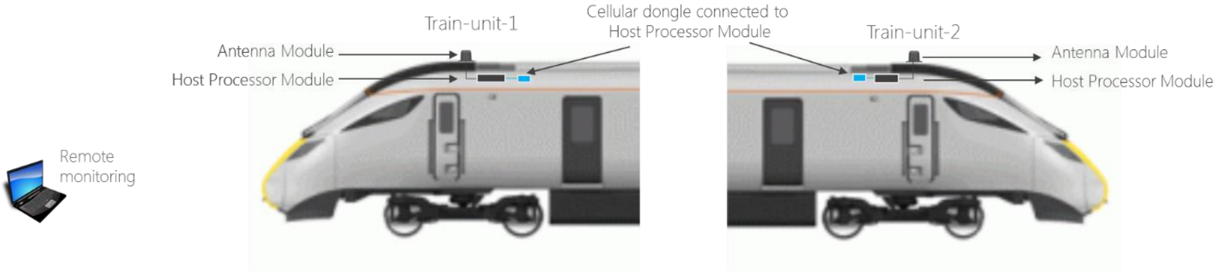


Figure 3-18: Remote monitoring via cellular dongle.

Figure 3-19: LTE antenna to connect the dongle for TN-201LC.

Option 3 required the use of a specific antenna, with a magnetic base inside the train cabin to connect the cellular dongle, as indicated in **Figure 3-19**.

This magnetic base LTE antenna attaches to any metal surface of the cabin so that it has LTE coverage from the outside. Inside the cabin attenuation of about 14 dB was expected. The dongle used had the possibility of connecting external antennas, but there was no issue in ensuring coverage inside the cabin with internal antenna.

Figure 3-20 shows the dongle with three male SMA connectors. Two of them are for LTE communications while the third one is for GPS reception. We only use the first two.

Figure 3-20. Huawei dongle E3372h-607 with external LTE antenna.

3.6.2.4 Train (TN-201LC) Host Processor Installation

The location of the Host-Processor Module was mounted in the roof of the cabin inside the train. ***Figure 3-21*** a) shows this space once the existing door above the cabin has been lowered.

The Host processor Module is powered by a 12V DC power supply (AC-DC adaptor: 240V AC in, 12 V out). Power consumption <50W.

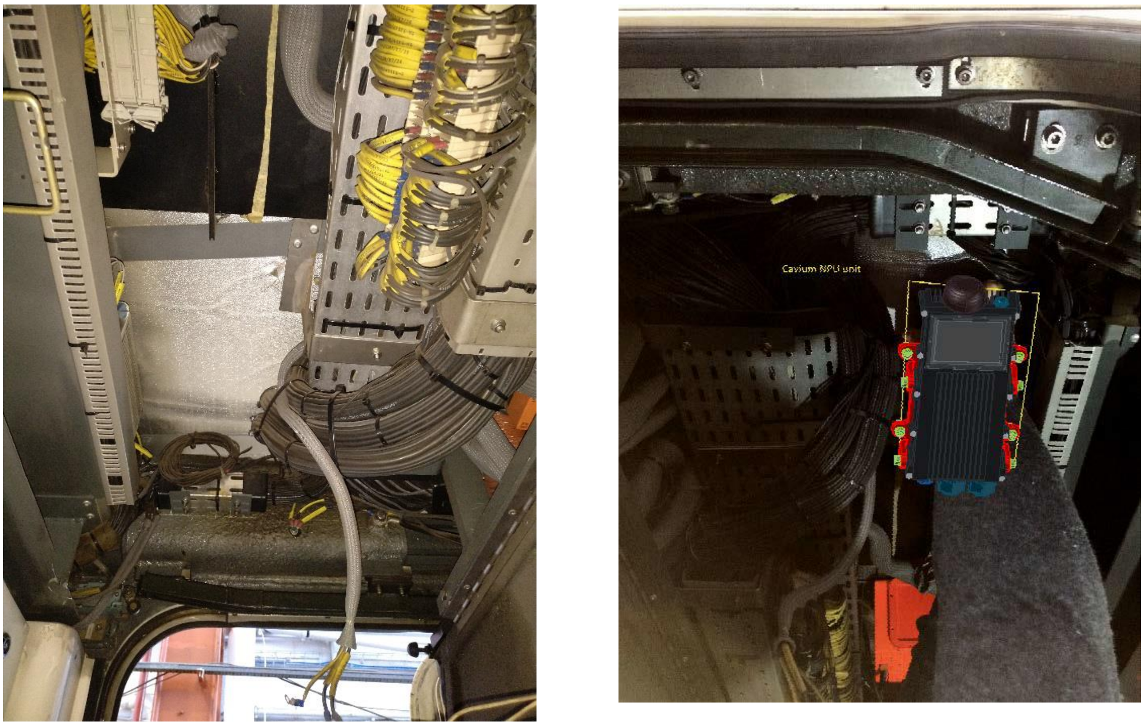


Figure 3-21: a) FGC train roof, b) Assembly of the equipment in the existing space in the cabin of the train

Figure 3-22 shows a design of a support for the Host-Processor Module. There are four screws to fix the equipment to the support. The support is fixed to the roof without screws as FGC required. The support is fixed using a pair of metal flanges to the existing transverse metallic beam in the roof of the train.

A separation was left between the base of the support and the HPU, with the aim of improving the thermal dissipation of the equipment and has a free space to fix the various cables.

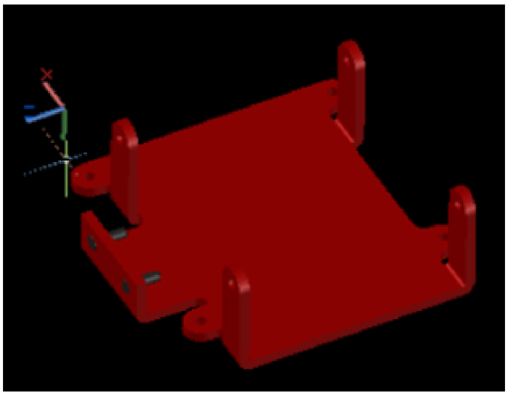


Figure 3-22: View of the special support for fixing for the equipment.

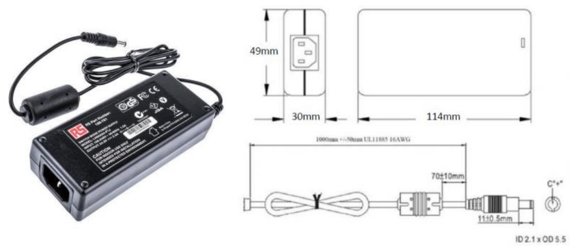
3.6.2.5Other considerations about the Host Processor

The Train Unit (TN-201LC) were fitted without remote power switch capability. The remote power switch would have been independent from the Ethernet cable that connects Blu Wireless computer with the NPU. It was found that this remote switch would have been very useful to avoid local power cycling during the tuning of the system.

Each Train Unit (TN-201LC) was equipped with GPS. This is essential for measuring key performance statistics such as range and speed of train.

During system installation some basic sanity tests were carried-out on the Train Units. This included air interface testing using a temporary mast/tripod situated a few meters from the train units. This required engineers to have access to the train during sanity tests. The electric cable was composed of three conductors of section 1.50 mm^2. Magneto thermic poles were needed in the electrical cabinet.

Figure 3-23 shows the data for the TN-201LC power supply installed inside the train. Note this unit conforms to the following safety standards: UL60950, UL6500, TUV: EN60950, EN60065.



Features:
- 60W external power supply
- Protections: Over voltage, Overload, Short circuit and Over temperature
- Input voltage range: 100 to 240VAC
- No load power consumption: <0.5W
- Fully enclosed plastic case
- LED indicator
- Efficiency: Up to 87%

Model		188-769	732-0272	732-0275	188-781
Output	DC Voltage	12V	15V	18V	24V
	Rated Current	5.0A	4.0A	3.3A	2.5A
	Current Range	0-5.0A	0-4.0A	0-3.3A	0-2.5A
	Rated Power	60W			
Input	Voltage Range	100-240V ac			
	Frequency Range	47-63Hz			
	Efficiency	87%			
Protections	Short Circuit	Auto Recovery			
	Overload	Auto Recovery			
Environment	Working Temperature	0°C - 40°C			
Safety & EMC	Safety Standards	UL60950, UL6500, TUV: EN60950, EN60065 approved			
	EMC Emission	Compliance to EN55013, EN55020, EN55022, EN55024, EN61000-3-2, 3			
Other	Dimensions	114*49*30mm (L*W*H)			
Connector Plug		2.1mm	2.1mm	2.1mm	2.1mm

Figure 3-23: TN-201LC Power Supply Details.

Figure 3-24: Final installation of host processor.

3.6.2.6 Train (TN-201LC) Antenna Module Installation

Antenna module (train roof) was mounted on the shelf shown in **Figure 3-25** at the train roof. The height of the roof is 3.976 mm above the rail head.

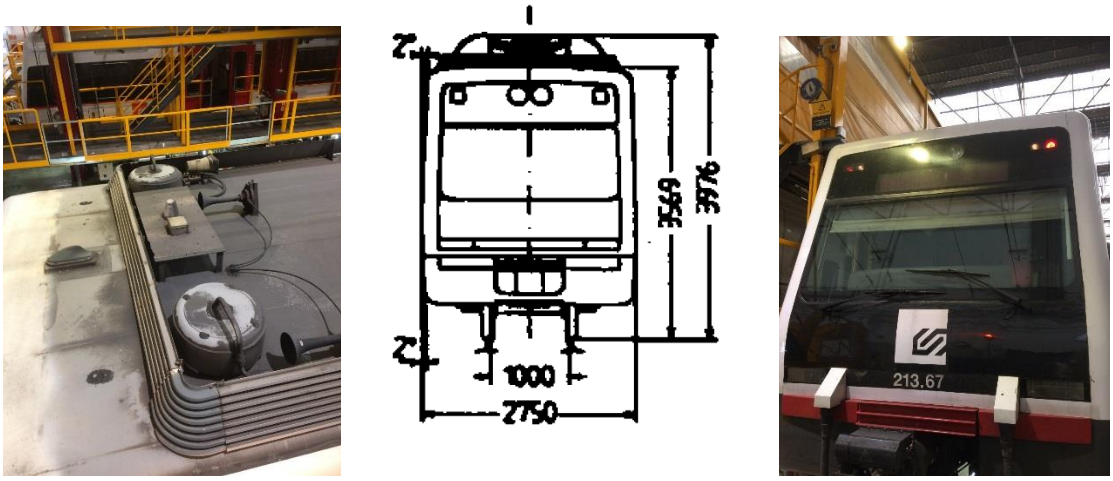


Figure 3-25: Train roof plate.

The installation of the Train Unit (TN-201LC) on the train required screw holes and hole for cabling gland on train roof platform (see below). Cabling tail needs to be threaded through roof hole and connected to the Host processor Module inside the train.

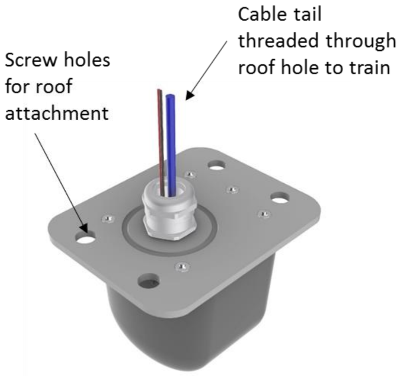


Figure 3-26: Train Unit (TN-201LC) attaching to train.

Figure 3-27: a) View of the Antenna Module of the TN-201LC system, b) View of the existing junction box.

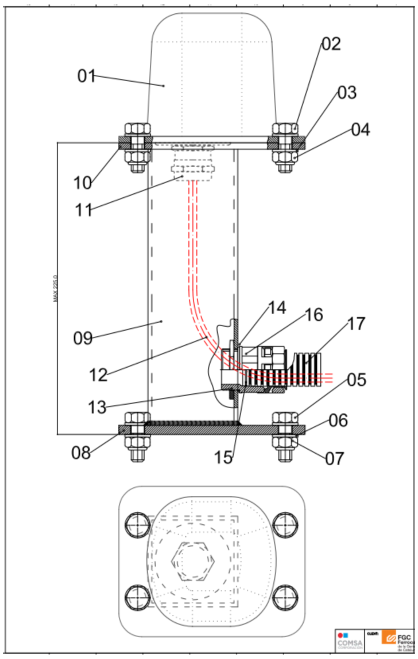


Figure 3-28: Antenna support

Figure 3-29: Final Installation of mmWave antenna on train roof.

As can be seen in **Figure 3-28**, the antenna support is a tubular structure with a base (fixed with four M8 screws) to the ground plane of the TETRA antenna, and a cover to fix the antenna with four screws. The height of the ground plane with respect to the roof of the train is 145 mm.

To comply with the Blu Wireless specifications that the antenna has Line-of-Sight visibility with the track modems located in the two catenary poles, it was necessary to position the antenna above the metal structure of the air conditioning unit.

For the antenna to exceed the air conditioning structure of the train it was necessary that the antenna support had a height of 225 mm (370 mm-145 mm).

The height of the set "ground plane/support/antenna" was 470.5 mm (370 mm + 100.5 mm). This height of 470.5 mm corresponds to the gauge of the 5G radiant system (see the antenna in **Figure 3-29**). This gauge was validated by FGC.

3.6.3 TCN Ethernet Ring

3.6.3.1TCN Ethernet Switch

ADVA provided two 10G Ethernet switches in the train to implement the TCN Ethernet ring. The proposed switch module was the FSP 150-XG116Pro, as shown in ***Figure 3-30***.

The switch chassis is a low-cost, compact, and temperature-hardened 10G programmable (SDN-enabled) demarcation NID with integrated AC and DC power units, consisting of the following components:

- 8 Ethernet sockets that support copper or fiber SFP/SFP+ transceivers.
- 100FX or 1GbE (ports 1-2).
- 1GbE or 10GbE (ports 3-8).
- Local Management LAN RJ-45 Port labeled MGMT LAN on front panel.
- Local Mini-USB Serial Port labeled MGMT on front panel.
- Fan Unit – required for all applications.
- Rack mounting brackets (separately).

The chassis fan module is hot swappable. It is required for operation, and the fan speed adjusts automatically to chassis temperature. It was necessary to avoid obstruction of the chassis air flow vents. The mechanical dimension is: 220mm (w) x 280mm (d) x 43.7mm (h), which can fit into a 300 mm (11.81 in) deep ETSI cabinet.

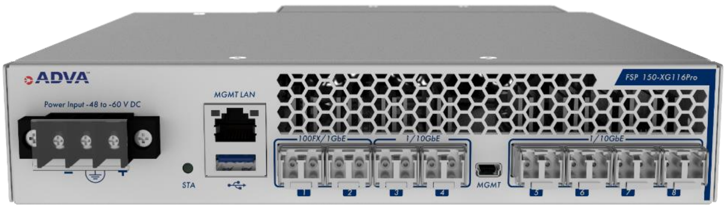


Figure 3-30: 10G Ethernet switch from ADVA

2x 100FX/1GbE ports (Port 1-2):
- 100FX via Optical SFP
- 1000FX via Optical SFP
- 10/100/1000Base-T via CuSFP

4x 1GbE/10GbE ports (Port 3-8):
- 1000FX via Optical SFP
- 10GbE via Optical SFP+
- 10/100/1000Base-T via CuSFP

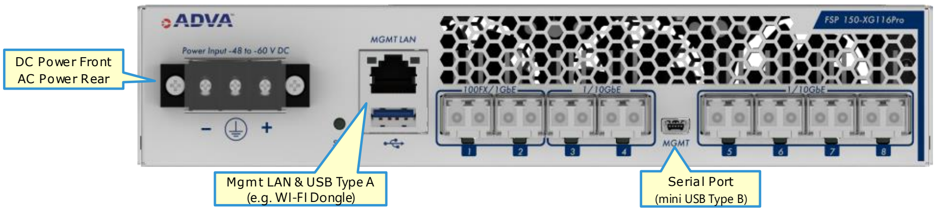


Figure 3-31: Chassis front view of FSP 150-XG116Pro

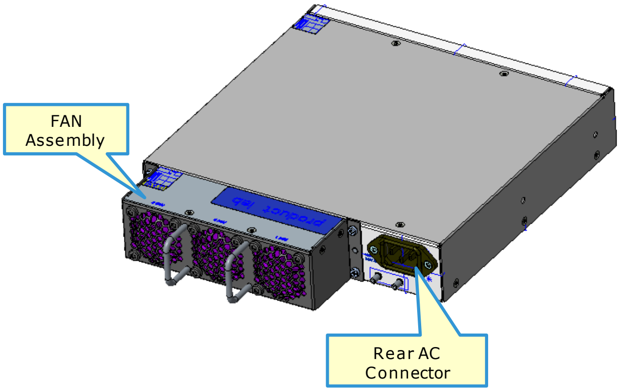


Figure 3-32: Rear view of FSP 150-XG116Pro.

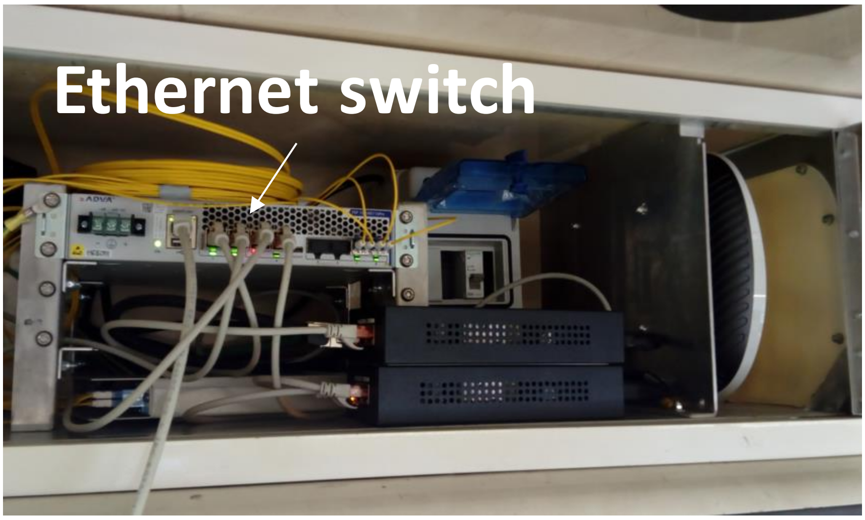


Figure 3-33: Ethernet switch mounted inside train cabinet.

3.6.3.2 TCN Ethernet switch installation

It was necessary to identify a physical space in each front and rear car to install the switch. It was found a U standard rack (Net Box) just behind the driver position inside the space reserved for passengers with enough free space to install the first switch. It was also required to verify that all the necessary cables could be carried to interconnect the switch with the rest of equipment. The chassis was installed finally as a standalone unit.

3.6.4 TCN FlowBlaze

The FlowBlaze node was a prototype using a NetFPGA SUME board, a PCB containing several intergated circuits and a power supply (see **Figure 3-34**). The prototype was hosted in a plexiglass box with dimensions 30x21x9 cm. The prototype required a maximum power of 150W.

Figure 3-34: TCN FlowBlaze Server

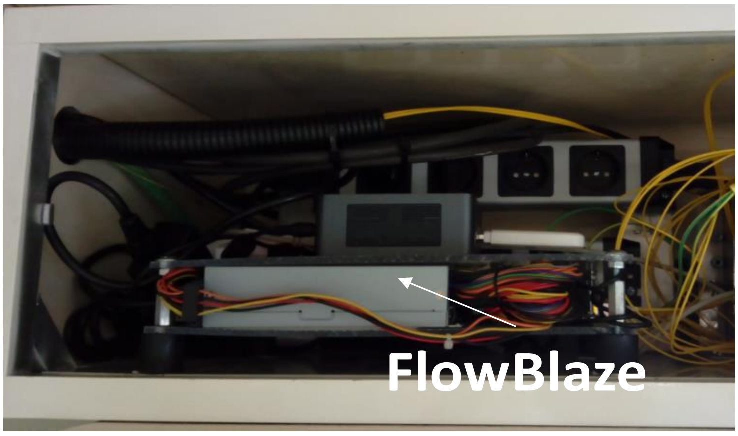


Figure 3-35: Final installation of TCN FlowBlaze Server inside train cabinet

Physically, the FlowBlaze on the train is the same equipment used for the Mobility Server Function in Martorell Station, even though has a different function.

See deliverable D6.1 [1] for a functional description of this component. The redundancy of this element in the demo was avoided for simplicity.

3.6.5 Comments

Intermediate vehicle equipment

A switch situated in the intermediate car was initially considered as an option but was finally discarded. To install a third switch would not add any value to the demo due to the performance of the different services demonstrated. The elimination of this need reduced capital and installation costs and avoided problems due to the lack of space and the need of AC voltage 240VAC inside a passenger's car..

For commercial deployments the inclusion of such a switch in every vehicle could be considered for reliability purposes, Wi-Fi coverage and vehicle homogeneity. However, the inclusion of this switch would have implications on the on-board FlowBlaze and would also introduce some performance implications.

Monitoring dongle

A cellular dongle was attached to the Host processor (in train ceiling) by a 2 m USB cable. The dongle was needed to receive a cellular/LTE signal for monitoring of the train unit. However, the dongle was not finally needed near a window, as the cellular coverage was sufficient. It is expected that final product will have inbuilt monitoring capabilities.

3.7 Track equipment description

3.7.1 TAN components description

TAN components are in several places:

- **mmWave** APs, distributed in some stanchions along the track.
- A **passive WDM** interconnecting the APs with fibre, with equipment distributed along the track and into Martorell and Olesa stations. In this case, both (primary and back-up passive WDM are located only near Olesa, due to the difficulty and the cost to interconnect the back-up passive WDM with Martorell station.
- An **Ethernet** Aggregation Level, exclusively in both stations.
- A **FlowBlaze** in Martorell station, to provide the Mobility NVF.

This section contains the information related with TAN trackside components.

The TAN will be deployed using ADVA's passive WDM technology. ***Figure 3-37*** illustrates the proposed system setup: HEE (Header-End Equipment) is in a station and RN's (Remote Nodes) are in the stanchions.

In successive sections, WDM components will be explained in more detail. The description of additional components of the track is included in Annex B.

3.7.2 Track section deployment

Deployment in track was composed of 4 towers from Olesa station to the south. Below figure shows the scheme of the points for installing the access points.

Figure 3-36: Stanchion

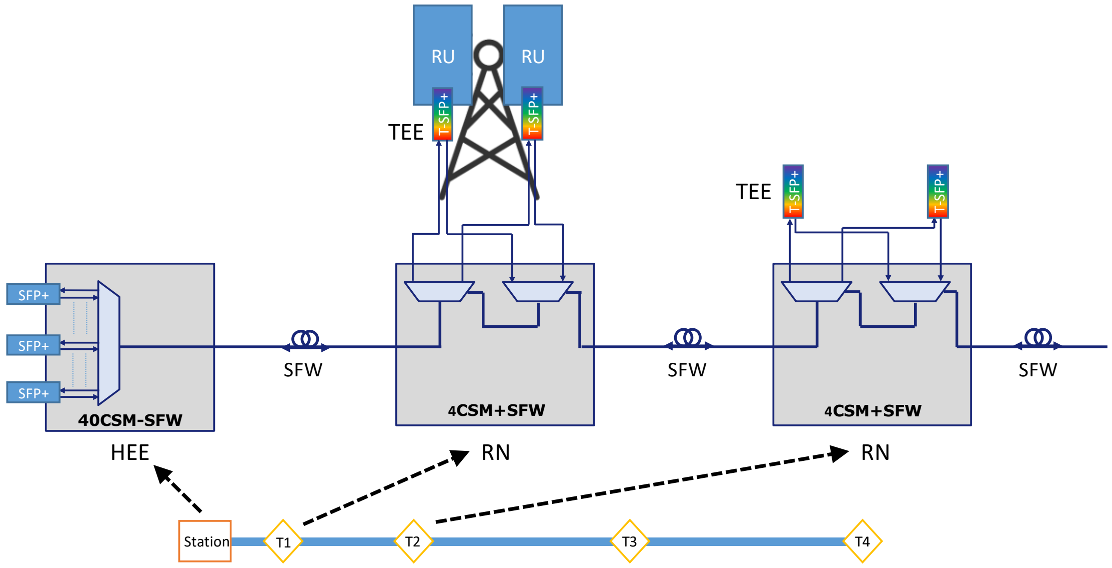


Figure 3-37: Passive WDM deployment for TAN

Figure 3-38: Exact stanchions location

Figure 3-39 shows the four stanchions used in the demo. The stanchion identities are shown in ***Table 3-11***.Note that AC power is provided exclusively from Olesa de Monserrat station.

Two fibres are used to interconnect the stanchions. Main and back-up fibres come from Olesa station, due to the excessive cost and difficulty to connect the back-up fibre from another station

An important detail: T2 is located at the opposite of the track (west side). This means that the new fibres and power cord must cross the track (underground).

Table 3-11: Stanchion identities

Tower	Stanchion identity	E or W of the track	Approx. position (taken from Towers Feb 14.kmz)	
			Latitude	Longitude
1	370	E	41°32'24.91"N	1°53'24.01"E
2	359	W	41°32'20.33"N	1°53'31.41"E
3	325	E	41°32'14.21"N	1°53'51.04"E
4	?	E	41°32'2.80"N	1°54'06.31"E

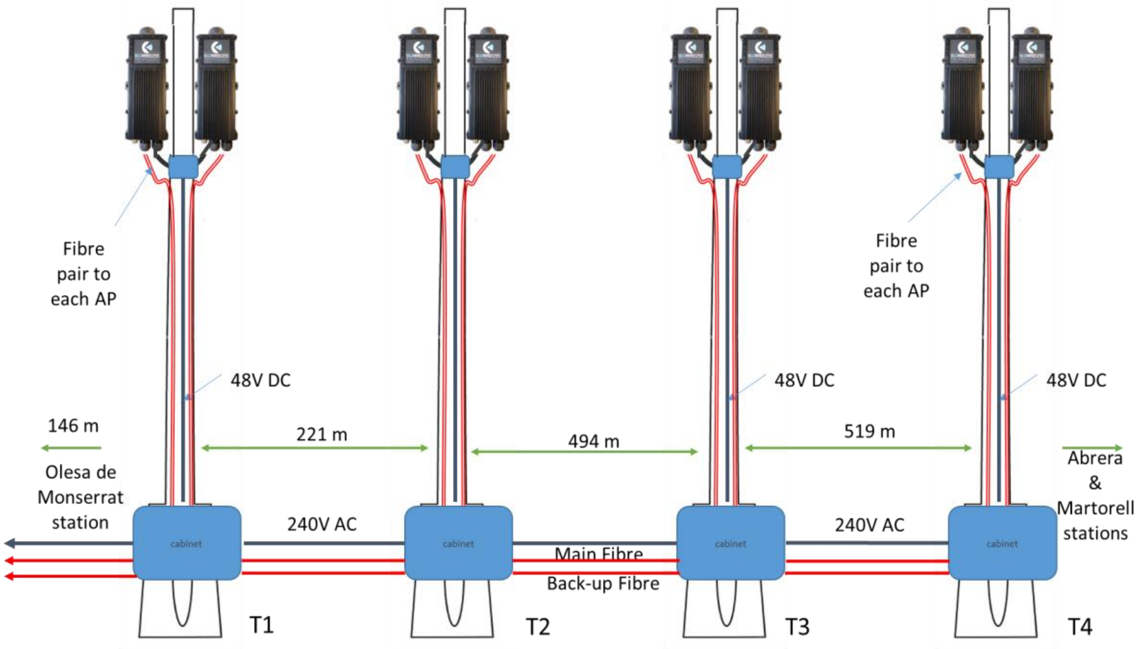


Figure 3-39: Detailed track deployment.

3.7.2.1Powering cable

The electrical circuit had a protection device installed in the non-critical busbar of the Main Switchboard in Olesa station. This switchboard is located at the first floor in the main building of the station.

According to the type of installation and the minimum short-circuit calculations, the size and type of cable to be provided will be RZ1F3Z1-k (AS), and low voltage armored cable specially designed for power electric circuits in outdoors railway infrastructures, 3x4 mm^2 cooper.

The main characteristics of this cable are shown in ***Table 3-12***:

Table 3-12: Powering cable main characteristics

Construction characteristics	
Halogen free	IEC 60754-1
Dimensional characteristics	
Conductor cross-section	4 mm^2
Conductor diameter	10.7 mm
Maximum outer diameter	16.3 mm
Approximate weight	415 kg/km
Number of cores	3
Minimum bending radius	165 mm
Electrical characteristics	
Max. DC resistance of the conductor at 40°C	36 Ohm/km
Inductance	0,287 mH/km
Design characteristics	
Conductor	Copper, flexible class 5
Insulation	Halogen-free cross-linked polyethylene
Inner covering	Halogen free thermoplastic polyolefin
Armour	Corrugated tinned steel tape
Outer sheath	Halogen free thermoplastic polyolefin

New electrical and optical cable was necessary to reach every cabinet placed at the bottom of the stanchion, direction Abrera station. Cables were installed inside new conduits. The installation was done directly on the floor level fixing the new conduit with plastic bridles, this was due to lack of space in the existing precast concrete rectangular ducts along the track. Note this option does not comply with the regulations as a permanent installation.

The cabinets have been designed with spare space for an automatic transfer switch that would select one of the two future electric supplies that could feed this cabinets, in case of power failure, from two different railways stations (Olesa and Abrera). In these cabinets there is a 48Vcc power supply that feeds the AP's on the top of the stanchion using a junction box that has also a 4G dongle for remote monitoring access to the AP's.

An undertrack crossing was required to interconnect stanchion T2. The conduits were placed at a minimum depth of 1.3 m below the level of the underside of the sleeper, according the national standard (ITC-BT-07). The cabinet's electric power was supplied with a single-phase, 230V AC.

3.7.2.2Fibre cable

The characteristics of fibre optic both on track and inside the cabinet are described below:

1. Single mode optical G.655 for the track fibre and into the cabinet. G.655 offers superior performance in the WDM system by minimizing the dispersion around 1550 nm. However, the cost was higher.
2. Although six fibres of the cable were available, only one was finally used to connect the different stanchions. The cost difference was irrelevant and at the ordering stage, as multiple fibres for protection purposes were considered.
3. Type of optical connector to be used between TAN passive WDM system and TN-201LC: Duplex single-mode fibre with LC/PC connectors on both ends between the WDM RN and the TN-201LC.
4. The type of polishing on the fibre optic connector was defined: LC/PC.
5. Types of patch cord: The patch cord defined here was exclusively used inside the stanchion cabinet.
    - Simplex, Length: 5 m, Connector and polishing (LC/APC): LC/PC, Type of fibre: monomode ZDF G.655, External diameter: Fibre core: OS2 9/125µm; Jacket diameter: 3mm.

3.7.3 Components located in a single stanchion

Figure 3-40 details the elements installed in a single stanchion:

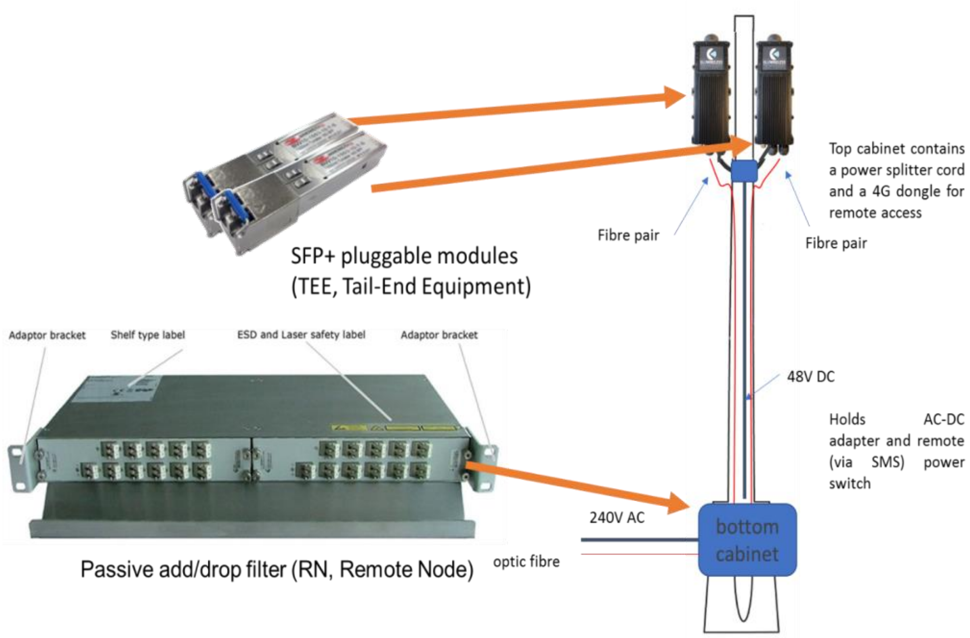


Figure 3-40: Single Stanchion Equipment Diagram

Thus, these are the elements contained in each stanchion:

- Two mmWave AP's, were provided by Blu Wireless, each one of them facing opposite directions. They were installed at 450 cm height on the stanchion using a bracket
- An ADVA SFP+ (acting as Passive WDM Tail End Equipment) Inside each AP box. Blu Wireless and ADVA worked in this project to have these components integrated together.
- A cabinet provided by COMSA and specifically designed for the demo. This box contains: an AC-DC adapter; a remote (via SMS) power switch (to reset the power corresponding to both mmWave APS if necessary), the passive add/drop filter (ADVA Passive WDM Remote Node), a power splitter cord and a 4G dongle for APs remote access (connected to the AP's USB Port)

3.7.4 TAN mmWave AP's (DN101)

Blu Wireless trackside units were fixed to stanchions, dimensions 20x20 cm. There are two units per stanchion facing up and down the track. Blu Wireless product name for the trackside unit is DN-101LC.

The recommendable maximum difference of height between TN201 and DN101 is 0.5 m, this is a recommendation not a rigid requirement.

Trackside node (DN-101LC) Characteristics:

- Single radio distribution node
- Operates in channel 2 or channel 3 of V-band
- Single carrier mode of IEEE 802.11ad with MCS 1 -12 (up to 4.6 Gb/s rate at the MAC-PHY interface)
- Cavium CN8130 Network Processor.
- Supports RJ45, SFP+ for 10Gb copper/fibre, single USB 3.0, 1G ethernet
- Aluminium enclosure with adaptor for standard VESA mounting.
- Power: +48V DC (alternative build: 14 to +12V)
- Case size - 131mm x 273mm x 50mm
- Weight - approx 1.6 Kg
- Power consumption approx. 30W

Figure 3-41: Trackside unit (DN-101LC)

3.7.5 TAN Passive WDM Remote Node

For the TAN passive WDM system along the track, the passive add/drop filters are assembled into a 19" rack-mount shelf with a fibre management tray on the front side, as shown in ***Figure 3-42***. The shelf is placed inside the stanchion cabinet for water and dust proof.

The two lower slots are two add/drop filters for the downlink and uplink, which already comprise the redundant parts (i.e. each module has two identical filter modules inside). The upper slot is an optional two-port optical combiner and splitter module prepared for the redundant link.

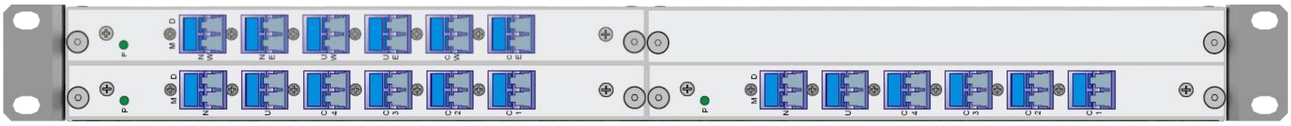


Figure 3-42: Actual configuration of passive add/drop filter shelf

Figure 3-43: Final track installation: a) mmWave modems on stanchions, b) new optical fibre and power cabling along the track, and c) stanchion cabinet

The mechanical dimensions without mounting brackets are 446 mm (width) x 71.5 mm (height) x 270.5 mm (depth) (17.6 in x 2.82 in x 10.65 in).

The connector type of all the filter ports is LC, and the necessary (hybrid) fibre patch cords with enough length between the filter shelf and the outside of the cabinet should be prepared.

3.7.6 Actual installation

Figure 3-43 shows the actual installation of the equipment in the track.

3.8 Stations Equipment Description

This section contains information about:

- Power Switches board in Olesa/Martorell stations
- TAN Components in Stations:
  - Ethernet Aggregation Level: Olesa and Martorell were interconnected through 100G aggregation equipment
  - Olesa Passive DWM components:
    - A HEE (Head-End Equipment) interconnect all the RN trackside nodes defined in section 5 using a new fibre
  - A Flow Blaze in Martorell station (as the station used as track header).
- Martorell Service Level Components (Martorell station simulates the Operational Control Centre):
  - Components to provide CCTV services.
  - Components to provide Internet Access.
  - Additional demo components (network management, collection of performance statistics, etc.).

The description of additional components of the TCN is included in Annex C.

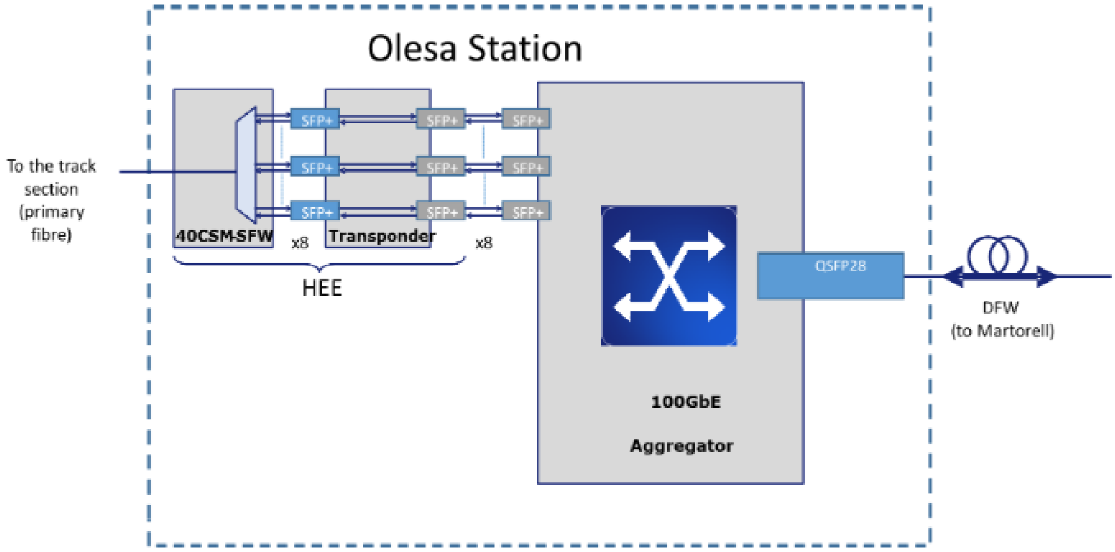


Figure 3-44: Olesa de Montserrat Deployment

3.8.1 A demo consideration for the TAN Components located into Rail Stations

TAN Components located in stations are basically three:

- Passive DWM Head-End Equipment (HEE).
- Ethernet Aggregation Level: 100G Switches.
- FlowBlaze located at Martorell station.

Typically, each station would contain one HEE and one Ethernet Switch, and a FlowBlaze in a specific station designed as header of track. In the demo a single HEE and Ethernet Switch was installed on the track (Olesa station).

3.8.2 Olesa de Monserrat Equipment

Figure 3-44 shows the deployment in Olesa Station:

3.8.2.1HEE equipment characteristics

The HEE at the station consists of all the provisioned SFP+s and one central de-/multiplexer, as shown in ***Figure 3-45***.

The HEE chassis is a rack-mountable, 1-HU rear power access shelf with redundant AC power supply. The shelf is the housing which holds the entire FSP 3000R7 system. The left slot contains the fan control unit (FCU). This slot is covered by the front panel that holds the shelf display and the status LED indicators. The separate ESD jack, rightmost on the front side of the shelf, is intended for the connection of a wrist strap.

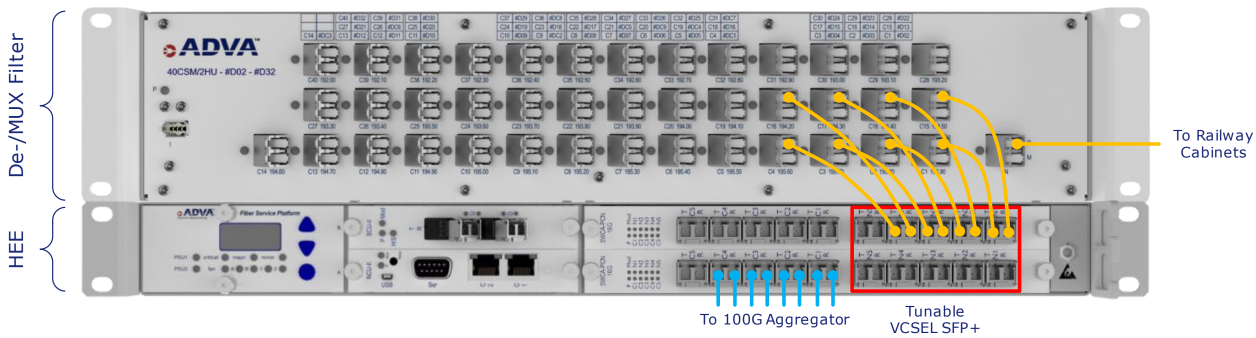


Figure 3-45: HEE shelf and filter.

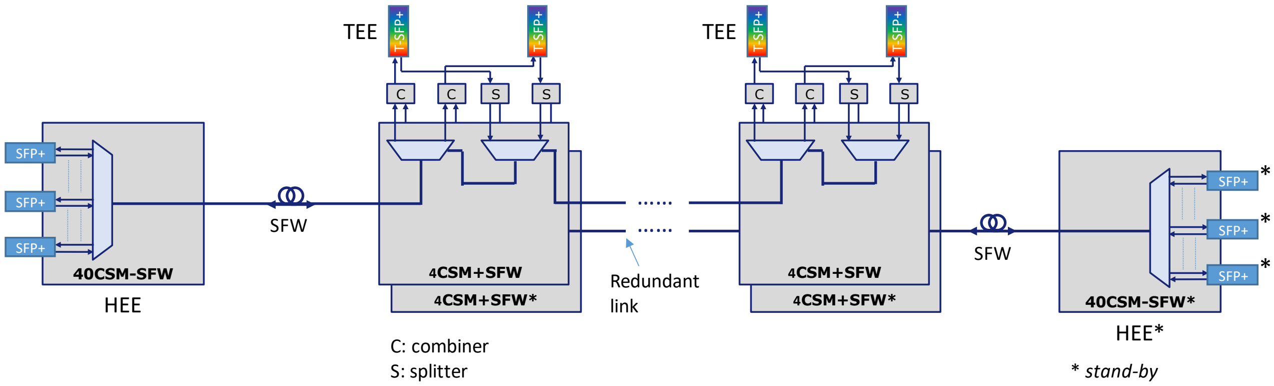


Figure 3-46: Link protection using the dedicated redundant link

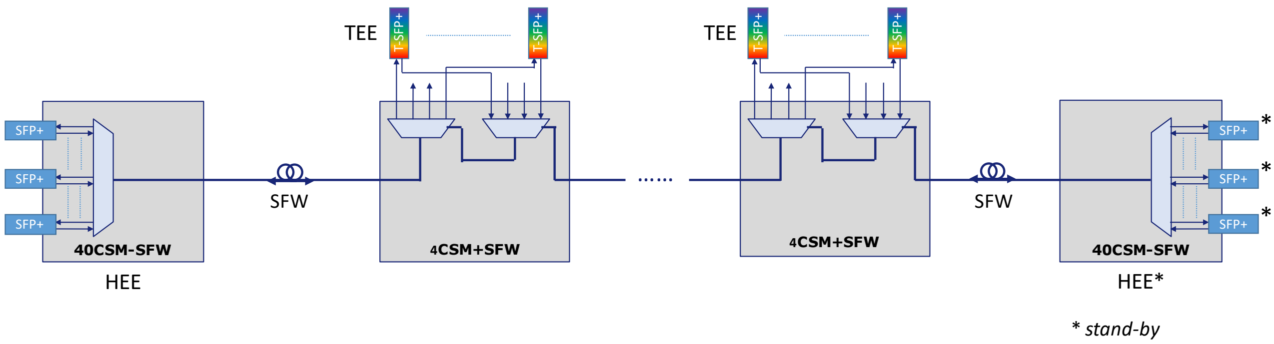


Figure 3-47: Horse-shoe link protection

The De-/MUX filter at the HEE is a monolithic shelf of 2-HU height without any kind of modularity. The filters multiplex and de-multiplex up to 20 C-band channels (#19590 through #19200 for 20 uplinks and 20 downlinks) into/from the network link in a single fibre working configuration.

3.8.2.2Passive WDM Redundancy Consideration

The passive WDM link protection could be divided into multiple redundant degrees. In the 5G-PICTURE railway use case, two link protection schemes are considered.

Dedicated redundant fibre link

The redundant HEE is installed at the neighbouring station on a dedicated fibre link, which may be deployed on the opposite side of the primary link along the track. The complete passive WDM system with redundancy is illustrated in ***Figure 3-46*** and ***Figure 3-47***.

During the normal operation, the redundant HEE is deactivated, while the redundant add/drop filters are always connected to the TEEs together with the primary filters. Given the fact that the filter does not have any active protection switch, each TEE receives the downstream and transmits the upstream through a power combiner and a power splitter, respectively. Additional insertion loss from the passive combiner and splitter must be taken into the link budget consideration.

Horse-shoe over single trunk fibre

In the case that only active equipment needs to be protected, the redundant HEE at the neighbouring station terminates the other end of the trunk line

During the normal operation, the downstream always travels west-east and the last downstream wavelength is dropped at the last node, while the upstream travels east-west. When the redundant HEE is activated, both the downstream and upstream will travel in the opposite directions, respectively.

Figure 3-48. Front view of FSP 150-XG480.

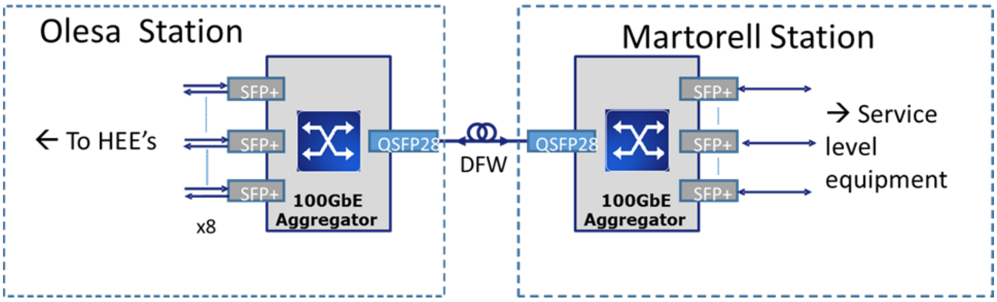


Figure 3-49. Aggregation between the HEE and the control centre.

3.8.2.3TAN 100G Aggregator equipment characteristics

The ADVA FSP 150-XG480 is designed for high-density aggregation of MEF CE 2.0/3.0 services, is showed in ***Figure 3-48***. The product features 25GbE and 100GbE interfaces for high-speed aggregation to the central office or core networks and supports hardware-based time distribution on all traffic ports (SyncE and IEEE1588 PTP). The XG480 supports standard Ethernet OAM and Y.1564 for service activation testing up to 100 Gbit/s. It supports network overlay capabilities, such as VXLAN, for the delivery of MEF services over IP networks. It also features a wide range of traffic protection mechanisms including IEEE 802.1AX DRNI for high service availability. The FSP 150-XG480 is a compact aggregation platform designed to work in locations with no temperature control.

100G Interconnection between Olesa and Martorell stations

To aggregate and transport the TAN data traffic to the remote operation centre, a pair of 100G Ethernet aggregators are commissioned at the station and the operation centre over a duplex fibre link, as shown in ***Figure 3-49***.

On the network transmission side, the aggregated traffic is transmitted using a QSFP28 pluggable (QSFP28/103G/LR4/SM/LC).

3.8.2.4Powering issues in Olesa station

In Olesa station it was necessary to install a new protection device in the non-critical busbar of the Main Switchboard to feed all the equipment along the track (see ***Figure 3-50***). This switchboard is located on the first floor of the main building of the station. This protection device was a Miniature Circuit Breaker switch (MCB) 2P, curve B and 4A associated to a residual-current device.

Figure 3-50: Non-critical busbar, Main switchboard Olesa station

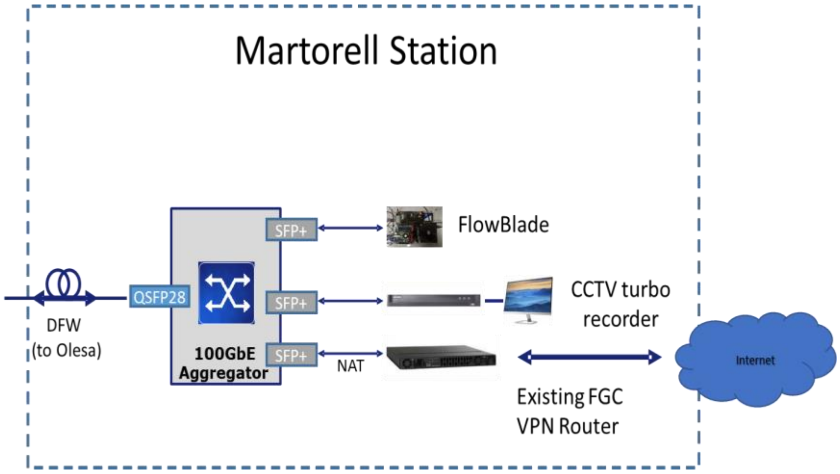


Figure 3-51: Martorell Deployment

According to the type of installation and the minimum short-circuit calculations, the size and type of cable to be provided was RZ1F3Z1-k (AS), and low voltage armored cable specially designed for power electric circuits in outdoors railway infrastructures, 3x4 mm^2 copper.

This cable was installed along the new conduits along the platform, direction Abrera station.

Also, it was necessary to install a new protection device in the non-critical busbar of the Main Switchboard in Olesa station to feed all the equipment in the communications room (Passive WDM HEE). This protection device was a Miniature Circuit Breaker switch (MCB) 2P, curve C and 10A associated to a residual-current device.

3.8.3 Martorell Equipment Description

The TAN only has two components at the Martorell station:

- 100G Ethernet Aggregation Switch (exactly with the same characteristics of Olesa switch. 100GbE traffic is disaggregated into multiple 10GbE client ports, which is connected to all the services, i.e. content, control and mobility servers, via the 1310 nm single mode optics.
- A FlowBlaze for (Mobility VNF).

The Martorell station also simulates a very simplified Operations Control Centre (OCC). Thus, a specific space was identified to install all the demo equipment (isolated from the common equipment room for security reasons). Note that in addition to the TAN equipment, this room also included:

- CCTV Turbo Recorder.
- File Server to storage ftp’s from train Wi-Fi connected equipment (or whatever).
- High Definition Screen.
- Remote Console to Manage TAN and TCN Equipment.
- Test Probe storage.

- Internet Access (for demo users and partners' access).
- MRR results storage (MMR is defined later, in Annex D).
- Additional minor equipment maybe identified and needed along the test plan definition.

3.8.3.1TAN FlowBlaze

The demo included a fast-data path solution that exploits the FlowBlaze technical component developed by CNIT for the 5G-PICTURE project, as described in deliverable D4.2 section 3.6. FlowBlaze is implemented using the FPGA based prototype boards (namely a NetFPGA SUME) equipped with several 10G Ethernet interfaces.

Figure 3-52: Mobility server (FlowBlaze)

Familiarly, we refer to this as "Mobility NFV" or simply "Mobility Function". FlowBlaze simply pushes the traffic to the correct AP along the track, maintaining network session continuity.

Physically, this is the same equipment used on-board the train, even though functionality is different. Redundancy was not provided for this element in the demo. The reader is referred to deliverable "*D6.1 Specification of Vertical Use cases and Experimentation plan"* for a functional description of this component.

An important reminder: all the data flows that must reach the TCN must traverse the Martorell FlowBlaze. Otherwise, the flow cannot locate the appropriate AP to reach the demo train.

3.8.4 Tasks related with Power Switches Board

In Martorell station it was necessary to install a new protection device in the non-critical busbar of the Main Switchboard to feed all the equipment in the communications room (VPN Router, CCTV recorder, etc.) This protection device consisted of two Miniature Circuit Breakers (MCB) 2P, curve C and 10A associated to a residual-current device.

3.8.5 Comments

FGC indicated that for security reasons it was not possible to give access to its internal private network for internet access to the pilot network. It was required, therefore, to install a VPN router 4G for this internet access in Martorell.

3.8.6 Actual installation

From left to right, from top to bottom: FlowBlaze, PC CCTV Pixelated, CCTV Recorder, 100G Aggregator, complete rack with monitor on top

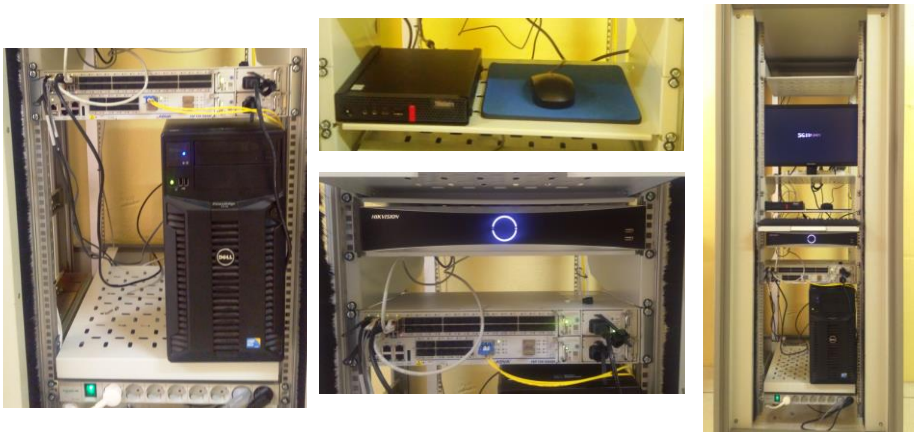


Figure 3-53: Final rack installation in Martorell

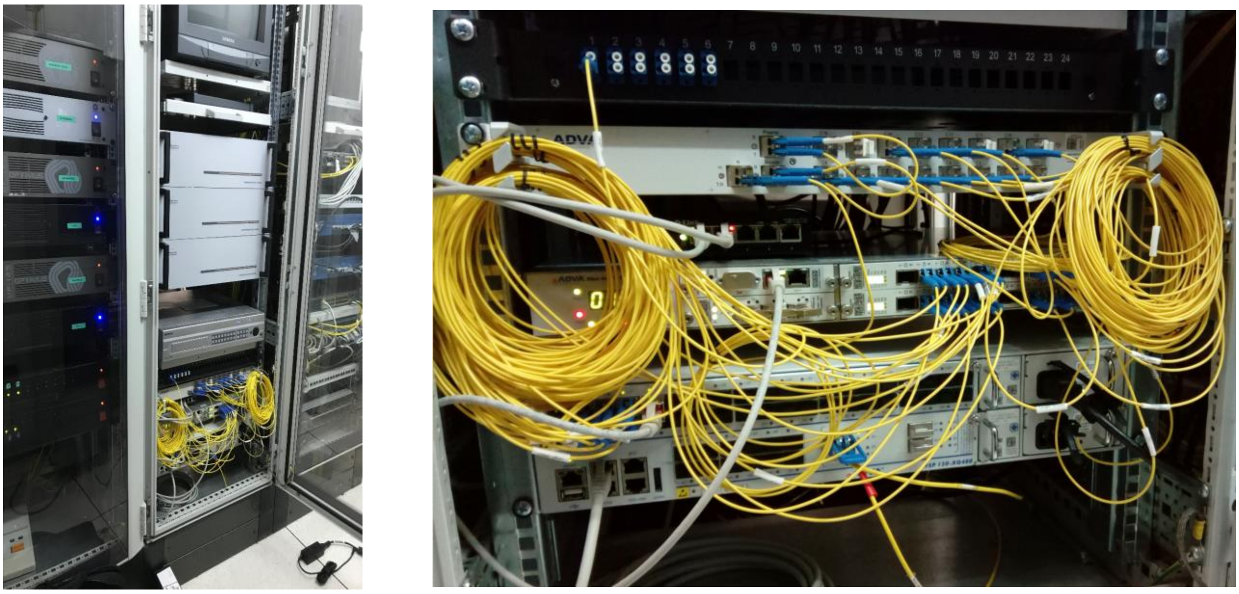


Figure 3-54: Final rack installation in Olesa

Figure 3-55: COMSA Madrid testbed building and FGC implementation scenarios.

From left to right, from top to bottom: complete rack, DWDM Mux / Demux, G.metro HEE and 100G Aggregator.

3.9 Work Process implementation

3.9.1 Work plan executed

5G-PICTURE railway case planned works took place in two different scenarios:

- **Testbed in COMSA** Madrid, where it was verified that all the equipment and configuration were working properly.
- **Live Network** in FGC Barcelona, where the implementation in the real environment was done.

For each scenario two **Sections** were considered:

- **Trackside Infrastructure and train Stations**, the first one including the Blu Wireless Access Points, G.metro passive WDM equipment, and the second one including the G.metro active WDM devices, 100GbE backhaul equipment, mobility server and CCTV recorder.
- **In-Train** section, consisting of the 10GbE ring network with on-board mmWave units, CCTV cameras and Flowblaze mobility equipment.

The activities were developed in two different **Phases:**

- **Phase 1 in June/July 2019**, starting with the lab tests and after that some partial installation works in-field were executed, both on-train and track.
- **Phase 2 in September/October 2019**, involving a new test period to validate the final solution, followed by the remaining installations and testing FGC infrastructure.

3.9.2 Activities performed at each Scenario

Before starting the deployment activities, health and safety procedures were followed and required documentation was completed.

The installation was carried out in collaboration with a subcontracted installation company specialized in the railway sector, managed and supervised by COMSA staff.

- **Testbed**

  The main activities performed in the lab are described below:

  - Setup of the test environment with the required HW equipment, i.e. DWDM, mmWave and Mobility Server plus all the connections needed to implement the defined topology.
  - Verification that there were no HW issues and all the equipment was working properly. Firstly, running partial tests in an isolated way and then with all the connections established.
  - Definition of the configuration for all the equipment in the lab according to the configuration that was going to be used in the final network.
  - Check that e2e connectivity had been achieved with all the services properly established and expected capacity available.
  - Run the full set of pre-defined test cases and measurements in order to determine the throughput and get the first reference KPIs of the system in a lab environment.

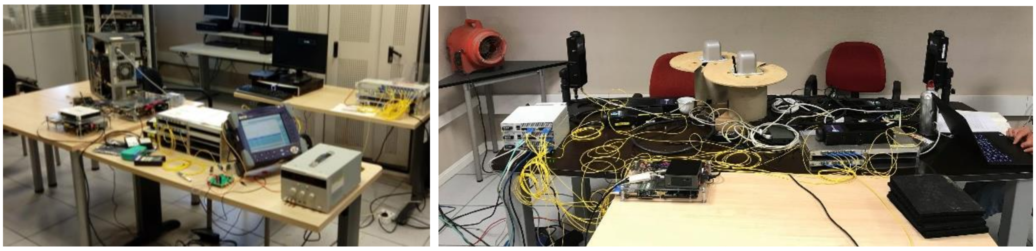


Figure 3-56. COMSA Madrid Testbeds.

- **Live Network**

  The main activities performed in the live network involved:

  - Deployment of the infrastructure needed for the physical installation of the equipment (supports and cabinets), feeding (electrical power line) and communication (fiber line).
  - Installation of transmission WDM and 100GbE equipment, radio mmWave units and mobility units on the trackside and train sections.
  - Setup and fine tuning of each equipment and verification of end to end connectivity of the system.
  - Execution of planned test cases and KPI measurements with test tool (Atlas – provided by Blu Wireless) and Iperf to verify that the network performance was aligned with the targets. The data collected by Atlas was logged onto a laptop connected to the train unit (TN-201LC) via a network cable. The Iperf information was managed via the PCs connected to Flowblaze mobility servers.

Figure 3-57. Stanchion and train installations in Live FGC Network.

3.9.3 List of specific installation works related to each Section

- **Trackside Infrastructure and Stations**
  - Electric ground line & fibre deployment along the railway.
  - Outdoor cabinets & AP´s supports on the stanchions
  - Passive DWDM equipment inside the outdoor cabinets.
  - mmWave antennas installation and alignment on supporting posts.
  - DWDM units, FlowBlaze and camera recorder inside the indoor cabinets at FGC sites.
- **In-Train**
  - Electric cabling to cabinets & fibre line throughout the wagons (end to end).
  - Front and rear cameras, antennas on train roof & HPUs supports inside the cabin.
  - Indoor cabinets for front and rear equipment close to the cabins.
  - Switches, FlowBlaze, NUC PC and AP´s WIFI in the cabinets.

Figure 3-58: Trackside installation and In-train installation

3.9.4 Phases

- **Phase 1, June/July 2019:**
  The first phase of the project execution started with the lab activities in order to test the prototypes and e2e compatibility. Initially not all equipment was available and also software versions did not contain all the required functionality, so only partial tests were possible and e2e compatibility was not fully verified. After the testing it was concluded that a re-design was needed at networking level involving a new release of FlowBlaze software.

  With the aim of advancing all possible activities, some installation works were also executed during this period, consisting of partial installations both on-train and trackside.

- **Phase 2, September/October 2019:**
  The second phase began after the delivery of the hardware, software and re-designs that were pending from the previous phase. Updated system was tested again in the lab reaching the targets for that milestone.

  After that the installations on train, track and sites were finalized with the complete design and equipment.

  Finally test cases were run with moving train in both directions and the whole system was deployed, being able to get the KPIs that had been defined.

  Testing/monitoring had to be done when the train was not in service, so special night works had to be arranged for most of the activities and only some of them were completed during daytime.

Table 3-13: Demo phases timing

	PHASE 1						PHASE 2				
	Jun			Jul			Sept		Oct		
	W24	W25	W26	W27	W28	W29	W37	W38	W41	W42	W44
TESTBED	X						X	X			
TRAIN		X	X						X		
TRACK				X	X	X			X	X	
SITES										X	
TESTs (moving train)										X	X

3.9.5 Main Challenges

Most of the equipment used in this project were prototypes, so it was necessary to set up a lab environment that allowed performance evaluation.

During the first phase several issues came up, such as hardware delivery delays, requirements for updated software and some system solution redesign. Therefore, different actions were required, and the initial time planning had to be changed and activities re-scheduled.

In the live network several constraints were found due to works in railway environment, involving night works and limited time schedule (less than 4 hours per night shift), additional safety measures and risk prevention resources and special machinery (lift platform and draisine) had to be used for installations.

Due to all these difficulties initial planned budget was exceeded, and extra costs had to be covered by the project.

Figure 3-59: Operational live railways challenging environment

3.10 Test Results

3.10.1 Trial services overview

To demonstrate the multi-tenant capability of such a combined optical and mmWave infrastructure, we evaluated the following services as typical examples on the trial testbed

- **Forward-looking critical video**
  The video stream of the two surveillance cameras mounted on the front and rear roofs of the train represents the critical services for the train operation. It requires moderate throughput but is most sensitive to transmission latency, especially during wireless link Handovers.
- **HD video streaming**
  This emulates the high-throughput traffic generated by passengers inside the train, to show the substantial E2E bandwidth provided by the testbed. It reflects the actual experience of end users.
- **Generated random data packets (Iperf3)**
  We use Iperf to generate different traffic patterns and analyze the transmission performance, such as maximum bandwidth, latency, packet jitter, etc.
- **Blu Wireless engineering mode**
  This is a mmWave telemetry tool to characterize the wireless link between each trackside AP and the train antennas. This approach excludes the trackside network and parts of the train onboard network.

Note that all these test cases were performed simultaneously, in order to demonstrate the capability of service slicing and convergence. Also, the test cases mentioned above were first carried out when the train was stationary at certain stop points along the demo track. These stop points were predefined according to different line-of-sight (LoS) distances between the AP and the train antenna, benchmarking the performance for the mobility scenario.

3.10.2 Expected design performances

3.10.2.1 Expected wireless link performance

The performance of a line of sight mmWave link between a Blu Wireless TN201LC modem on a train and a DN101LC modem on a trackside post has been modelled. The figures below (***Figure 3-60*** and ***Figure 3-61***) show the performance under typical conditions when the range is approximately 350 m – in other words the lowest MCS, MCS1 can be supported up to this distance. The range is sensitive to the amount of precipitation and the radio channel (the degree of multipath). In the simulation we assume SNR requirements of an ideal AWGN channel and adjust the link budget to align with the typical range observed in the field. The SNR is also capped at a maximum value of 25 dB commensurate with a real device.

The expected performance may not be realized in practice for several reasons:

- Obstructions to the line-of-sight path
  - Stanchions.
  - The pantograph on the roof of the train (for radios that transmit down the length of the train).
- Multipath
  - Scattering and reflections from the track and line side equipment (stanchions, fencing, OLE equipment).
- Software issues
  - The firmware and driver software are very complex, and under certain conditions it can prevent modem associations or data throughput.

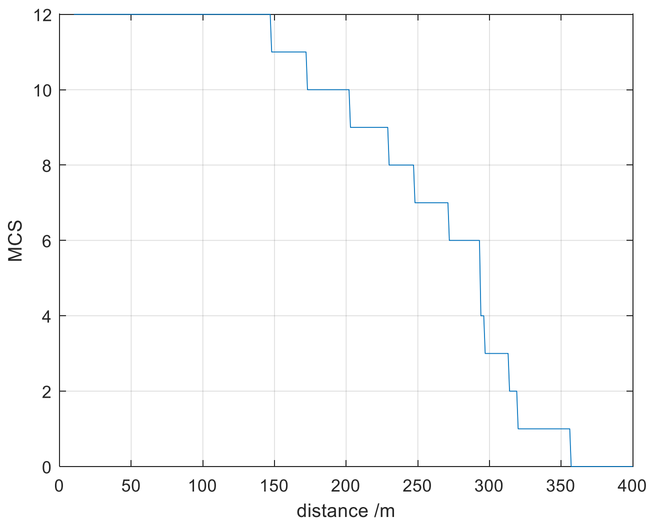


Figure 3-60: Modelled MCS versus distance for the mmWave track to train link

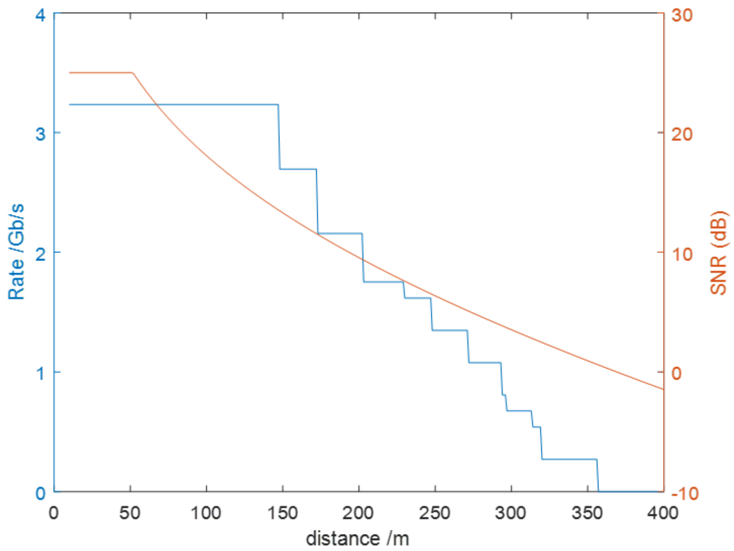


Figure 3-61: Modelled data rate and SNR versus distance for the mmWave track to train link

Other KPIs of the mmWave train backhaul are captured in ***Table 3-14***.

Table 3-14: Expected Solution KPIs table (mmWave component)

	Data Rate DL+UL to the train [1]	One-way Latency ms (mean/min/max) [2]	Packet error rate [3]	Residual packet loss rate [4]	Mobility Km/h [5]	Power W/km [6]
mmWave backhaul	Up to ~6 Gbit/s	0.1/ 0.05 / 3	1%	10^{-4}	90	149

NOTES:

1. This occurs when the train straddles a post giving two short links to two APs
2. These are measured values on an unloaded and fixed link
3. The packet error rate is the target loss probability for a single MAC PDU sent over the air interface.
4. The residual packet loss rate is the probability that an IP packet is lost despite retransmission attempts over the air interface
5. This is the maximum speed of the train. The system would support higher speeds up to 400 km/h, albeit with some performance degradation

This KPI is for the deployed system. Power consumption depends on the post separation, and thus on the mean throughput requirement. Only trackside equipment is included, not train equipment.

3.10.2.2 Expected G.metro passive WDM link performance

The G.metro system was deployed between the station aggregator and mmWave APs, where the down- and upstream traffic of each AP are conveyed on separate optical wavelengths by WDM, such that only a single trunk fibre is needed along the track. As shown in the following figure, the G.metro transponder converts the grey signals to WDM colored signals from the client ports on the aggregator, and a passive optical de-/multiplexer is used in the hub. At each stanchion on the track side, a passive add/drop (A/D) filter drops two specific downstream wavelengths assigned for those two APs, while the others are bypassed. On the upstream direction, another two specific wavelengths emitted from the G.metro tunable transceivers are multiplexed by the A/D filter and transmitted back to the hub. As such, each AP is linked up with an individual client port on the aggregator through a dedicated optical channel (i.e. up- and downstream wavelengths) over a bidirectional trunk fibre.

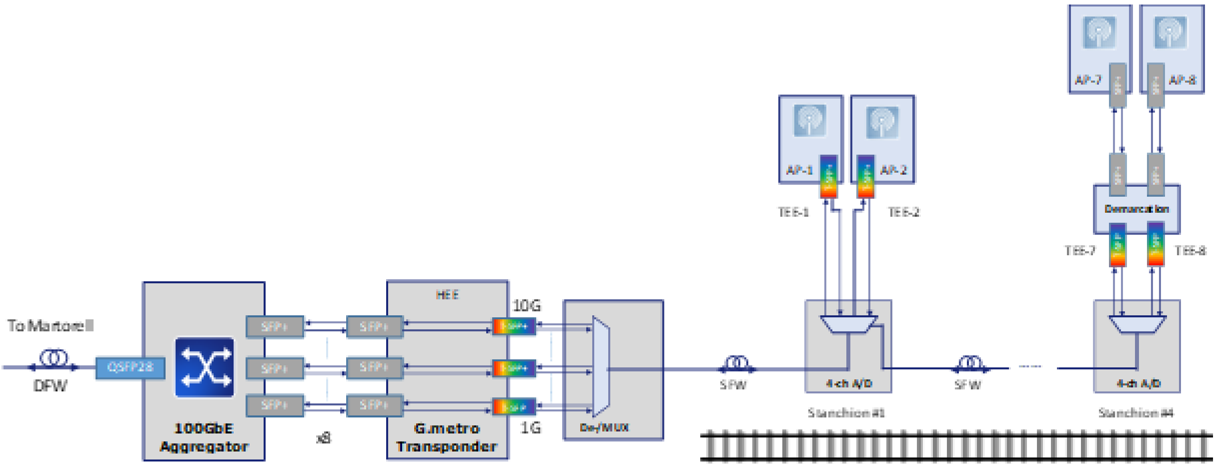


Figure 3-62: G.metro system configuration

Table 3-15: G.metro transceiver specification

Transceiver pluggable	1G	10G
Interface type	Duplex	BiDi
Tuning range (channels)	8	40
DWDM channel coverage	40 (5 bands)	40
Reach (km)	40	40
Optical power budget (dB)	26	21
Frequency grid (GHz)	100	100

In the demo setup, we evaluated both 1G and 10G variants of G.metro tunable transceivers. For the first four APs (AP1-4), the 10G transceivers were directly plugged in the APs, and it features a bidirectional connector interface that filters the up- and downstream frequencies within a single 100 GHz channel space. While for the rest of four APs (AP5-8), the 1G transceivers with a normal duplex interface were used and plugged in an Ethernet NID which converts the wavelengths between grey and WDM color. The NID is temperature hardened and was installed together with the passive A/D filter inside the last two stanchion cabinets.

The single channel specification under both 1 Gbit/s and 10 Gbit/s is shown in ***Table 3-15***. The receiving sensitivity of the 10G transceiver is slightly worse due to the higher chromatic dispersion penalty.

However, unlike the tree or star networking topology, such a linear add/drop topology could limit the number of add/drop nodes due to the accumulated insertion loss when passing through each node. To minimize the link loss, especially for the 1G transceivers with the duplex interface, we interleave the up- and downstream frequencies by 100 GHz, i.e. even frequencies for the upstream and odd frequencies for the downstream. On average the add/drop port of the node filter should cause less than 3 dB loss, while each bypass port should cause less than 1 dB loss.

3.10.2.3 Expected Mobility Server performance

The mobility server is composed of several functionalities intended to guarantee session continuity in the mobility scenarios described in this document. However, these functionalities are distributed across several devices (2 FPGAs implementing FlowBlaze, 1 NUC, 1 PowerEdge server). Therefore, the overall behaviour can be evaluated by understanding the proper function of each device:

1) The FPGA board installed in the train (FBT) will provide the FlowBlaze node executing the following functionalities:

- Packet generation: it will generate a probe/keep-alive signal to the FlowBlaze node (in the station) to update the binding between the source address of the train Access Point (AP) and the VLAN-id of the antenna connected to the train.
- Packet deduplication: it will remove duplicated traffic originated from the FlowBlaze node (in the station), when it is configured to minimize packet loss using multiple destination antennas.

2) The FPGA board installed at ground (FBS) will provide the FlowBlaze node executing the following functionalities:

- VLAN learning: the FlowBlaze node (in the station) will learn the antenna connected to the train binding the AP source address with the incoming VLAN id.
- VLAN tagging: the FlowBlaze node (in the station) will set the VLAN id previously learned to the packet coming from the server toward the NUC (that it is behind the AP).
- Packet deduplication: it will remove duplicated traffic originated from the network, if multiple antennas are used to forward the traffic coming from the train.

3) The NUC is a standard linux box which will provide basic network tools (ping/tcpdump/wireshark etc) and will be connected to the rest of the system using a 1000Base-T Ethernet interface. The NUC is also equipped with a WiFi interface (IEEE 802.11ac) that can be used to simulate the user behaviour on the WiFi connection. And it will be also configured to act as an iperf client/server to provide throughput and packet loss measurements.

4) The PowerEdge is a Linux server which will provide basic network tools (ping/tcpdump/wireshark etc) and will be connected to the rest of the system using 2x10 GbE interfaces and a management 1000Base-T Ethernet interface. This server will be used to simulate an internet server for the train users, and it will be also configured to act as an iperf client/server to provide throughput and packet loss measurements.

Analysis of the individual devices provides useful information on correct functioning of the proposed architecture, however, performance of the e2e connection by traversing the components when integrated is more important.

The architecture is expected to work correctly in both environments: i.e. when static (same VLAN) or when dynamic (different VLANs).

To make the mobility server work properly, several performance specifications were needed to guarantee both for the E2E connectivity and for the single FlowBlaze nodes. In particular, the specifications reported in ***Table 3-16*** needed to be satisfied.

Table 3-16: Expected FlowBlaze KPIs

Component	Parameter	Expected value
FBT	Packet generation rate	1pkt/msec
FBT	Packet generation jitter	<100 µs
FBT	Packet deduplication	0 duplicated packets
FBT	Throughput	10 GbE per port
FBS	Throughput	10 GbE per port
FBS	Packet deduplication	0 duplicated packets
FBS	VLAN learning latency	1 µs
e2e	Latency	<10 ms
e2e	Throughput	10 GbE

Table 3-17: Expected Solution KPIs

	Data Rate DL+UL to the train	One-way Latency ms (mean/min/max)	Residual packet loss rate	Mobility Km/h[4]	Power W/km[5]
Overall system	Up to ~6 Gbit/s	0.1/ 0.05 / 3	10-4	90	200

3.10.2.4 Expected Overall solution performance

According to design specifications. The combined G.metro and mmWave segments were expected to provide the KPIs shown in ***Table 3-17***. Note that the solution is capable of accurate clock distribution to allow synchronization of network nodes, although there wasn't time or resource to evaluate the performance in the trial.

3.10.3 Performance testing in COMSA Madrid lab

3.10.3.1 MmWave performance tests and results

No performance testing of the mmWave radio was undertaken in COMSA Madrid lab. Instead the main objective was to integrate all components of the system such that E2E connectivity and data transfer could be achieved. The test bench employed one or two TN201 devices (representing the train), and two DN101 devices representing two trackside APs, ***Figure 3-63***.

The following functionality was demonstrated:

- Management messaging tested for all nodes.
- End to end traffic for CCTV and Wi-Fi.
- Seamless handover demonstrated for CCTV with a single TN (and two APs).

Testing showed that the Blu Wireless DN101s did not work with 1G WDM SFP supplied by ADVA, although with the 10G WDM SFP it worked fine. A workaround involved using a switch to act as a media converter between a 10G conventional “grey-light” SFP and WDM SFP. These switches were needed for two posts unless more 10G WDM SFPs can be sourced.

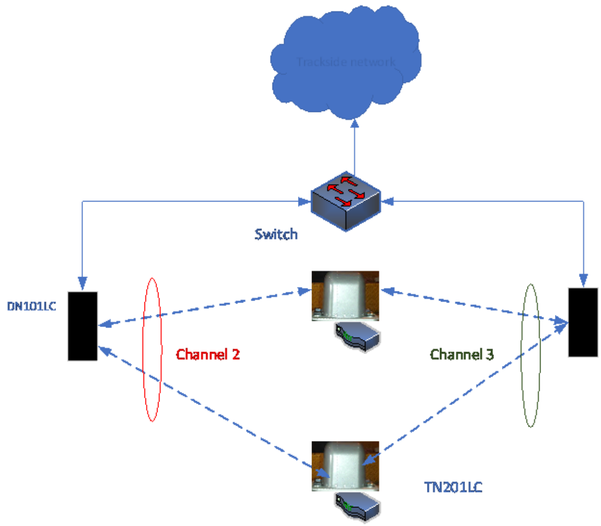


Figure 3-63: mmWave equipment set up in Madrid

[4] This is the maximum speed of the train. The system would support higher speeds (see notes on mmWave design performance)

[5] This KPI is for the deployed system. Power consumption depends on the post separation, and thus on the mean throughput requirement. The indicated power per km figure includes only equipment on trackside. The power includes 4 waveleghts at 10G per radio site.

A VLAN tagging issue was found in the TN201 and only partly addressed: a workaround was devised using on-train switch configuration to add the missing tag, but this forces all user plane traffic onto a single VLAN. Original design used two VLANs for user plane – network slicing concept.

3.10.3.2 G.metro passive WDM performance tests and results

The primary purpose of the Madrid lab test was to check the interface compatibility between the G.metro system and the mmWave devices as well as the mobility server. In the lab test, four DWDM channels were provisioned to verify the system functionalities, including the wavelength auto-tuning and 1/10GbE interfaces. Two of them were used to transmit data between the two mmWave APs and the mobility server.

Given that the mmWave AP does not have access to the diagnostic information of the G.metro pluggable, we further exploited the out-of-band communication channel (OOBC) developed on the G.metro pluggable which was initially only used for enabling auto-tuning. We used the pluggable at the HEE as the host to send commands and retrieve the operation status of the remote pluggable via the OOBC and read the information on the HEE console. It became especially crucial and handy when monitoring the case temperature of the remote pluggable, as the AP would be later deployed outdoors without active cooling.

We also verified all the VLAN and interface settings on the 100G aggregators during the lab test. Similar test was also done for the onboard network.

3.10.3.3 Mobility Server and overall solution performance tests and results

In the Madrid lab, we organized tests to check the functionalities that composed the mobility server operations, to check that the expected specification described in section 3.10.2.3 has been fulfilled.

For the FPGA board installed in the train, we evaluated both the packet generation (by checking if the internally generated packets are correctly forwarded to the output port which will be connected to the train antenna) and the packet deduplication (by sending duplicated traffic to the FPGA and check if it is correctly deduplicated).

For the FPGA board installed at the station, we sent packets with a specific VLAN id to the interface port connected to the internal network and checked if the VLAN id is correctly stored in the internal FlowBlaze memory. Then we sent packets to the interface port which will be connected to the external network and we checked if the VLAN id is correctly set and forwarded to the internal network. Then, by sending duplicated traffic to the FPGA, we checked if it correctly deduplicates.

Finally, after having performed the individual test to verify the proper functioning of each devices, we checked a basic e2e connectivity. We deployed a static connection in which a ping has been generated from the NUC and we checked if the reply is correctly returned. Then, we implemented a dynamic connection from the NUC to the server: we changed the VLAN id of the NUC while the ping test was going continuously. And at the end we performed a netcat based test: we instantiated a nc client/server connection to check the TCP/UDP connectivity

The last useful analysis performed has been a throughput test: an iperf client/server connection has been instantiated between the NUC and the server. The test has been performed both in a static condition and changing the VLAN id associated to the NUC.

Table 3-18 reports the actual performances of the different elements used for the mobility function and the results for the end to end connection.

Table 3-18: FlowBlaze performance results

Component	Parameter	measured value
FBT	Packet generation rate	1pkt/msec
FBT	Packet generation jitter	<1 µs
FBT	Packet deduplication	0 duplicated packets
FBT	Throughput	10 GbE per port

FBS	Throughput	10 GbE per port
FBS	Packet deduplication	0 duplicated packets
FBS	VLAN learning latency	< 1 µs
e2e	Max latency	3 us
e2e	Throughput	10 GbE

Finally, to emulate the wireless handover from one mmWave AP to another, in the test lab we used a plastic foam to block radiation of one AP at a time. We then monitored the video streaming of the surveillance camera connected to the onboard network. The result showed that the video played smoothly without any interruption.

In the lab, we used Iperf3 to analyze the link performance for the two provisioned mmWave links (i.e. AP1 and AP2). For the downstream, the packets were generated from the FlowBlaze at the central station and received by the mini-PC connected to the onboard FlowBlaze. The client/server role of was toggled for the upstream. The results are shown in the following figure. Note that the bottleneck of the end-to-end throughput exists at the onboard mini-PC, as it only has a 1GbE copper interface to generate and receive the traffic.

In addition, we used Ping command to characterize the end-to-end service latency (round trip) as well. The result is shown in **Figure 3-65**:

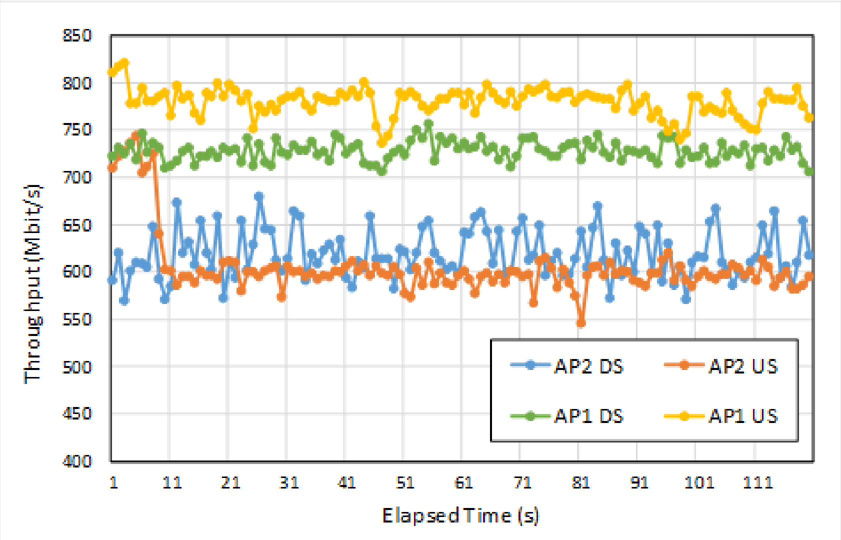


Figure 3-64: End-to-end throughput performance (static w/o handover)

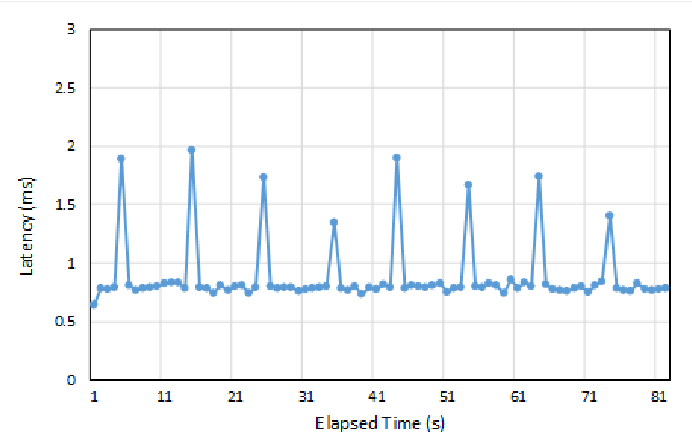


***Figure 3-65.* End-to-end service latency.**

3.10.4 Performance testing in FGC demo

3.10.4.1 MmWave performance tests and results

Besides the E2E testing described in this document, mmWave specific tests were performed up to a few days before the Demo Event. These employed the engineering mode in which an iperf3 TCP downlink session is created by each AP to the TN201 host device when an association exists to one of the modems of the TN (on the train).

The data rate that can be achieved does not necessarily reflect the maximum bandwidth of the radio link since the host CPU performance at the DN101 or the TN201 can cap performance. This remains an area of investigation and refinement at Blu Wireless today. With engineering mode, the TN201 runs a tracing tool called Atlas (a commercial product from McLaren Applied Technologies) that captures radio parameters and other KPIs that can be displayed in real-time or at a later date. Two examples are shown below. These show the performance of the radios of a single TN, labelled 'Train-1'. The second TN was found to be mounted back-to-front. Fixing this required a configuration change (software) and then other issues were found. In the demo week Train-2 was working properly but there was no time to execute engineering mode with it.

The trace is fully labelled in the figures below. In ***Figure 3-67*** it can be seen how the front and rear radios alternately demonstrate high throughput as the MCS is adjusted according to the SNR. In the direction of travel here the rear radio is pointing forwards away from the train, and the front radio is pointing backwards down the length of the train. Between Post 1 and Post 2 both radios are connected at the same time. In this trace there is no connection achieved from the TN to either of the APs on post 3. Although sometimes connections were achieved this post continued to give problems up to the day of the Demo Event, and the cause is unknown. The SNR curves demonstrate considerable fading, especially for the front radio that must transmit/receive through the pantographs that are mounted on the roof of the train. This is one possible explanation for why the front radio performs worse than the rear radio. Looking at the sector ID plots we can see which beam has been chosen by the TN radios. Low beam numbers are close to boresight, whilst the highest numbers (up to 13) imply beam steering up to 45 degrees away from boresight. The erratic sector selection from the front radio is consistent with strong shadowing and reflections from the roof-top equipment. Finally, we can say that the peak data rate observed was 2 Gb/s to a single radio.

In the ***Figure 3-68***, the train is parked at Olesa station. Train-1 is located at the end of the train furthest from Post 1, and the only connection possible is from the front radio (approx. 150 m from Post 1). There is a fluctuation in the SNR which leads to an MCS oscillation through the link adaptation algorithm. The TCP data rate is about 800 Mb/s.

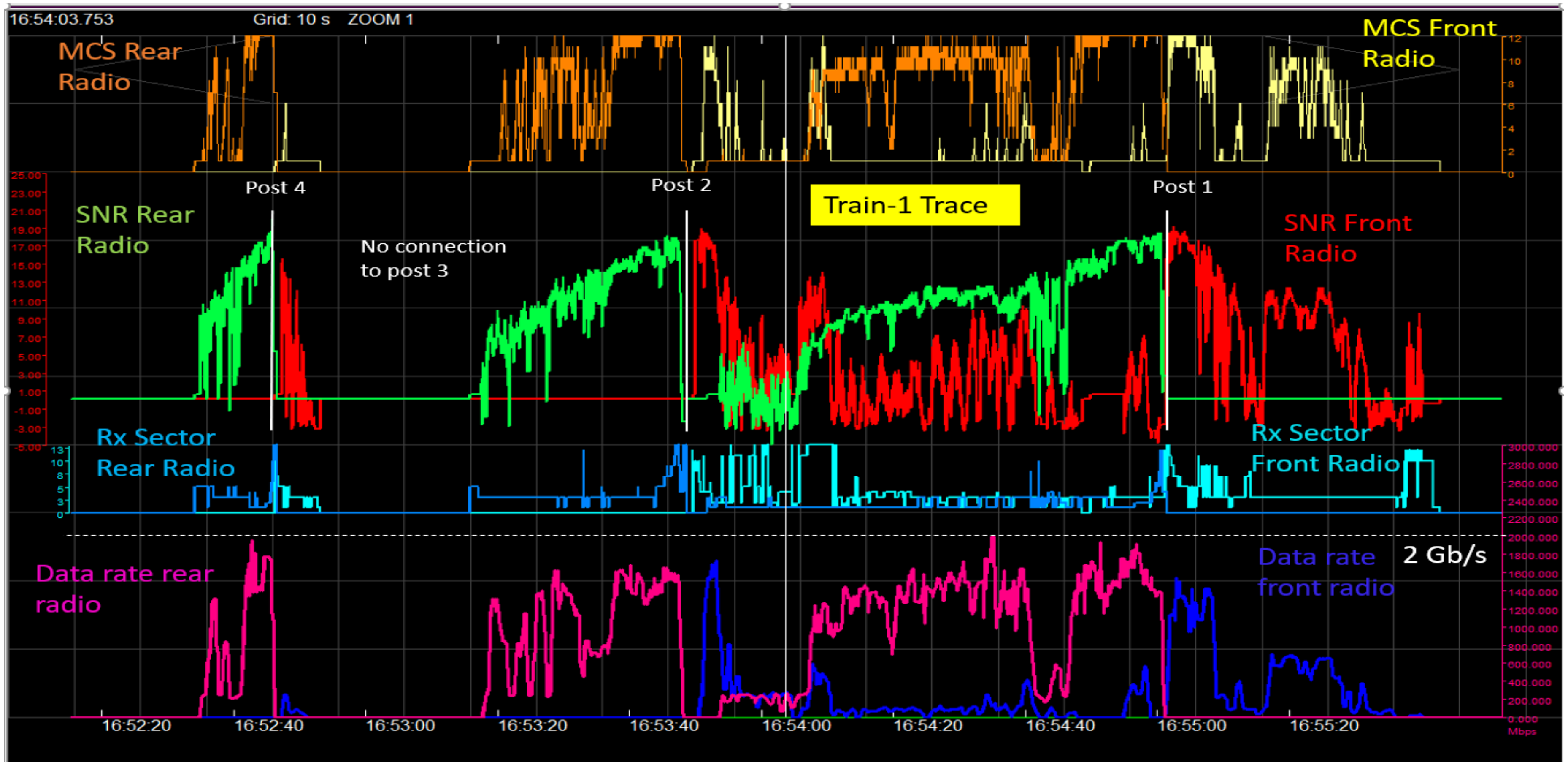


Figure 3-67: Atlas trace of front and rear TN201

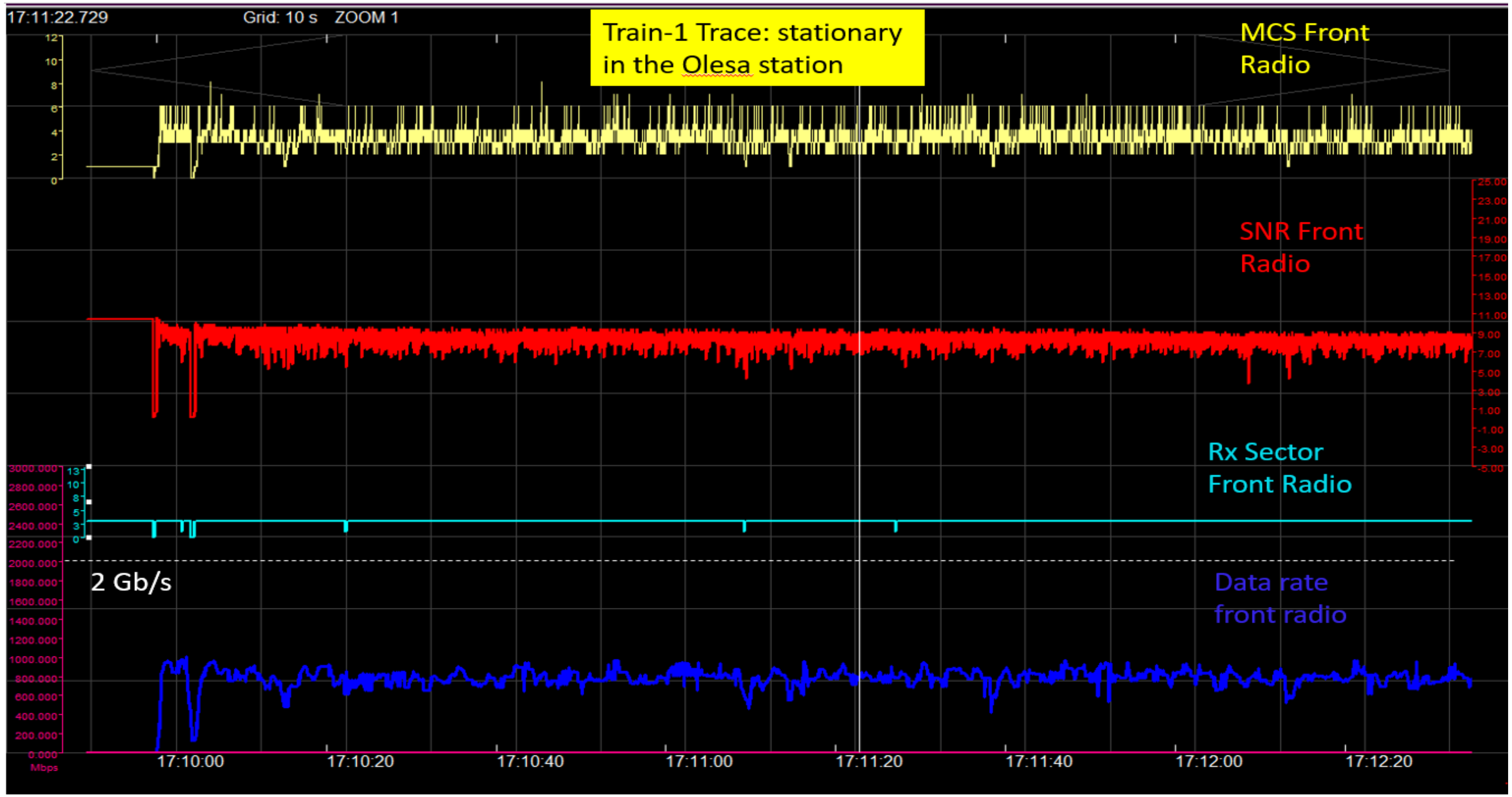


Figure 3-68: Atlas trace of a single TN201 stationary at Olesa station

3.10.4.2 G.metro passive WDM test results

Table 3-19 summarizes the different insertion losses of the WDM links used in the testbed. Note that an additional 5 dB attenuator was used in the trunk fibre, in order to prevent excessive input power to the receiver. To minimize the link loss, especially for the 1G transceivers with the duplex interface, we interleave the up- and downstream frequencies by 100 GHz, i.e. even frequencies for the upstream and odd frequencies for the downstream. In the test it was verified that the add/drop port of the node filter exhibits 2 dB loss, while the bypass port exhibits around 1 dB loss.

Based on the measured link loss, we can project the scalability of such a system design, as shown in below figure. The blue dots depict the insertion loss caused by filters for each AP, leaving out the fibre propagation loss. Theoretically, the link loss is linearly proportional to the number of APs. The margin between the link loss at the last AP and the transceiver receiving sensitivity is the applicable transmission distance. In practice, depending on the data rate and transceiver modules, the chromatic dispersion may reduce the maximum transmission distance by few dB.

Table 3-19: WDM link loss of G.metro system

APs	Tx @HEE (dBm)	Rx @HEE (dBm)	Tx @AP (dBm)	Rx @AP (dBm)	Link Loss (dB)
#1 (10G Simplex)	1.0	-10.8	1.0	-10.7	11.8
#2 (10G Simplex)	1.0	-10.4	1.0	-10.3	11.4
#3 (10G Simplex)	1.0	-10.3	1.0	-10.1	11.3
#4 (10G Simplex)	1.0	-12.1	1.0	-11.9	13.1
#5 (1G Duplex)	-2.6	-14.1	0	-15	14.1
#6 (1G Duplex)	-2.4	-14.8	-1.0	-16	13.8
#7 (1G Duplex)	-2.1	-17.4	-1.0	-18	16.4
#8 (1G Duplex)	-2.2	-17.2	-1.0	-18	16.2

*Note: including additional 5 dB attenuation for input power protection

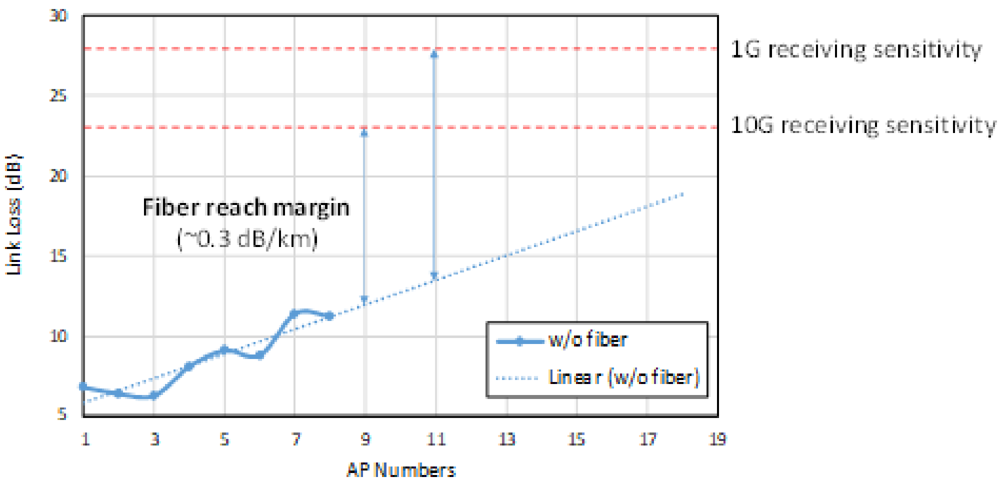


Figure 3-69: **Link budget projection of linear add/drop G.metro system**

Table 3-20: Measured G.metro system KPIs table

	Data Rate per λ [Mb/s]	One-way Latency ns (mean/min/max)	Residual packet loss rate	Power W/λ
G.metro system	1250 or 10312.5	129/130/131	0%	5 (1G) 6.5 (10G)

Note that the one-way latency was measured without fibre transmission (i.e. from the HE interface to the TE interface). The power consumption includes both HE and TE pluggable modules, and the one of the transponder shelves is shared per wavelength.

3.10.4.3 End-to-end link tests with stationary train

Prior to the moving train test, we first determined several stop points along the route, in order to check the link connectivity and measure the static performance as a benchmark. Depending on the relative position between the train antenna and the AP, we concluded all the possible scenarios in **Figure 3-70**. As such, we marked the stop points according to Google Map.

At each stop point, we ran a bidirectional Iperf analysis and Ping between the FlowBlaze PC and the onboard PC. At the same time, we also carried out the mmWave link telemetry, and checked for the CCTV camera link whether there was interruption.

As an example, at stop point "2" as depicted in **Figure 3-71** both end-to-end throughput and round-trip latency were measured, as shown in subsequent figures with the inset table of latency decomposition.

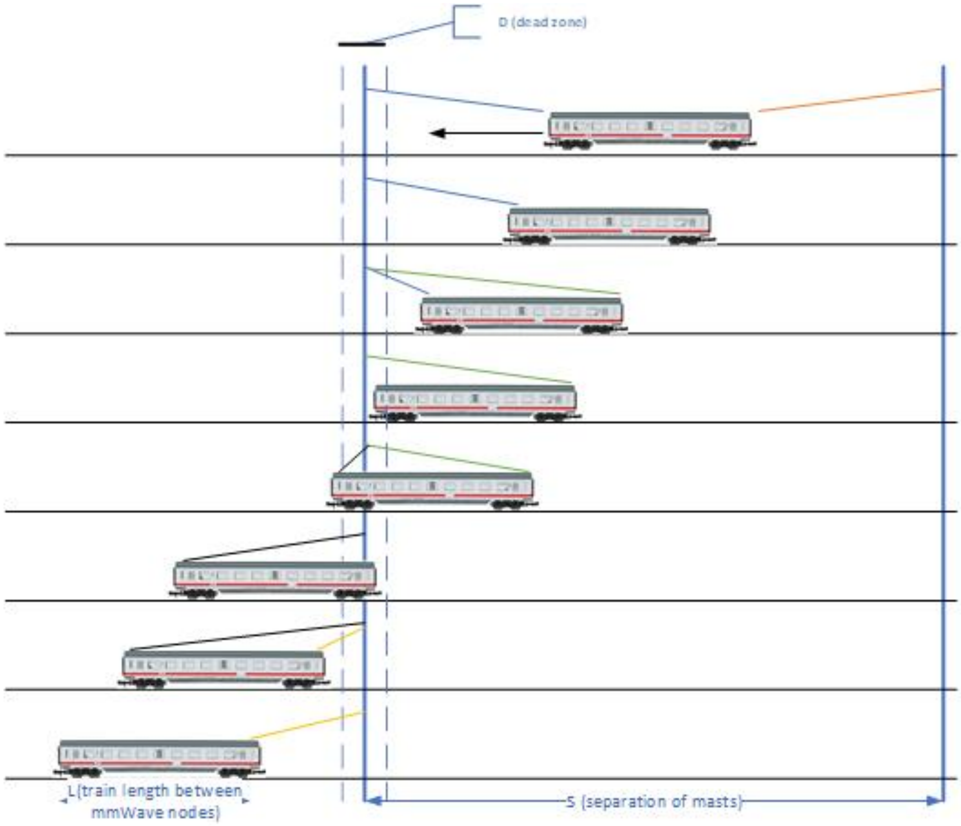


Figure 3-70: Connectivity scenarios when train passing by a stanchion

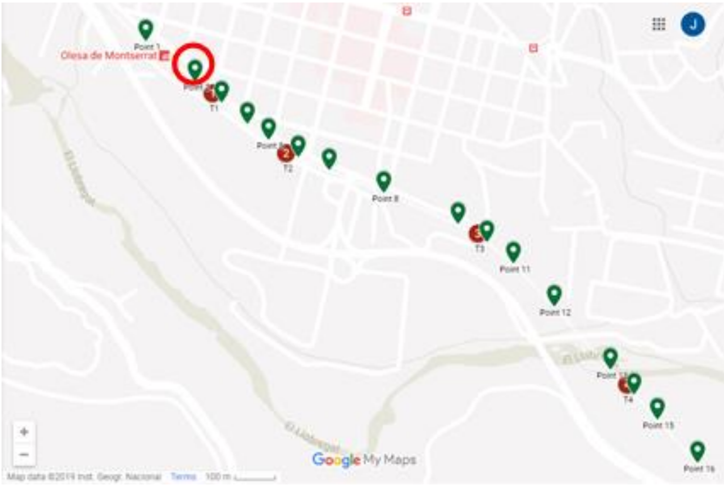


Figure 3-71: Link budget Stop points on the map

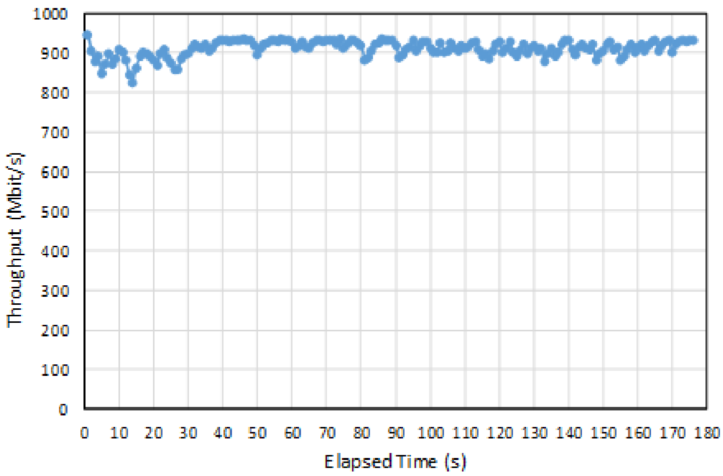


Figure 3-72: End-to-end throughput at stop point “2”

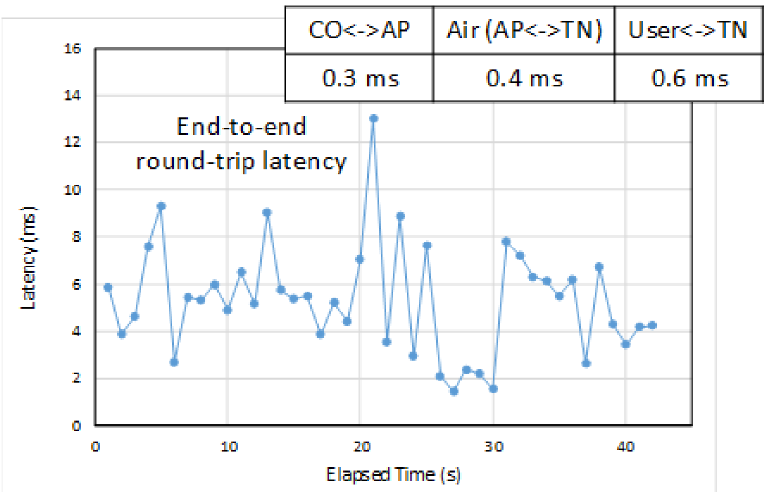


Figure 3-73: End-to-end service latency at stop point “2” (inset: latency decomposition)

Table 3-21: Measured Solution stationary train KPIs

	Data Rate [Mb/s]	One-way Latency ms (mean/min/max)	Residual packet loss rate	Mobility Km/h	Power W/km
Overall system	910.8	1.96/0.28/4.62	0%	0	199.5

Table 3-21 shows the KPIs measured when the train was stationary Both the Iperf data generation and ping are active. The table reports the average value of data rate, which is basically bounded by the 1GbE interface of the mini PC in the train. For the end-to-end one-way latency, the minimum, maximum and average values are reported. It is worth noting that the values are slightly higher than those collected when only the ping is active. The experiment also measured the packet loss rate measured checking the sequence numbers of the ICMP packets of the ping application.

3.10.5 End-to-end link tests with moving train

After the stationary test and troubleshooting/optimizing all the APs, we repeated all the test items but with a moving train. Two test results are presented in this section. In the first test, the moving direction and the associated APs in each section are depicted in **Figure 3-74**.

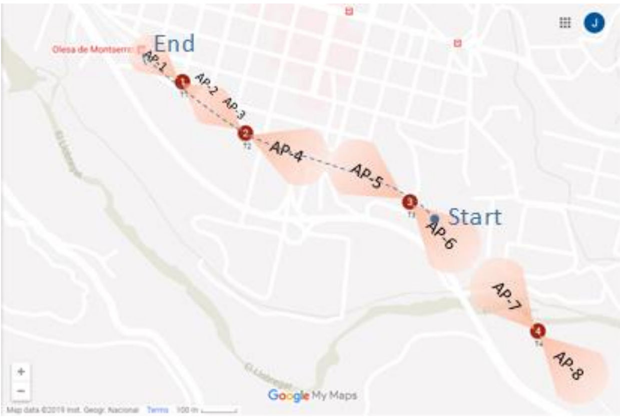


Figure 3-74: Train moving trajectory in test #1

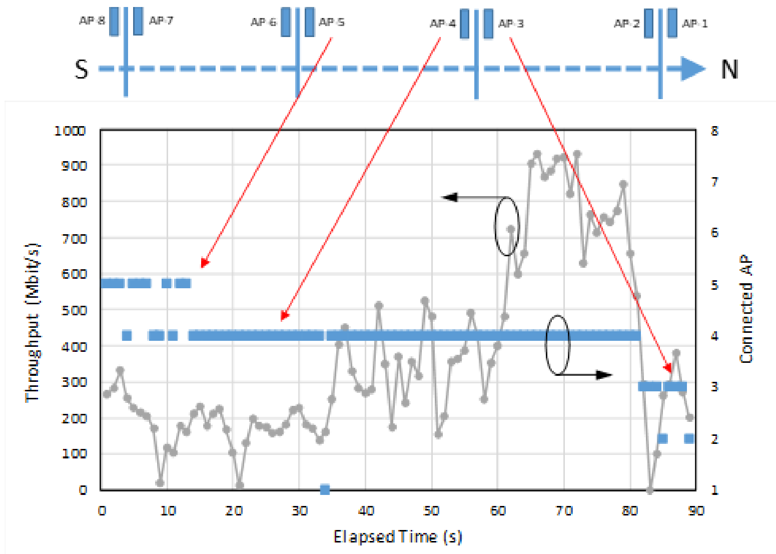


Figure 3-75: Throughput performance when handover in test #1

During the ride, the Iperf throughput analysis was kept running to evaluate the link handover. The grey points in the following figure indicate the instant end-to-end throughput every one second, while the blue points indicate the connected AP at the same time. The throughput was increased when the train was closer to the AP and decreased when leaving the coverage. Since there are four antennas (two at the front facing forward and backward, and two at the rear) equipped on the train roof, multiple radio links might be established. According to mobility control, only one link was used for data transmission, and the duplicated data from other working links were dropped.

In the second test, the moving direction and the associated APs in each section are depicted in **Figure 3-76**. It started in front of the stanchion 4 and passed by all the deployed APs.

Similarly, the throughput performance during the handover is shown in the following figure. There was a "dead zone" close to stanchion #3 (AP-5 and 6), because there was a problem associating these two APs with the train antennas.

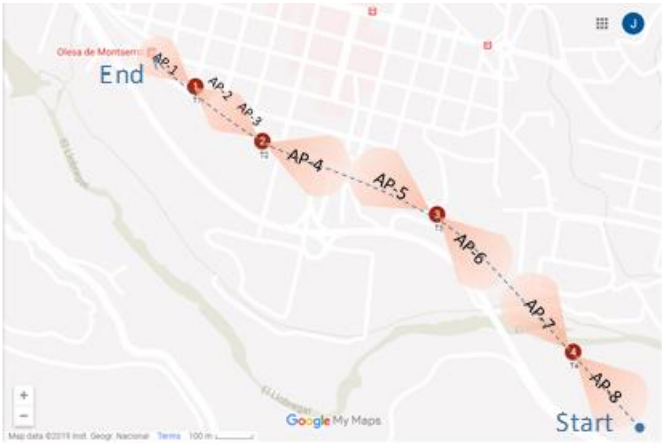


Figure 3-76: Train moving trajectory in test #2

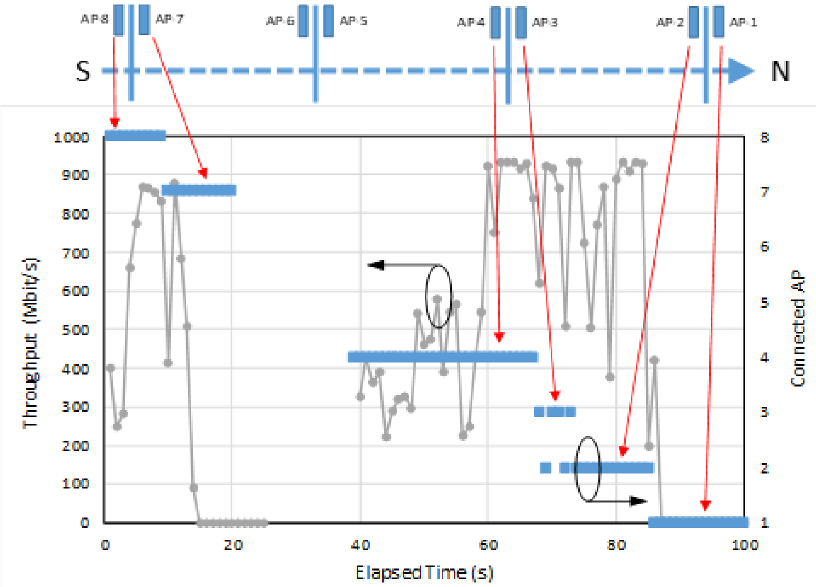


Figure 3-77: Throughput performance when handover in test #2

Table 3-22 shows the KPIs measured when the train is moving. Both Iperf data generation and the ping are active. The table reports the average value of data rate. Differently from the previous case, the data rate changes depending on the distance of the train from the stanchions, ranging from a minimum of 223 Mb/s to the maximum case of 933 Mbit/s (similar to the stationary case). For the end-to-end one-way latency, the minimum, maximum and average values are reported, again similar to the stationary case.

The packet loss rate is measured counting the number of TCP retransmission occurred during the experiment. However, this includes both packet loss due to the channel and packet loss due to the TCP congestion control algorithm. Therefore, it represents an upper bound of the actual packet loss rate. This choice was necessary since during the experiment we were unable to collect enough data points using a UDP configuration of the iperf application client. In fact, the UDP configuration would have provided a better estimation of the packet loss but would also have provided a worst estimation of the maximum data rate.

Table 3-22: Measured Solution moving train KPIs table

	Data Rate [Mbit/s]	One-way Latency ms (mean/min/max)	Residual packet loss rate (measured on TCP retransmissions)	Mobility Km/h	Power W/km
Overall system	539 - 223 - 933	2.35 - 0.36- 17.4	0.06 %	90	199.5

4. Smart City Demonstration

4.1 Network Integration and Demo setup

The University of Bristol (**UNIVBRIS**) has deployed a rich test network comprising several networking and Radio Access Technologies (RATs), interconnecting a significant area in the Bristol city centre. This test network provides a managed platform for the development and testing of new solutions delivering reliable and high-capacity network services to several applications demonstrating 5G-PICTURE Use Cases (UCs) as a tenant project within the test network.

The state-of-the-art RATs deployed at Millennium Square delivered high-bandwidth, high-bitrate and reliability connections to devices and to User Equipment (UE) as part of the test network. This way we enable the usage of this network-intensive distributed applications for the 5G-PICTURE demonstration.

In particular, we leverage the availability of LTE-Advanced (LTE-A) and 5G New Radio (NR) Non Stand Alone (NSA) with a NSA evolved EPC core network as part of the 5G-PICTURE demonstration to showcase applications that require mobility while keeping continuity of the user experience across multiple technologies.

4.1.1 Network architecture

To integrate the 5G-PICTURE equipment and its solution within the 5GUK test network, the network was designed and implemented as per the high-level architecture illustrated in ***Figure 4-1****.* This solution is spread across three different physical locations:

i. Smart Internet Lab (5GUK Test network) – also referred to as HPN research lab – housing the Data Centre (DC) and the cloud core network,
ii. Millennium Square and We the Curious (WTC), where the experiments were executed as part of the demonstration, and
iii. the M-Shed building and its rooftop, which hosts the 5G NR radio along with surveillance cameras as part of the smart city safety cameras.

Mobile Edge Computing (MEC) capabilities located both at the HPN lab in the form of an available DC and at the WTC site. The optical transport network exploited the installed fibre connecting the HPN lab with the WTC and the Millennium Square sites across the city of Bristol leveraging the Time Shared Optical Network (TSON) technology developed by **UNIVBRIS** in the framework of 5G-PICTURE [1].

Three different access technologies (5G, LTE and Wi-Fi), currently available at Millennium Square, were used for connecting the UE's to the network. **IHP**'s mmWave technology was exploited to support the wireless access network requirements of the UCs as well as end user equipment provided by the **UNIVBRIS** test network. In addition, Xilinx Dresden (**XDE**) active massive MIMO (mMIMO) Antenna Proof-of-Concept platform [1] was installed at the "Millennium Square" connected via TSON to the HPN Lab as part of the overall 5G-PICTURE demonstration.

Figure 4-2 shows the connectivity of the different access technologies integrated in the 5GUK test network and how TSON aggregates all the links and then disaggregates and delivers them to each specific destination at the Smart Internet Lab Data Centre.

The following sections provide more details regarding the **IHP** and **XDE** solution integrated with 5GUK test network.

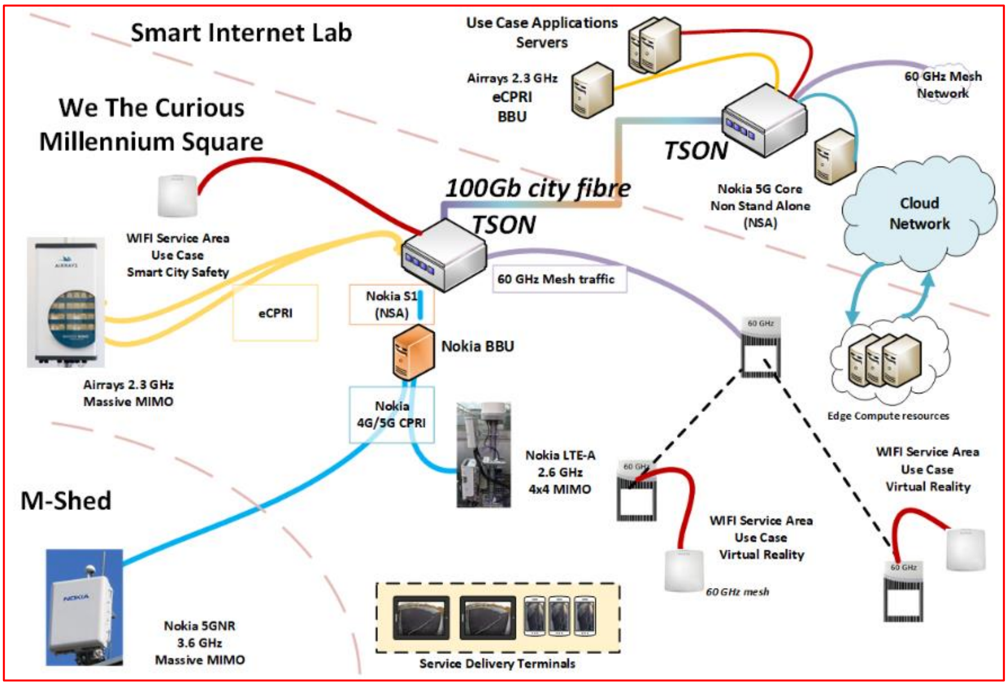


Figure 4-1: Overall connectivity and partners' equipment integration

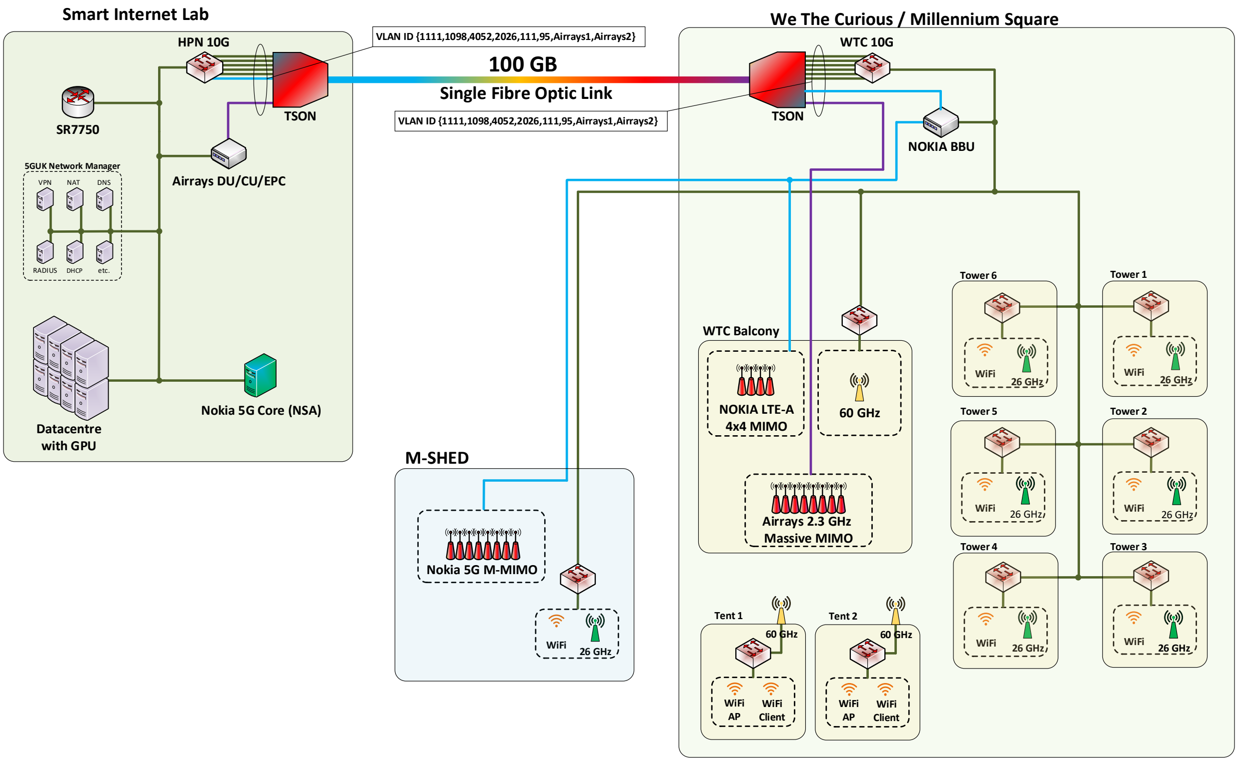


Figure 4-2: Top level design, Different access technologies and connectivity

4.1.2 IHP 60 GHz mesh network

To support the 5G-PICTURE's Smart City demo, **IHP** integrated three devices operating in the unlicensed 60 GHz band to the test network. These were used for backhaul wireless connectivity for the two abovementioned use cases - the Virtual Reality and the Safety Camera.

The master antenna located on the WTC balcony facing to the square, the other two antennas were installed on the tripods within the square near to the two tents. Each mmWave slave device acted as a standalone client and connected to master device using mmWave to create a bridge between service area Wi-Fi access point and the core network. During the demo, different UEs based on the two different use cases connected to these two Wi-Fi access points and those mmWave master slave connection provided a robust high capacity network connection to the Smart Internet Lab network. **Figure 4-3** shows the deployment of the mmWave solution within the 5GUK test network.

4.1.2.1 Setup description

One 60 GHz device (noted as AP) was installed on a specially designed fixture on the balcony of WTC building facing to the square, as shown in **Figure 4-4**. The uplink of the master was directly wired connected to the TSON using two separate switches on different levels of WTC building.

The AP installation height is at approx. 13 metres from the ground. The AP has a wired connection to the Smart Internet Lab, where the application servers for the two UCs are residing, via two TSON nodes and a fibre cable (see ***Figure 4-1*** OR ***Figure 4-3***).

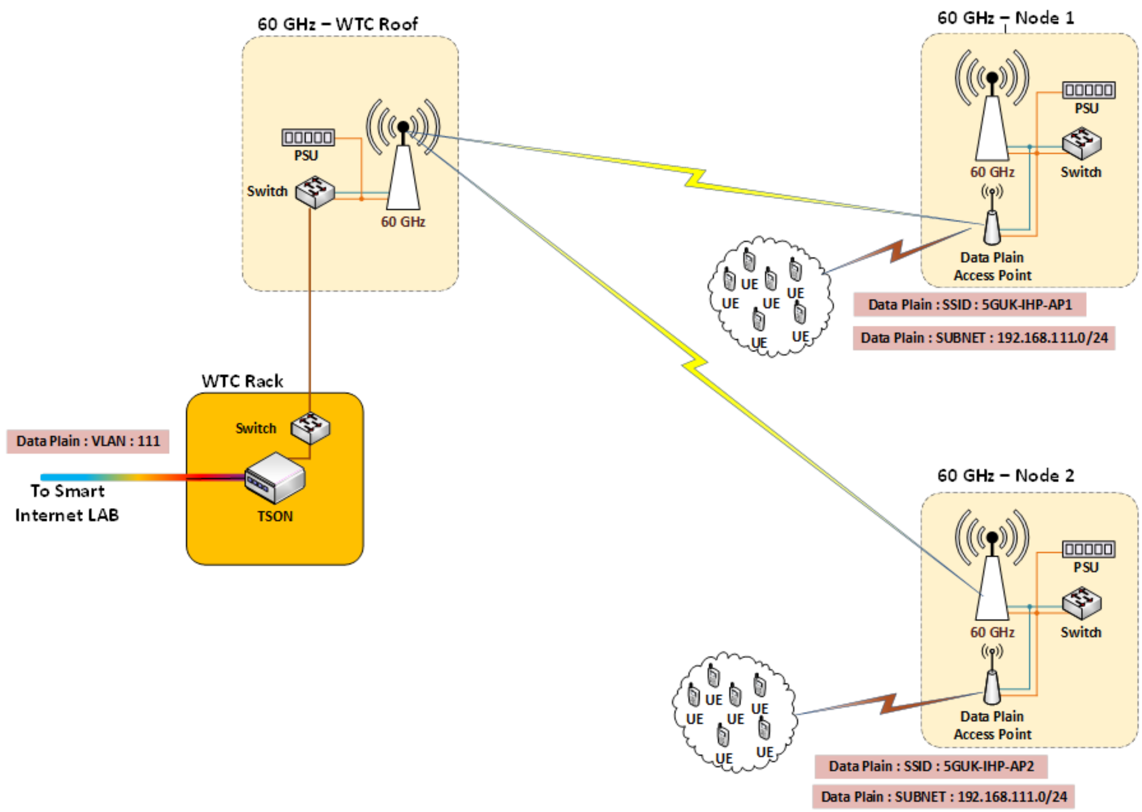


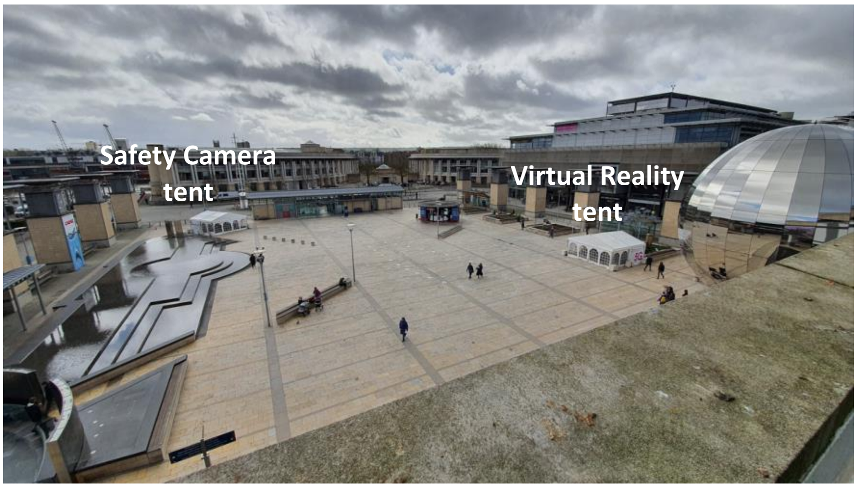
Figure 4-3: IHP 60 GHz network connectivity and integration with 5GUK Test network

Two tents are installed at Millennium Square at specifically selected locations, each for a distinct UC (see section 4.2 for more details), to host end-users (audience) during the demonstration. ***Figure 4-5*** shows the location of the tents at the square and the tents themselves.

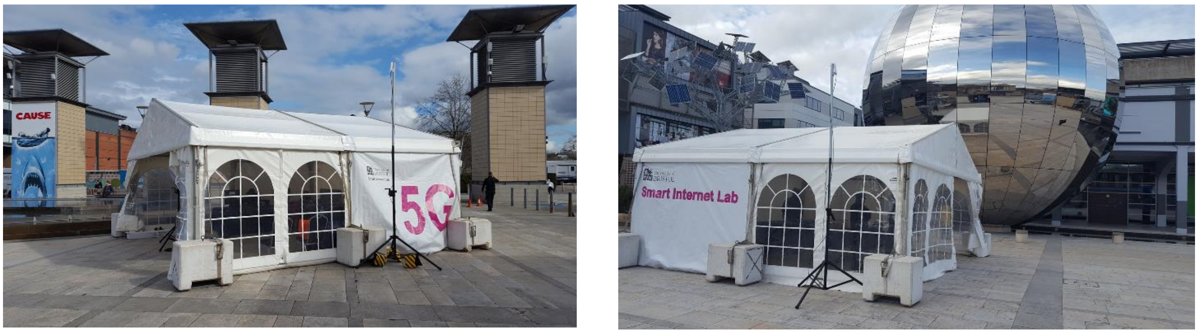
The real deployment in the field is shown in ***Figure 4-5*** a). At the same locations, near the tents, two 60 GHz devices (denoted STA) are deployed as depicted in ***Figure 4-5*** b) and c). Each 60 GHz STA is installed on a tripod at the height of 3 metres and faced towards the AP situated in the balcony of WTC. The approximate distances to this AP are 60 and 80 metres, respectively.

The three 60GHz devices form two mmWave wireless links in a Point-to-MultiPoint (P2MP) configuration. From the two end-points of the mmWave links at the square, additional connectivity is brought to the tents installed at the Millennium Square using a 10-m Ethernet cable. Each Ethernet cable is then attached to a 1 Gbit/s Ethernet switch to which a Wi-Fi Access Point (AP) operating in the 2.4/5 GHz bands was connected. The Wi-Fi APs are acting as service area Wi-Fis and are providing connectivity to end-users (i.e. audience) for the purpose of the demo.

Figure 4-4: Deployment of the 60 GHz AP at the rooftop of the WTC. The left figure shows the building seen from Millennium Square, and the right figure shows the 60GHz AP device mounted on a fixture. In the background, a massive MIMO antenna from XDE is visible.



a)



b) c)

Figure 4-5: a) Tents installed in Millennium Square. Two 60 GHz STA devices mounted on tripods at approx. 3 metres height and deployed in the Millennium Square near b) the tent for the Safety Camera use case and c) the tent for the Virtual Reality use case.

Because of unforeseen complications due to the COVID-19 pandemic, **IHP** was not able to provide its proprietary 60 GHz solution for the demonstration, but has instead used commercial-of-the-shelf (CoTS) devices from Mikrotik as a replacement.

In the next subsection, we provide a brief overview of the hardware (HW) that was used in the mmWave part of the Smart City Demo. **IHP**'s 60 GHz solution is covered in section 4.1.2.3.

4.1.2.2Hardware used in the Demo

For the final 5G-PICTURE Smart City demonstration we used three 60 GHz devices from Mikrotik to set up the P2MP mmWave configuration. Two Wi-Fi APs from GL-iNet were used to provide wireless coverage in the tents together with additional equipment such as Ethernet switches, cables, etc. These devices are shown in ***Figure 4-6***.

The main features of the 60 GHz Mikrotik device are summarised in the following bullets.

- Mikrotik 60GHz wAPx3 solution
- WiGig/802.11ad compliant
- Supports all four IEEE 802.11ad channels, each 2.16 GHz wide
- Supports SC-PHY; up to Modulation-Coding Scheme (MCS) 8 (max PHY data rate 2.3 Gbit/s)
- 180-degree Field of View (FoW) with three (3) phased-array antennas (each 60-degree FoW)
- Single antenna array has 32 antenna elements (64 beam patterns)
- EIRP < 40 dBm
- 1 Gbit/s Ethernet connection with PoE
- Supports P2MP up to 8 stations
- Power consumption < 5 W

As a service area Wi-Fi inside the tent, we have used a solution from GL-iNet, called GL-AR750s/Slate. The main features are given bellow.

- Dual-band Wi-Fi 2.4/5 GHz
- 802.11 b/g/n/ac
- 3x LAN Port with 10/100/1000 Ethernet connection
- Transmit power of 20 dBm
- Two external antennas of 2 dBi each

In addition, we have used two 8-port manageable 1 Gbit/s network switches from Netgear.

60 GHz device

[source: www.mikrotik.com]

a)

Service area Wi-Fi

[source: www.gl-inet.com]

b)

Switch

[source: www.netgear.com]

c)

Figure 4-6: The equipment used in the mmWave part of the Demo a) 60GHz wAPx3 from Mikrotik, b) 2.4/5GHz Wi-Fi AP from GL-iNet, and c) 8-port manageable Eth. switch from Netgear

4.1.2.3 IHP's 60 GHz solution

Device description

In recent years, **IHP** has been working on a new, improved version of its 60 GHz solution to support beamforming and point-to-multipoint (P2MP) functionality. To this end, in the scope of 5G-PICTURE project, we have developed an FPGA-based platform that supports software-defined radio (SDR) for baseband and MAC processing. This platform has been reported in deliverables D3.1-D3.3 [1][20]. Furthermore, we have also developed a P2MP MAC processor that has also been reported in D3.3. The main characteristics of the developed 60 GHz solution are given in the next following paragraphs.

Baseband

The baseband core is based on a proprietary C-OFDM solution [21]. The employed OFDM physical (PHY) layer uses in-total 1024 subcarriers, out of which 768 are data and 60 are pilot subcarriers. The remaining 196 subcarriers are guard and zero subcarriers. With the sampling frequency of 2160 MHz, the subcarrier spacing is approximately 2.11 MHz, and the duration of an OFDM symbol equals 592.6 ns. The effective modulation bandwidth is around 1.76 GHz. To cope with channel errors, a Forward Error Correction (FEC) based on an inner code and an outer code is used. The inner code is a standard (133, 171) convolutional code and the outer code is a (239, 255) Reed-Solomon code. The baseband processor supports 7 modulation-coding schemes, spanning from 630 Mbit/s using BPSK to 3.9 Gbit/s PHY data rate using 16QAM modulation.

P2MP MAC

The P2MP MAC processor has been presented in details in deliverables D3.2 and D3.3 [19] [20]. Here, we give a brief overview of main features:

- Master – slave TDMA approach
- Single hop communication
- Currently two slave nodes are supported (extension up to eight is possible)

RF BF transceiver

The RF Beamforming (BF) module is based on a commercial 60 GHz beamforming chipset from SiversIMA [22][23]. It operates in the 57-66 GHz frequency band and uses zero-IF architecture. The beamforming transceiver comprises of 16 Tx and 16 Rx channels with separate Tx and Rx antennas. It supports maximum 64 beam vectors in a beam book and achieves the EIRP of 40 dBm. The integrated 60 GHz device is shown in ***Figure 4-7***.

Figure 4-7: IHP's 60GHz solution

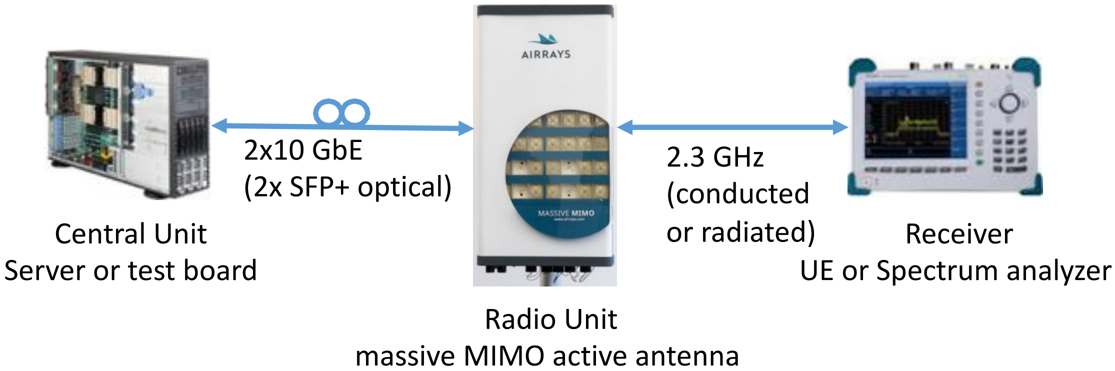


Figure 4-8: Xilinx Dresden setup

4.1.3 Xilinx Dresden 2.3 GHz Massive MIMO

XDE brought an active massive MIMO Antenna Proof-of-Concept platform Radio Unit (RU), along with a Central Unit (CU) server solution emulating the base band processing along with a spectrum analyser as receiver emulating a UE function. An overview of the targeted setup is shown in ***Figure 4-8***.

The massive MIMO antenna unit was installed on the WTC balcony shining to the square while the DU/CU Emulator was located at the Smart Internet Lab Data Centre. These two nodes were connected via two dedicated fibre links (one for Control Plane and another for Data Plane) between the RU and the DU/CU through TSON. The control plane integrated with 5GUK test network core to serve services such as DHCP, DNS and remote access to the equipment via Internet using OpenVPN. The receiver was a spectrum analyser installed in one of the tents during the demonstration day.

The Fronthaul interface between CU and RU transports were eCPRI/xRAN frames as payload of standard 10 GbE Ethernet and the link was established using the TSON. ***Figure 4-9*** shows the implementation and the integration between DU/CU and the radio unit using 5GUK test network.

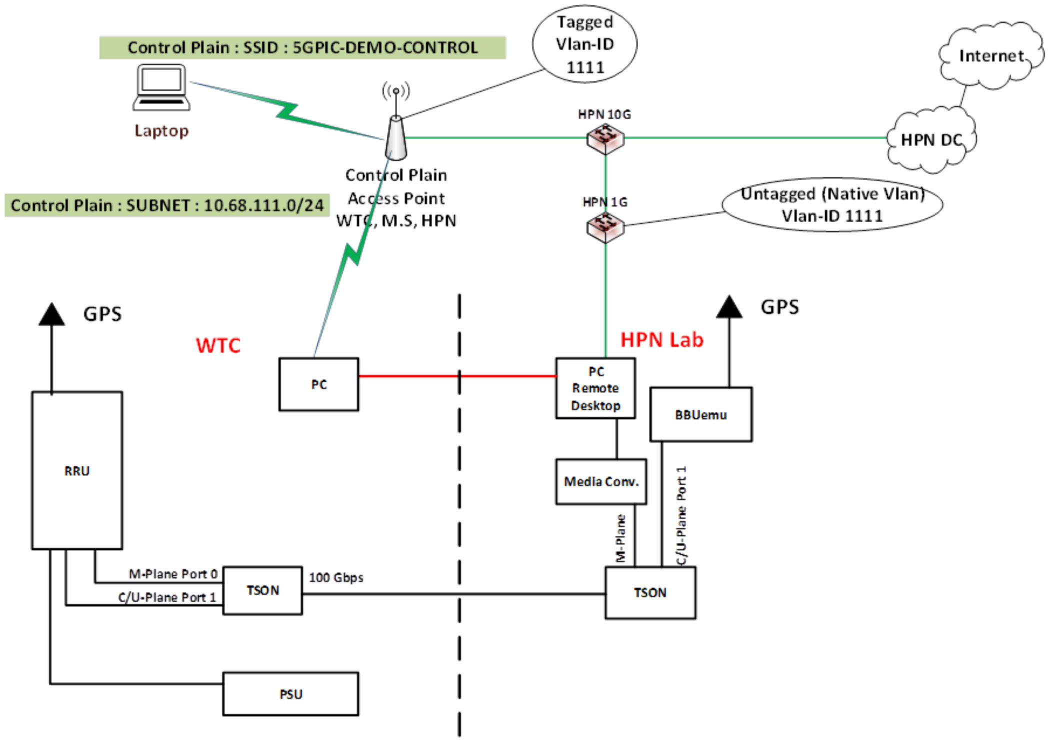


Figure 4-9: XDE network connectivity and integration with 5GUK Test network

4.1.3.1Evaluation overview

As discussed in previous deliverables, the XDE massive MIMO RU is a proof-of-concept platform to demonstrates the benefits both of Sub-6 GHz mMIMO as well as the functional split 7.2 and corresponding fronthaul interface. Initial testing of the antenna had already taken place at an outdoor site at TUD. For final evaluation, the RU was deployed at the 5GUK Testbed in Bristol, where it was also integrated with UNIVBRIS's TSON technology. The challenges addressed by this evaluation where:

- mMIMO is a very challenging technology, which requires a tightly calibrated hardware to produce sharp and steerable beams. The evaluation aimed at showing that this works in the field.
- Due to the new functional split 7.2, the RU has to perform a large amount of digital processing, which requires the integration of additional functions and hardware directly in the antenna deployed at an outdoor pole. The evaluation aimed at showing that these functions have been successfully implemented in the XDE proof-of-concept platform.
- The RU implement a fronthaul interface based on the new eCPRI/O-RAN fronthaul standard, which uses packetized Ethernet as an underlying technology. The evaluation aimed at showing that the interface has been successfully implemented and packetized fronthaul performs as expected.
- The RU implements O-RAN's management interface, also referred to as management Interface (M-Plane). The M-Plane provides a standardized interface and API that allows operators to control and manage RAN equipment without the need to deal with vendor-proprietary interfaces as currently is still the case. This new approach will greatly simplify network management and deployment of new equipment. The evaluation aimed at showing that this interface has been successfully implemented and is working as expected.
- In the fronthaul link, TSON technology will be used to connect the RU to its baseband and aggregate fronthaul and M-Plane traffic onto a single link. The evaluation aimed at showing that TSON can interoperate with the mMIMO RU and RAN performance is not affected.

4.1.3.2Setup

An overview of the setup is given in ***Figure 4-10*** The RU was deployed on the roof of the WTC museum at Millennium square in Bristol. The RU has two 10G Ethernet links, one for the fronthaul traffic (in O-RAN called C-/U-Plane), and one for the M-Plane. Both are connected to a TSON node, which aggregates the 2x10G links onto a single 100G link.

The 100G link connects to the Smart Internet Lab in **UNIVBRIS** where a second TSON node dis-aggregates the 100G again to 2x10G links. One of the 10G links is connected to the **XDE** Distributed Unit (DU) emulator, which provides a baseband for the RU. The DU emulator basically just streams stored I/Q samples to the RU.

The second 10G links is connected with **UNIVBRIS** network, which is accessible via Wi-Fi at Millennium Square. A control laptop is deployed in Millennium square to manage the RU and for showing the final demonstration. Furthermore, a portable spectrum analyser is deployed at Millennium square, which receives the radio signal form the RU via a simple dipole antenna and evaluate the radio link performance.

The overall setup was successfully deployed and tested in the 2 weeks before the final demonstration from March 2 – March 13 2020.

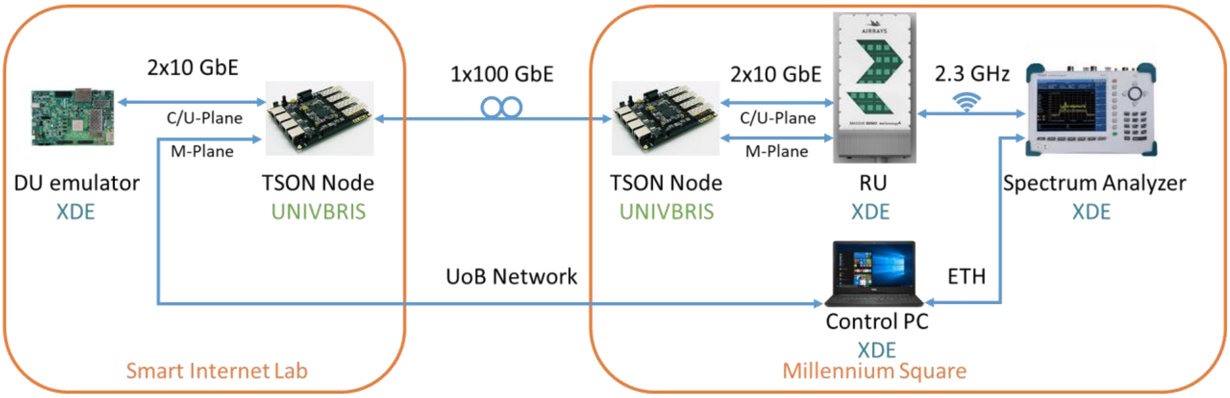


Figure 4-10: Overview over mMIMO setup

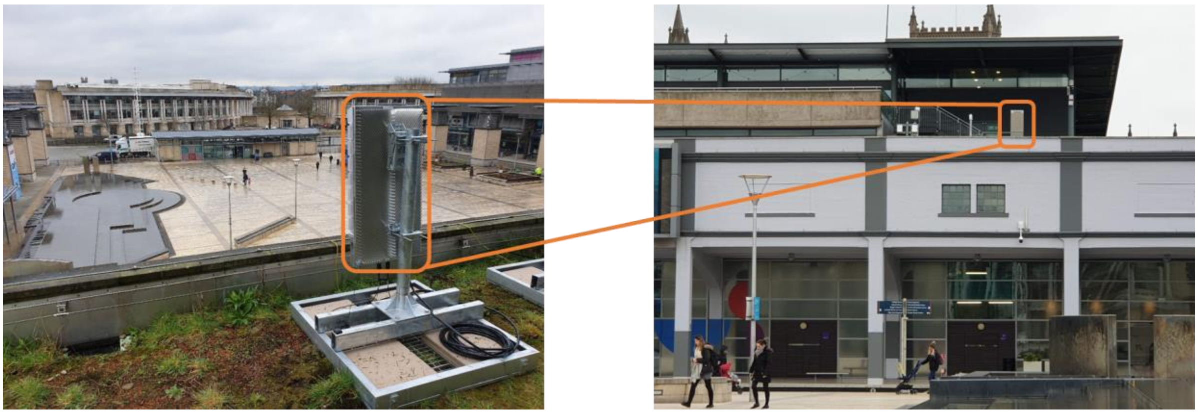


Figure 4-11: mMIMO deployment in Bristol Testbed: radio unit mounted on top of "We the Curious"

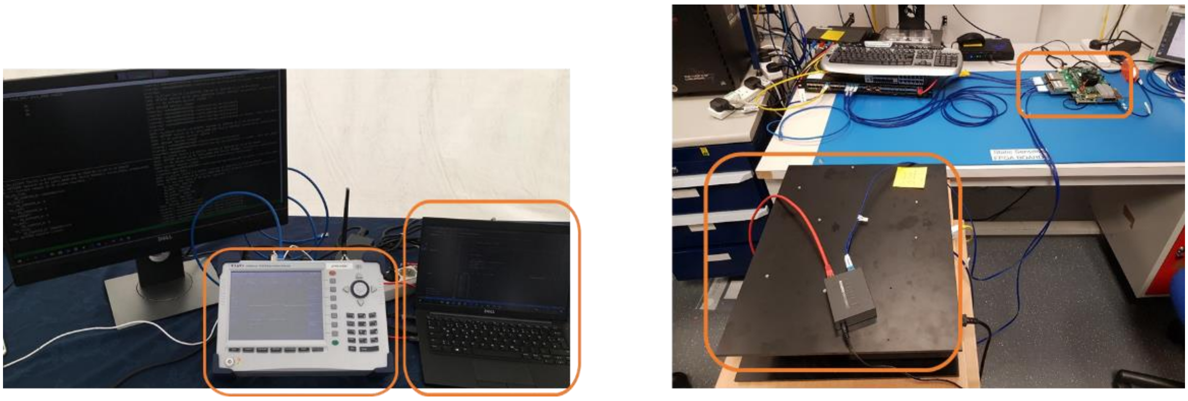


Figure 4-12: mMIMO deployment in Bristol Testbed: Left side: spectrum analyser (centre) and control laptop (right) at Millennium Square. Right *side: distributed Unit Emulator (bottom left) and TSON Node (top right) at Smart Internet Lab*

Table 4-1: The access and fronthaul technologies implemented for the use cases

	Access Technologies	Fronthaul Technologies
5G-PICTURE Technologies	Wi-Fi (5GHz) from IHP's 60 GHz	IHP's 60 GHz multi-gigabit single-hop wireless communication
Smart Internet Lab Infrastructure	5GNR (3.5 GHz), LTE (2.6 GHz), Wi-Fi (5 GHz)	Fibre Optic Links

Figure 4-11 shows two photographs of the RU deployed on the roof of "We The Curious". ***Figure 4-12*** shows the spectrum analyser and control laptop deployed inside a tent on Millennium square. A monitor for better viewing is also visible. Finally, ***Figure 4-12*** shows the DU emulator (covered under a black protective board, the DU emulator is in principle an evaluation board similar to the TSON nodes), as well as the TSON node at the Smart Internet Lab.

4.2 Use cases

Based on the integrated solutions, two use cases demonstrated in the Millennium Square. The access and fronthaul technologies implemented can be seen in ***Table 4-1*** for these UCs:

4.2.1 Smart City Safety

This use case monitored the area with audio and video sensors. These sensors were deployed in a bike helmet while attached to a Raspberry PI (RP) that communicates via Wi-Fi to the Cloud or Edge (MEC – Mobile Edge Computing). The RP sends video and audio to be processed in a DC. Using VNFs. The overall ecosystem is designed to perform audio and video transcoder functions within the network. In addition, audio and video processing are possible using machine learning at the Edge or core to detect suspicious activities in the area (city). Once the suspicious activities have been detected the system is able to notify the security department with the right information. Based on the information the security guards spread in different location will be able to take the right action.

Figure 4-13 shows the smart city UC architecture. The setup equipped with the following cameras:

- 2 x 360-degree cameras on 2 bike helmets with each attached to a Raspberry Pi.
- 2 x Fixed IP cameras that installed on the M-Shed roof to create alerts when anybody become close to the 5GNR during its operation on the roof top.

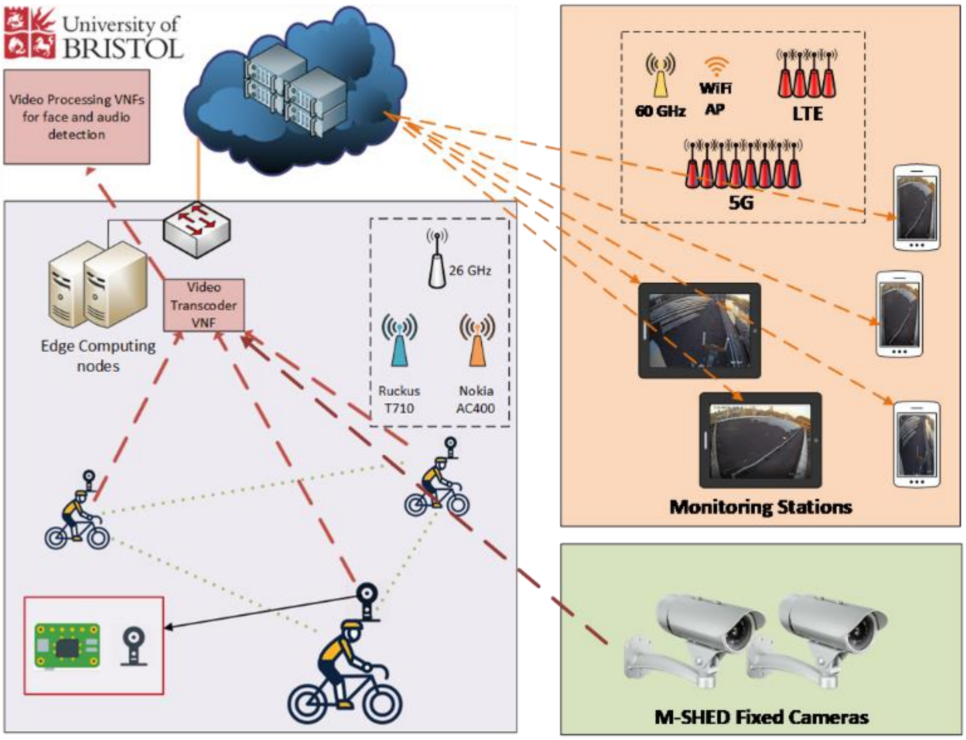


Figure 4-13: Smart City Safety use case architecture

All cameras sending video to the cloud network using the face detection software for illustration at the demonstration. Other analytics capture or functions such as face recognition were disabled in the network to comply with the GDPR for the demonstration.

The processing functions run as VNFs on the 5GUK test network cloud infrastructure. The end-user (e.g security officer) can access the video server to use the services, for this purpose 6 x monitoring station were deployed for real time monitoring and watching the analysed video from the cameras. On the demo date we had a following setup of monitoring stations:

- 2 x Samsung S10-5G phones with 5G network connectivity.
- 1 x Samsung S9 with LTE network connectivity.
- 1 x Samsung S9 with Wi-Fi network connectivity based on **IHP** 60 GHz Mesh network.
- 1 x Tablet with Wi-Fi network connectivity based on **IHP** 60 GHz Mesh network.
- 1 x Tablet with LTE network connectivity.

Figure 4-14 shows the smart city safety UC equipment.

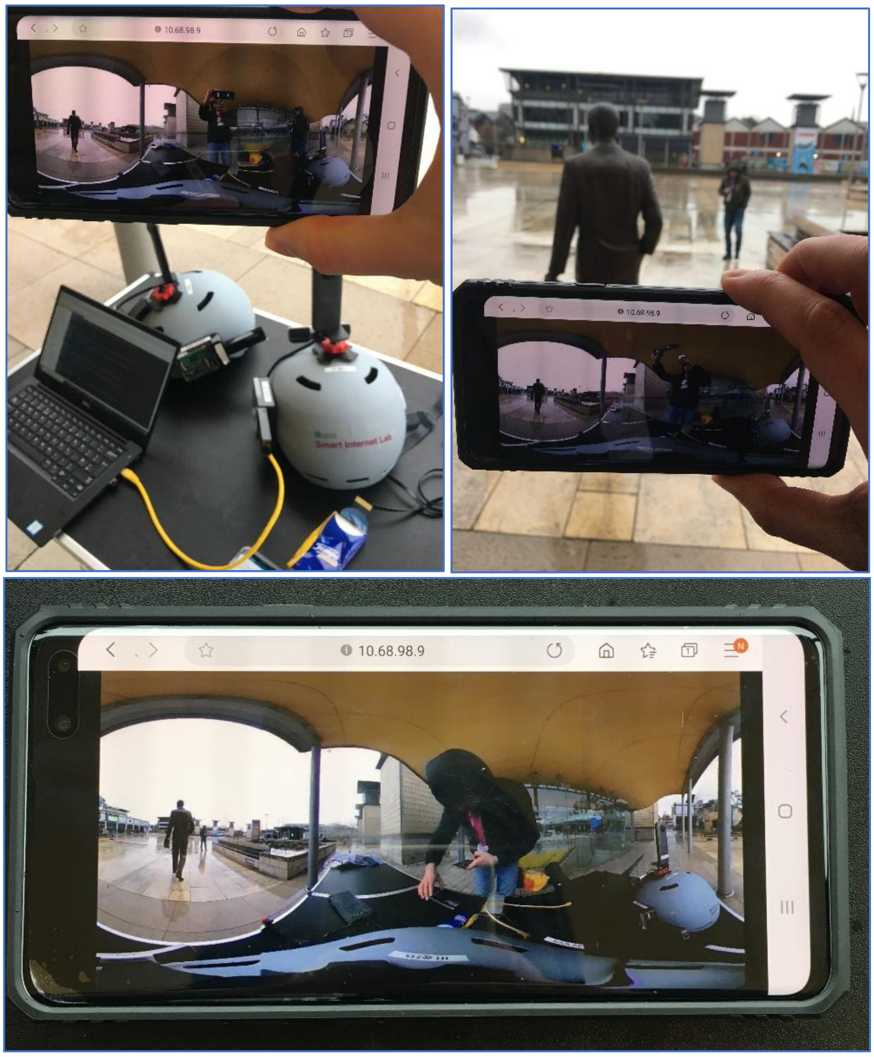


Figure 4-14: Smart City Safety UC

4.2.2 Virtual reality

This creative & production processes includes visual and audio data capture of an artist performing in a private space in Bristol. The use case creation will involve working with the artists and development team in order to expand the visuals into a real-life environment around Millennium Square in Bristol. An audio specialist will work on the soundtracks, so it adapts to the environment, while the development team further creates the data into an Augmented Reality experience.

The music artist leads the ritual-like audio experience through her holographic persona, whilst each participant assumes the virtual form of an anthropomorphic character. The experience allows a group of guests wearing VR headsets and headphones to get lost within a 10-metre virtual space, alongside the holographic capture of Devi herself. Individual instrument tracks from the featured music piece are scattered around the environment, making the music sound different from every position; whilst guests can playfully interact with each other through their virtual avatar alter-egos.

Figure 4-15 shows the Virtual reality screenshot captions and presents the virtual reality experiment at demo day displays the target KPIs for this demonstration.

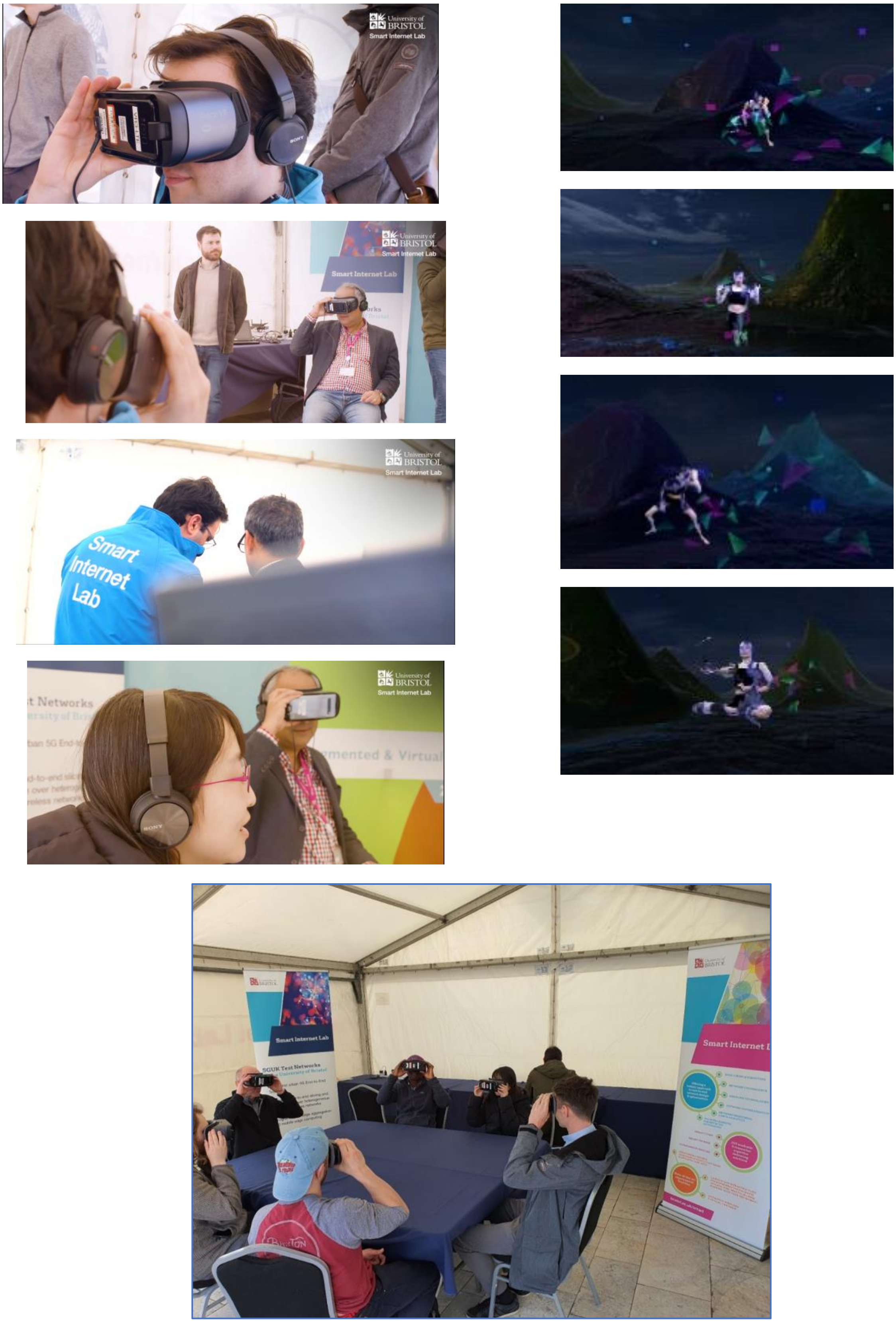
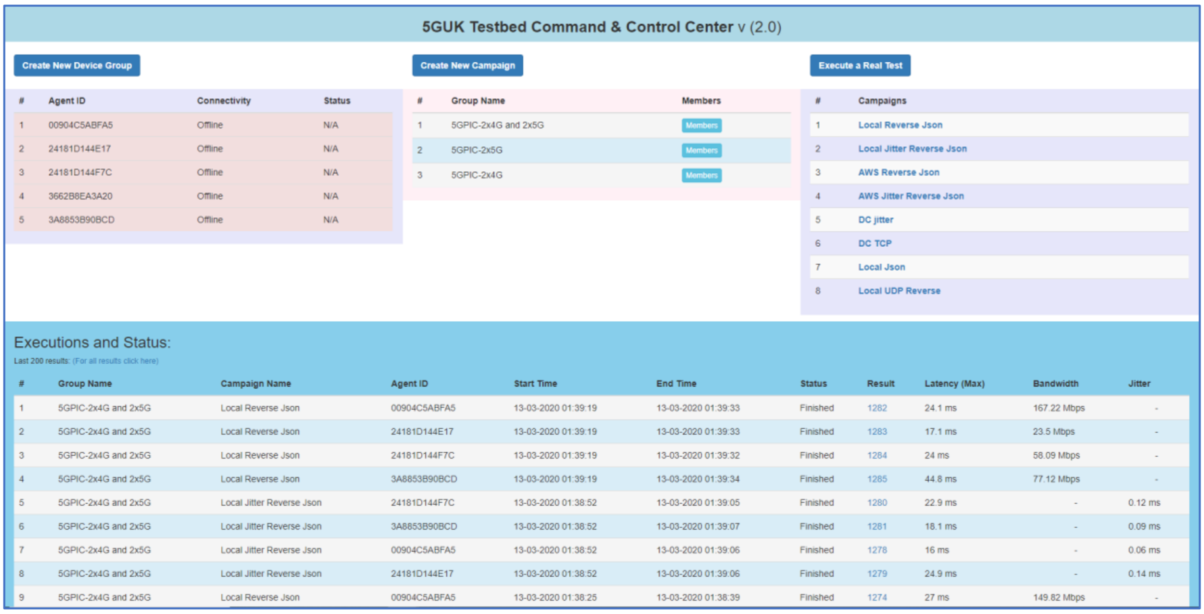


Figure 4-15: Virtual Reality experiment at demo day

4.3 Demonstration tools and results

4.3.1 Tools for monitoring and measurements

As it can be seen in ***Figure 4-16***, 5GUK test network used its owned developed tool for measuring and monitoring the capacity of designed network on different access technologies, especially for 5G and LTE.


5GUK Testbed Command & Control Center v (2.0)

Create New Device Group

Create New Campaign

Execute a Real Test

#	Agent ID	Connectivity	Status
1	00904C5ABFA5	Offline	N/A
2	24181D144E17	Offline	N/A
3	24181D144F7C	Offline	N/A
4	3662B8EA3A20	Offline	N/A
5	3A8853B90BCD	Offline	N/A

#	Group Name	Members
1	5GPIC-2x4G and 2x5G	Members
2	5GPIC-2x5G	Members
3	5GPIC-2x4G	Members

#	Campaigns
1	Local Reverse Json
2	Local Jitter Reverse Json
3	AWS Reverse Json
4	AWS Jitter Reverse Json
5	DC jitter
6	DC TCP
7	Local Json
8	Local UDP Reverse

Executions and Status:

Last 200 results: (For all results click here)

#	Group Name	Campaign Name	Agent ID	Start Time	End Time	Status	Result	Latency (Max)	Bandwidth	Jitter
1	5GPIC-2x4G and 2x5G	Local Reverse Json	00904C5ABFA5	13-03-2020 01:39:19	13-03-2020 01:39:33	Finished	1282	24.1 ms	167.22 Mbps	-
2	5GPIC-2x4G and 2x5G	Local Reverse Json	24181D144E17	13-03-2020 01:39:19	13-03-2020 01:39:33	Finished	1283	17.1 ms	23.5 Mbps	-
3	5GPIC-2x4G and 2x5G	Local Reverse Json	24181D144F7C	13-03-2020 01:39:19	13-03-2020 01:39:32	Finished	1284	24 ms	58.09 Mbps	-
4	5GPIC-2x4G and 2x5G	Local Reverse Json	3A8853B90BCD	13-03-2020 01:39:19	13-03-2020 01:39:34	Finished	1285	44.8 ms	77.12 Mbps	-
5	5GPIC-2x4G and 2x5G	Local Jitter Reverse Json	24181D144F7C	13-03-2020 01:38:52	13-03-2020 01:39:05	Finished	1280	22.9 ms	-	0.12 ms
6	5GPIC-2x4G and 2x5G	Local Jitter Reverse Json	3A8853B90BCD	13-03-2020 01:38:52	13-03-2020 01:39:07	Finished	1281	18.1 ms	-	0.09 ms
7	5GPIC-2x4G and 2x5G	Local Jitter Reverse Json	00904C5ABFA5	13-03-2020 01:38:52	13-03-2020 01:39:06	Finished	1278	16 ms	-	0.06 ms
8	5GPIC-2x4G and 2x5G	Local Jitter Reverse Json	24181D144E17	13-03-2020 01:38:52	13-03-2020 01:39:06	Finished	1279	24.9 ms	-	0.14 ms
9	5GPIC-2x4G and 2x5G	Local Reverse Json	00904C5ABFA5	13-03-2020 01:38:25	13-03-2020 01:38:39	Finished	1274	27 ms	149.82 Mbps	-

Figure 4-16: Monitoring and Measurements tools developed by 5GUK test network

To achieve this purpose, 2 x Samsung S10 5G and 2 x Samsung S9 LTE phones used (***Figure 4-17***). Using this tool an end to end test run between all UEs to the 5GUK test network Datacentre simultaneously. This means that the 4 UEs start to download or upload data to specific server in the DS to measure their links capacity several times. During these 100 tests that run in a different location in the Millennium Square, parameters like bandwidth, latency and jitter recorded in a database then results analysed by Elasticsearch and Following graphs are showing the results. ***Figure 4-18*** shows the maximum throughput between UEs and the server in different access technologies within all tests. The minimum, average and maximum latency and jitter are presented in ***Figure 4-19*** and ***Figure 4-20***, respectively. ***Figure 4-21*** shows the maximum re-transmitted packets. In addition, the geolocation distribution of throughput for the download scenario, and latency are reveals in ***Figure 4-22*** and ***Figure 4-23***, respectively.

Figure 4-17: Phones which were used for Measurements

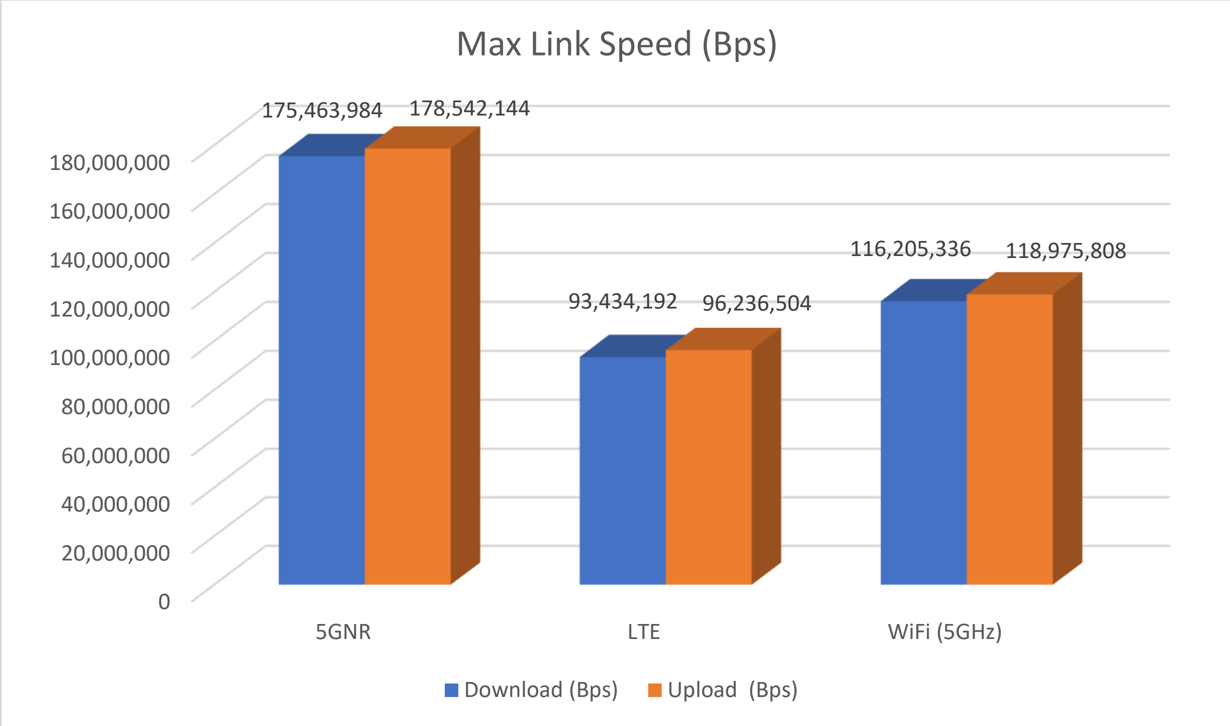


Figure 4-18: End-to-end Maximum throughput

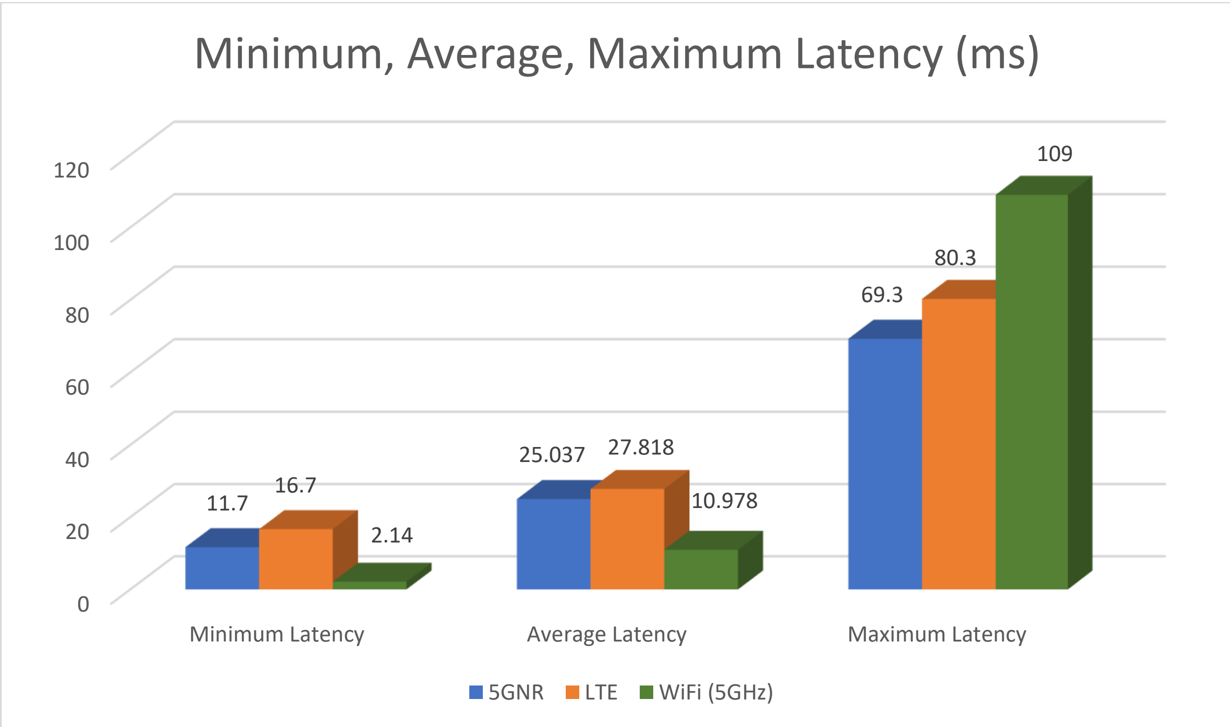


Figure 4-19: Minimum, Average and Maximum latency

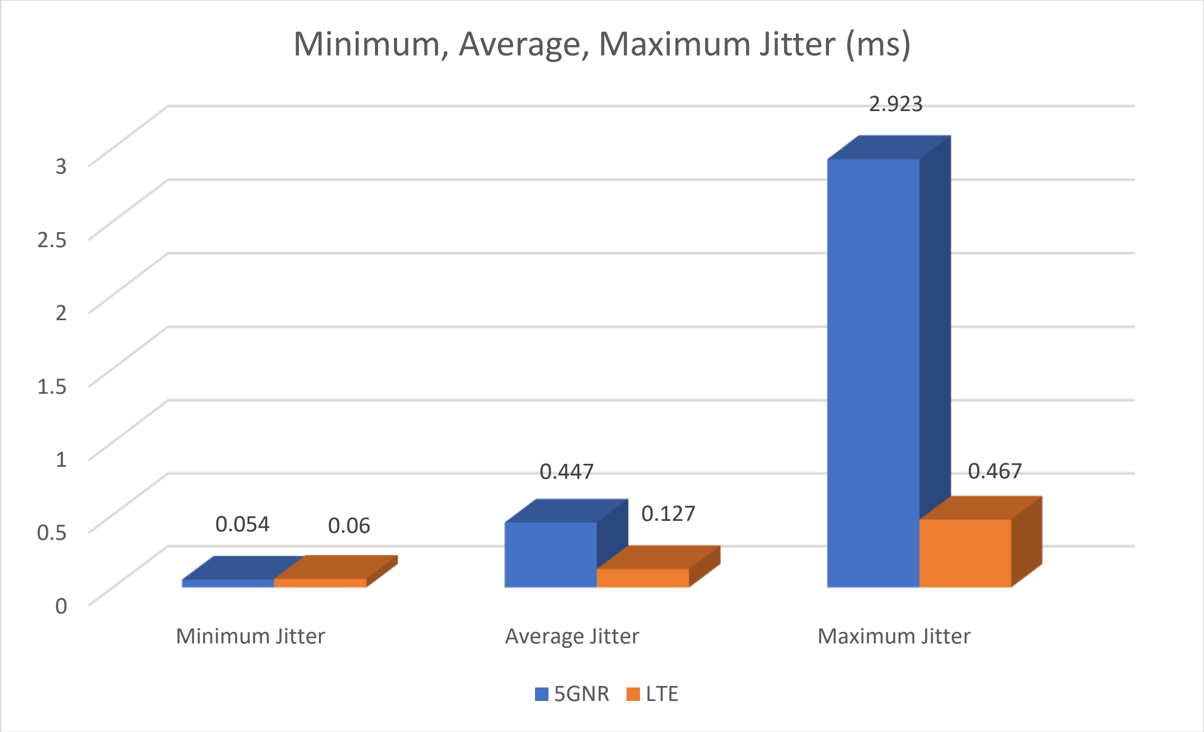


Figure 4-20: Minimum, Average and Maximum jitter

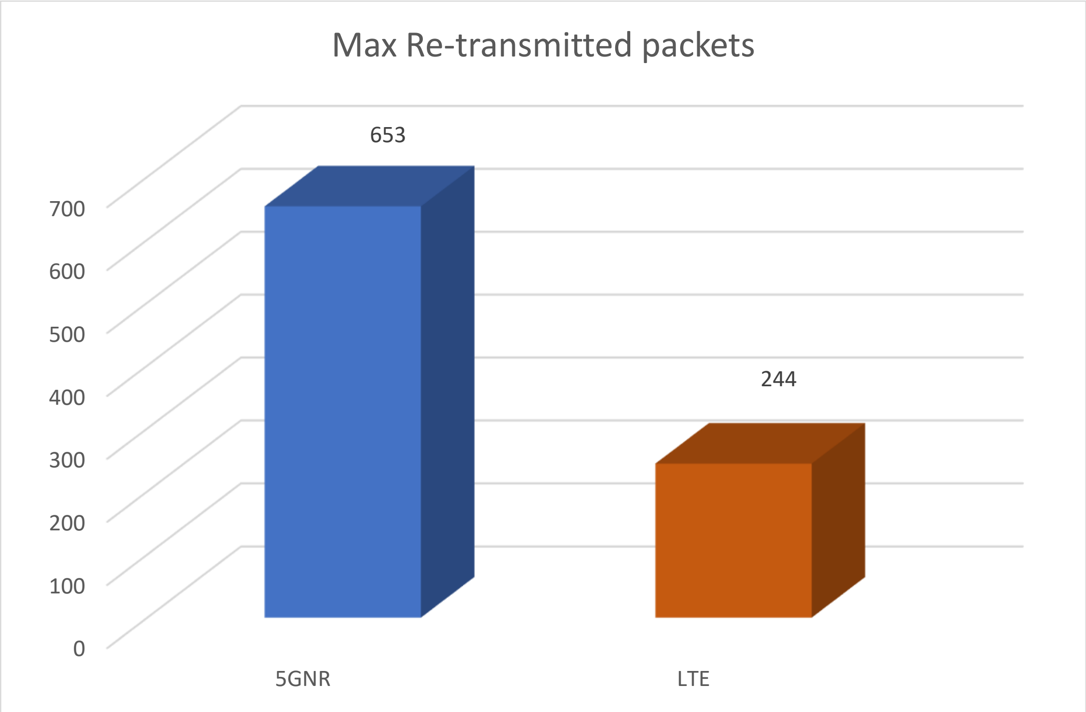


Figure 4-21: Maximum re-transmitted packets

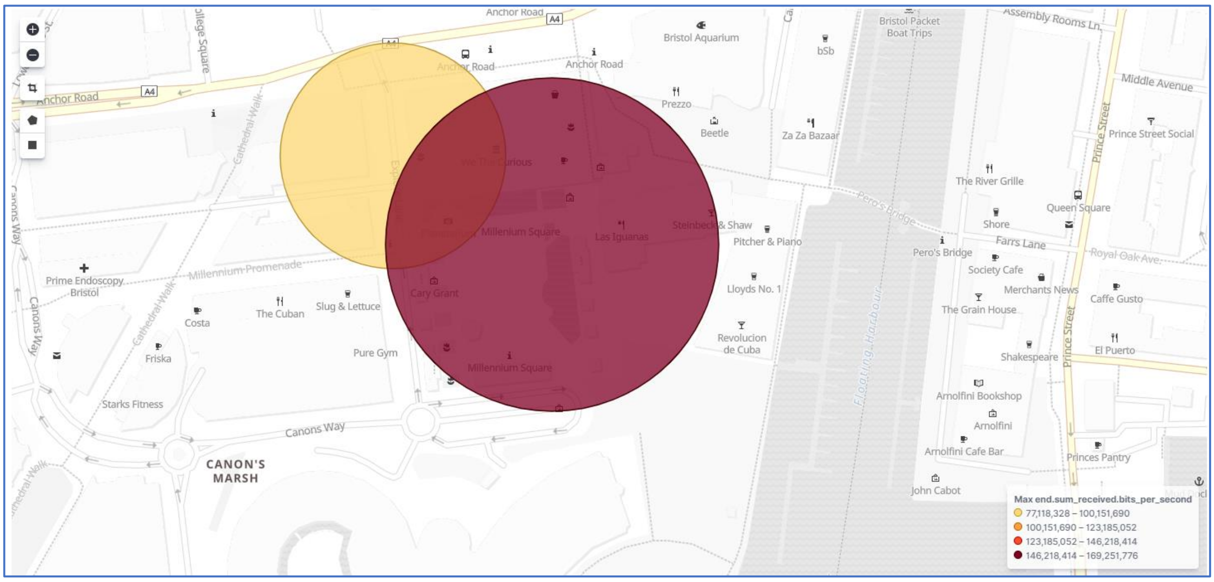


Figure 4-22: Geolocation distribution of throughput (Download)

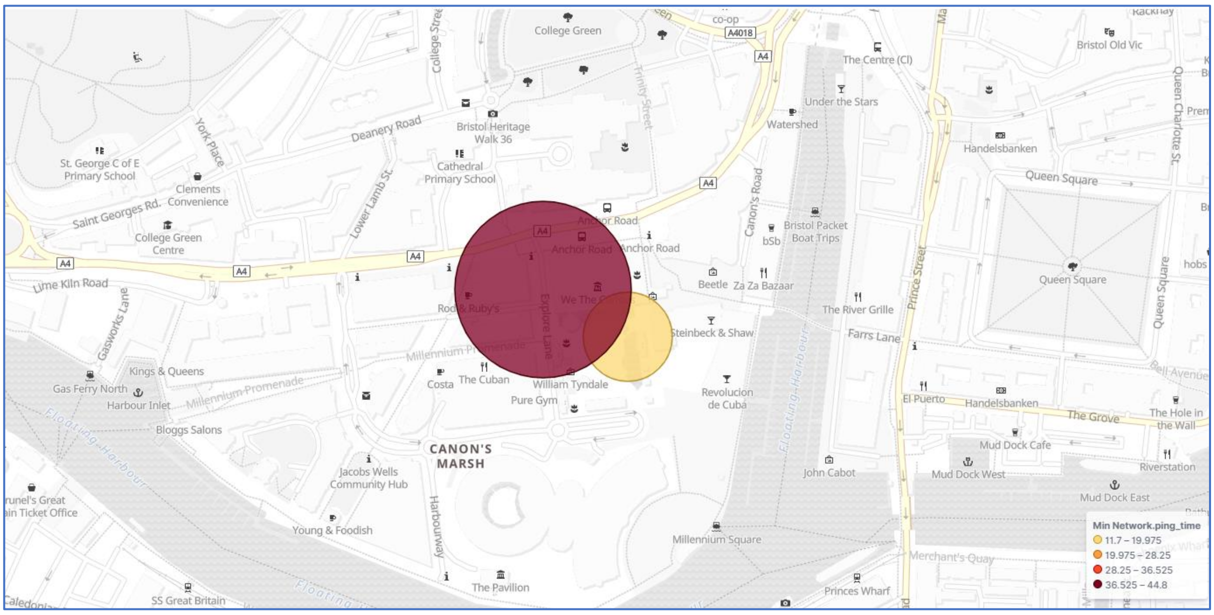


Figure 4-23: Geolocation distribution of Latency

4.3.2 Results and KPIs

For each UC, different validation of KPIs was considered. ***Table 4-2*** shows the KPIs and the type and expected values for each UC. For the KPIs, the radio network node capacity, minimum throughput, at acceptable latency was considered.

Table 4-2: UCs Demonstrator expected KPIs

Use Cases KPIs	UC1: Smart City Safety	UC2: Virtual Reality
Radio Network node capacity	Equipment – Specific to the Access Technology Expected to be greater than 50 Mbit/s	Equipment – Specific to the Access Technology Expected to be greater than DL ~ 30 Mbit/s & UL ~ 1 Mbit/s

Throughout	Equipment – specific to the cameras used Expected to be greater than 3 Mbit/s per device	Equipment – specific to the cameras used Expected to be less than DL ~ 3 Mbit/s & UL ~ 100 kbit/s
Latency	Between the Device and the Cloud serving node Expected < 50 ms	Between the Device and the Cloud serving node Expected < 35 ms

Based on the mentioned KPIs, during the demonstration, data were captured by 5GUK test network based on Zabbix monitoring tool by putting monitoring probs on different equipment of the testbed network. The graphs (***Figure 4-24***, ***Figure 4-25***, ***Figure 4-26*** and ***Figure 4-27***) show the bandwidth (Download and Upload) for data plane at different times of the day and the graphs (***Figure 4-28***, ***Figure 4-29***, ***Figure 4-30*** and ***Figure 4-31***) show the bandwidth usage by each use case.

At present no conclusion is provided other that it should be noted this is an experimental test network and radio technology parameters are not as optimised as a commercial network.

To explain the relationship between the captured data and the KPIs, let's start from the overall data transferred between the 5G capable UEs and also the UEs which are connected to the Network using WiFi with **IHP** fronthaul connection.

In figures ***Figure 4-24*** to ***Figure 4-27***, total network throughput is presented, where ***Figure 4-24*** and ***Figure 4-25*** are the total throughput of the 5GNR radio. In these figures, the light blue indicates the overall download speed in Mbit/s and the dark blue indicate the overall Upload speed in Mbit/s by the UEs under test. These are the sum of all 5G enables UEs including two UEs for Smart City Safety use case and two UEs for Virtual Reality use case. As it is visible the maximum throughput was about 30 Mbit/s and the average was about 5 Mbit/s during the demonstration day.

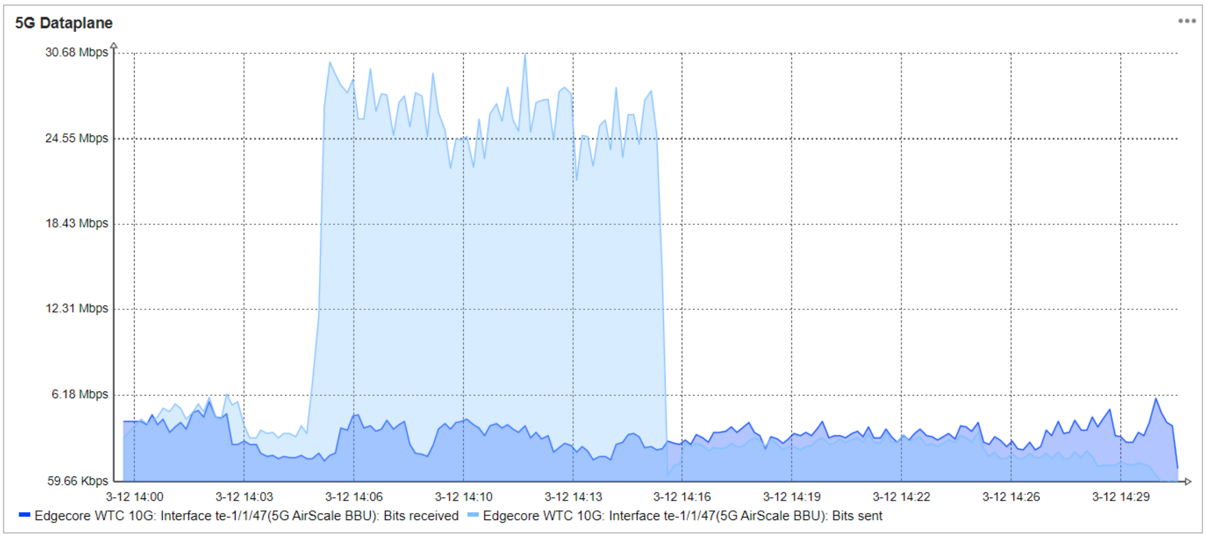


Figure 4-24: 5GNR Data plane network traffic – March 12th between 14:00 to 14:30

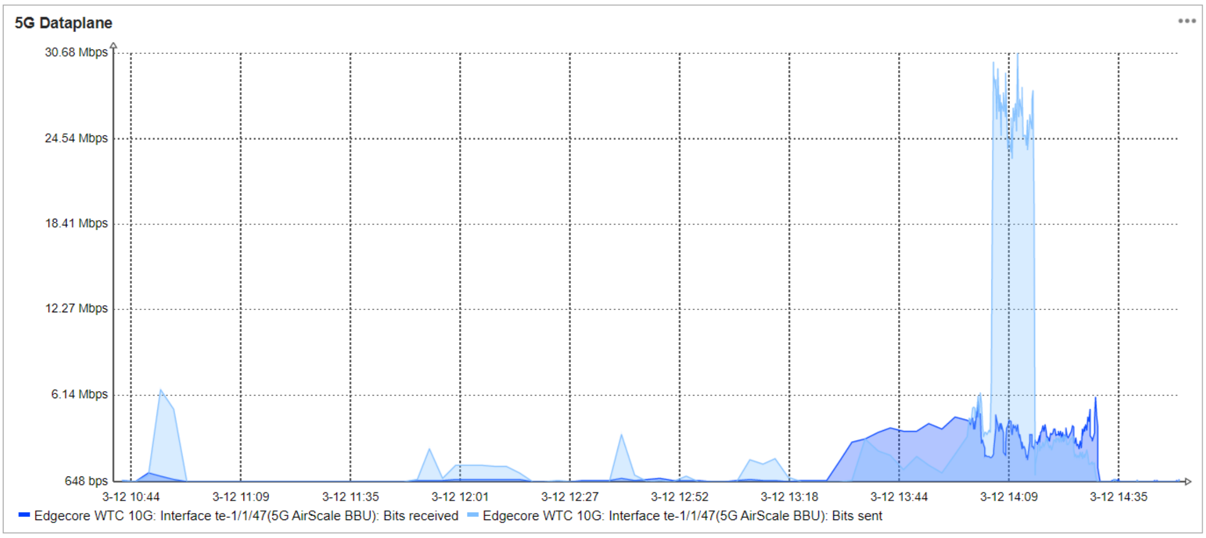


Figure 4-25: 5GNR Data plane network traffic – March 12th whole day

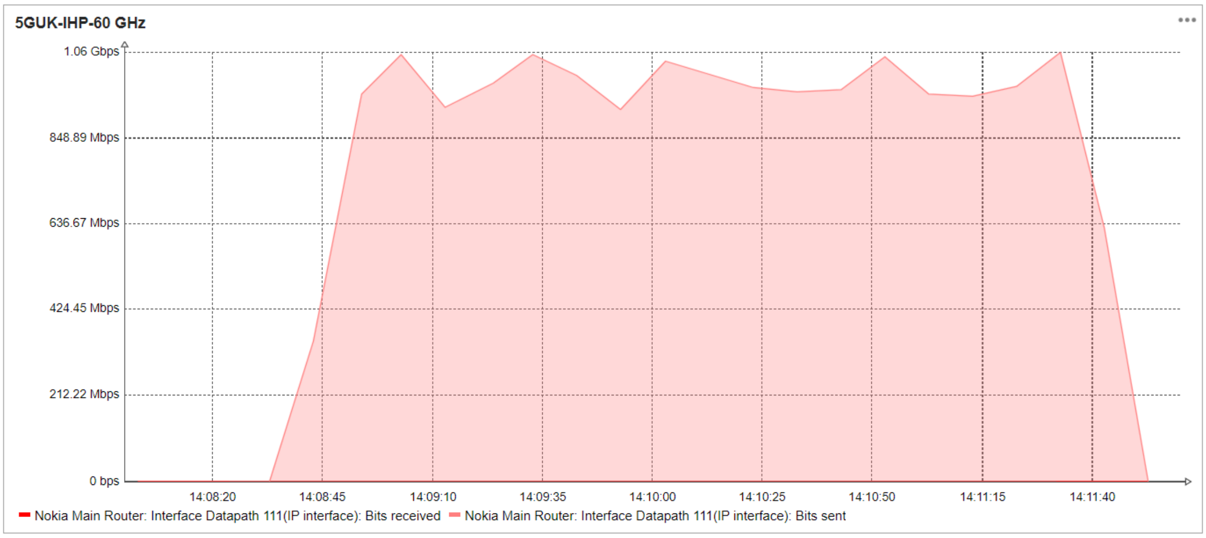


Figure 4-26: IHP 60GHz radio Data plane network traffic – March 12th between 14:08 to 14:12

Figure 4-26 and ***Figure 4-27*** are related to the throughput of **IHP** 60 GHz network, It was used as a fronthaul connection for the Wi-Fi service areas, and all the Wi-Fi enabled UEs' which their traffic was sent through them (two UEs for Smart City Safety UC and two UEs for Virtual Reality UC). In these figures, the light red area indicates the overall download speed in Mbit/s and the dark red area indicates the overall upload speed in Mbit/s, as it is visible in the graphs, the maximum Download speed was around 1 Gbit/s and the average was about 10 Mbit/s during the demonstration.

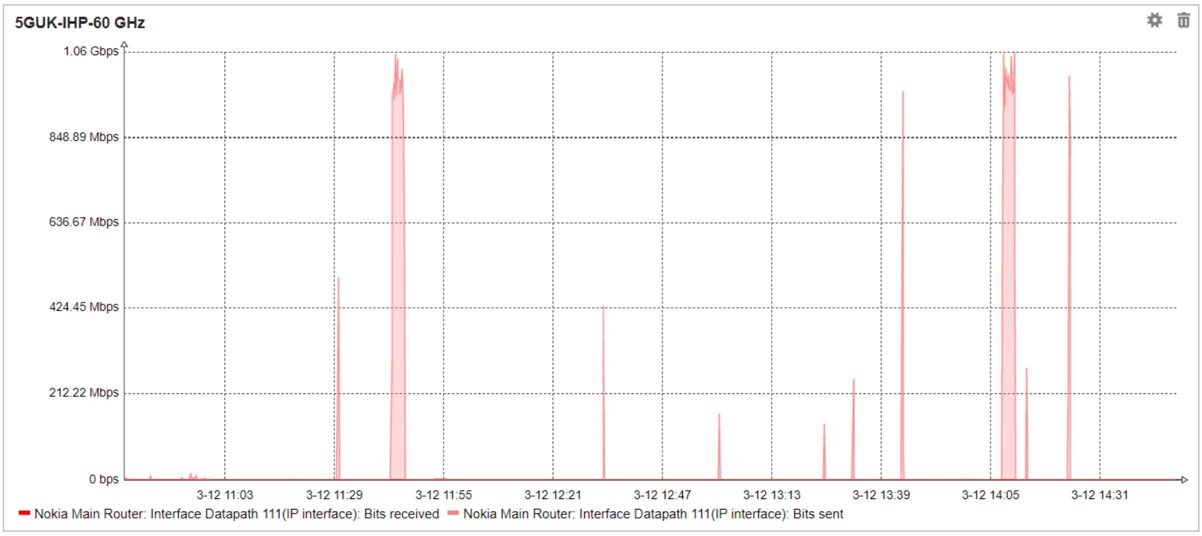


Figure 4-27: IHP 60 GHz radio Data plane network traffic – March 12th whole day

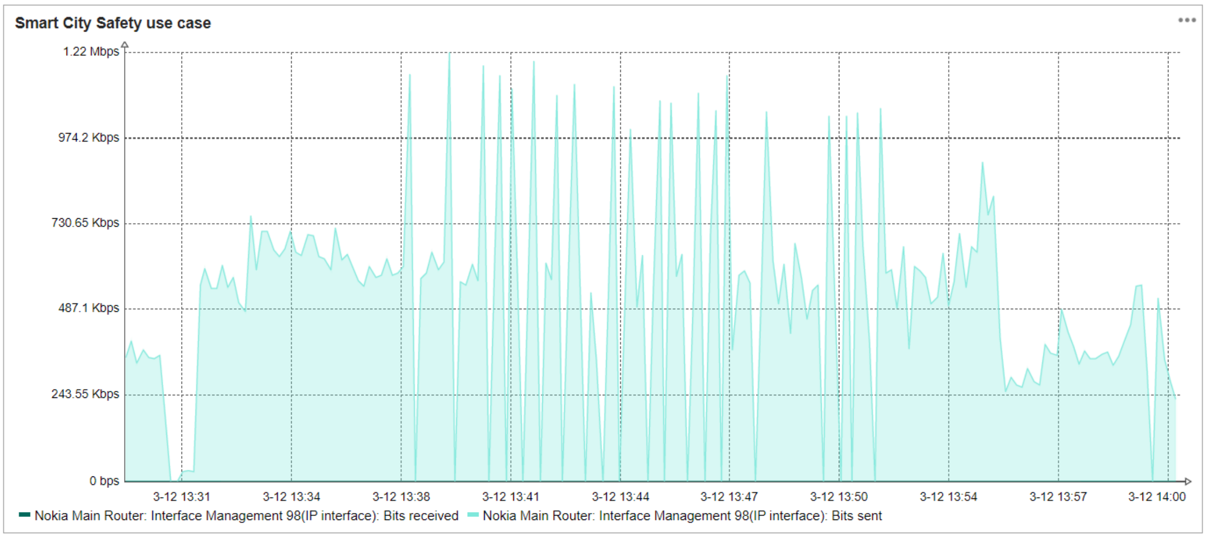


Figure 4-28: Smart city safety use case network traffic – March 12th between 13:30 to 14:00

Figure 4-28 and ***Figure 4-29*** are related to the Smart City Safety UC overall network throughput during the demonstration day. The light green indicates the download speed, and the green indicates the upload speed. The average download speed per UE without considering the UE connection type (5G/ Wi-Fi / LTE) was about 1 Mbit/s and the maximum download speed was about 4 Mbit/s. For as much as the UEs was used as a monitoring station there is not much uploaded data to the network, so the green line is almost close to the zero bps and not visible in the graphs.

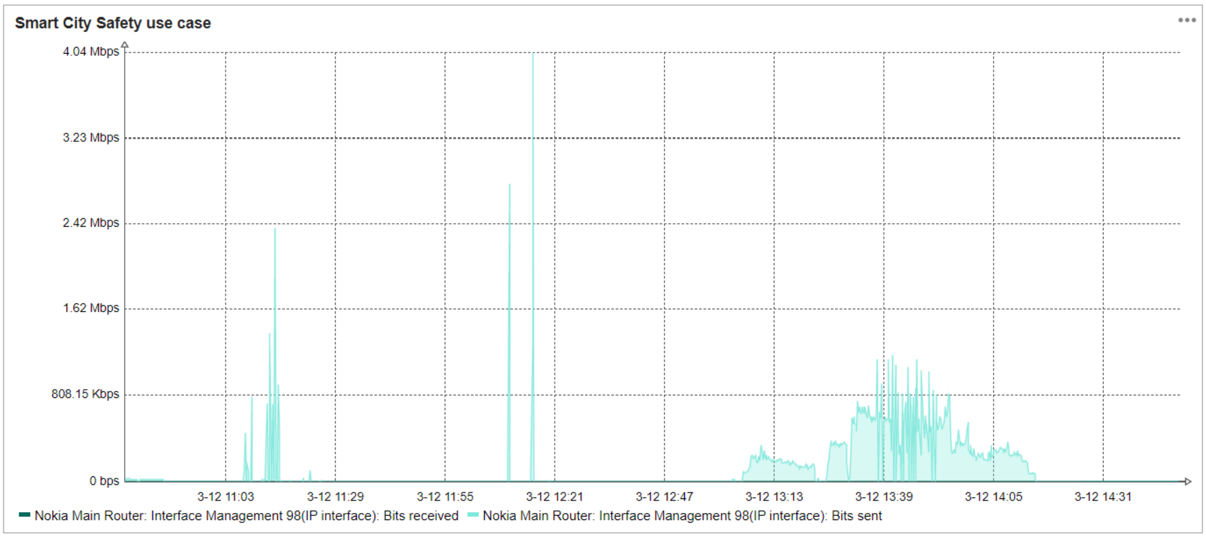


Figure 4-29: Smart city safety UC network traffic – March 12th whole day

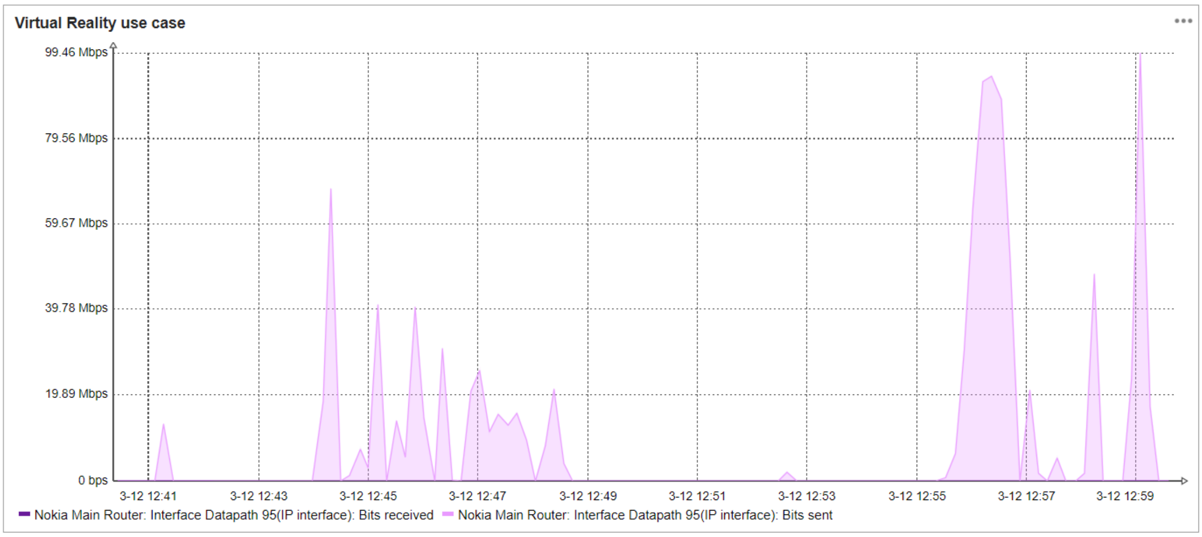


Figure 4-30: Virtual Reality use case network traffic – March 12th between 12:40 to 13:00

Figure 4-30 and ***Figure 4-31*** are showing the Virtual Reality UC overall network throughput during the demonstration day, Light purple indicates the download speed, and the purple which is not well visible indicates the upload speed, the maximum throughput of the use case was about 100 Mbit/s and the average was about 3 Mbit/s during the demonstration day.

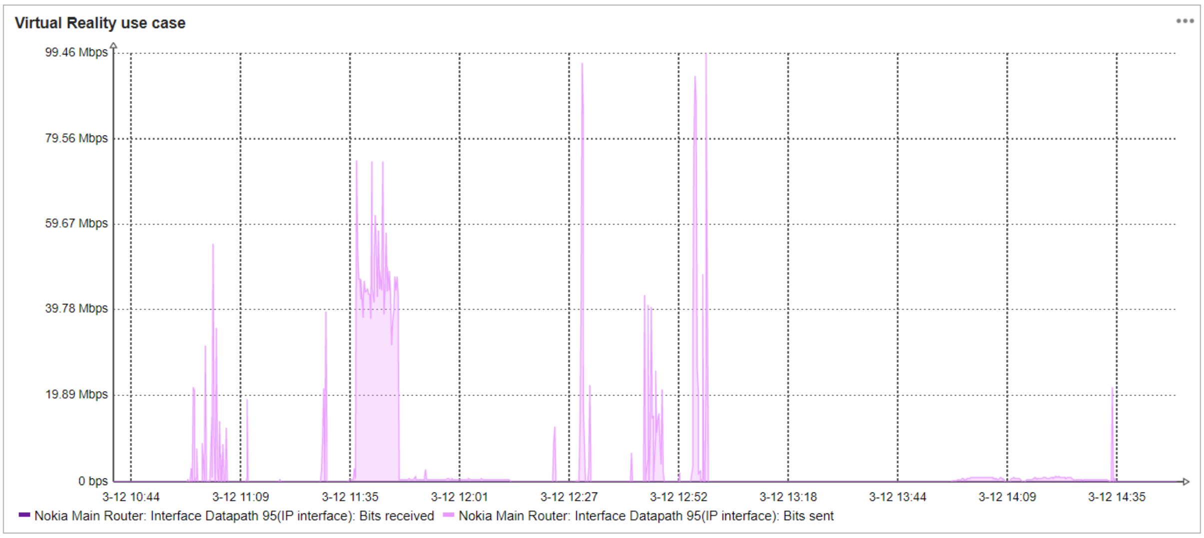


Figure 4-31: Virtual Reality UC network traffic – March 12th whole day

Table 4-3: Measured KPIs

UE connectivity KPIs	5G	LTE	WiFi
Radio Network node capacity (maximum throughput)	Download: 175 Mbit/s Upload:178 Mbit/s	Download: 93 Mbit/s Upload: 96 Mbit/s	Download: 116 Mbit/s Upload: 118 Mbit/s
Latency	Between the Device and the Cloud serving node Measured < 26 ms	Between the Device and the Cloud serving node Measured < 28 ms	Between the Device and the Cloud serving node Measured < 11 ms

In case of KPI validation for both UCs, it was mandatory to measure the maximum throughput, capacity and latency for each radio access technology between the UE and the data centre, for this purpose the monitoring and measurements tool was developed and used by 5GUK test network. The results and the measurements details are available in section 4.3.1.

Based on all measurements result shown in ***Figure 4-18*** ,***Figure 4-19*** and ***Figure 4-20***, plus captured data during demonstration (***Figure 4-24*** to ***Figure 4-31***), ***Table 4-3*** presents the measured values of the KPIs during the demonstration and in comparison with the ***Table 4-2*** it is completely visible that all KPIs are validated.

4.3.2.1 Test results – mmWave part of the Smart City Demo

To evaluate the performance of the mmWave (60 GHz) part of the infrastructure, we performed both throughput and latency measurements during the process of integration and testing of the demo. The measurement tests were done at the application layer using tools like iPerf and ping. The results reported here present only a portion of datasets recorded during our activities in demo preparation.

We have used the following notation to address a location in Millennium Square where measurements have been made:

- **Location A** – location of the tent used for Virtual Reality UC (see ***Figure 4-38***).
- **Location B** – location of the tent used for safety Camera UC (see ***Figure 4-38***).

The next subsections summarise the obtained KPIs of the two mmWave links.

4.3.2.2 Throughput measurement

For the purpose of network evaluation and testing, two Intel NUCs were installed at different locations in the network, one residing at WTC's IT room and another at the Smart Internet Lab. A laptop/PC with Ubuntu OS is connected to each 60 GHz STA using a 10-m Ethernet cable to measure the throughput and latency to the particular test points. For the throughput measurements, a TCP traffic is generated using the *iPerf3* tool from the PC to the two NUCs (both running iPerf3 server). The duration of each test was 3 minutes.

The result of a 3-min downlink throughput measurement batch for the 60 GHz STA device at Location A (Virtual Reality UC) are shown in ***Figure 4-32***. The distance between the 60 GHz STA and 60 GHz AP was of about 60 metres. The average downlink data rate at the application layer measured to the NUC at WTC was 941 Mbit/s (first seconds are omitted due to slow TCP/IP start) with a very small standard deviation of 0.67 Mbit/s, as shown in the plot. The downlink measurement to the NUC at SIL reports an average throughput of 934.5 Mbit/s with a standard deviation of 5.1 Mbit/s. Compared to the first measurement, in this case, packets do not end at the NUC in WTC, but traverse through the network infrastructure connecting the Smart Internet Lab and WTC sites (including two TSON nodes connected via fibre) and end up being sinked by the NUC at the Smart Internet Lab. Therefore, the throughput is a bit lower. Significant variations could be explained by the fact that during the measurement, other tests were ongoing, hence causing the variations.

Figure 4-33 shows the results of the 3-min downlink throughput measurement for the second 60GHz STA device located at an approximated distance of 80 metres to the 60GHz AP device at location B (Safety Camera UC). The average downlink data rate measured to the NUC at WTC equals 940.9 Mbit/s (first seconds omitted due to slow TCP/IP start). The standard deviation is about 2.4 Mbit/s, as shown in the plot. Also, we have done the same test to the NUC in SIL, reporting an average throughput of 936.3 Mbit/s with a standard deviation of 2.7 Mbit/s. The same comments as above hold here.

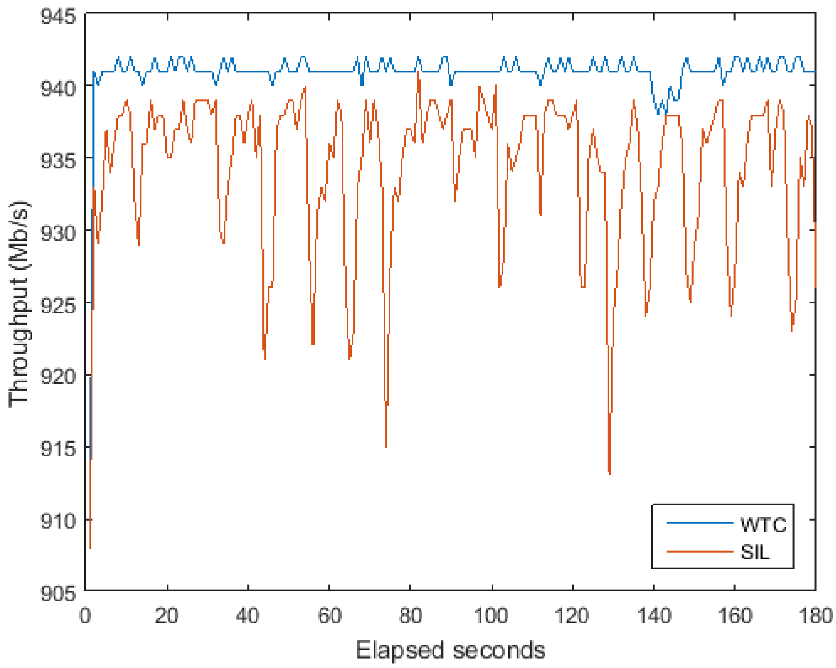


Figure 4-32: DL throughput measured at Location A (Virtual Reality UC). Approximate distance 60 GHz AP to 60 GHz STA is 60 metres.

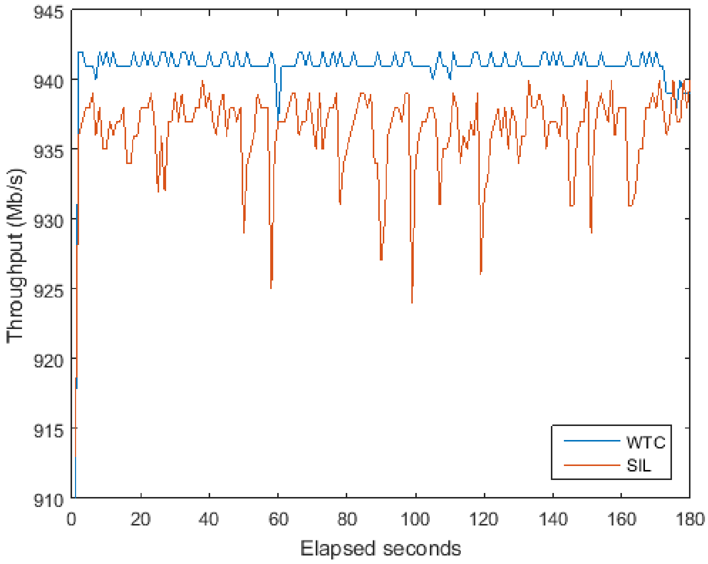


Figure 4-33: DL throughput measured at Location B (Safety Camera UC). Approximate distance between 60 GHz AP and 60 GHz STA is 80 metres.

The statistic of the throughput measurements at location A and location B are summarised in ***Table 4-4***.

During the performance testing, we observed MCS 8 (corresponds to the PHY throughput of 2.3 Gbit/s), as shown in ***Figure 4-34***, as a net data rate. This is a maximum supported by these devices. However, the used nodes have only 1 Gbit/s Ethernet connection, therefore we were able to achieve only up to 1 Gbit/s at the application layer.

Table 4-4: Throughput measurement report

Throughput (Mbit/s)	Location A		Location B	
	NUC WTC	NUC SIL	NUC WTC	NUC SIL
Minimal	913	908	910	913
Average	941	934.5	940.9	936.3
Maximal	942	941	942	940
St. deviation	0.67	5.08	2.44	2.77

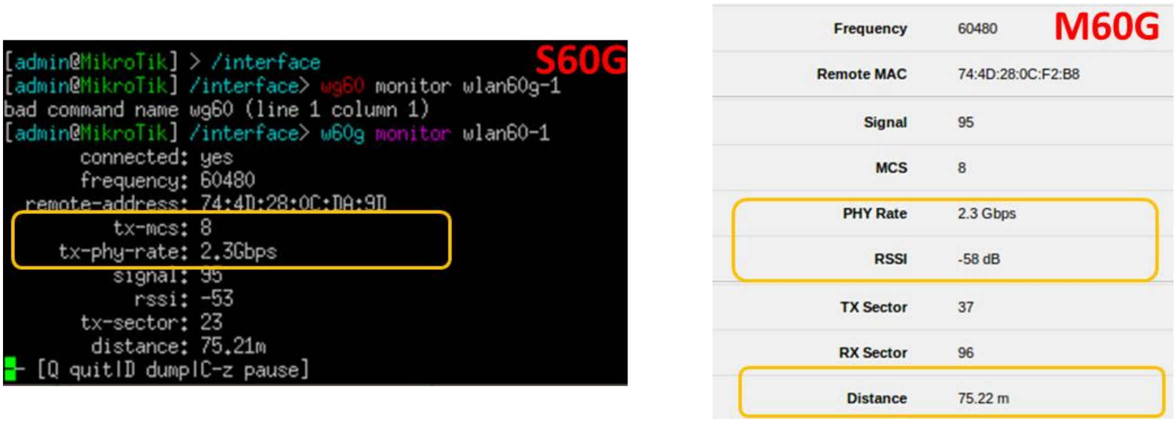


Figure 4-34: Screenshots of PHY-data rates at 60 GHz STA and AP during performance testing at one of two use case locations.

4.3.2.3 Latency measurement

For latency measurements, we followed the same approach, as explained above. Here, the ICMP traffic is generated using the ping tool from a PC attached to a 60 GHz STA device to selected test points such as 60 GHz AP at WTC and a gateway in the UNIVBRIS Smart Internet Lab. The ping tests lasted for 3 minutes.

Figure 4-35 shows the latency results at location A (Virtual Reality use case). The average Round-Trip Time (RTT) latency measured to the 60 GHz AP device is 0.72 ms with the standard deviation of around 0.2 ms. On the other hand, the RTT latency measured to the gateway in SIL has the average value of 1.04 ms and the standard deviation of 0.07 ms.

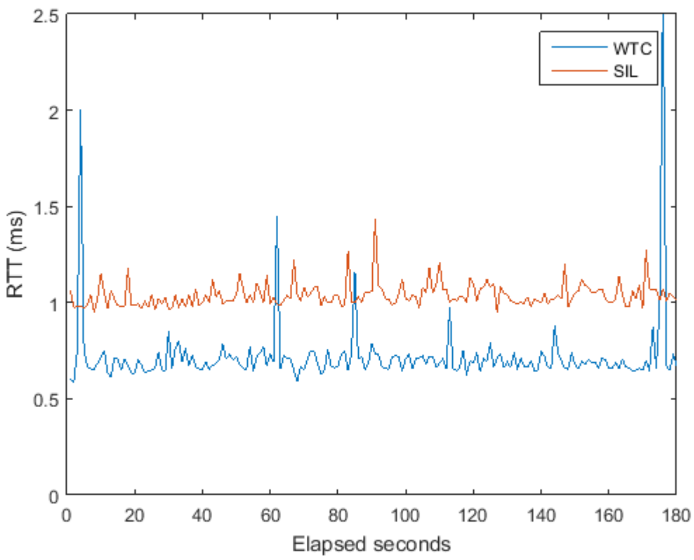


Figure 4-35: The round-trip time latency at Location A (Virtual Reality use case). Approximate distance between 60 GHz AP and 60 GHz STA is 60 metres.

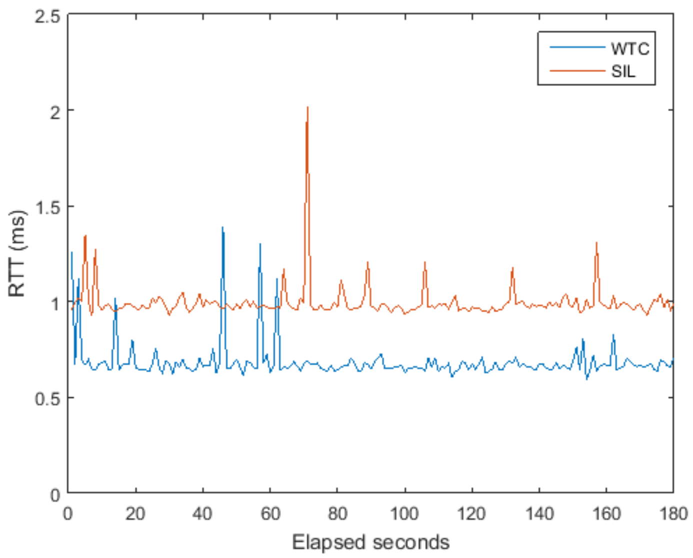


Figure 4-36: The round-trip time latency at Location B (Safety Camera use case). Approximate distance between 60 GHz AP and 60 GHz STA is 80 metres.

The same measurements were performed for location B (Safety Camera use case), and they are shown in ***Figure 4-36***. The average RTT latency to the 60GHz AP was 0.69 ms with an st. deviation of 0.1 ms.

Pinging the gateway revels the average RTT latency of 1 ms and a standard deviation of 0.1 ms. The measurement statistics for Locations A and B are summarised in **Table 4-5**.

Table 4-5: Latency measurement report

RTT latency (ms)	Location A		Location B	
	60 GHz AP	Gateway	60 GHz AP	Gateway
Minimal	0.58	0.95	0.59	0.92
Average	0.72	1.04	0.69	1.00
Maximal	2.65	1.43	1.39	2.02
Standard deviation	0.19	0.07	0.10	0.10

From the above average values, we expect that the RTT latency from the 60GHz AP to the gateway in SIL is around 0.3 ms. Therefore, we performed a 3-m ping test from the NUC in SIL to the 60 GHz AP at WTC. The results are shown in ***Figure 4-37*** and reveal the average RTT of 0.27 ms, which is close to our expectation. Furthermore, to get more insights into the latency of the mmWave link, we did the latency break down by measuring the RTT latency of the wired connection between the laptop/PC and the 60GHz STA (see Figure ***Figure 4-37***). The average RTT latency of this link is 0.16 ms and the variance equals 0.04 ms. Based on these calculations, an average RTT latency of 540-560 µs (or one-way latency of 270-280 µs) is expected for the 60 GHz link.

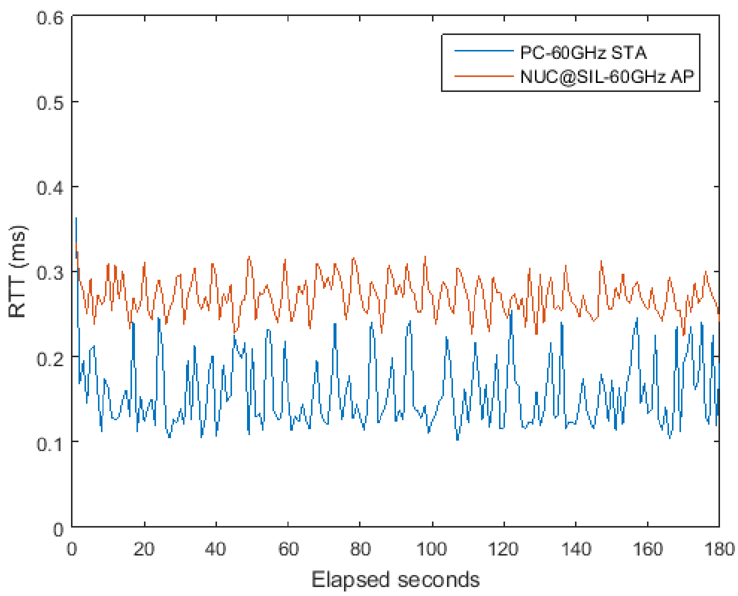


Figure 4-37: Measured latency for different wired parts of the tested e2e link.

Figure 4-38 illustrates the latency to different test points in the network. (One should note that this is a simplified representation of the network during latency tests. There is additional network equipment at different sites of the overall network.) Finally, ***Table 4-6*** summarises the latency break down for mmWave links (i.e. locations).

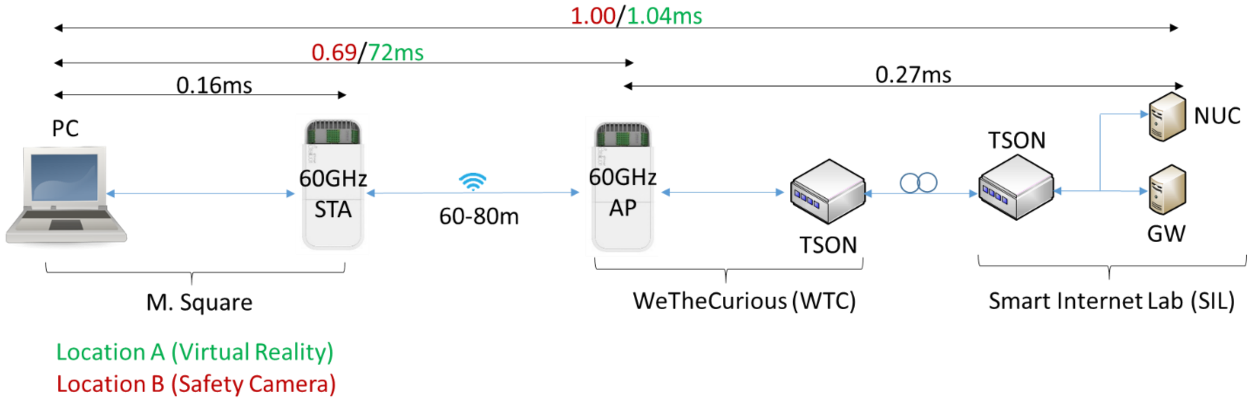


Figure 4-38: The illustration of the latency break down for different parts of the network.

Table 4-6 Latency break down for Locations A and B

Link	Average RTT latency at Location A in ms	Average RTT latency at Location B in ms
PC – 60G STA	0.16	0.16
PC – 60G AP	0.72	0.69
NUC – 60G AP	0.27	0.27
PC – GW (E2E)	1.04	1.00
60G STA – 60G AP	**0.56**	**0.54**

4.3.3 Test results – IHP's 60GHz solution

This section provides the throughput and latency measurements of the **IHP**'s 60GHz solution performed in-house. The measurement tests were obtained at the application layer using tools like iPerf and ping.

First, testing has been performed in a laboratory environment shown in ***Figure 4-39***. Results of 2-min measurements of RTT latency using ping and throughput test using iPerf (TCP) are given in ***Figure 4-40*** and ***Figure 4-41***. The average RTT latency is 0.56 ms for each direction with a standard deviation of ~0.12 ms. This is the measurement of an unloaded link. In general, the latency and the jitter are dependent on the current parameters of the MAC protocol and the load of the link. Regarding the achievable throughput, we have obtained the median value of 937 Mbit/s. Variations are small as proved by the standard deviation of 0.88 Mbit/s. Statistics are given in ***Table 4-7*** and ***Table 4-8***.

Figure 4-39: Measurement setup in a lab in IHP.

Table 4-7: Statistic of the latency measurement in milliseconds

Min	Max	Mean	Std	Median
0.383	0.911	0.562	0.117	0.530

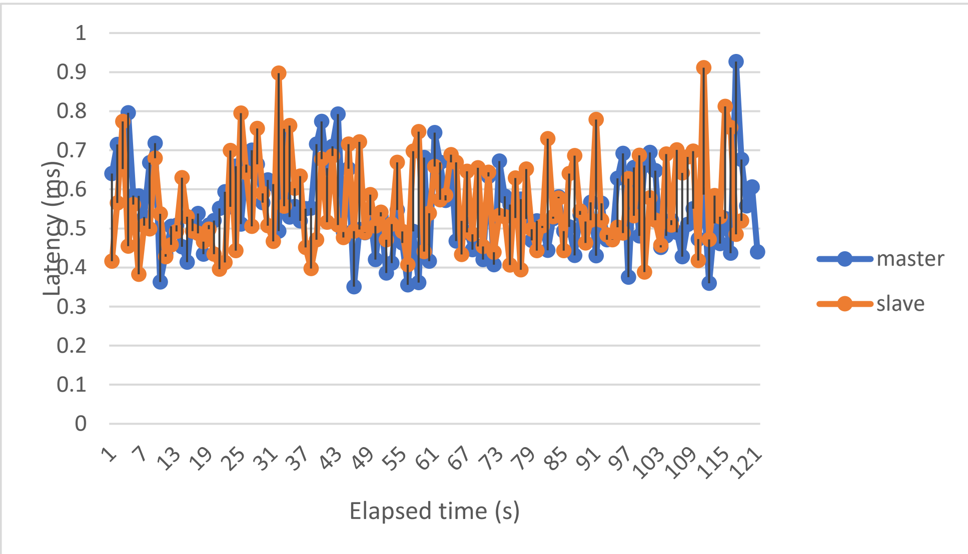


Figure 4-40: A 2-min measurement of RTT latency using ping

Table 4-8: Statistic of the throughput measurement in Mbit/s

Min	Max	Mean	Std	Median
796	937	936.62	0.88	937

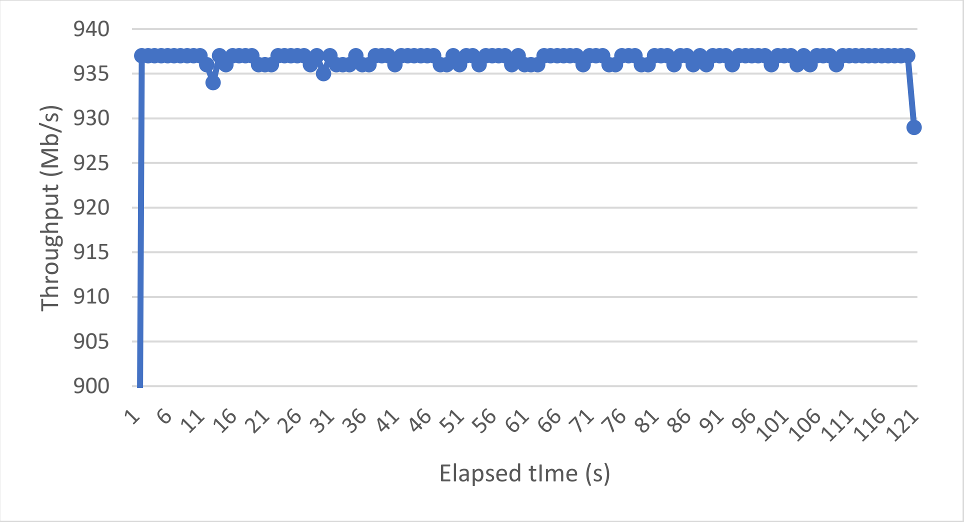


Figure 4-41: A 2-min measurement of throughput using iPerf (TCP) in a lab

Then, we performed the throughput measurement in a hallway at a distance of around 20 metres, as shown in ***Figure 4-42***. This way, a possibility of having ground reflection is avoided. The results of 30-min test are seen in ***Figure 4-43***. Once again, data rates around 937 Mbit/s are reached.

Figure 4-42 Throughput measurement in a hallway in IHP. Devices are mounted in a housing for outdoor deployment.

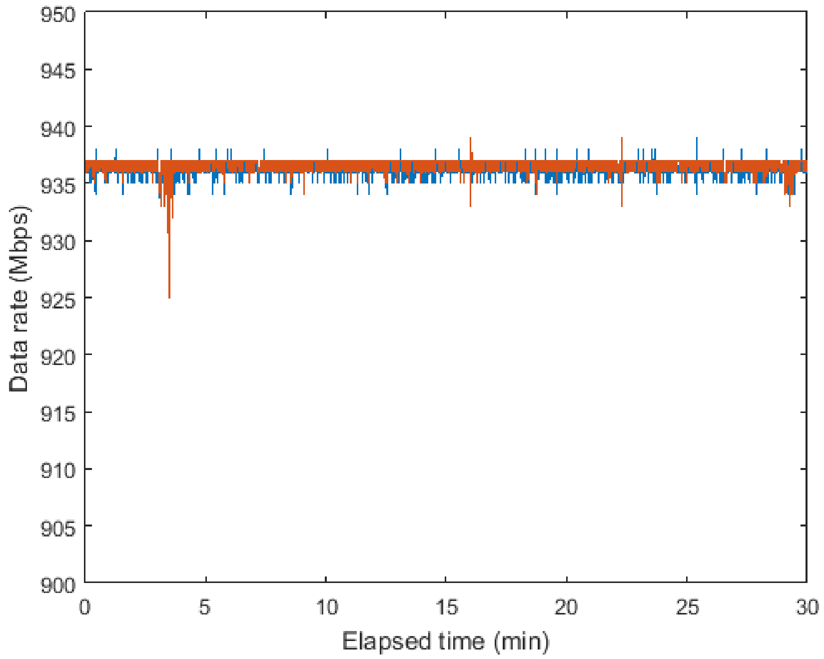


Figure 4-43: The result of a 30-min measurement of throughput using iPerf (TCP) in a hallway

4.3.4 Test Results – XDE's Massive MIMO

The first evaluation measured the beam radiated from the RU, while being steered in different directions. For this the beam was swept between -60° and +60° from boresight in horizontal direction and from -30° to 30° in vertical direction, and the received power at the spectrum analyser was measured. ***Figure 4-44*** and ***Figure 4-45*** show the relative received power in horizontal and vertical direction, respectively. To evaluate the performance, the plots are compared to measurements performed at TUD as mentioned earlier. In the TUD measurements, a highly directive receive antenna was used that was deployed directly in line of sight of the RU. As such, the TUD measurements are very close to an "ideal" measurement as could, for example, be also conducted in an anechoic chamber. In contrast, the Bristol measurements show field conditions, with the diploe antenna used for reception being subject to different reflections and multipath propagation in Millennium square. As such, the Bristol measurements show the beam that a real UE would experience in field deployments.

As can be seen in the figures, the main lobe of the beam in both directions is relatively close to the one expected from the TUD measurements, especially in its main characteristic, the half-power beam width, which is approximately 14° for horizontal and 9° for vertical. We can also see from the figure that the beams are not centred at 0°, and that the receiver was approximately located at 2.5° horizontal and 0.5° vertical off the boreside direction (not that the antenna was mechanically tiled towards the ground, hence the low vertical offset.) Also, similar sidelobes are somewhat visible, and we observe, that the highest sidelobes are approximately 10 dB below the main lobe. The deep fades between lobes as seen in the TUD measurement are not as apparent in the Bristol measurements. In general, these results can be expected. First, as mentioned above, the dipole antenna is subject to reflection and multipath, resulting in the small ripples seen throughout the Bristol measurement. It also prevents sharp fades, as in points where in an ideal setup radio wave interfere destructively, reflections will disturb this by providing additional phase components.

In conclusion, however, we can see that narrow beams are produced even under field conditions that will supress signals from neighbouring angels by more than 10 dB, hence enabling spatial multiplexing, which is the basis for massive MIMO.

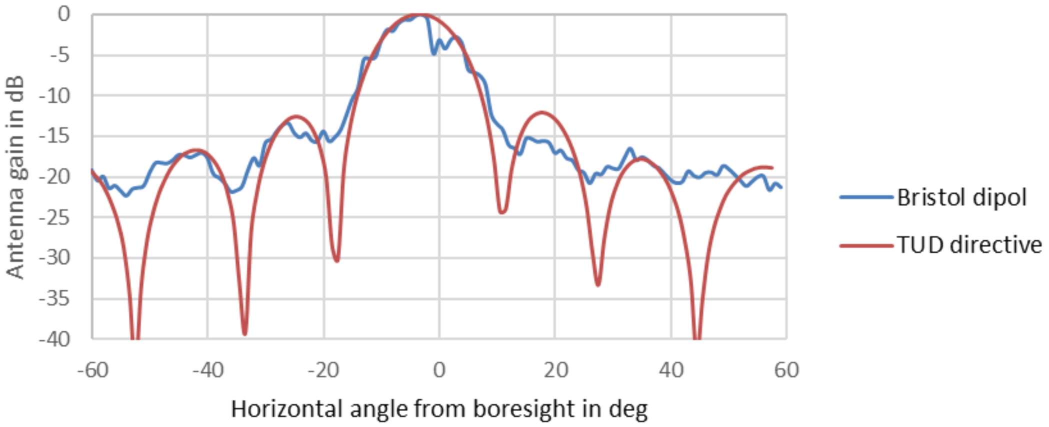


Figure 4-44: Relative received power for horizontal beam under field conditions in Bristol ("Bristol dipole) vs. under controlled conditions ("TUD directive").

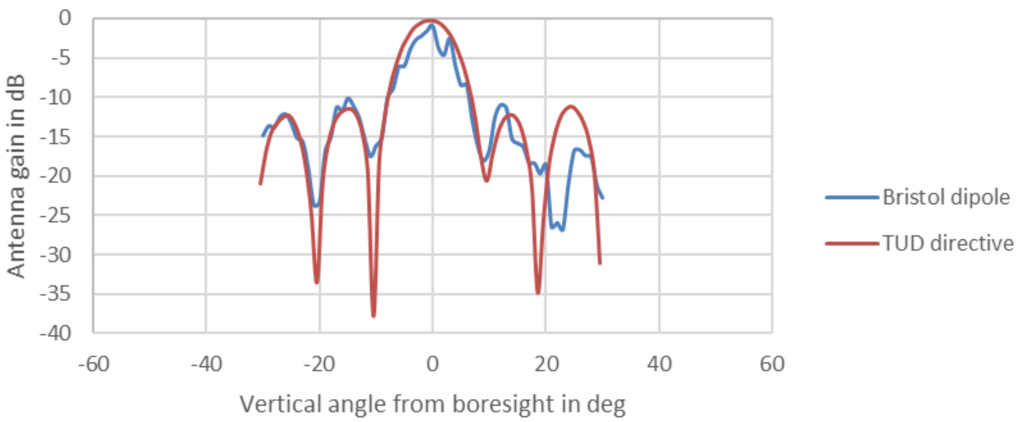


Figure 4-45: Relative received power for vertical beam under field conditions in Bristol ("Bristol dipole) vs. under controlled conditions ("TUD directive").

Figure 4-46 shows the constellation of the received signal at the spectrum analyser. AS can be seen, 64 QAM was used and the EVM is 3.7 %. The 3GPP requirement for base station transmit quality is 8 % for 64 QAM, so this demonstrates the good quality of the signal.

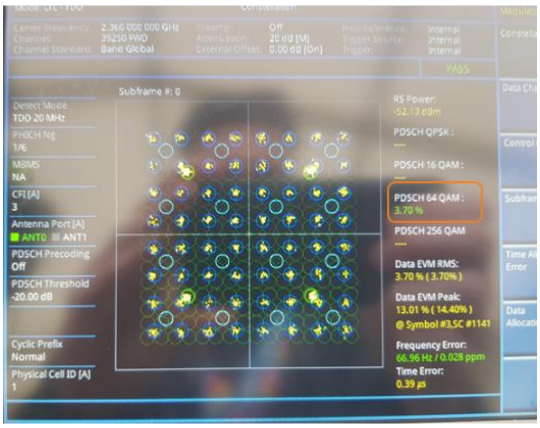
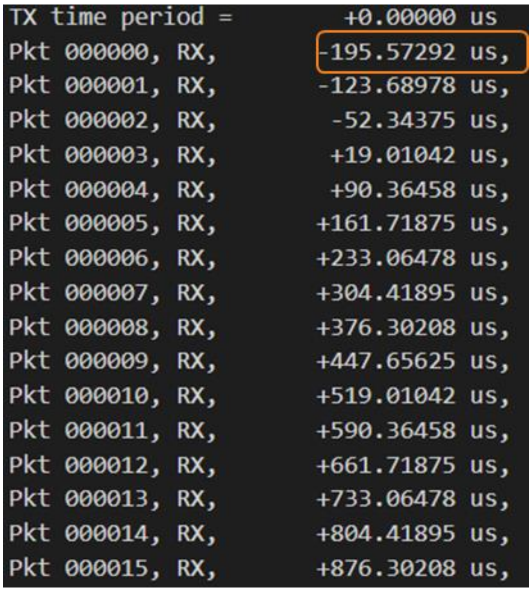


Figure 4-46: Received constellation of mMIMO radio unit



```
TX time period =          +0.00000 us
Pkt 000000, RX,         -195.57292 us,
Pkt 000001, RX,         -123.68978 us,
Pkt 000002, RX,          -52.34375 us,
Pkt 000003, RX,          +19.01042 us,
Pkt 000004, RX,          +90.36458 us,
Pkt 000005, RX,         +161.71875 us,
Pkt 000006, RX,         +233.06478 us,
Pkt 000007, RX,         +304.41895 us,
Pkt 000008, RX,         +376.30208 us,
Pkt 000009, RX,         +447.65625 us,
Pkt 000010, RX,         +519.01042 us,
Pkt 000011, RX,         +590.36458 us,
Pkt 000012, RX,         +661.71875 us,
Pkt 000013, RX,         +733.06478 us,
Pkt 000014, RX,         +804.41895 us,
Pkt 000015, RX,         +876.30208 us,
```

Figure 4-47: Fronthaul packet timing log of mMIMO radio unit.

Figure 4-47 shows a screenshot of the fronthaul packet logs as captured by the RU. It shows the beginning of a packet stream and from the timestamps the latency of the overall fronthaul link including the 2 TSON nodes can be calculated. The nominal timing of the first packet would be 200 µs, i.e. the logs show an offset of 4.43 µs. Due to the used synchronization scheme, the true latency is twice that, totalling in 8.86 µs. The RU features a receive buffer of 142 µs, so the measured delay did not impact the performance.

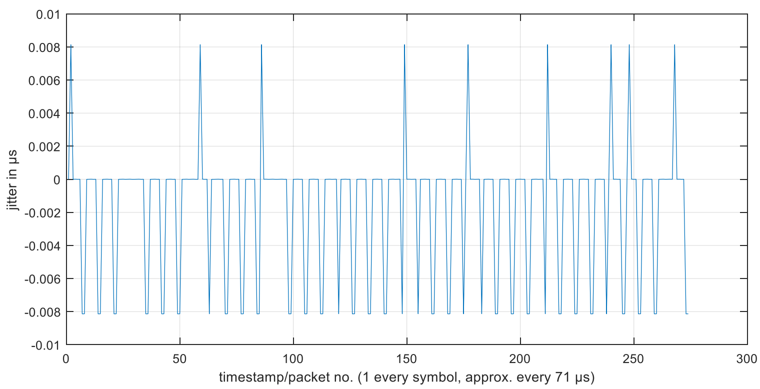


Figure 4-48: Fronthaul packet jitter.

Figure 4-48 shows the jitter of the C/-U-Plane fronthaul link. The jitter was calculated by comparing the timestamp from the packet logs to the expected symbol timing. As can be seen there is an offset of approx. ± 8 ns occurring frequently, but overall the jitter is stable. The offset is probably caused by the imprecision of the timestamping clock, as it runs on 122.88 MHz, corresponding to a precision of 8.13 ns.

```
INFO: *** Current values of RX window counters: ***
    RX_ON_TIME:
        PE_CARRIER_0: 8360533
    RX_EARLY:
        PE_CARRIER_0: 0
    RX_LATE:
        PE_CARRIER_0: 0
    RX_CORRUPT:
        PE_CARRIER_0: 0
    RX_DUPL:
        PE_CARRIER_0: 0
    RX_TOTAL:
        PE_CARRIER_0: 8360533
INFO: NETCONF session closed!
```

Figure 4-49: Fronthaul packet counters of mMIMO radio unit.

Finally, ***Figure 4-49*** show packet counters of the Ru. The Ru counts packets that exceed its buffering window and therefor would cause problems. As can be seen, all packets were received on time and without error, showing again that the fronthaul was performing as expected both in terms of packet errors and latency. Furthermore, the read-out of the counters was performed via the M-Plane, verifying that its functionality. Further use of the M-Plane functionality was successfully shown during the live demonstration on March 12, 2020.

5. Stadium Demonstration

5.1 Existing Infrastructure at the Stadium

5.1.1 Existing Infrastructure and evolution

This section describes a 5G network solution as outlined in 5G-PICTURE's deliverable D2.1 [17] for Ashton Gate Stadium in the city of Bristol. The stadium has an existing production network which provides its current IT services and in addition, a public Wi-Fi service for match days. To achieve a 5G solution, the network of the stadium had to be extended with a Zeetta Networks (**ZN**) *lab on wheels* which consists of four switches and six servers to provide compute capability. Included in the solution were the I2CAT Wireless Access Points (WAPs) (see **Figure 5-1**).

The main focus of 5G networking is the provision of both network level elasticity (bandwidth variable resource allocation, slicing, NFV, etc.) and application level elasticity (Edge Compute, Cloud Computing, etc.). For example, the crowdsourced video application (Watchity) is one such use-case that requires this dynamic adjustment of the control and data plane given the physical network constraints and application requirements. For this use case, the application is running on an end-user device (tablet) (connected to the extended Wi-Fi network) accessing a backend Server in the Public Cloud. The traffic and QoS requirements were the same for the Wi-Fi and the transport network since all the traffic has to be delivered to the Public Cloud.

5.1.2 Selected KPIs

The traffic application type most suited for this demonstration is high definition video streaming, which requires low jitter and low latency. User metric that were evaluated: Quality of Experience (QoE) of application user via the Media KPIs. Network Metrics that were evaluated are jitter, latency, utilisation and congestion. The target KPIs are: Low jitter, low latency and low instances of congestion. Below we summarize the metrics and KPI targets of interest:

- User Metrics: QoE of App user, Media KPIs.
- Network Metrics: jitter, latency, utilisation and congestion.
- KPI Target: Low jitter, low latency and low instances of congestion.

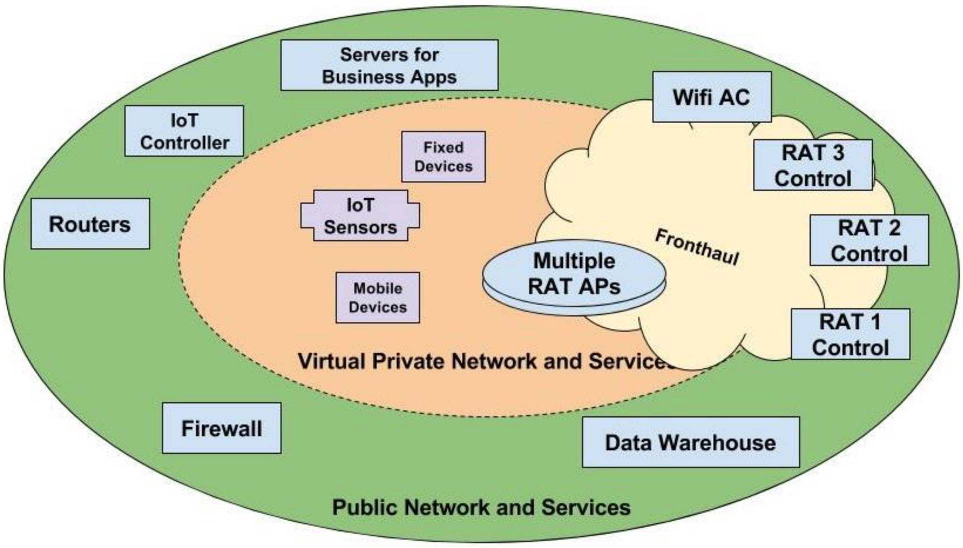


Figure 5-1: 5G Enabled Stadium Deployment

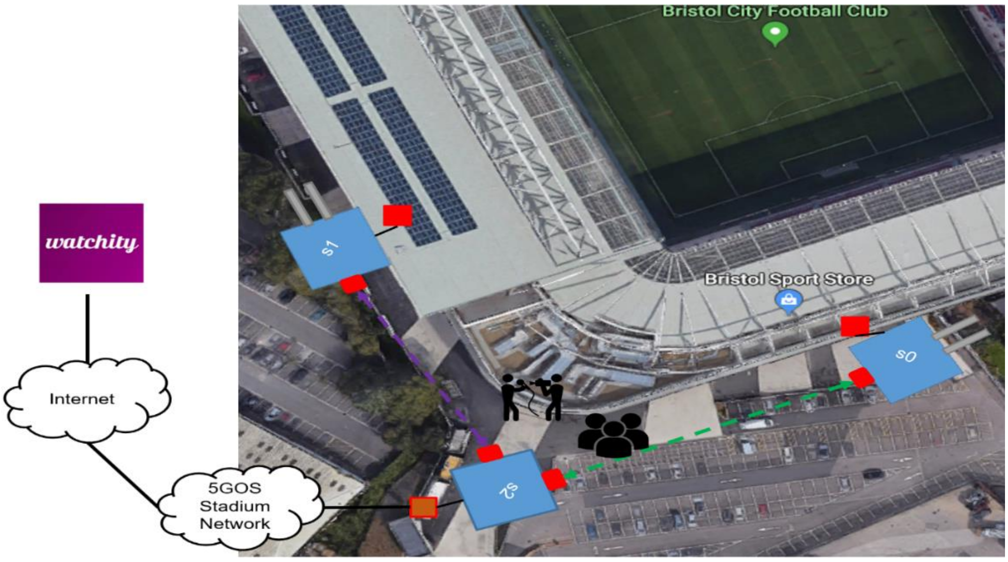


Figure 5-2: Stadium demonstration deployment

5.2 5G-PICTURE Demonstrator. Introduction

The system architecture for the stadium UC was developed as per 5G-PICTURE deliverable D6.1 "Specification of Vertical Use cases and Experimentation plan" section 5 (Stadium Use Case) [1]. The demo deployment was carried out in two phases and the final UC scenario was successfully executed at the Ashton Gate stadium in Bristol. The network architecture, the deployment of technologies, and demo results are detailed in the following sections. Moreover, the different domains of the network architecture are described along with the time plan for the different phases, namely, the lab testing and the final demonstration.

The project deployment is shown in **Figure 5-2**, which represents the configuration needed at the stadium in order to enable the 5G network solution. This included the installation and configuration of the I2CAT Wi-Fi access points in the Fan Zone; the deployment of the *lab on wheels* (provided by Zeetta) which comprises the transport and compute domains along with the MDO. This setup also required integration with the stadium's network to forward the traffic between the different domains and out to the Internet in order to access of the crowd-source content application (Watchity) located in the Public cloud.

The deployment and integration of the equipment at the stadium was complex as we were dealing with a production environment. Furthermore, availability of stadium staff was limited, thus, the support for our integration work was problematic. The rehearsal activities were impacted by bad weather conditions which did not allow us to test the Wi-Fi antennas in the specified locations.

5.2.1 Watchity application

To support the 5G OS stadium UC we selected a real crowd-sourced video production application called Watchity [29]. **Figure 5-3** depicts an overview of the Watchity components and architecture, including the ingest devices (either mobiles devices or professional cameras), the cloud-based core (including processing, mixing and editing components), and the final players (which can be the Watchity app installed on mobile phones, or streams ingested in Social Media channels).

The Watchity platform component are normally deployed in a public cloud (AWS), and so was the case for the stadium demo. The only Watchity components physically in the stadium were the tablet devices with the Watchity software acting as content producers, which resembles a real deployment set up for this type of applications. In order to support the KPI analysis we contacted Watchity and they set up a special account for us where we could have access to the server logs in their AWS servers. For this purpose, a *tshark* [4] script was run just after the load balancer sub-component (see red dot in **Figure 5-3**). Then, the captured data (*.pcap* file) were sent to an AWS S3.

The video streams generated by the Watchity devices are RTMP streams over UDP addressed to port 1935 with a static video coding rate. As part of the stadium demo we developed mechanisms to detect the Watchity application traffic in real-time and prioritize the devices acting as Watchity producers.

5.2.2 Demo impacts due to COVID-19

The timing of the demonstration was impacted by COVID-19. Most of the people in the consortium were unable to attend the meetings and some partners returned home due to health concerns. However, the key partners supported the demonstration remotely via videoconference, so the deployment and configuration of the demo components were possible on time even though with less people available. The demonstration setup had installation and deployment issues, for example the antennas were not positioned correctly hence the signalling between the wireless nodes was not ideal.

5.2.3 Multi Domain Network

As described in D5.2 [31] previously, the 5G OS architecture is mapped to the deployment of the stadium network. In this case, the deployment has per-domain orchestrators and controllers to manage wireless, transport and compute resources (**Figure 5-4**, **Figure 5-5**). Finally, a Multi-Domain Orchestrator (MDO) as lightweight layer implementing end-to-end service logic and gluing together the resource domains.

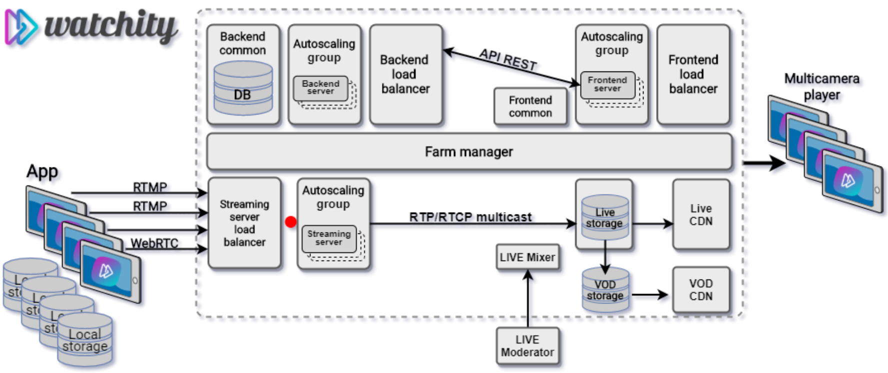


Figure 5-3: Watchity architecture and main components

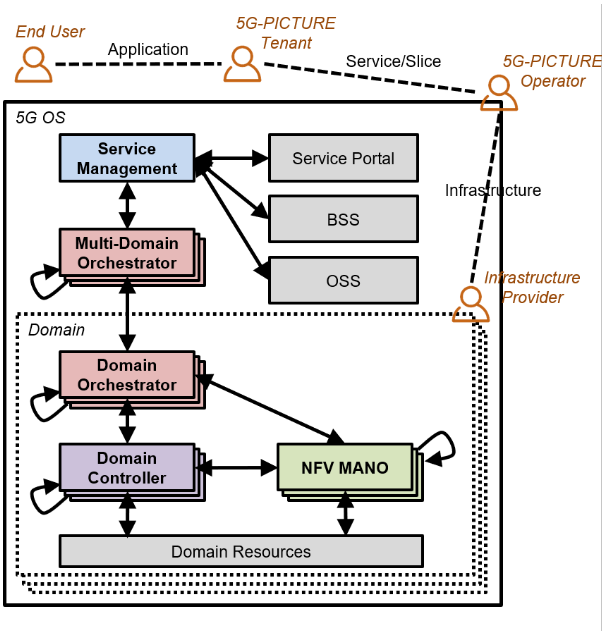


Figure 5-4: 5G OS Architecture

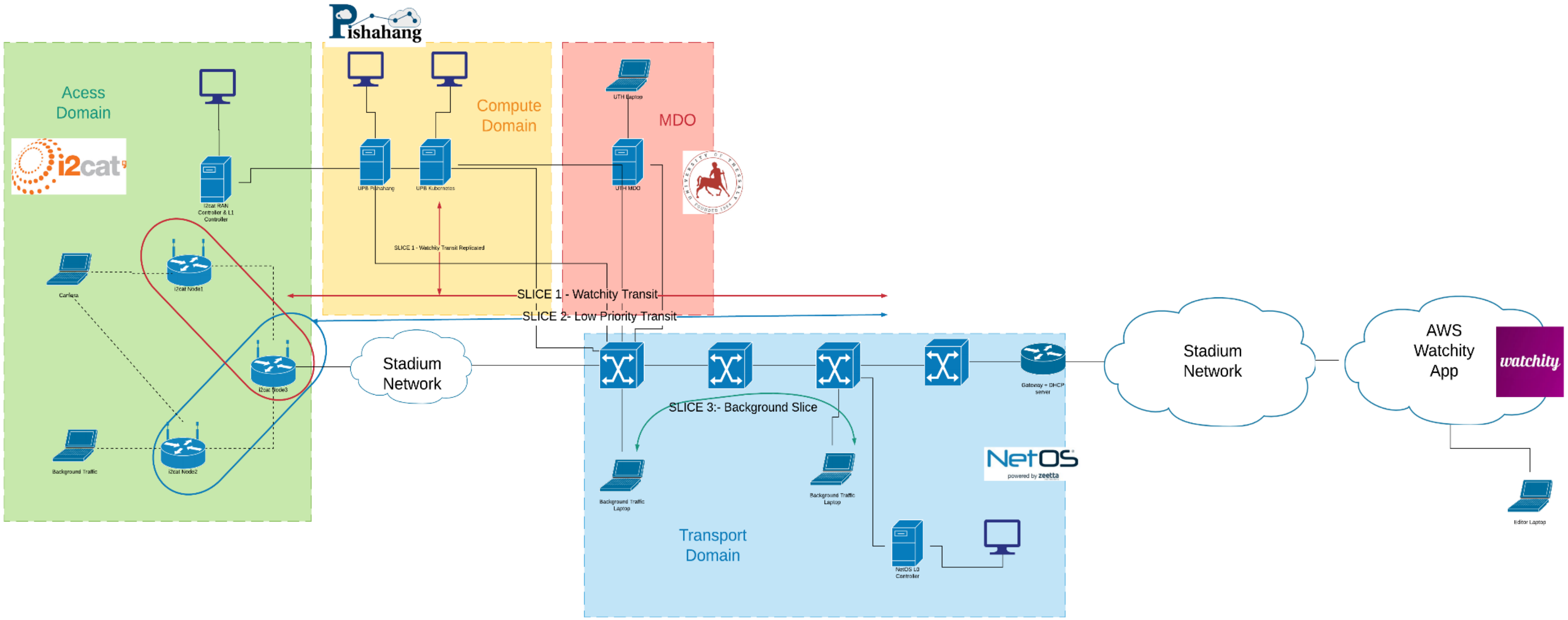


Figure 5-5: Multi Domain Diagram

5.3 Demo objectives

This section provides additional detail regarding the UCs and the key objectives achieved in the demo.

The first UC involved running the end-user application over the stadium's network in order to establish a baseline. Then we tested the application over the 5G Network. Here we did not have programmable connectivity between the application and the network. Following this, we implemented network awareness in the end-user application. Finally, we showed the use of VNFs in a network slice. There was also the physical test of the massive MIMO at the edge from the University of Bristol.

5.3.1 Key objectives

- To validate an implementation of the 5G OS technology developed in WP5 in a complex production network environment.
- To demonstrate how 5G OS can enable seamless creation of value-added network services in less than 1 minute.
- To illustrate how 5G-PICTURE intelligent network can autonomously detect and prioritize Watchity traffic in order to enhance QoE.

Access Domain

- Wi-Fi Small Cells with joint access and BH capabilities.
- Deployment and demo of crowd-source application across a production network.

Transport Domain

- Dynamic creation of slices with specific Class of Service (CoS).
- Deployment of 3 switches and many servers in the production network of the stadium seamless.

Compute Domain

- Dynamic creation and orchestration of VNFs which analyse the traffic.

Multi Domain Orchestrator

- Orchestration across multiple domains.

5.3.2 Performance tests general description

The stadium demonstration shows the feasibility of upgrading a production network to a 5G network with specific capabilities to enhance QoE of a novelty application (in this case the crowd-source application Watchity).

KPIs were measured in two different ways depending on if it was a network KPI or application KPI:

- The network KPIs were measured by capturing traffic at different points in each domain and measuring the deployment times in the different domain orchestrators.
- The application KPIs were measured at the clients and at the server side of the application in the Public cloud.

5.4 Demo Location – Ashton Gate Stadium

The demo was executed at Ashton Gate Stadium in Bristol (**Figure 5-6**). The stadium is used for football and rugby matches, concerts as well as private functions such as exhibitions, meetings, and trade shows. The network is equipped with Wi-Fi Access Points from different vendors throughout the stadium (approx. devices: 150). The network is connected in a hub and spoke topology. It is a venue with multiple network services, namely, IPTV, CCTV, public Internet access and event-based intranet access. The Fan Zone, which is located outside of the stadium, does not have any kind of Wi-Fi connectivity.

Figure 5-6: Ashton Gate Stadium

The AGS network is a production network environment and required coordination with the stadium's internal support staff and this could be challenging at times. For example, installation of the Wireless Access Nodes in the Fan Zone needed to be installed by AGS staff. The production network was extended with our *lab on wheels, while this work was predominantly carried out by Zeetta, it had to be done in coordination with the stadium*. The deployment of our transport domain, as part of the 5G OS, had to be carried out with extra care so as not to disrupt the live network. During the rehearsal in February, the Wireless Nodes were not able to be installed due to adverse weather conditions.

5.5 Access Domain

5.5.1 Integrated Access and Backhaul Wi-Fi technology

The technology used in the access domain is the integrated access and backhaul Wi-Fi technology developed by **i2CAT** in 5G-PICTURE. This technology is composed of HW platforms with SDN (NETCONF) based APIs developed in WP3, a control plane to forward packets along the mesh and enable network-controlled handovers developed in WP4 and a management plane to provision wireless slices developed in WP5.

Deliverable D5.4 [32] describes in detail the developed management plane and introduces the concepts of Wireless Chunk and Wireless Service. A wireless chunk is a logical assignment of a sub-set of the infrastructure resources to one tenant of the wireless infrastructure, whereas a wireless service is the instantiation of one or more virtual Access Points radiating a Service Set Identifier (SSID), configured with security credentials, connected to the set of paths across the wireless mesh, and tagging the traffic connected to that service with a given VLAN in the transport segment.

To support the Stadium demonstration we used a three node wireless mesh topology depicted in **Figure 5-7**. The three nodes are names 's0', 's1' and 's2', with 's0' and 's1' equipped with one access and one backhaul physical interface, and 's2' configured with two backhaul interfaces. Node 's2' is connected via Ethernet to the Stadium network. Figure 5-7 indicates the wireless channels in the 5GHz band where the different physical interfaces in each node have been configured and depicts inside the green and blue boxes the detail of the chunk and service configurations. We can see that the Low Priority service includes physical interfaces from nodes 's1' and 's2' and deploys a service identified by SSID: 'PICTUREDEMO' supported by a virtual AP with MAC address (02:00:00:00:00:0f). All traffic connecting to the low priority service is connected to a backhaul path between 's1' and 's2' and is tagged with VLAN 130 when delivered to the wired network in node 's2'. The high priority chunk and services are configured in nodes 's0' and 's2', where customer traffic is delivered to the transport domain in node 's2' using VLAN 140. It is worth noting that both the low and high priority wireless services use the same SSID and BSSID. This configuration is used for a dual purpose. First, from the customer devices are completely unaware of the configured wireless access slices and simply connect to the same service, i.e. the PICTUREDEMO service. Second, the network can select how it wants to move devices between the low and high priority slices using network-controlled handovers. However, as we will explain later in this section, network-controlled handovers require virtual APs to have the same BSSID.

Figure 5-8 depicts the visualization in the dashboard of the wireless chunk and services used in the stadium demo. The configuration though is a bit different than the original design described in **Figure 5-7** because a single chunk was used to support the high and low priority services. In this set up using one or two chunks has no impact because the physical resources used by each service are non-overlapping. We can see in the main part of the dashboard the wireless topology composed of the three nodes 's0', 's1' and 's2', with different physical interfaces available inside each node, namely a square indicating an Ethernet interface, a circle a wireless backhaul interface, and a triangle a wireless access interface. On the right panel we see the two wireless services configured over this chunk with the SSID *PictureDemo*.

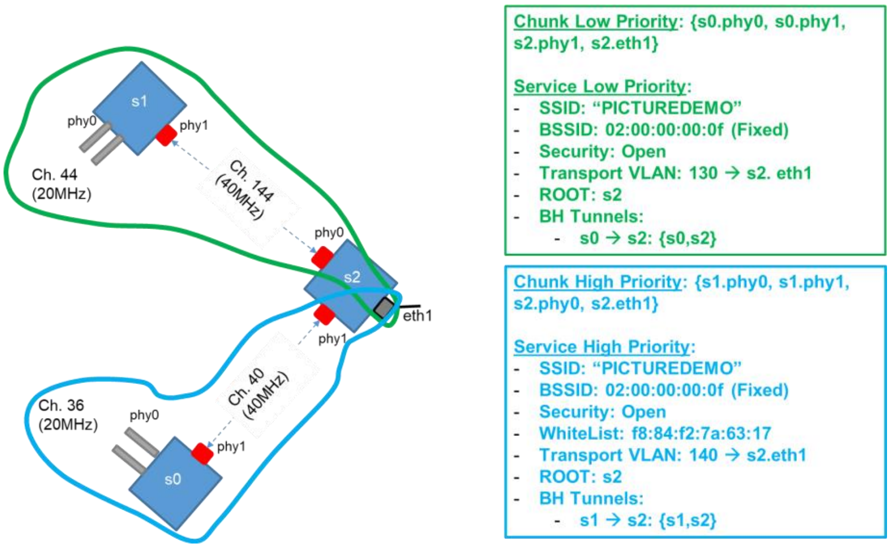


Figure 5-7: Topology, chunks and services in the access domain of the stadium demo

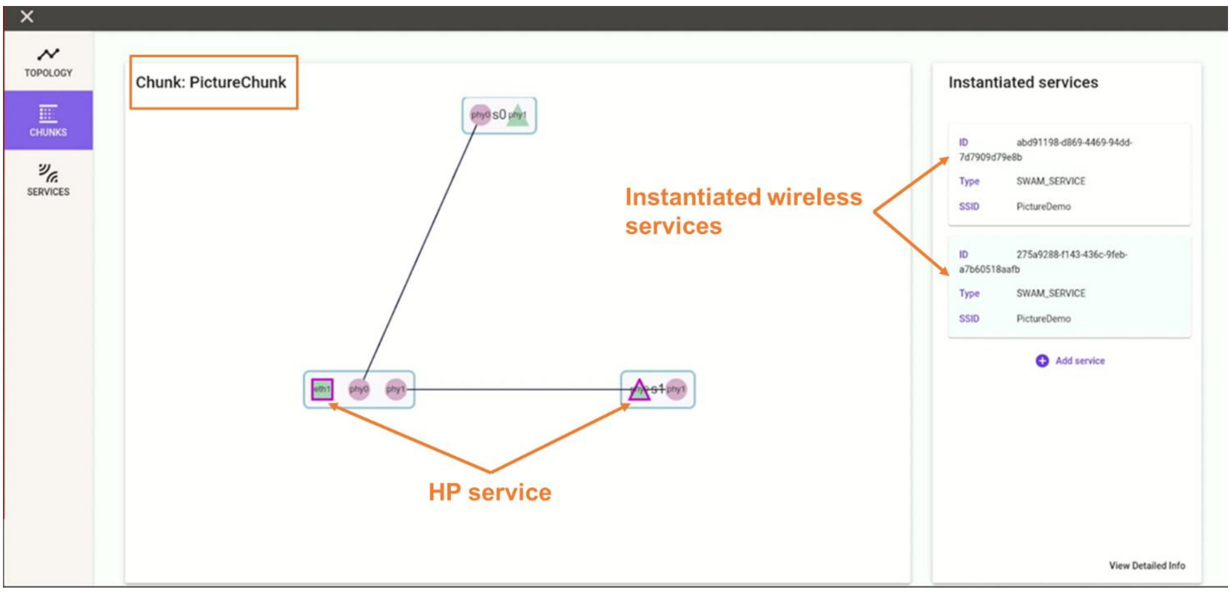


Figure 5-8: Visualization of the configured chunk and services in the 5G OS dashboard

5.5.2 Physical Integration in the stadium

Figure 5-9 illustrates the final deployment of the wireless access nodes in the stadium. Node 's1' supporting the high priority slice was installed on top of the West Stand and powered by a cable connected inside the stadium, node 's0' was deployed on top of the Store and plug to a wall socket, and node 's2' was mounted on top of the ticket box outside the stadium, using the power and network available therein.

Node 's2' connected to a switch inside the ticket box that was part of the stadium network, and was therefore not controlled by the 5G OS, and from that switch it reached the 5G OS transport domain provided by Zeetta Networks.

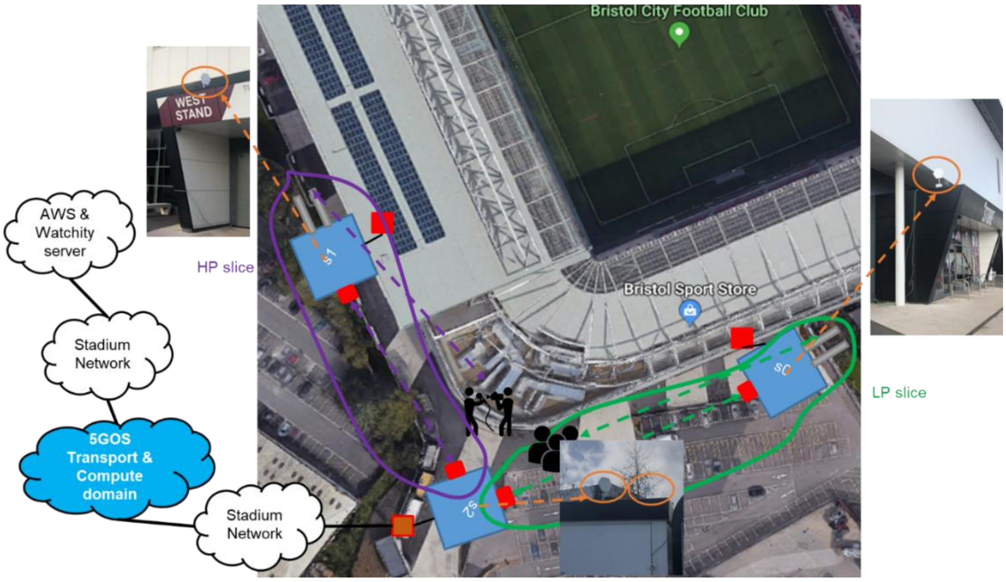


Figure 5-9: Deployment of wireless access in the stadium

5.5.3 Integration with 5G OS

As discussed in detail in D5.4 [32] the wireless access domain is connected to the rest of the 5G OS using the i2CAT RAN Controller, which exposes a set of REST APIs that enable the MDO to configure Chunks and Services as needed. In this section though we discuss in detail the use of network-controlled handovers by the 5G OS control plane, which is a feature used in the stadium demo that was not described in deliverable D5.4.

As we describe later network-controlled handovers are triggered by the Video Traffic Sniffer VNF upon identifying the devices transmitting Watchity traffic, which need to be moved to the high priority slice. Underlying the network-controlled handover mechanism developed in 5G-PICTURE is the Channel Switch Announcement (CSA) feature developed in the IEEE 802.11ah standard. This feature was originally developed to address the requirement of Dynamic Frequency Selection (DFS) in the 5 GHz band, where Wi-Fi APs coexist with weather radars. According to the DFS requirements, a Wi-Fi AP must scan for radar presence and if a radar is detected it needs to vacate the current channel and move to a new one in the 5 GHz band. In order to notify associated stations that it is moving to a new channel the AP transmits, either as broadcast or unicast, a CSA frame that includes the destination channel, but does not include the BSSID since it is assumed to be the same as the current AP. In 5G-PICTURE we leverage this feature to enable network-controlled handovers in the following way. First, we configure source and target APs in different channels but using the same BSSID. Second, we develop an API in the Wi-Fi APs that enables the RAN Controller to trigger the transmission of a CSA frame for a target station at any moment. Third, we develop another API that allows to migrate the station context, e.g. sequence number, encryption keys, etc, from the source to the target APs before executing the handover.

The complete control plane is illustrated in ***Figure 5-10***, where we can distinguish the following elements:

i. The RACOON RAN Controller used to provision chunks and services, which offers through its north-bound interface the list of available APs, their BSSID and connected stations

ii. A Handover manager module that oversees all the steps required to execute a handover, including CSA triggering and station context migration between virtual access points.

iii. An SDN Handover Controller that is in charge of obtaining the topology and list of APs in the network from the RAN Controller and triggering the network-controlled handover when needed. To do so the SDN Handover Controller periodically polls the Video Traffic Sniffer VNF to identify if the VNF has discover the MAC address of a station that is transmitting Watchity traffic. Upon receiving a station match from the VNF the SDN Handover Controller triggers the station handover from the low priority to the high priority slide using the Handover manager.

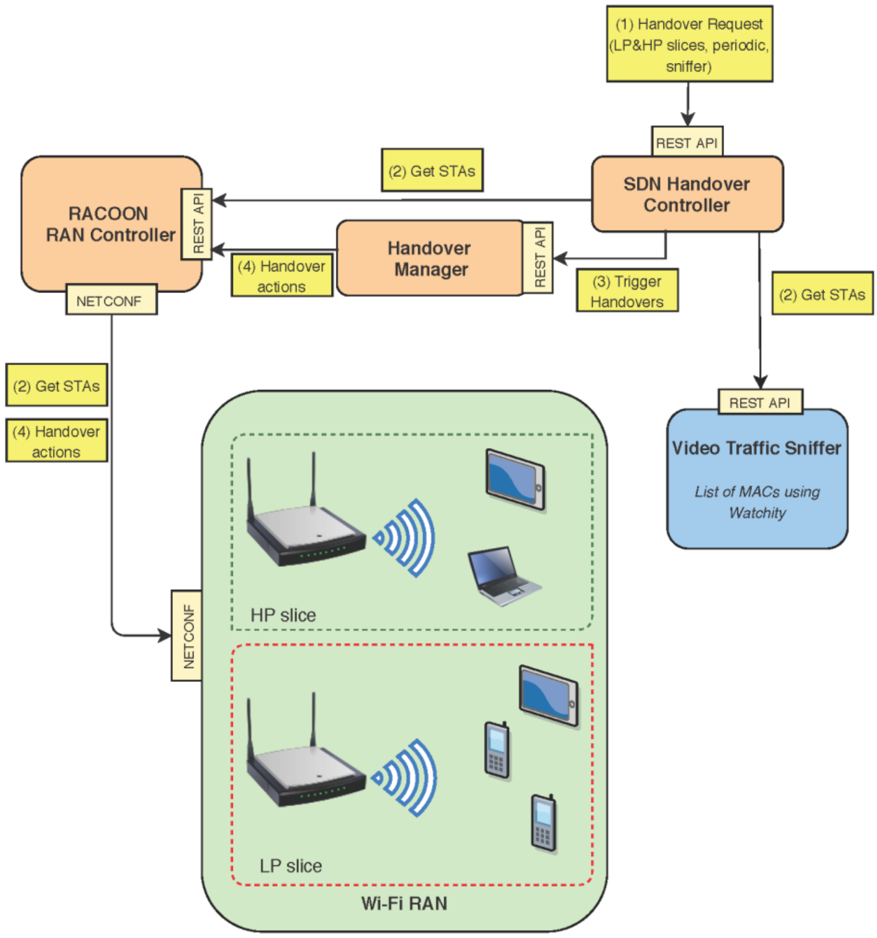


Figure 5-10: Control plane used to enable network-controlled handovers

Figure 5-11 depicts the result of an experiment to validate the network-controlled handover where we see an uplink stream that starts in the low priority slice (shown in blue), and at time 120 seconds we move the uplink stream to the high priority slice (shown in red). As depicted in the figure the uplink stream is not affected by the network-controlled handover.

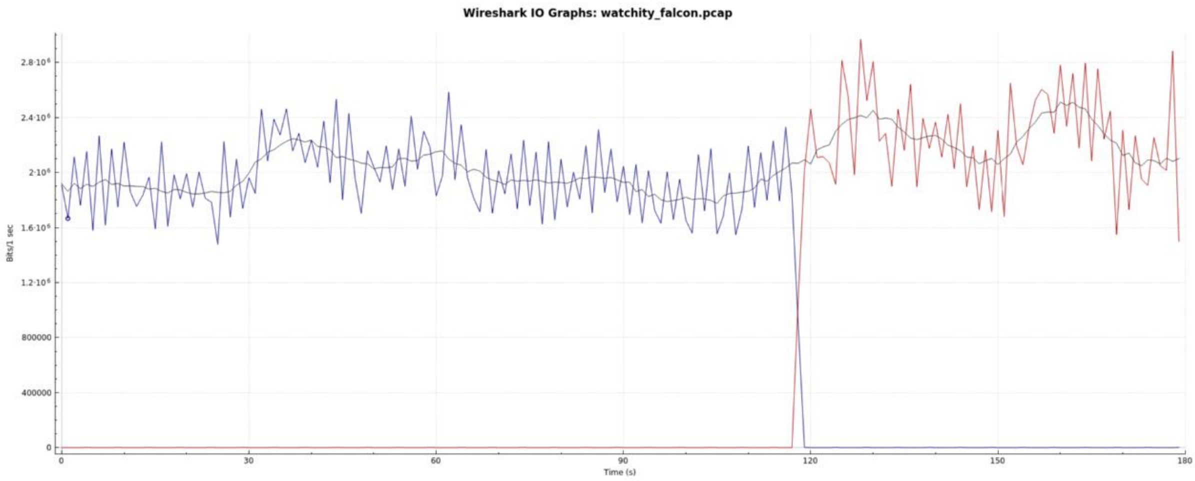


Figure 5-11: In-lab validation of network-controlled handover

5.6 Transport Domain

This section describes the Transport domain of the demo. The transport domain comprises four switches, a domain orchestrator and the SDN controller NetOS as part of the 5G OS architecture defined in D5.1. The domain orchestrator computes the different solutions providing valid slices with different CoS to provision the network. The slice definitions are received from the MDO through the Control Orchestration Protocol (COP) interface defined in D5.1 [33].

5.6.1 Stadium Network integration

The transport and the access domains were connected to the stadium network directly. We requested a control VLAN (120) and two different data VLANs (130 and 140) to interconnect the access and the transport domain across the stadium network. The stadium network was configured accordingly with these three VLANs establishing an end to end Layer2 network between the I2CAT WAPs and the Edgecore 311 at the transport domain.

In this project it is necessary to "merge" the two test slices (VLANs 130 and 140) into a single VLAN. We achieve this by "translating" the slice VLAN IDs to a common VLAN ID (in this case 902) using a switch located between the transport network and firewall. The network diagram in Figure 6 shows test switch E310 connected to switch E311. A trunk port is configured (on both switches) with VLAN 130 and 140 as members. Consequently, E311 will transmit/receive frames to/from E310 with 802.1Q tags.

On E311, two access ports are configured with VLAN ID's 130 and 140, respectively. Tagged frames from the trunk will be forwarded down the respective access port as the native VLAN for that port (i.e. untagged). Each access ports are "looped back" to another port on E311. Both ports are configured with VLAN ID 902 as their respective native VLAN. In summary, frames received from the slices are translated between the slice VLANs (130 and 140) and the common VLAN 902.

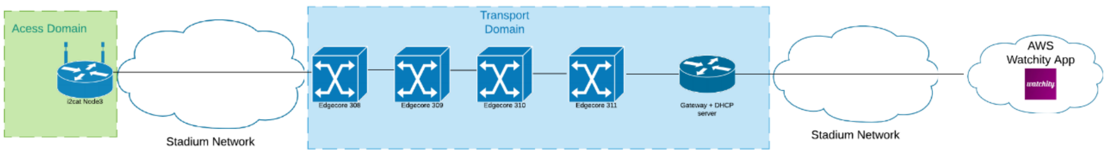


Figure 5-12: Stadium Network Integration

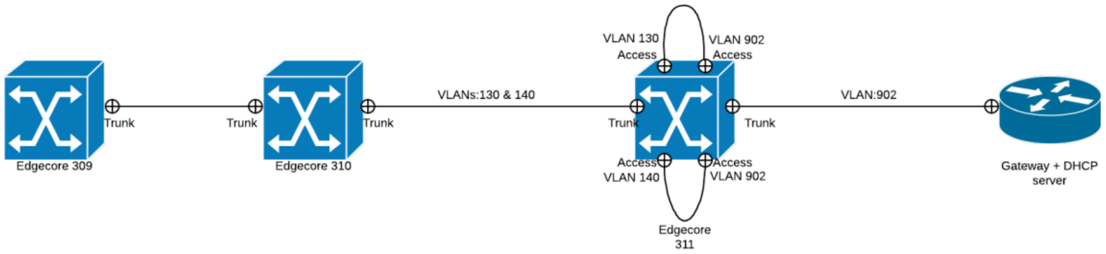


Figure 5-13: VLAN Merge Solution

For "downstream" traffic we rely on the MAC forwarding tables to forward frames tagged with the common VLAN ID to the "correct" slice.

5.6.2 Lab-on-wheels architecture

The lab-on-wheels (***Figure 5-14***) is a fully configured hardware and software solution which enables and controls the fast setup for temporary or “pop-up” networks. For this demo we provided two lab-on-wheels with two Edgecore AS4610-54P and three MEC servers on each, besides one of the boxes is equipped with a Peplink Balance 305 Router as a Gateway.

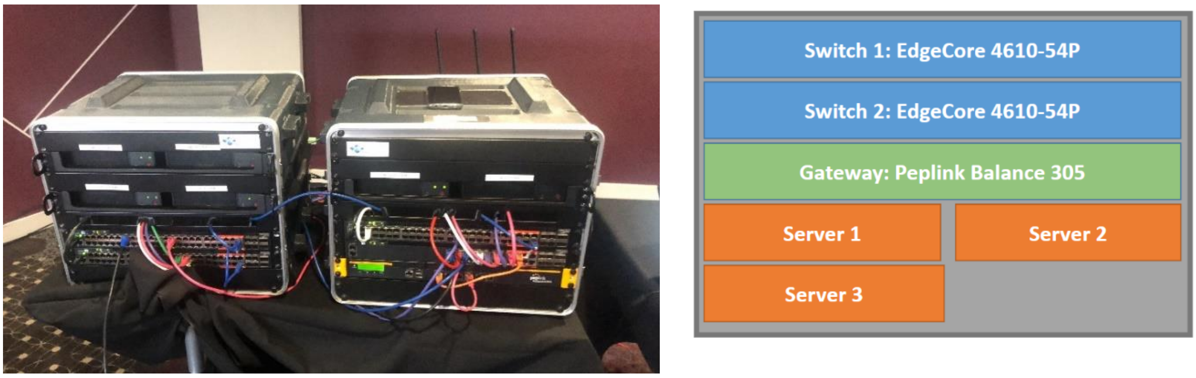


Figure 5-14: Lab on wheels deployed at the stadium(left), Lab on wheels diagram(right)

5.6.3 Cross domain integration

The network is represented as different domains integrated with the stadium network as shown in ***Figure 5-15***. The Access domain is connected to the stadium network as explained above, the Compute domain and MDO are connected to the first switch in the Transport domain to minimize delay and complexity. The Compute domain needs to receive the traffic from the different slices (high and low priority). To achieve this, the first switch has port-mirroring setup enabled to replicate the traffic from the Access Domain into the Compute domain. The Transport domain has two different laptops connected for the purpose of generating traffic inside of the domain. Moreover, this background traffic will be executed as part of the demonstration to prove that the priority and capacity assured by the slices are guaranteed.

The network domains have a common Layer 2 control plane, which is VLAN 120. The MDO is able to trigger the creation of the high and the low priority slices. The MDO will create the slices using the COP interface which was defined in D5.2 to communicate with the Access and Transport adapters.

During the demo, the Transport domain had three different slices created. The low priority slice (Priority 3) and the high priority slice (Priority 7) were created in the VLAN 130 and 140 respectively to carry the application traffic. Moreover, we created a third slice to generate background traffic inside of the transport domain with the lowest priority (Priority 1), in this case this slice was created in the VLAN 150. The background traffic slice proves that the other slices are not affected because they have a higher priority even though the background traffic is saturating the capacity of the links.

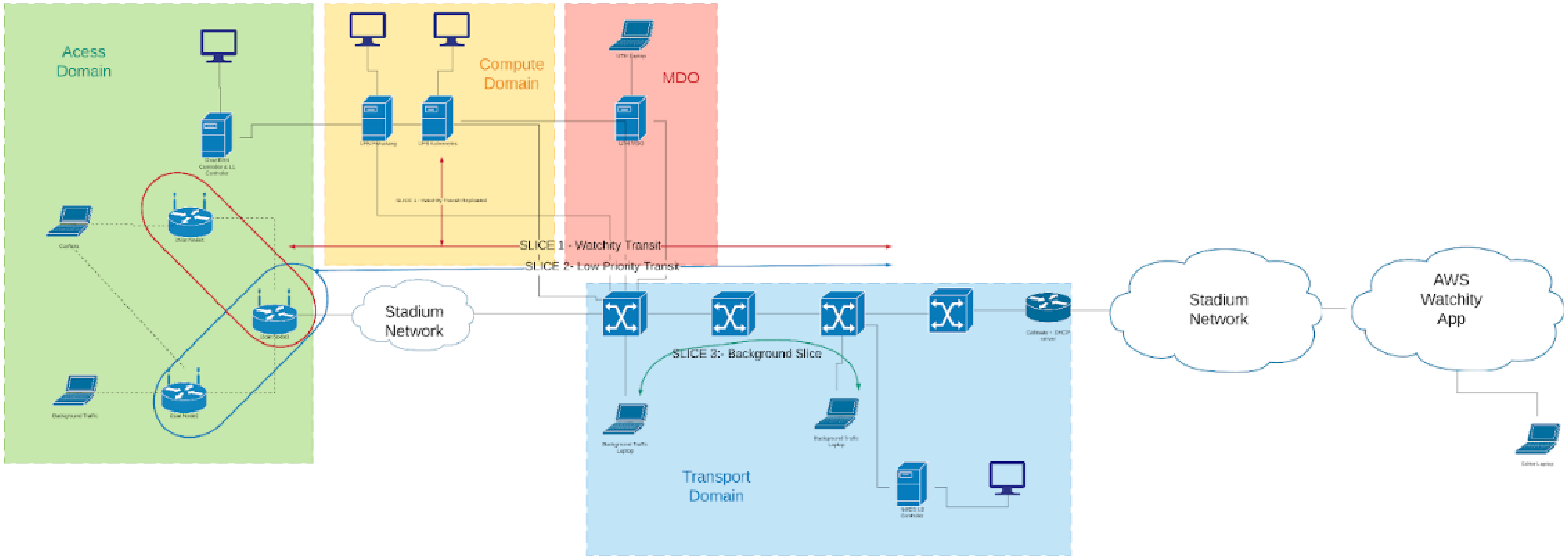


Figure 5-15: Multi Domain Network Diagram

5.7 Compute Domain

In this section, we describe the compute domain of the demo which is used to run an NFV service. This service is helping the 5G OS to identify the need for switching to the high-priority slice. To manage the compute domain, we used Pishahang as MANO framework. Pishahang is a multi-domain NFV MANO framework that supports orchestration of services across Kubernetes, OpenStack and AWS domains. Pishahang was used in WP5 to support multi-version services and also as part of 5G OS to manage VNFs based on Virtual Machine and Container.

Pishahang utilizes Kubernetes to manage container-based network functions. Unlike the other MANO frameworks (e.g., OSM) that run Kubernetes on top of a virtual machine, Pishahang runs Kubernetes on bare metal compute resources. This improves the performance of the services running under Kubernetes and also accelerate management of the services.

In this demo, Pishahang was used to deploy a container-based network service that can detect when a handover from a low-priority to a high-priority slice should take place.

5.7.1 Network Service

The network service implemented for this demo follows the microservice-based architecture. It consists of four containers, namely message broker, database, packet sniffer, and endpoints. **Figure 5-16** illustrates the architecture of the network service.

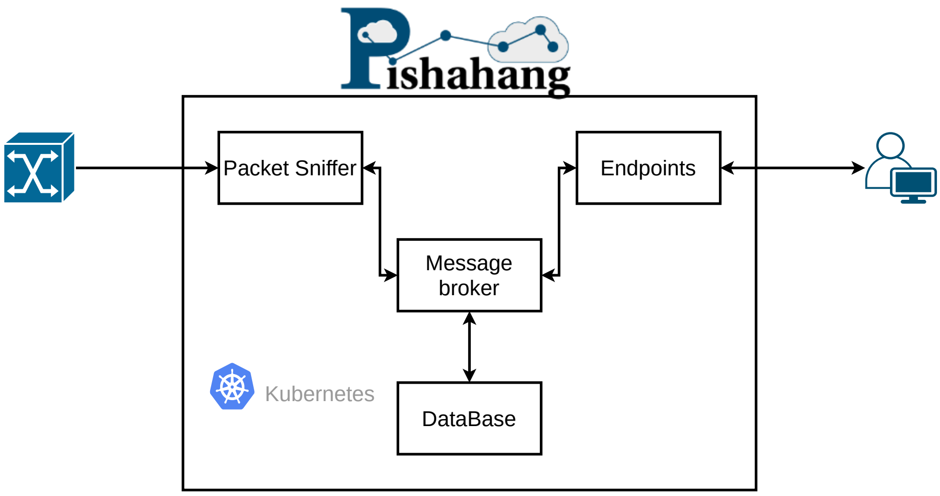


Figure 5-16: High-level architecture of the network service

As mentioned before this network service allows 5G OS to detect the need to switch to the high-priority slice. This is done by inspecting the Watchity application traffic, extracting the IP and MAC addresses of these traffics and storing them along with a time stamp in the database. This information is provided to 5G OS for further analysis through REST API to decide when the handover should take place. The detail explanation of each component is as follows.

- Endpoints: is based on Flask which provides REST APIs to retrieve the stored data.
- Packet sniffer: based on Python socket library which extracts TCP packets distained to port number 1935.
- Message broker: is based on RabbitMQ allowing microservices to exchange messages with one another.
- Database: is based on MongoDB and is used as storage for the extracted data.

The data stored in this dataset belongs to I2CAT and, therefore, there is no issue associated with GDPR. In a commercial solution, such data will not be stored. Instead, the VNF makes the handover decision on its own and notify the 5G OS directly when a handover is needed, without storing or exposing any data.

5.8 Multi Domain Orchestrator

In this section, we describe the implementation of the Multi Domain Orchestrator (MDO), which is based on the Postman API platform. Postman offers a desktop where we have built collections of requests to the interfaces of the underlying domains. The requests are parameterized, meaning that there is a set of variables, organized in an environment, which are given as parameters to the requests for controlling their behaviour. Due to this environment, we are able to store the output of a request and control the sequence of the following requests. For example, if the output of a request indicates an error, then we repeat this request until its successful call and then we proceed with the following one. We use scripts to build integration test suites, pass data between API requests, and build workflows that mirror our use case. We also use collection runner for customizing the order of the execution of the requests.

More specifically, we have developed a collection, named 5GPICTURE-MdO-Bristol, and an environment with the same name, as it is depicted in the following **Figure 5-17**:

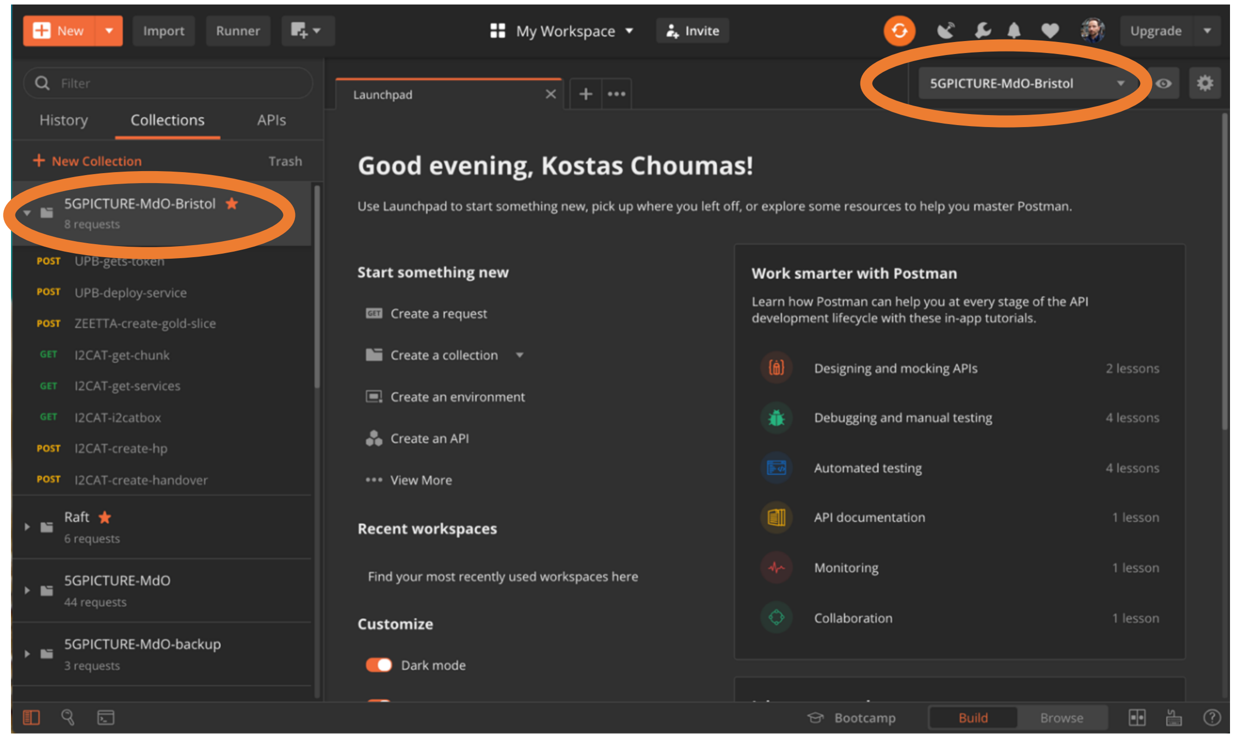


Figure 5-17: Postman Collection and Workspace

As you can see, the collection includes requests to the compute, transport and wireless domains. Depending on the domain that each request is related to, its suffix is either “UPB”, “ZEETTA” or “I2CAT”, being the name of the partner that is responsible for this domain. The following **Figure 5-18** shows the request to the wireless domain for creating the high priority chunk, named as I2CAT-create-hp.

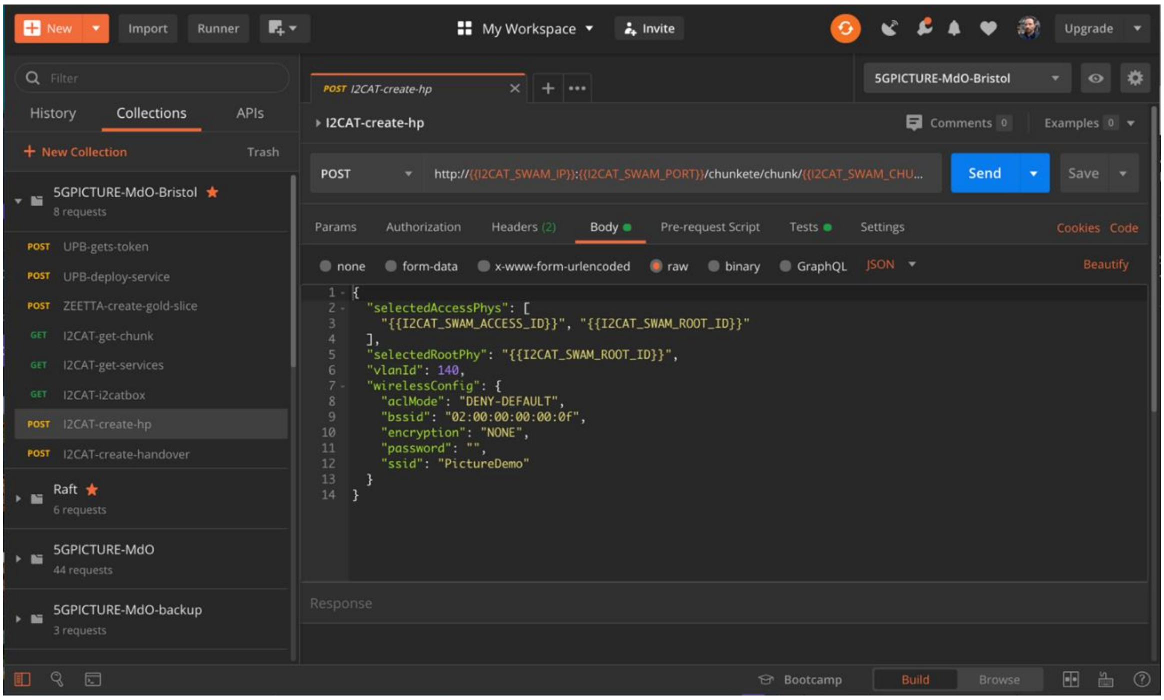


Figure 5-18: Postman request to wireless domain for creating the high priority chunk

As you can see, the request is a REST POST with a URL that is not hardcoded and fixed but parameterized, using variables of the 5GPICTURE-MdO-Bristol environment, which are filled with values given by the post-scripts of the previous requests. For example, the variable {{I2CAT_SWAM_CHUNK_ID}} is filled with the appropriate value after running the I2CAT-get-chunk request and its post-script, where the latter filters the output of the former and finds the aforementioned value. We have also defined variables for configuring the workflow for either creating a high or a low priority slice. Finally, we use a variable for estimating the time needed for deploying an end-to-end slice, either a high or a low priority slice, including resources from the compute, transport and wireless resources.

Figure 5-19 shows how Postman Collection runner is used for the execution of the requests of this UC.

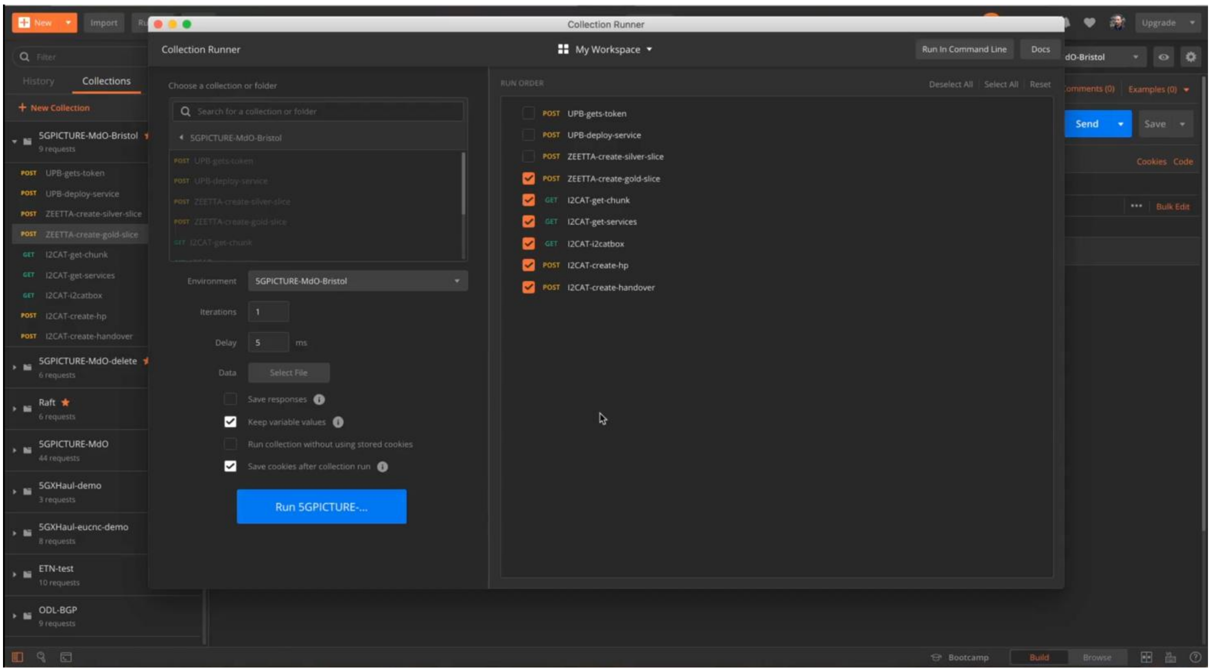


Figure 5-19: Postman Collection runner

Finally, **Figure 5-20** shows how Postman indicates the successful execution of all requests by our Postman-based MDO. You can see each request, when it is executed and how much time was needed for its execution.

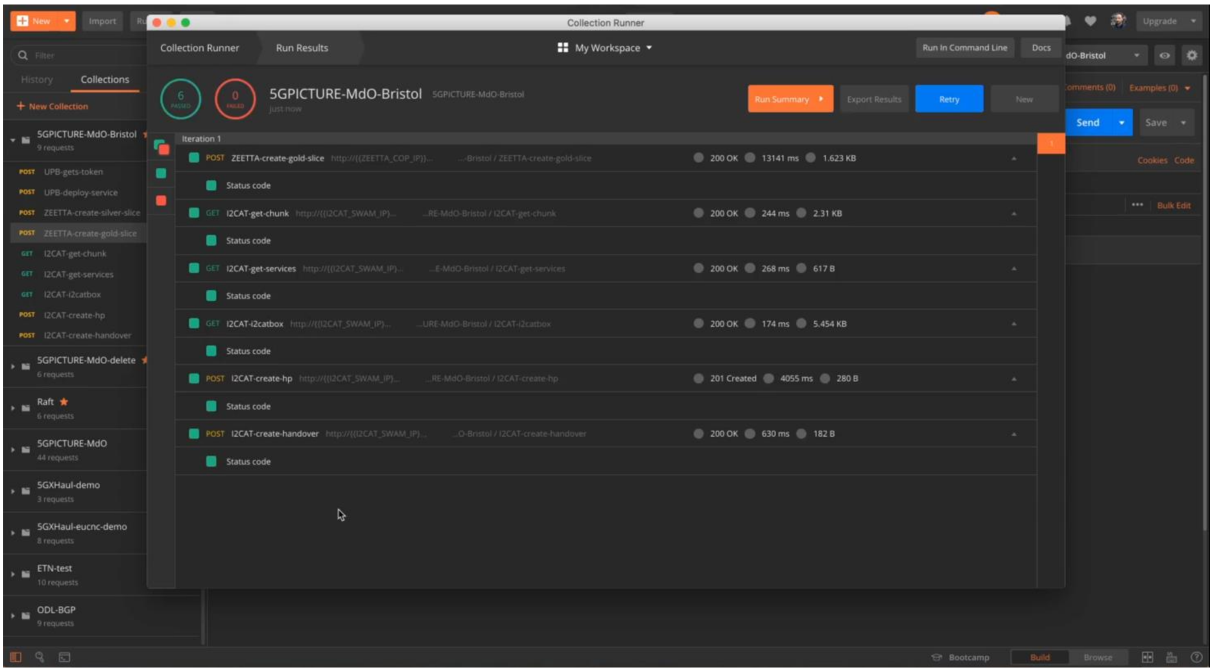


Figure 5-20: Postman Collection successful execution

5.9 Work Process and results

In this section, we describe the integration plan executed in four phases from September 2019 until the Final Demo in March 2020. This plan was executed as an extension of the integration work done during

D5.4 [32] but in this case, 5G OS architecture was tested at the stadium in a production environment. Finally, the results obtained in each phase are described in detail.

5.9.1 Trial overview and definition

The aim of the demonstration was to showcase the differences between a "legacy" network and a 5G Network. In the first part, we demonstrated the limitations of the stadium network. Later, we enabled the 5G OS components to enhance the network as a 5G network and demonstrated its benefits.

Existing Network Scenario

1. The existing network was pre-configured which would be the equivalent to the Low priority slice.
2. The tablet was connected to the existing network and started to record using Watchity, the editor was able to watch and edit the video.
3. From another wireless client, we generated background traffic to saturate the wireless link, consequently, the performance of Watchity was downgraded. However, in the stadium demo, due to the signal attenuation mentioned in the previous section, moving the client between the WAPs was enough to disrupt the wireless link.

In a 5G network with the 5G OS architecture in place, the initial steps are similar, but this time, after the application was downgraded, the network reacted.

5G Network

1. We repeated the first three steps of the previous scenario, but in this deployment the traffic was mirrored to **UPB**'s VNF in Kubernetes to analyse the traffic.
2. MDO triggered the creation of a new High priority slice using the COP interface to notify Zeetta's controller (Transport domain) and I2CAT's controller (Access Domain).
3. The initial tablet performed the handover to the High priority slice automatically, improving the quality in the Watchity application.
4. Finally, in the Transport Domain, we generated traffic between two laptops to increase the utilisation of the network and prove that the priority of the slices was guaranteed.

5.9.2 Phases and Results

5.9.2.1 Phase 1: Network In-lab integration

During the first phase of the integration we tested the Wireless Domain independently at **I2CAT** Lab in Barcelona. The goal of this first test was to validate that we could execute the demo considering only the wireless domain

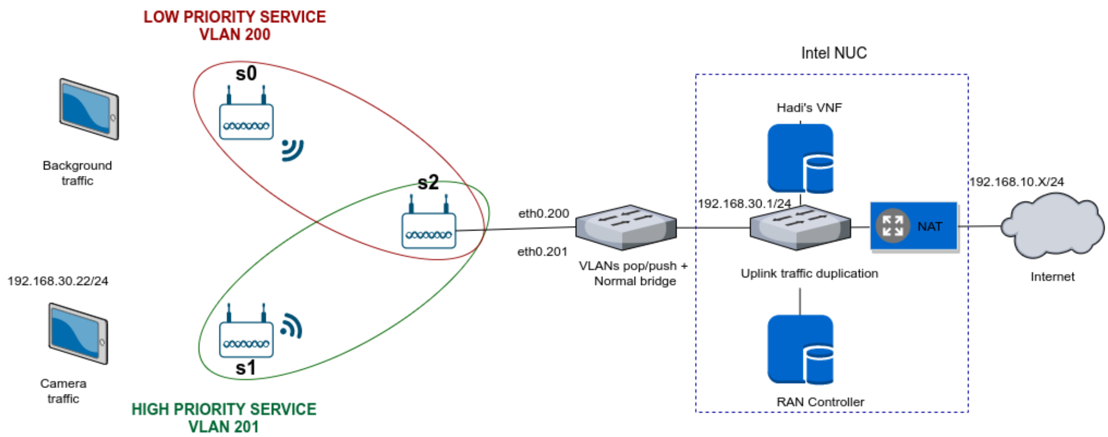


Figure 5-21: Lab Setup at I2CAT

Figure 5-21 summarizes the local testbed deployed in i2CAT's lab, which fulfils the following features: i) It resembles accurately the physical topology that is used in the stadium network, ii) it simplifies the stadium network and the 5G OS Transport domain using an Intel NUC device with an internal configuration that allows to distinguish the traffic coming from the low priority and the high priority services, maintain the device IP after the network-controlled handover, and provide Internet connectivity for the low and high priority services.

The "root" node (s2) pushes the VLAN 200 to the traffic in the low-priority service and the VLAN 201 to the traffic in the high-priority service. Node s2 is connected to an APU (PC Engines) which has an OpenvSwitch (OvS) switch. This switch has two VLAN interfaces (on for each services) and a port to the Intel NUC. It behaves as a NORMAL bridge, that is, it learns the port associated with the MAC address of our Watchity device.

The Intel NUC contains UPB VNF as well as the RAN Controller. In order to send the traffic to the VNF as well as to the Internet we use another OvS which duplicates the uplink traffic. Preferably, the traffic should be duplicated in the downlink; otherwise, the VNF has to be slightly modified. Finally, we have an iptables rule in the NUC that NATs all the traffic coming from the 192.168.30.0/24 network to the IP of the NUC in the i2CAT network.

In a first phase (Phase 1, P1), we prepared the evaluation setup shown in **Figure 5-22** to be able to confirm the successful performance of the Watchity app when capturing a live video stream from a tablet.

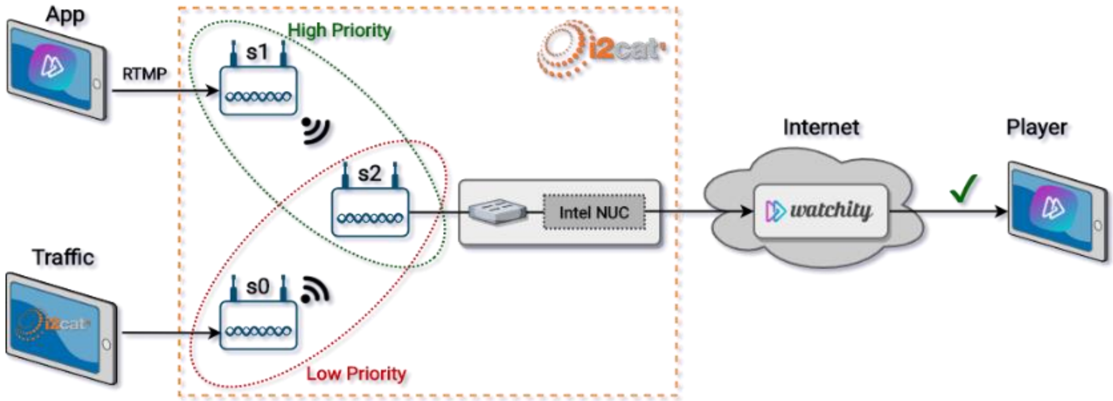


Figure 5-22: Session starts with only Watchity traffic

Next, a second phase (Phase 2, P2) was triggered by adding another tablet sending a traffic flow of 20Mbit/s by using the iPerf [8] tool (see ***Figure 5-23***). A high priority was assigned to the iPerf traffic and a low priority was assigned to the Watchity traffic with the goal of having a bigger impact on the Watchity stream, simulating a severe congestion situation.

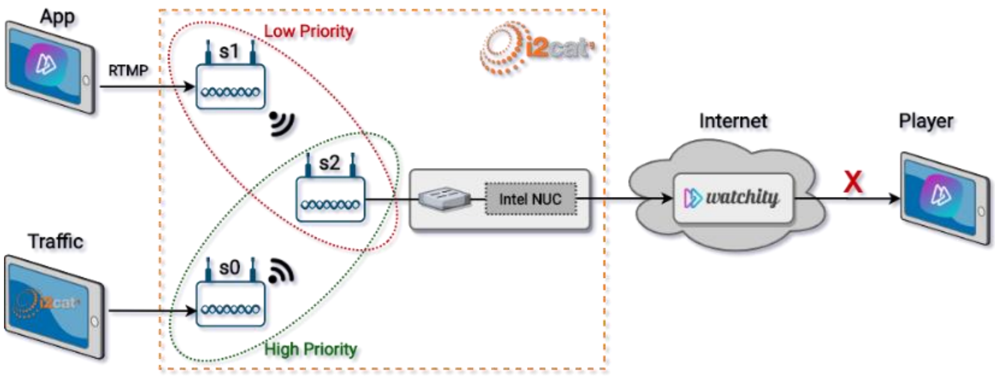


Figure 5-23: A tablet sending background traffic (using iPerf) with high priority is added.

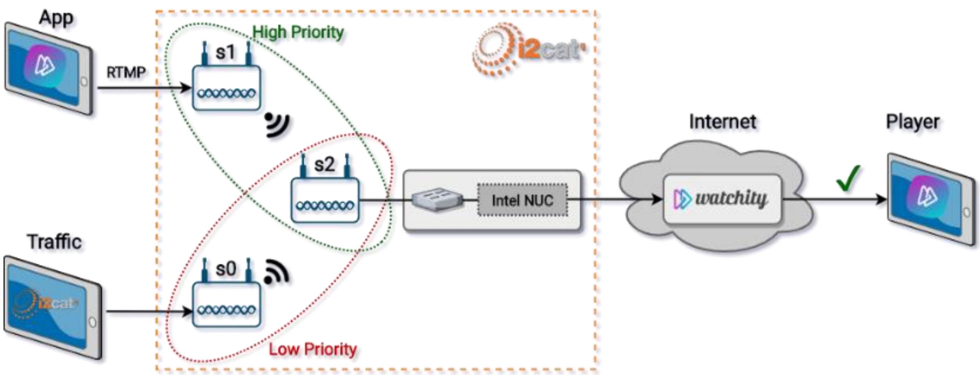


Figure 5-24: 5G-PICTURE slice is activated with traffic

Finally, a third phase (Phase 3, P3) was triggered in order to assign high priority to the Watchity traffic, by activating the HO technology (see ***Figure 5-24***).

Each phase had a duration of approximately 180 seconds.

After successfully demonstrating the setup, the equipment was shipped to UK for running the pilot, but first a very similar controlled evaluation setup was replicated, with three adjustments:

- It included the fixed network segment by Zeetta Networks, and not only the wireless segment, as in the Barcelona lab test.
- The iPerf traffic intensity was adjusted to 25 Mbit/s to have a bigger impact on the QoS / QoE for the Watchity service.
- The triggering times for the three phases was slightly different: P2 was triggered approximately at 78 s, and ~113.

Before the rehearsal at the stadium, we integrated all the components at Zeetta's lab. A VPN connection was configured to allow the different partners to connect remotely and configure their setup before coming to Bristol.

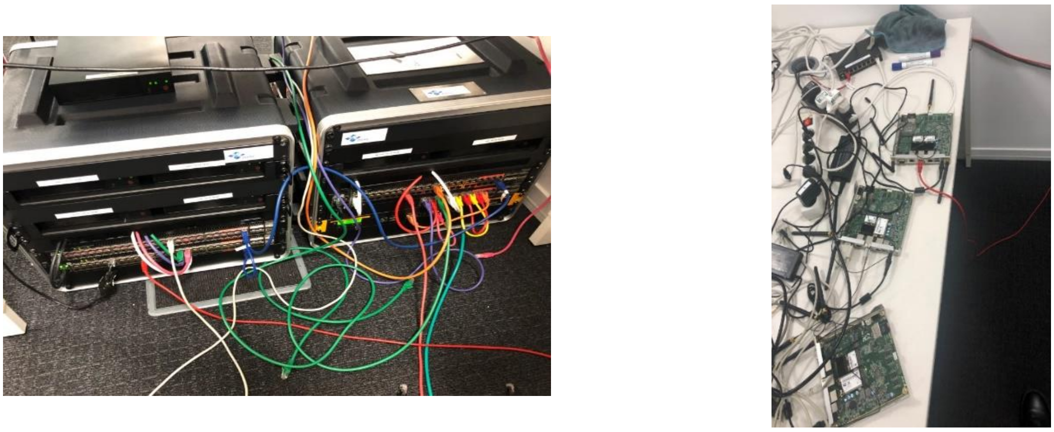


Figure 5-25: Lab on wheels configured in Zeetta's lab(left), WAPs provided by I2CAT at Zeetta's lab (right)

Performance Tests at I2CAT Lab

The results are obtained by analyzing the captured *.pcap* file, by loading it in Wireshark. As the three phases were triggered in a continuous single session, then the results are provided in graphs including the statistics / KPIs for the three phases. This allows for an intuitive visual comparison.

Figure 5-26 shows the evolution of the video traffic bandwidth (i.e. number of bytes per unit of time) during the whole session. It can be observed that the bandwidth was quite stable during P1, but it started how highly fluctuate when P2 was triggered due to the forced congestion situation. Indeed, it can be observed how low data rates and TCP errors occurred quite frequently, thus having an impact on the provide QoS and perceived QoE. Once P3 was triggered, the bandwidth for the video traffic was recovered and kept quite stable until the end of the session. Even, it seems that the bandwidth was slightly higher than in P1. No TCP errors occurred in P3. ***Figure 5-27*** provides very similar the evolution statistics, but focusing on the average TCP throughput (graph with identical behaviour than the one in ***Figure 5-26***) and on the segment length. As can be seen in the figure, it seems that the addition of traffic background also had an impact on the segment length. Finally, ***Figure 5-28*** show that the addition of traffic load and the application of the HO / Slicing technology did not have an impact on the Round Trip Times (RTT) for the TCP stream carrying out the Watchity video.

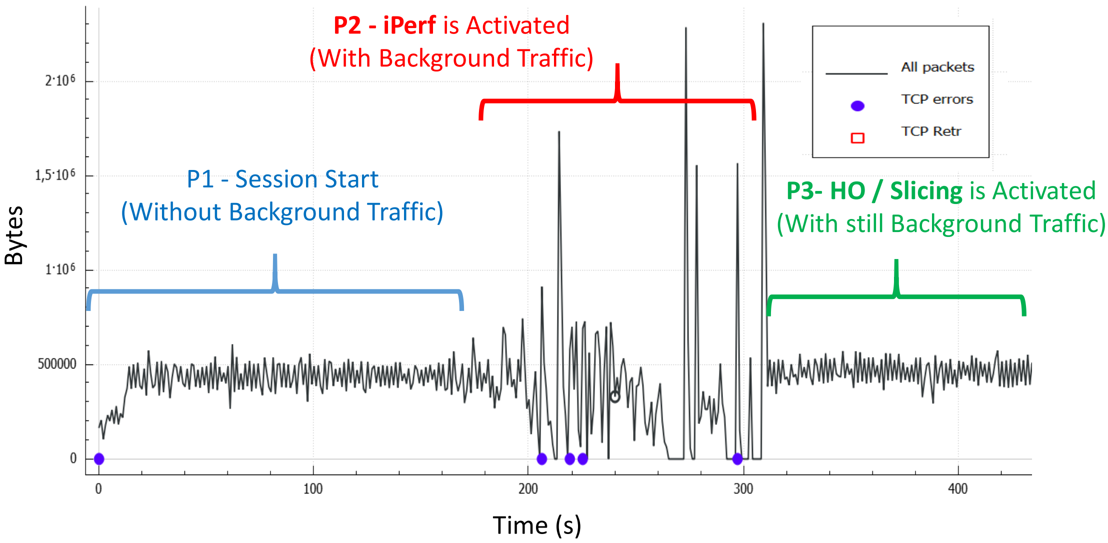


Figure 5-26: Bandwidth Evolution and TCP errors / retransmissions (Barcelona lab test).

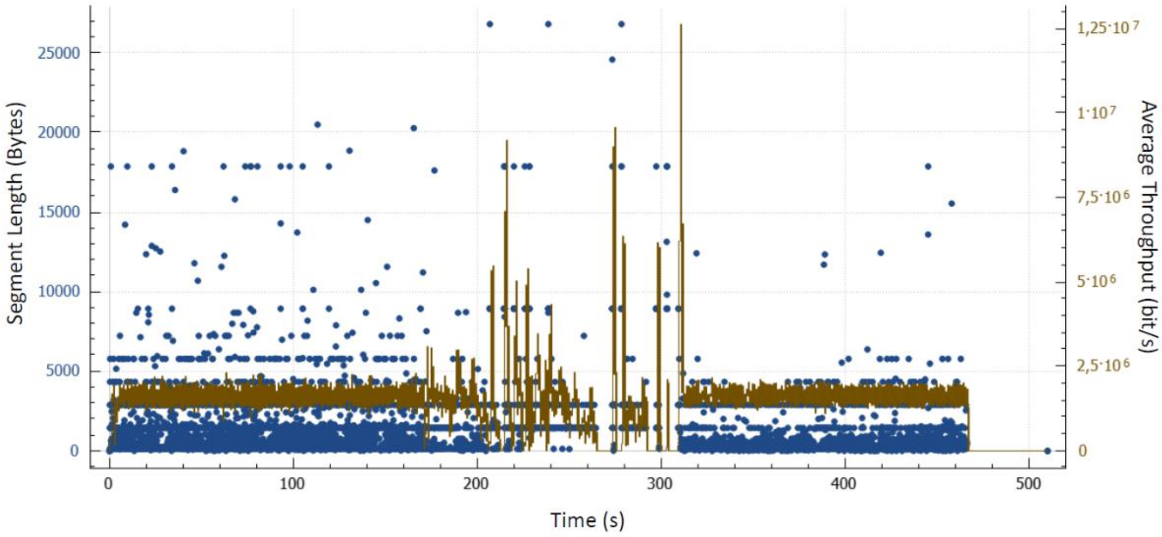


Figure 5-27: TCP Segment length and average throughput (Barcelona lab test).

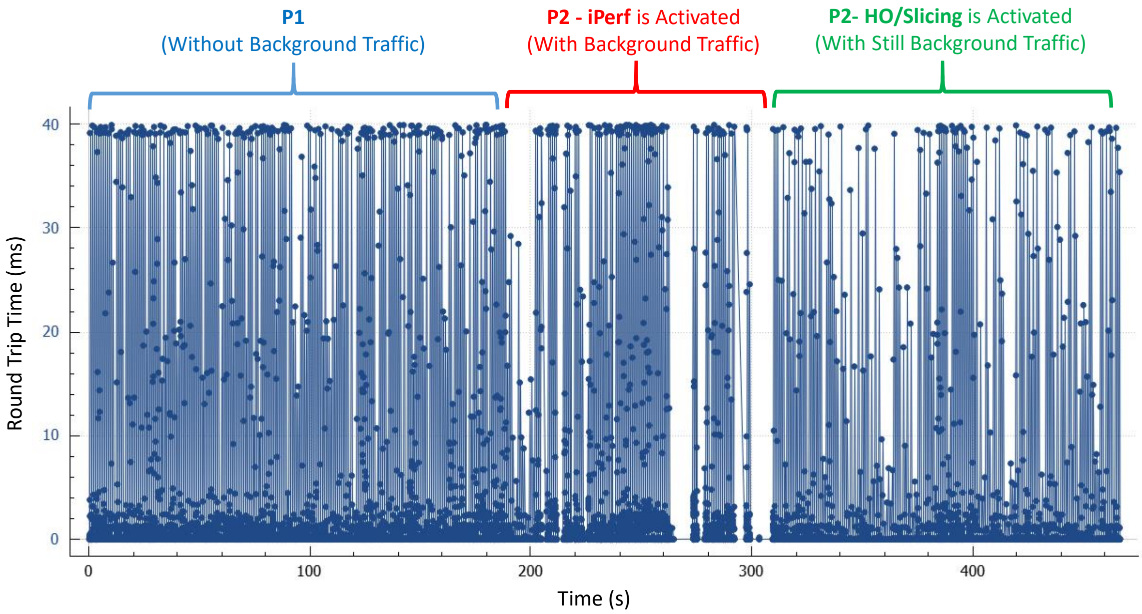


Figure 5-28: Round Trip Ties (RTT) for TCP segments (Barcelona lab test)

5.9.2.2Phase 2: Stadium Demo rehearsal

During the first week of February, every partner came to Bristol (UPB, UTH, I2CAT and ZN) for the demonstration rehearsal at Ashton Gate stadium. All the equipment and infrastructure, including the lab on wheels and the antenna stands provided by Zeetta and the WAPs provided by I2CAT were transported to the stadium.

During these two days, the weather conditions were adverse and the stadium staff could not install the antennas with the stands at height. Due to this situation, we decided to put the stands with the antennas in the West Concourse integrating the WAPs with the stadium network (**Figure 5-29**).

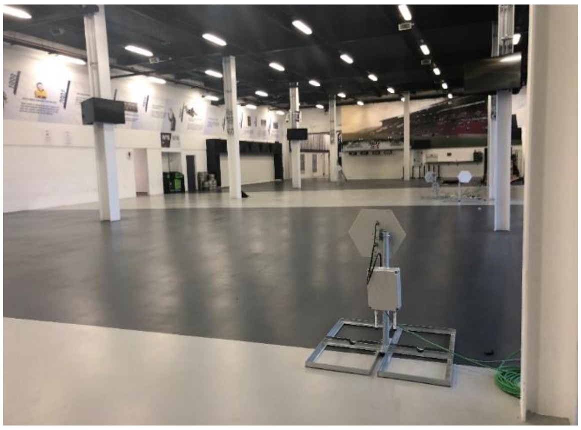


Figure 5-29: WAPs and antenna stands in the West Concourse

We integrated the Transport Domain provided by the lab on wheels (**Figure 5-30**), which was deployed in a small meeting room, was integrated with the stadium network. This integration was challenging because the stadium network was in an unstable state and we experienced some connectivity issues. Despite all this, we managed to prove the integration with the stadium network and we were able to send the application traffic across the stadium network to the Public cloud.

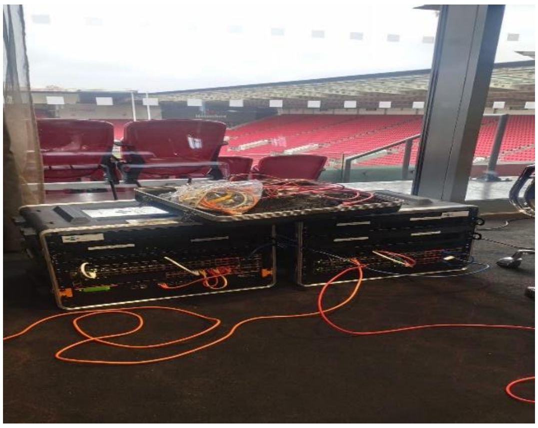


Figure 5-30: Lab on wheels at stadium during demo rehearsal (left), demo partners at Stadium during demo rehearsal (right)

5.9.2.3Phase 3: Application In-lab integration

After proving the deployment at the stadium during the demonstration rehearsal, we transported all the equipment back to Zeetta's lab for further testing until the final demo in March. We reconfigured the entire setup so that it could be reintegrated with Zeetta's lab network.

Figure 5-31: WAP and antennas deployed in Zeetta's lab

During this time we tested, recorded, and measured results of the whole demonstration as a backup plan due to the COVID-19 uncertainty. The WAPs and the antennas were deployed in the lab as shown in the **Figure 5-31**.

As shown in the **Figure 5-32**, the WAPs were connected directly to the Transport Domain and then connected to the Internet. We reproduced the whole demonstration with this setup in order to obtain the KPI results. The first switch in the Transport Domain mirrored the traffic of the low priority slice to the UPB server with the VNF analysing the traffic.

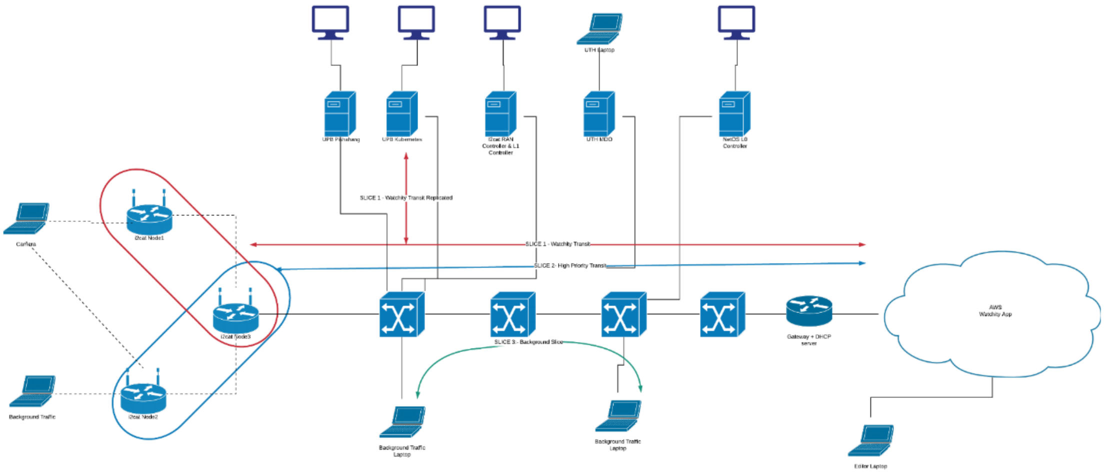


Figure 5-32: Network Diagram at Zeetta's lab

Performance test in Zeetta lab

The results in Zeetta lab were recorded and showed during the demo presentation. **Figure 5-33** provides very similar results than in ***Figure 5-26***. However, it can be seen that a higher number of TCP errors and re-transmissions occurred than in the Barcelona test, probably due to the use of a more complex/complete topology. This especially happens in P2, due to the higher background traffic added by means of iPerf (25 Mbit/s vs 20 Mbit/s in the Barcelona test). Interestingly, the number of TCP errors and re-transmission was significantly reduced when triggering P3.

Figure 5-34 can be also interpreted identically than ***Figure 5-27***. With regard to the delays, it can be seen that the forced test conditions did not have a major impact either, but a significant peak was registered when triggering the HO, which is very reasonable. Finally, **Figure 5-36** shows how the evolution of the TCP sequence numbers during the media session, for each of the triggered phases. As expected, the slope was less pronounced in P2, due to the TCP errors and retransmissions during that phase. The slope was recovered in P3, after activating the HO / Slicing.

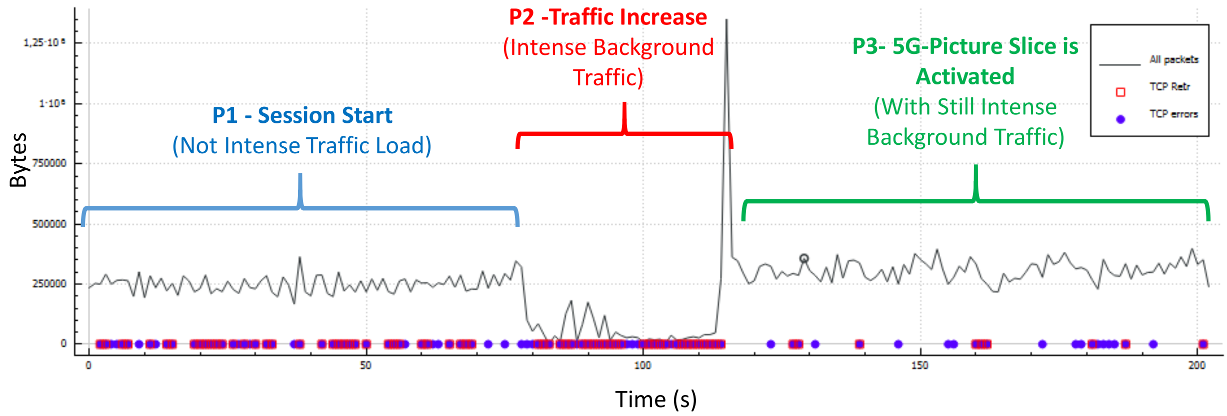


Figure 5-33: TCP Segment length and average throughput (UK lab test).

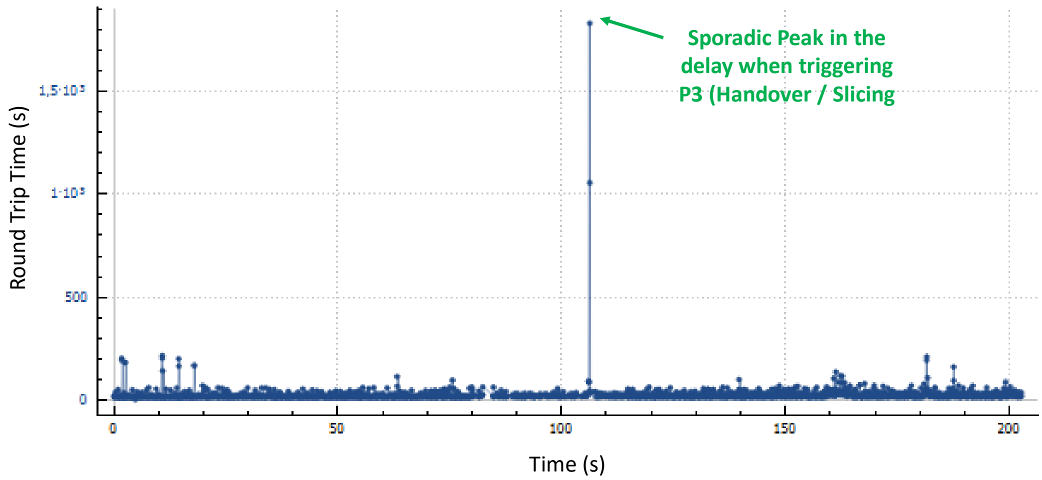


Figure 5-34: Round Trip Times (RTT) for TCP segments (UK lab test)

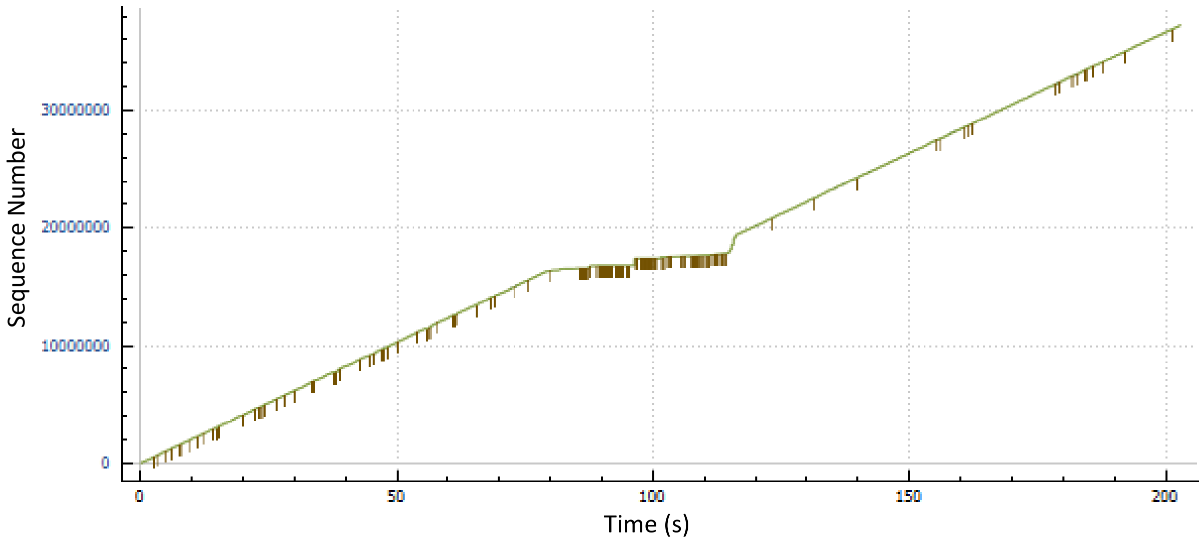


Figure 5-35: Evolution of the TCP Sequence numbers (UK lab test)

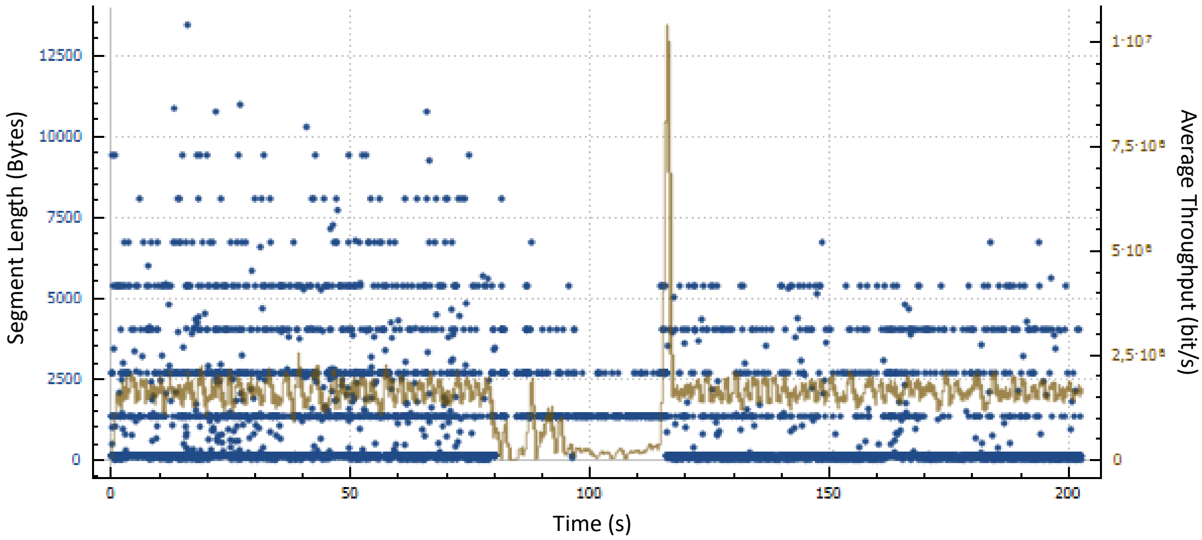


Figure 5-36: TCP Segment length and average throughput (UK lab test)

The next figures show a walkthrough of the demo explained before. ***Figure 5-37***, ***Figure 5-38*** and ***Figure 5-39*** show the Low priority slice created in the network as the first step. In this situation, Watchity is performing properly. As it can be seen in ***Figure 5-38*** the RSSI is between -20 dBm and -35 dBm, which is quite good because the antennas were located really close in the lab.

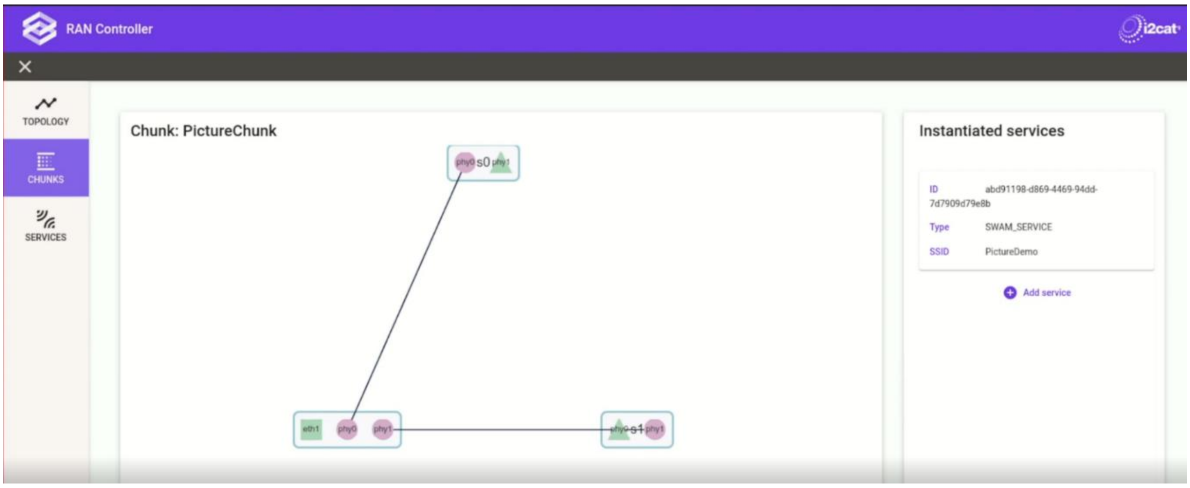


Figure 5-37: RAN Controller, Low Priority Slice

Figure 5-38: I2CAT Wireless Monitoring, Low Priority Slice

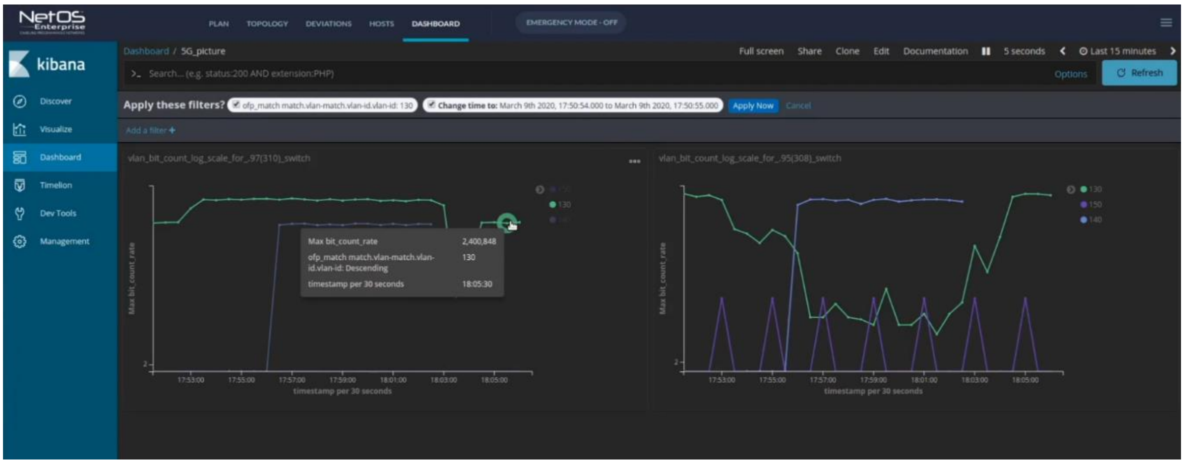


Figure 5-39: Zeetta Network Monitoring, Low Priority Slice

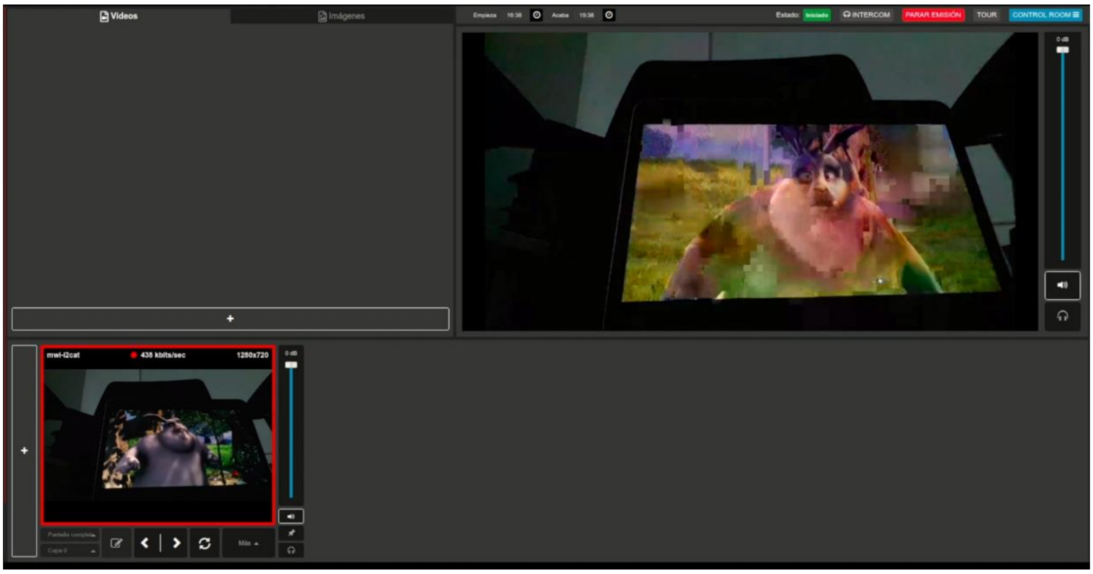


Figure 5-40: Watchity Dashboard. Video downgraded

Figure 5-40 shows how the video was downgraded after initializing the wireless traffic from a different client. At this point MDO will trigger the creating of the High priority slice and the VNF at the Compute domain will be instantiated (**Figure 5-41**).

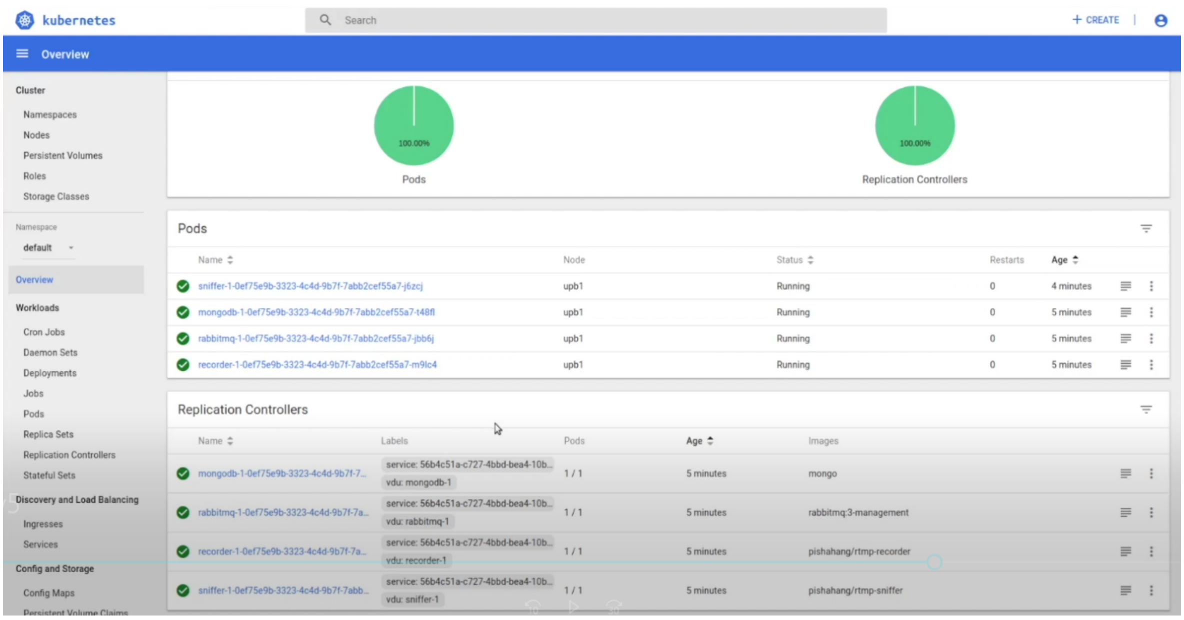


Figure 5-41: Kubernetes Dashboard with the VNF instantiated

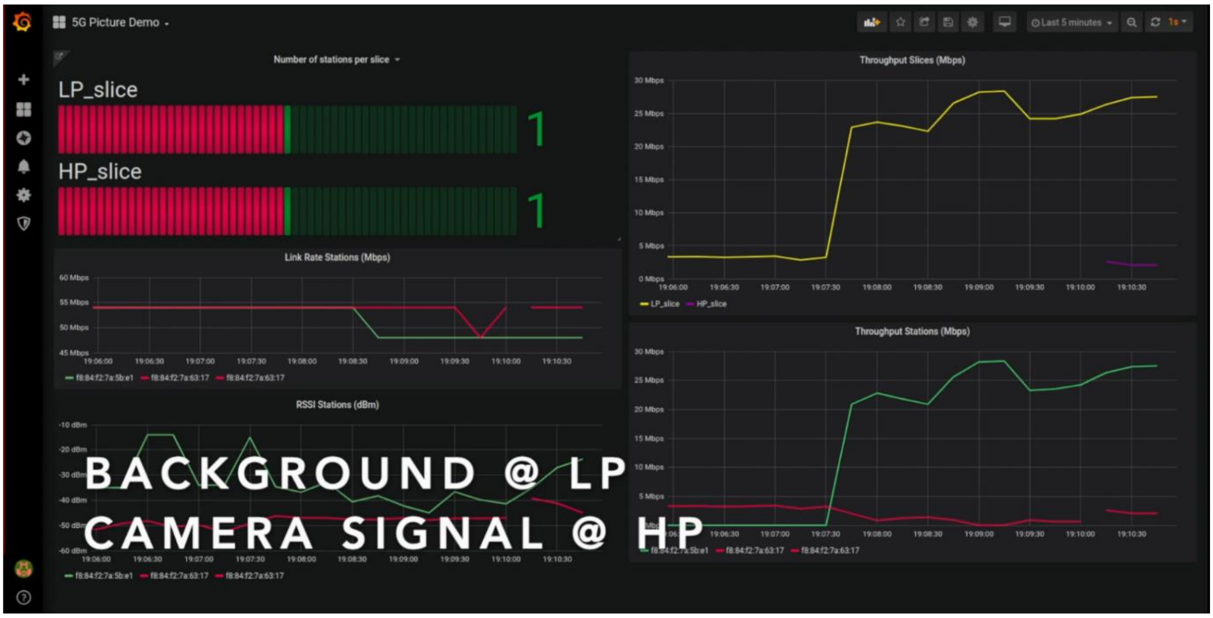


Figure 5-42: I2CAT Wireless Monitoring, High Priority Slice

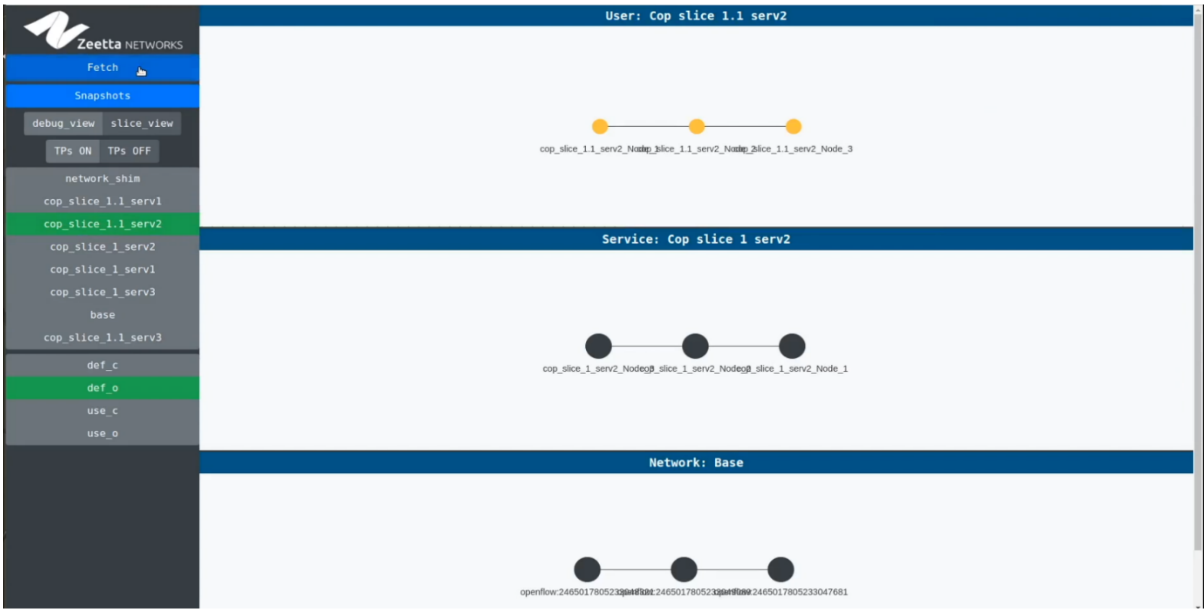


Figure 5-43: ZN Network Slicing GUI.

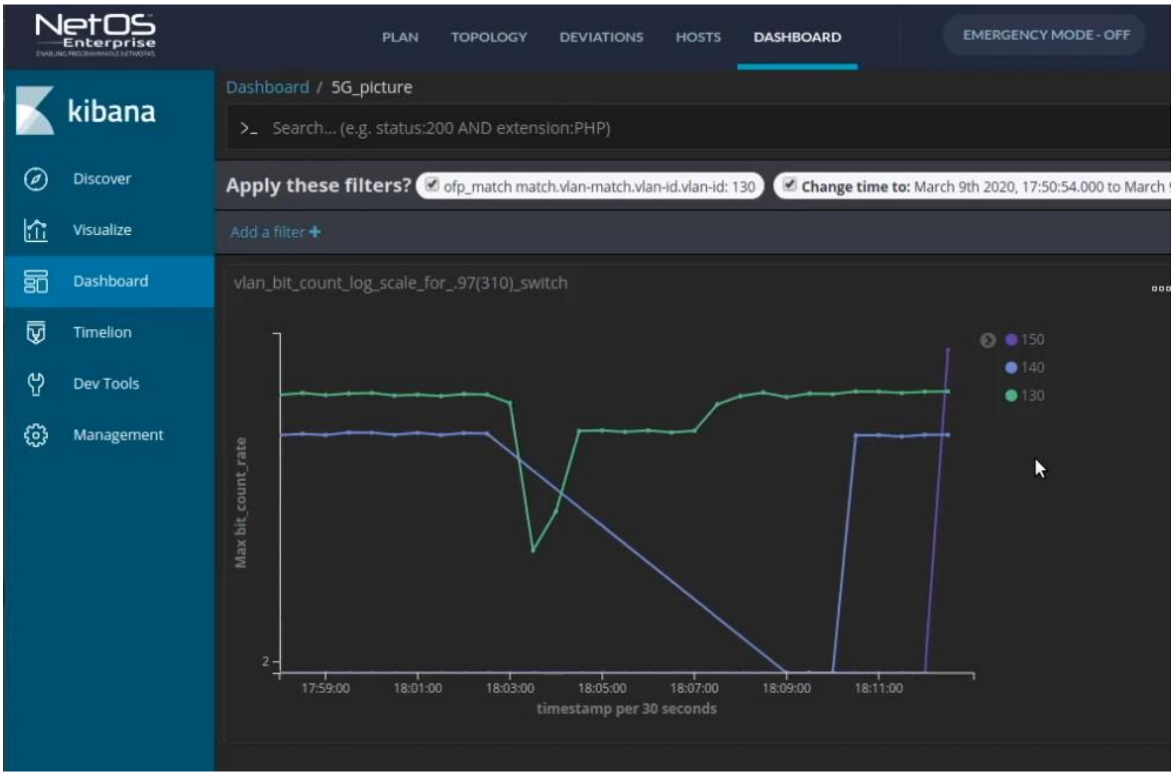


Figure 5-44: ZN Dashboard, Throughput of every slice.

The background traffic is generated in the Transport domain, but it does not affect the quality of the application due to the higher priority of the slices. As it is shown in ***Figure 5-44***, the Low priority and High priority slices are not impacted by the background traffic.

Finally, a demo video showcasing the lab setup, the employed devices and tools and the impact on the video streaming quality of each one of the triggered phased can be watched here.

5.9.2.4Phase 4: Demonstration at the Stadium

The final demonstration at the stadium was carried out between March 12th and 13th 2020. The first day was the setup of the equipment at the stadium. On this occasion, the weather conditions were suitable to put the WAPs and antenna stands at height in the Fan Zone and the network was more stable.

The stadium staff installed the first WAP node on the overhang of the VIP entrance (***Figure 5-45*** left), the second and third one where located on top of the ticket office (***Figure 5-45*** middle). Finally, the last one was located on the overhang of the Sports Shop ***Figure 5-45*** right). Every node was connected to a power supply available outside of the stadium and we had to integrate the middle node with a switch in the ticket office. The setup of the WAPs was configured by Zeetta's staff with the remote videoconference support from I2CAT.

Figure 5-45: (left) WAP on top of the VIP entrance, (middle) WAPs on top of the ticket office, (right) WAP on top of the store

The location of the WAP antennas on top of the overhangs had an unexpected issue that we could not spot during the rehearsal. The overhangs are metallic, and it caused severe attenuation of the Wi-Fi signal. Therefore, when the application client was connected to the antennas it experienced a lower power signal than expected. The demonstration plan had to be adapted at the last moment to address these issues which it is explained in the next section.

The Transport domain, Compute domain and the MDO, which comprised two labs on wheels, were deployed in the Heineken Lounge (***Figure 5-46***, ***Figure 5-47*** and ***Figure 5-48***), which was the room designated to present the live demonstration. The labs on wheels had to be integrated with the stadium network in a different way as for the demonstration rehearsal. As we were in a different room, we were connected to a different switch in the stadium's network.

Figure 5-46: Labs on wheels at the Heineken Lounge

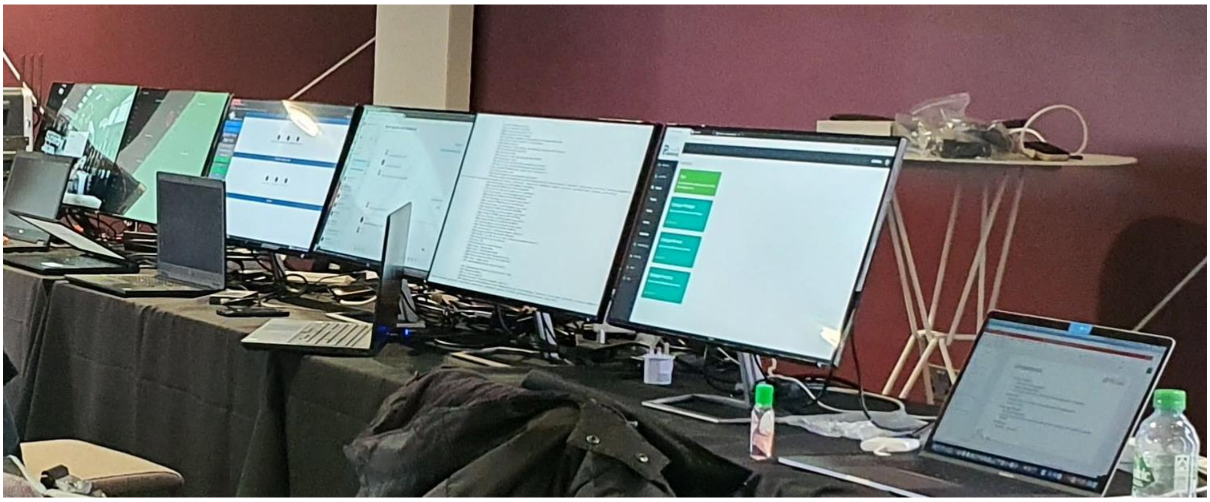


Figure 5-47: Multi Domain Setup at the Heineken Lounge

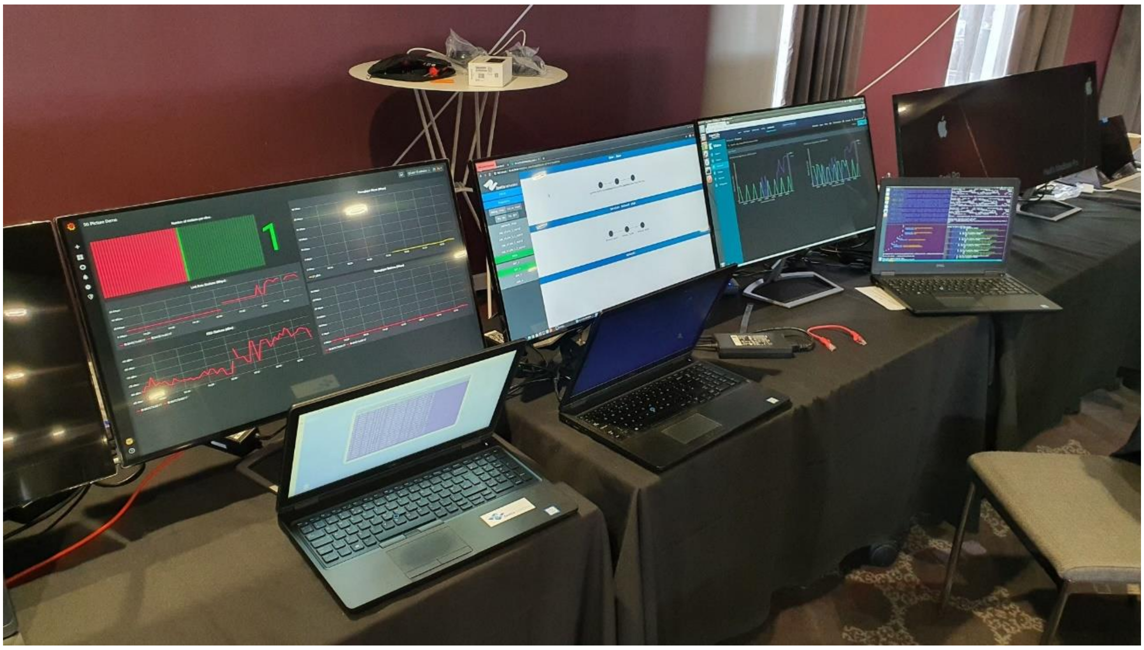


Figure 5-48: Dashboards from different Domains

Performance test in Stadium demonstration

During the stadium demonstration we captured traffic at different points of the Transport domain in order to analyse the traffic patterns. **Figure 5-49** represents the throughput of the Transport domain along the whole demo. During the first 40s the traffic was generated in the Low priority slice from the first wireless device connected to Watchity. Afterwards, the wireless device moved between the antennas to cause attenuation in the wireless link, hence the video was downgraded, and the throughput was impacted. Following this, the High priority slice was triggered from the MDO enforcing the handover of the wireless device and improving the quality of the video stream. Finally, at around 135s there is background traffic triggered inside of the Transport domain, but it does not impact the quality of the video stream or the throughput of the High priority slice because the background traffic has a lower priority.

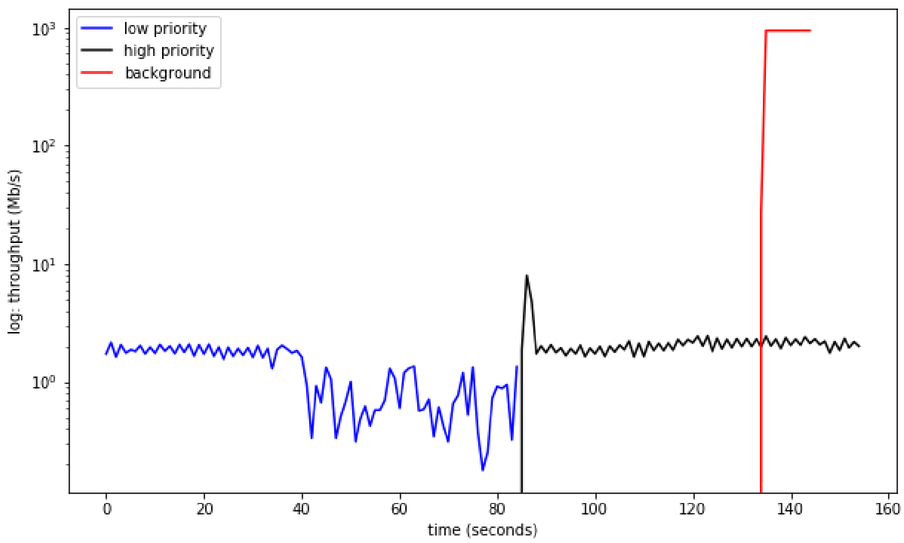


Figure 5-49: Throughput of the different slices over the Transport Domain

We attempted to measure latency and jitter through the lab on wheels LAN by taking packet captures from mirror ports on various switches along the data plane path. We matched packets from different capture files by matching the TCP sequence numbers. We then computed latency by taking the difference of the timestamps for matched packets.

However, while we used a relatively high specification computer to perform the packet captures, it was not sufficient to accurately capture timestamps given how low the latency was through the lab on wheels switches. In some cases, the latency values were negative. We attributed this to the nature of a time-sharing operating system. As we had multiple capture processes running concurrently on multiple Ethernet ports (for multiple switches in path). The process scheduler introduced a race condition between the capture processes. It was, therefore, conceivable the process schedule ordering would have a significant impact on the timestamping of captured packets. Coupled with the fact that the latency would be in order of microseconds, negative latency values were to be expected.

In summary, latency and jitter were too low to accurately measure without specialist equipment. However, a corollary of this is that latency and jitter within the lab on wheels would have had negligible impact on the video application.

As it is shown in **Figure 5-50**, the RSSI at the stadium is much worse than the one presented before at the lab. In this case, the RSSI is between -68 dBm and -80 dBm due to the issues mentioned before.

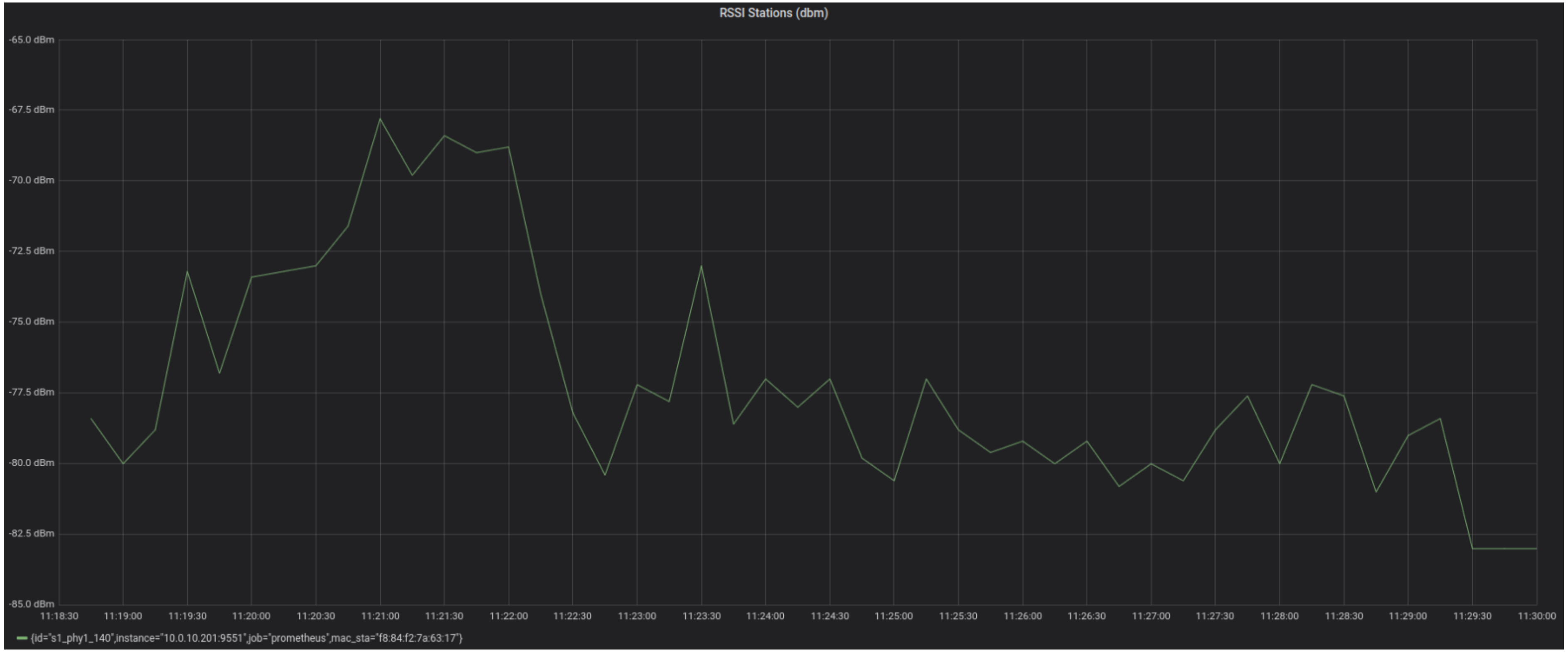
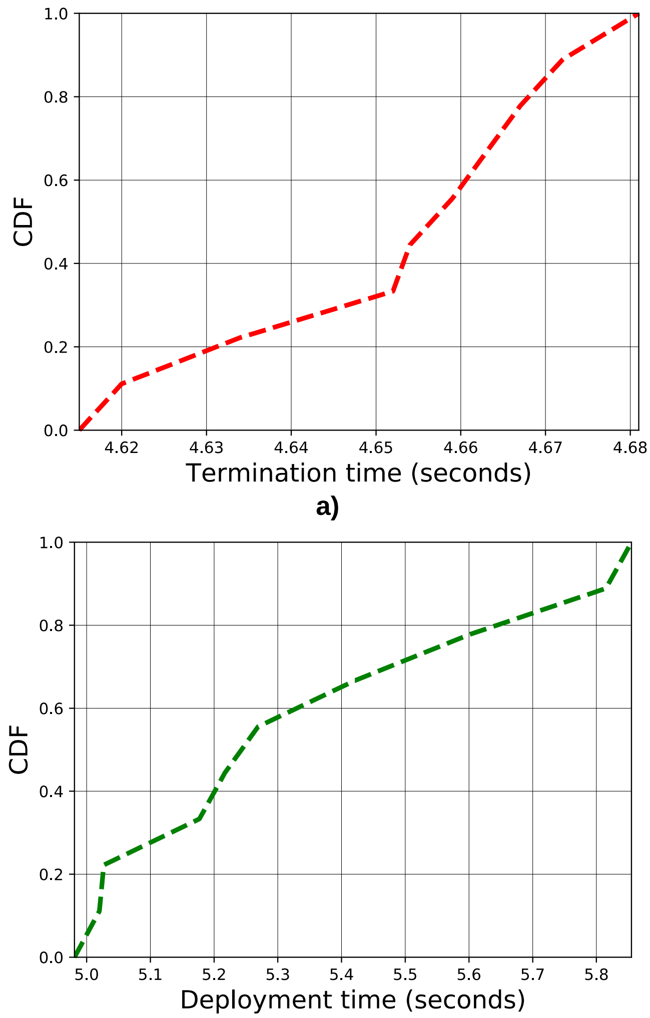


Figure 5-50: RSSI at stadium demonstration



b)

Figure 5-51: a) Service termination time, b) Service deployment time in the Compute Domain

We measured the service deployment and termination time of the described service in the Compute Domain. ***Figure 5-51*** depicts the results of the measurement. The results show that Pishahang is able to deploy and terminate a service consisting of four VNFs in less than 6 and 5 sections, respectively. This is much faster than a VM-based solution which could takes minutes to deploy such a service.

In the Transport domain the service provisioning time is quite similar to the time measured during D5.4 [32]. In the stadium demonstration the network is composed by the same number of devices, therefore the deployment time is around 19.8 seconds. The service provisioning time depends on the time that takes to configure the devices remotely and the computation time to find a valid slice solution.

In the wireless domain service provisioning requires to instantiate the virtual access points in the target physical devices via NETCONF, to configure a dedicated path across the wireless backhaul for this service using OpenFlow, to configure a transport VLAN in the node acting as root for this service and to provision a set of software bridges in the different devices using OVSDB. We tested said provisioning time for the high priority slice using the setup of the stadium demo obtaining a value of 10 seconds, which demonstrates the scalability of the developed management plane for integrated access and backhaul wireless nodes.

To summarise, the overall slice service provisioning time is **37.8 seconds**, which is much lower than the KPI objective.

5.10 Discussion on extensions to enable AI driven control in 5G OS

AI and ML are not new topics in the context of telecom. They have seen renewed interest due especially to the rising complexity of network technology and to address the challenges of virtualization and cloud computing. Increased complexity in networking is driving the need for increased network automation. Network automation platforms have incorporated ML components like DCAE in ONAP, which receives the models from a catalogue and generates the required metadata artifacts to configure and onboard a new Microservice.

5.10.1 Potential architectural extensions to enable AI driven network control

The original design of the 5G OS did not consider the application of AI/ML mechanisms as autonomous network management agent. However, given that the 5G OS is based on SDN/NFV principles, it can be naturally extended to enable the operation of AI/ML functions operating on top of multi-domain environments controlled by the 5G OS. Two main problems need to be addressed to enable the deployment of AI/ML functions into a network: i) the collection of telemetry data from the network and how to make this data available to the AI/ML functions, and ii) how to provide a simplified interface to allow AI/ML functions to act on the network. Being a multi-domain service provisioning platform, the 5G OS can be naturally extended to address the previous two aspects.

Figure 5-52 provides an example 5G OS deployment highlighting in pink the additional features that would be required to enable AI/ML based autonomous network management. Let's first look at the 5G OS capabilities that have been developed in 5G-PICTURE. First, we observe in **Figure 5-52** a multi-domain network composed of several wireless access domains, including small cells and macro-cells, a heterogeneous transport network composed of three separate transport domains, including wireless transport, Ethernet and MPLS, and three different compute domains, each with a full ETSI MANO stack. Enabling the provisioning of multi-domain connectivity services we have a hierarchy of SDN controllers (L0 and L1 controllers). Finally, the 5G OS enables the provisioning of end-to-end services composed of wireless access, transport and compute services. The interested reader is referred to deliverable D5.4 [6] for an in-depth description and validation of the 5G OS platform.

In order to extend the 5G OS to support AI/ML functions that can manage the network, we propose for future work the inclusion of the following two components:

- A multi-domain data-lake, which will collect telemetry data recovered from the different network domains administered by the 5G OS operator. An access control module should be considered to police access to the data lake. Data available in the data lake will be used by the ML models for training purposes, but also in on-line mode if the models are based for example on Reinforcement Learning.
- An AI/ML platform hosting the ML models. The AI/ML platform will access data sources from the multi-domain data lake and output network actions towards the MDO. The actions output by the ML models can be at the service level, for example triggering the deployment of a new end-to-end service, and also at the resource level, for example reconfiguring some network parameters in the access, transport or compute domains. The value of the MDO is to act as a unified multi-domain configuration and service provisioning API towards the AI/ML platform, which greatly simplifies the development of the AI/ML models.

Having in mind the presented architecture we discuss in the next sections the data and actions that the 5G OS could make available to future AI/ML models managing the network.

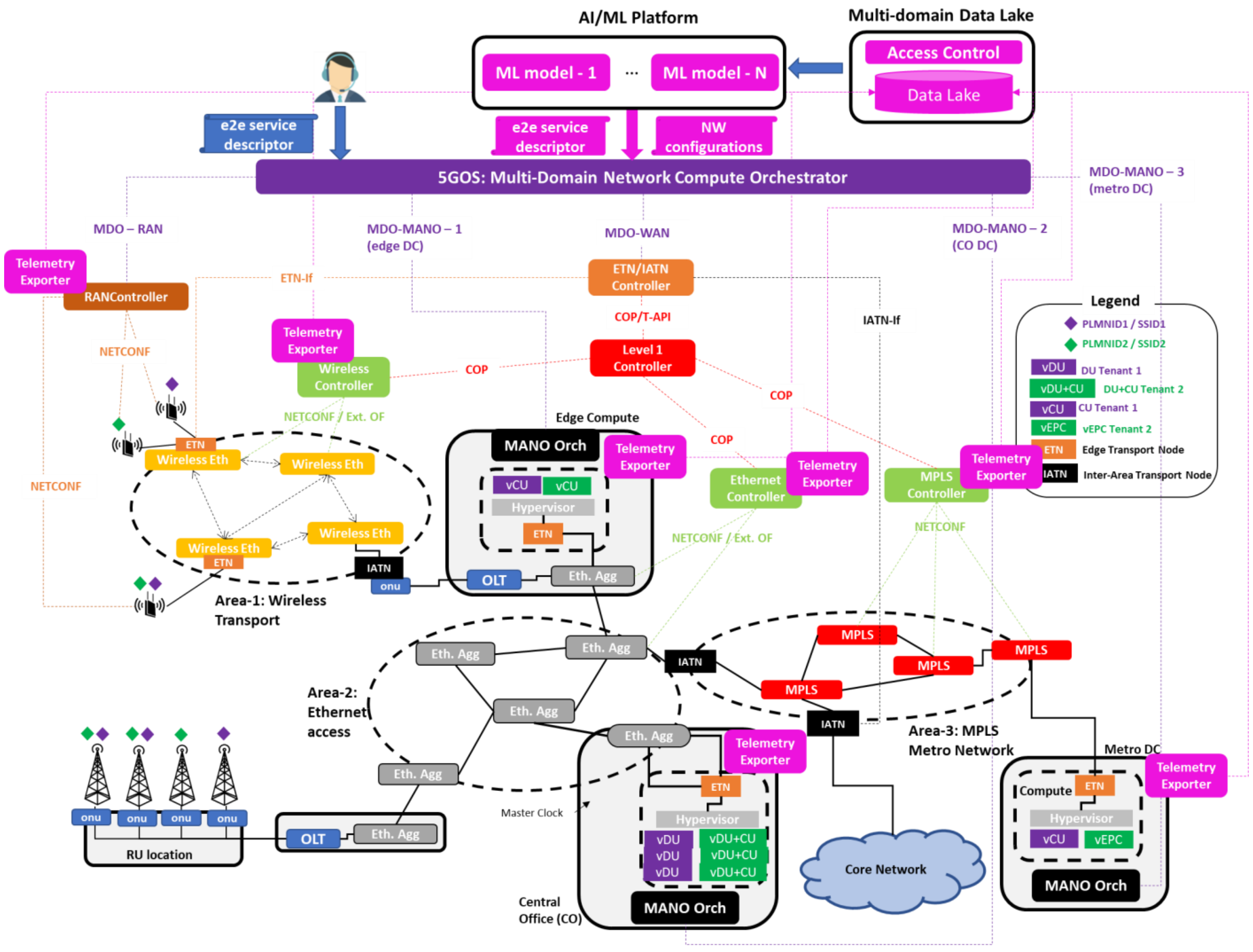


Figure 5-52. AI/ML architectural extensions on the 5G OS

5.10.2 5G OS APIs for AI control

5.10.2.1 5G OS telemetry

Wireless domain telemetry

The available RAN Controller telemetry is split at different levels: i) telemetry a the vAP level, ii) at station level, and ii) at the service level. To extract these parameters a Prometheus exporter for hostapd was developed and open-sourced, which makes available the following parameters on a vAP and station level: https://bitbucket.i2cat.net/users/miguel_catalan/repos/hostapd_prometheus_exporter/browse

Table 5-1: Telemetry available for each vAP deployed as part of a SWAM service

Main parameters (for all vAPs)	slice_id, frequency, channel, max tx power, number of associated stations
Complementary	num_sta_non_erp, num_sta_no_short_slot_time, num_sta_no_short_preamble, olbc, num_sta_ht_no_gf, num_sta_no_ht, num_sta_ht_20_mhz, num_sta_ht40_intolerant, olbc_ht, ht_op_mode, cac_time_seconds, cac_time_left_seconds, secondary_channel, ieee80211n, ieee80211ac, beacon_int, dtim_period, ht_caps_info, ht_mcs_bitmask, supported_rates, bss, bssid, ssid

Table 5-2: Telemetry available at station level

Main parameters (for all STAs)	Mac_address, rx_bytes, tx_bytes, inactive_msec, signal, rx_rate, tx_rate, tx_airtime, rx_airtime, total_airtime, connected_time
Complementary	flags, aid, capability, listen_interval, supported_rates, timeout_next, ht_mcs_bitmask, ht_caps_info, ext_capab

This data is exported to a Prometheus [35] based system using a configurable periodicity that can be as low as every 2 seconds, hence enabling non real time autonomous network management functions.

At the service level the i2CAT RAN Controller allows the management system to query the status of the currently deployed chunks and services.

Transport domain telemetry

The Transport controller is populated with telemetry at the OpenFlow flows and at the switch level. As a monitoring system we utilise Prometheus which uses a combination of node_exporter and snmp_exporter to extract interface statistics, for example Tx/Rx packet counters. Apart from this, we implemented an external OpenFlow collector to gather the packet and byte counters per flow and per interface. The OpenFlow collector gathers the statistics in a periodic interval which can be configured in the SDN controller or in the switches themselves; for this demonstration it was configured to fetch the data every 5 seconds. This monitoring information is stored in the Northbound API of the Transport controller allowing a management system to query the status of the network slices.

Moreover, with the data extracted from these collectors, we plotted the throughput of every network slice in the GUI. We were able to visualize the network slices periodically as it was presented during the demo and has been represented in the results section.

Compute domain telemetry

The compute domain is managed by Pishahang which uses IA to predict the load imposed to the deployed service chains. This is done by gathering datasets of the traffic demands of service chains over a certain period of time and dynamically performing time series analysis on these datasets. In Pishahang, the traffic demand information is fetched by a monitoring tool called Netdata and periodically pushed to the IA plugin. The IA plugin uses a neural network technique called Long Short-Term Memory (LSTM) to forecast the future trends of traffic for a particular service chain. The forecasting information is then used by two Pishahang's plugins, namely scaling and multi-version services plugins. Scaling plugin uses this information to decide how many instances of a service chain and its constituted VNFs should be running at a certain time. Multi-version services plugin also uses this information to decide which version is best suited to be used at a particular period. This helps the service provider to better utilize their resources and improve service quality.

5.10.2.2 5G OS network actions

Wireless domain network actions

On the configuration side the main actions enabled by the i2CAT RAN Controller are:

- i. the creation of chunks and SWAM services composed of virtual access points and paths in the wireless backhaul
- ii. the provisioning of paths across the wireless backhaul
- iii. triggering a handover for an associated station

The chunk and service creation APIs are described in detail in deliverable D5.4 [32]. Regarding the path-provisioning API we detail next the rpc end-point made available by the RAN Controller that would allow an external entity, e.g. an AI/ML model, to decide on the path across the wireless backhaul followed by a given flow.

```
rpc create-tunnel {
    input {
        leaf tunnel-id {
            type int32 {
                range "2..4094";
            }
        }
        leaf source-node {
            type string;
        }
        leaf destination-node {
            type string;
        }
        leaf-list main-path {
            type string;
            ordered-by user;
            description "List of desired nodes and ports to be traversed";
        }
        leaf-list backup-path {
            type string;
            ordered-by user;
            description "List of desired nodes and ports to be traversed";
        }
    }
    output {
        leaf status {
            type string;
        }
        leaf tunnel-id {
            type int32;
        }
    }
}
```

Figure 5-53: RAN Controller API that allows to control forwarding path across backhaul (in red highlighted the sequence of nodes to traverse that can be provided by an AI/ML model)

An AI/ML model can also optimize the wireless access segment by balancing stations across Access Points through the RAN Controller network triggered handover API. Let's illustrate through an example the behaviour of this API. Consider a configuration where you have one chunk and two services with the following vAPs and associated stations:

Service 1

- VAPS: `s0 phy0 111`, `s2 phy0 111`
- Stations: `f8:84:f2:7a:63:17`, `f8:84:f2:7a:5b:e1`, `f8:84:f2:7a:5a:bf`

Service 2

- VAPS: `s1 phy0 200`
- Stations: None

The AI/ML model driving the network triggered handovers needs to decide what are the source and target vAPs for a given station. Then to move a station or example, to move the stations `f8:84:f2:7a:63:17` and `f8:84:f2:7a:5a:bf` to the Hight Priority service, POST a request to `/handoverController/picture/service/{instanceId}/handover`. The following figure provides an example where two stations are moved to a new vAP.

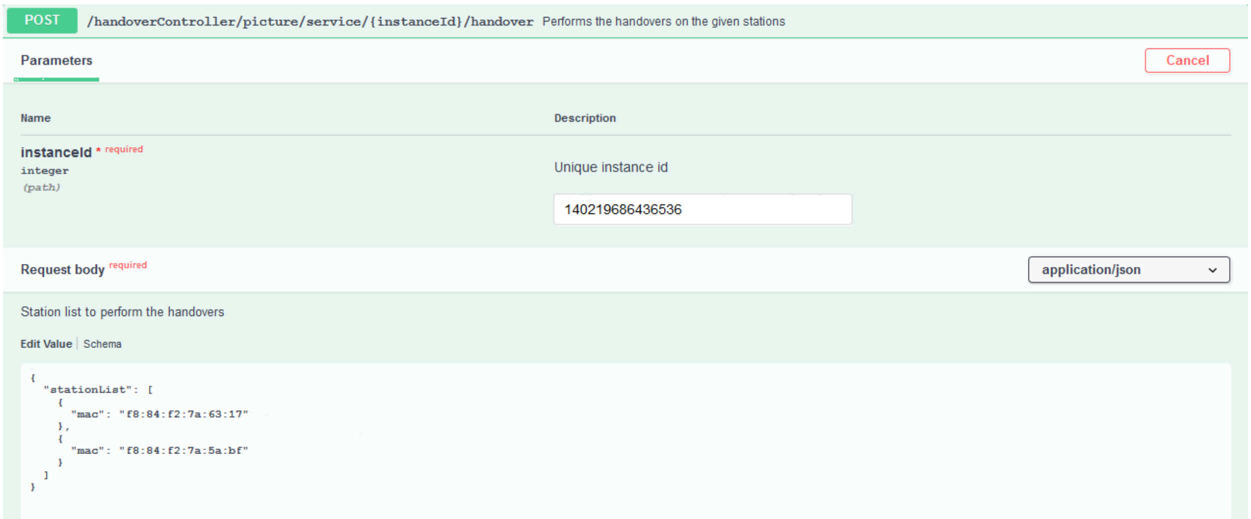


Figure 5-54: RAN Controller API to perform network triggered handovers

Transport domain network actions

The Transport controller allows the slice definer to create a network slice, in this case the MDO was acting as a slice definer through the COP interface. Depending on the slice definition introduced, the Transport orchestrator computes the network slice solution to be provisioned by the Transport controller using stochastic search. On top of this, there is a Use-API which allows a user to operate with the resources allocated in the network slice, for example enabling and disabling a specific port or even enabling a VLAN ID from a specific range.

The AI/ML model can implement a stochastic optimization in the computation side of the Transport orchestrator. Moreover, ML algorithms can improve prediction and trigger a proactive slice creation or on the other hand detect anomalies and provoque a reactive slice creation based on defined policies. For example, the video degradation demonstrated during the demonstration would be a perfect reactive slice creation use case for a ML. AI optimization should take into account multiple information sources and make more complex decisions like multiple slice operations (activate/deactivate/modify/remove).

Compute domain network actions

As mentioned in the previous section, IA is already used in Pishahang MANO framework to predict the service load. This has been supported in Pishahang using a Microservices called IA plugin. The telemetry data gathered by Netdata are pushed to the IA plugin which is then used to predicts the future load of the services running on Pishahang cluster using LSTM algorithm. The prediction results are then provided to Multi-version services plugin and Scaling plugin. The IA plugin has been implemented after the demo in Bristol.

5.11 Massive MIMO Demonstration at University of Bristol

The mMIMO work in 5G-PICTURE partially entailed investigation of the employment of mMIMO systems in a railway environment. As presented in D2.2 and D2.3 in detail [5][2], we have explored the performance merits (throughput and spectral efficiency) of a Massive MIMO architecture deployed in two railway environments: a) Bristol Temple Meads, and b) London Paddington. In WP6, the aim was to deploy the National Instruments (NI) Massive MIMO platform of the CSN lab (University of Bristol) as part of the Ashton Gate Stadium Demo, to demonstrate how such an architecture can provide a reliable and high throughput/spectral efficiency network in real-time scenario. In this context, we wanted to investigate co-located and distributed Massive MIMO, further to show that the latter can result in superior performance compared to the former.

Unfortunately, the COVID-19 situation that has arisen during the final meeting week in Bristol, has imposed restrictions to personal contact and risks related to moving the equipment, and therefore the Massive MIMO demo was performed in the CSN lab, in the University of Bristol. The following sections describe the live demo as well as additional demos performed that day, providing the acquired results.

5.11.1 Massive MIMO TestBed

The Massive MIMO testbed, depicted in ***Figure 5-55***, comprises a base station (BS) and up to 24 available users. The BS is divided into 4 racks, providing 32 RF ends each, i.e. 128 in total. The RF ends are connected to a patch panel antenna array in a 4x32 configuration with vertical and horizontal polarisations operating at 3.51 GHz. The BS can serve, simultaneously: a) up to 24 users with single antenna from 12 USRPs, or b) up to 12 users with two antennas, Video streams can be transmitted in both uplink and downlink using User Datagram Protocol (UDP) ports. The Massive MIMO testbed transfers data between the racks via MXI-Express fibre cables.

The Demo that was presented from the CSN lab included 6 single antenna users and a 32 antenna Massive MIMO BS. The KPIs that were measured are: Spectral Efficiency, UL Throughput, Signal-to-Interference-plus-Noise Ratio (SINR), Error Vector Magnitude (EVM) (%) and Average EVM (%). The main goal was to demonstrate the superiority of Massive MIMO regarding spectral efficiency, employing spatial multiplexing.

Finally, two configurations were demonstrated: a) centralised, and b) distributed, in order to also include a comparison between the two settings during this demo.

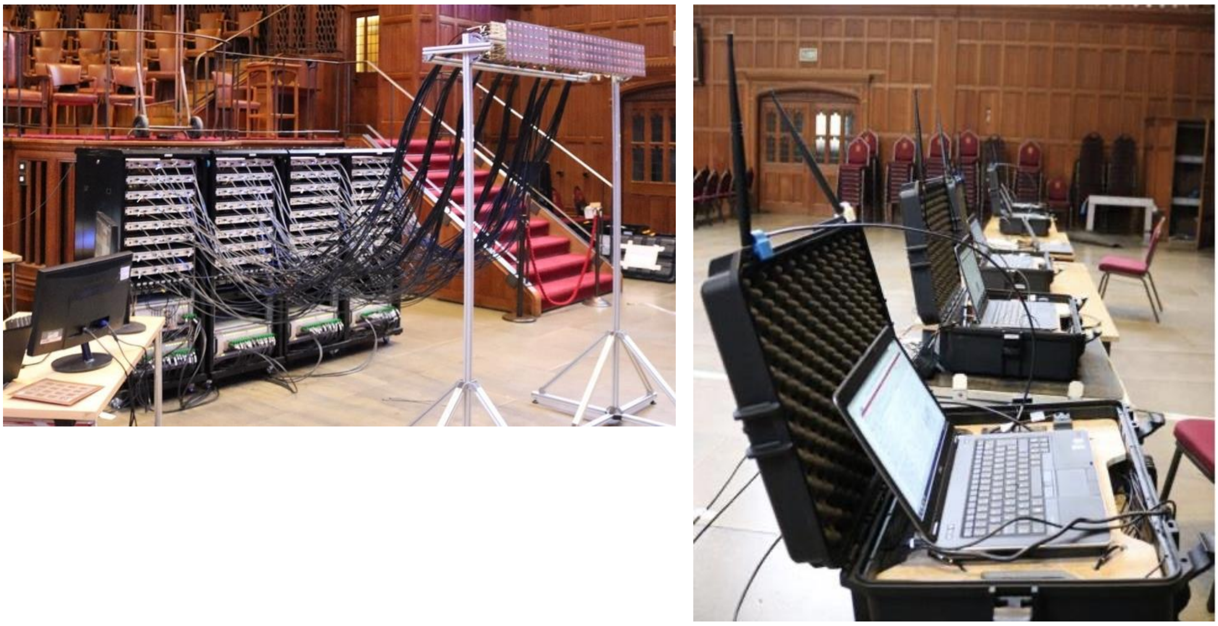


Figure 5-55: Massive MIMO Testbed: (left) Base station end, (right) Users end

5.11.2 Massive MIMO Demo Description and Results

The Massive MIMO testbed, investigating Uplink (UL), deployed in the CSN lab included three scenarios: a) centralised (32/64/128 antennas) Massive MIMO, b) distributed (8x4/16x4) Massive MIMO, and c) distributed (16x2/32x2) Massive MIMO (AxB: A is the number of antennas at each AP, B is the number of APs). In total, maximum 6 users, divided into 2 clusters and transmitting raw UDP data streams (QPSK), were deployed. Attenuators were added to all UEs in order to reduce the transmitted and received signal strength from all UEs. The effect of this would be almost equivalent to increasing the distance between the BS antennas and the UEs.

In this section, the live demo configuration and results will be discussed in the beginning. Additional scenarios, which compare different deployments of the Massive MIMO equipment, were tested on that day and will be also presented.

5.11.2.1 Massive MIMO Live Demo

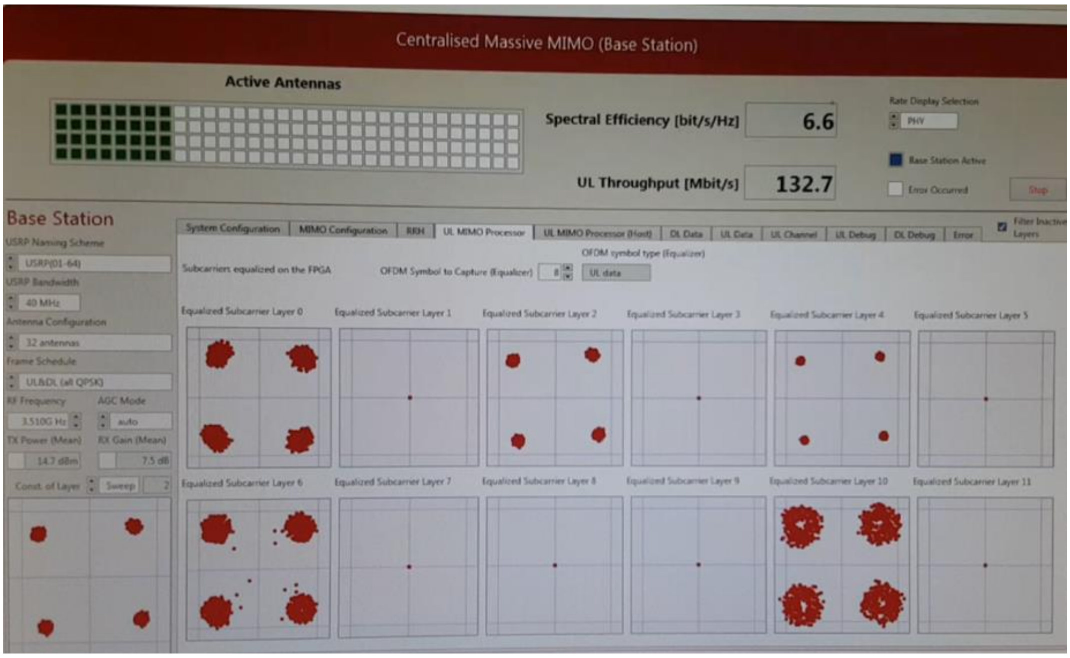
During the live demo, two scenarios were shown: a) centralised (32 antennas) Massive MIMO, and b) distributed (8x4) Massive MIMO, as depicted in **Figure 5-56**. Maximum six users (shown in ***Figure 5-57***, divided into two clusters, were deployed, with a 50 cm separation between them.

Figure 5-56: Live Demo Massive MIMO testbed deployment at CSN: (left) Centralised scenario, (bottom) Distributed scenario

Figure 5-57: Live Demo Massive MIMO testbed deployment at CSN: a) UEs Cluster 1 – users 1, 2, 3, and b) UEs Cluster 2 – users 3, 4, 5

a) Centralised (32 antennas) Massive MIMO

The four Access Points (APs) were placed in a line, as shown in ***Figure 5-57***, in a centralised configuration. The maximum number of users that could be deployed was five. The results from the live demo Massive MIMO simulation are depicted in ***Figure 5-58***. It can be observed that the achieved Spectral Efficiency (SE) was 6.6 b/s/Hz, and the UL throughput 132.7 Mb/s.



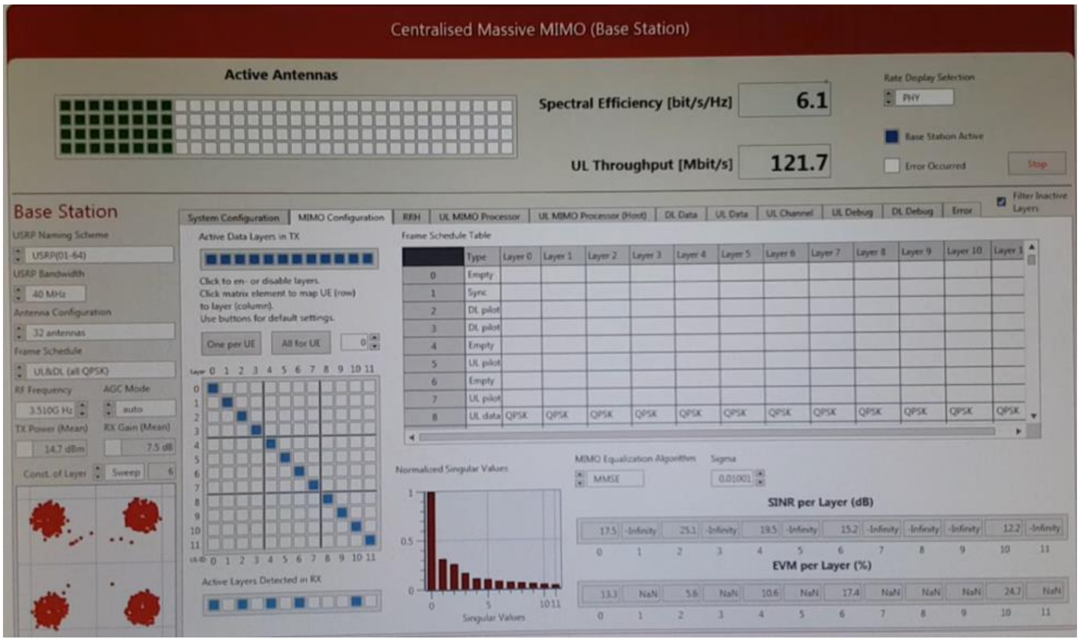


Figure 5-58: Live Demo Simulation results (Centralised Scenario): (left) constellation maps, and (right) SINR and EVM (%) per user

<u>b) Distributed (8x4 antennas) Massive MIMO</u>

The four APs racks (A, B, C, D) of the Massive MIMO BS were distributed in four corners and users were deployed in between into two groups of three users each, as depicted in **Figure 5-56**. The separation between users was 50 cm.

At this point, it should be noted that in ***Figure 5-57*** b), it can be observed that users 1 and 2, and 5 and 6 are in line to the AP closest to them (rack A and rack C respectively). However, as it will be shown in a later Section this configuration challenging due to the high spatial correlation and channel state information similarity between users on the same line. This could be avoided by changing the antenna array configuration and increasing number of antennas at the BS. Thus, users 1 and 6 were slightly moved during the demo to avoid being in a straight line with users 2 and 5 respectively.

Each one of the four racks had activated 8 antennas, "in a row", resulting in an 8x4 distributed Massive MIMO system. The antenna array at each rack is depicted in ***Figure 5-59***. It can be seen that it is a 4x8 antenna array. In the live demo experiment, the first row was activated (8 active antenna elements).

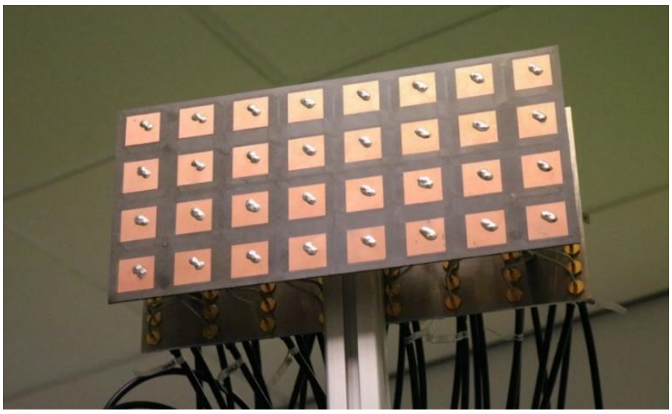


Figure 5-59: Antenna array at each rack of Massive MIMO kit

The results from the live demo Massive MIMO simulation can be seen in ***Figure 5-60***. It can be observed that all users were uploading data and that the achieved Spectral Efficiency (SE) was 8.2 b/s/Hz, and the UL throughput 164 Mb/s.

Overall, the distributed Massive MIMO configuration resulted in higher, by 20%-25%, UL throughput and spectral efficiency, due to the fact that antennas are separated at a greater distance, by having four APs with 8 antennas each.

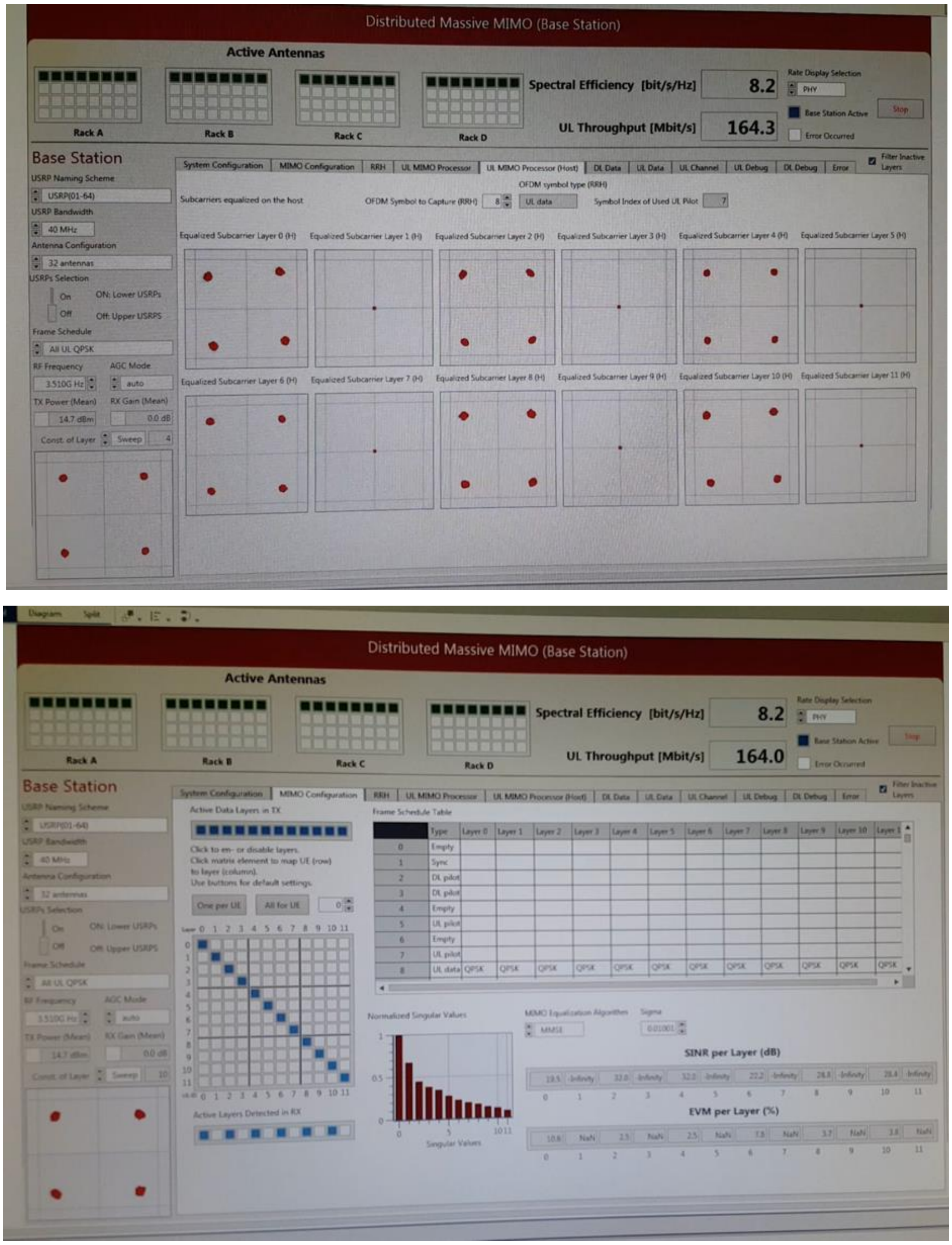


Figure 5-60: Live Demo Simulation results (Distributed Scenario): (left) constellation maps, and (right) SINR and EVM (%) per user

5.11.2.2 Centralised Massive MIMO

In this configuration, the four racks were placed next to each other in a straight line as depicted in **Figure 5-61**, in order to investigate the performance of a centralised Massive MIMO configuration. Users were grouped into two clusters. Three different scenarios were tested:

32 antennas Massive MIMO BS and four users

In this scenario, at each one of the four racks, 8 antennas (in one row), were activated, resulting in 32 antennas at the BS end. Four users were served, two groups of two users each, as employing six users (three users per group) resulting in failure due to two users, with similar channel state information, in each group being in a straight line. In this scenario, as shown in ***Figure 5-62*** a), the achieved SE was 5.5 bit/s/Hz and the UL throughput 109.6 Mbit/s.

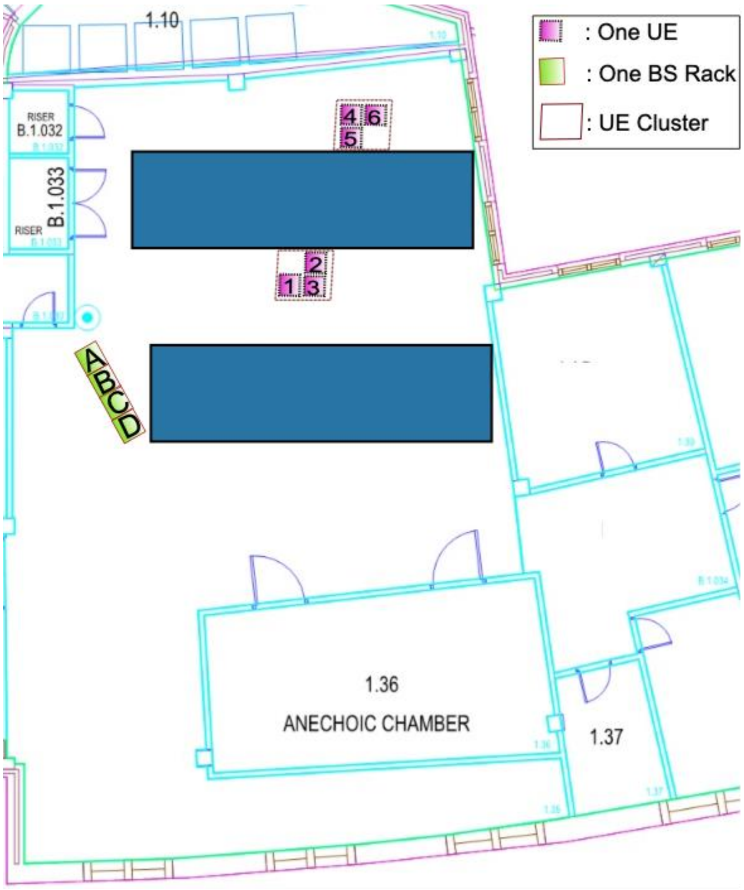
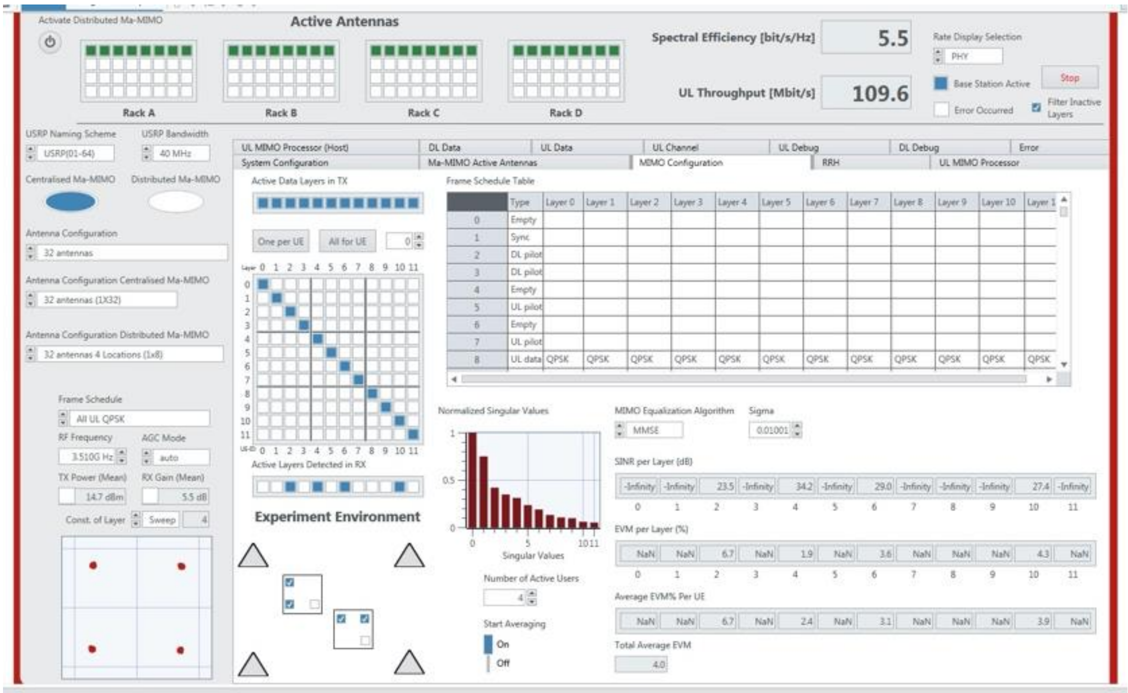
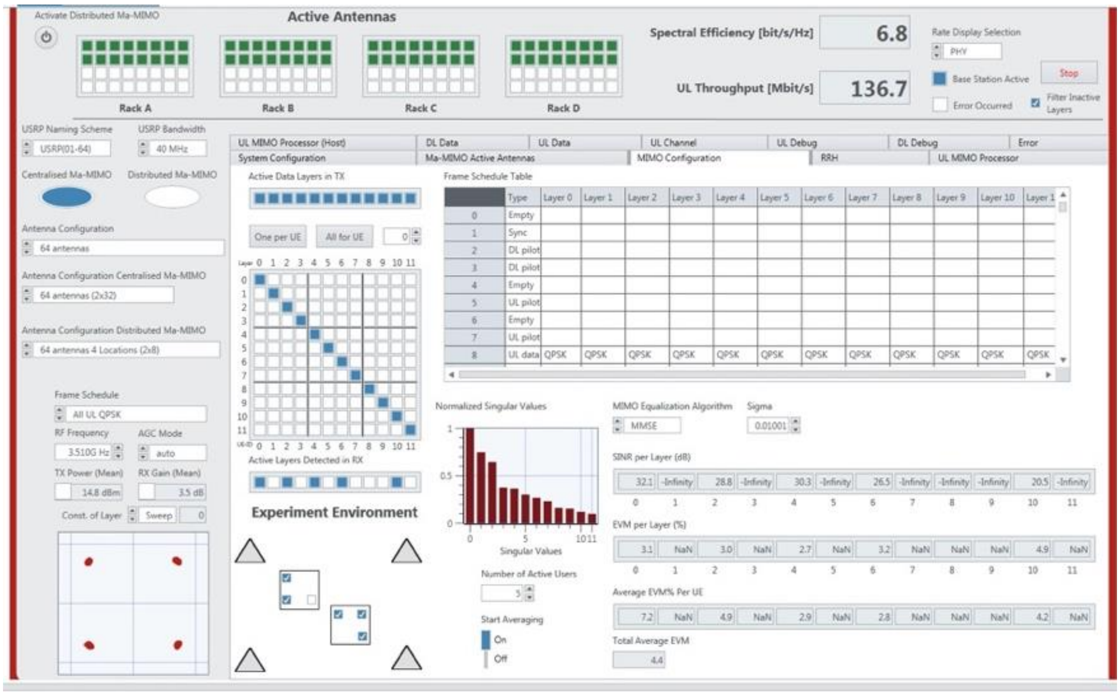


Figure 5-61: Centralised Massive MIMO configuration



a)



b)

Figure 5-62: a) Centralised Massive MIMO configuration with 32 antennas at BS, (right) Centralised Massive MIMO configuration with 64 antennas at BS

<u>64 antennas Massive MIMO BS and five users</u>

In this scenario, at each one of the four racks, 16 antennas (two rows), were activated, resulting in 64 antennas in total at the BS end. Five users were deployed into two groups (one group of two users and one group of three users). In this scenario, we are giving more flexibility to the beams received by the BS, since we are working also on elevation (3D) due to two rows in the antenna array being activated. As a result, one more user can be added to the network without a compromise on the overall performance. ***Figure 5-62*** b) depicts the results of the aforementioned test. The SE achieved was 6.8 bit/s/Hz and the UL throughput 136.7 Mbit/s.

<u>128 antennas Massive MIMO BS and four users</u>

In this scenario, at each one of the four racks, 32 antennas (four rows), were activated, resulting in 128 antennas in total at the BS end. Four users were deployed and grouped into two clusters. In this scenario, the achieved SE achieved was 5.5 bit/s/Hz and the UL throughput 109.5 Mbit/s, as shown in ***Figure 5-63***.

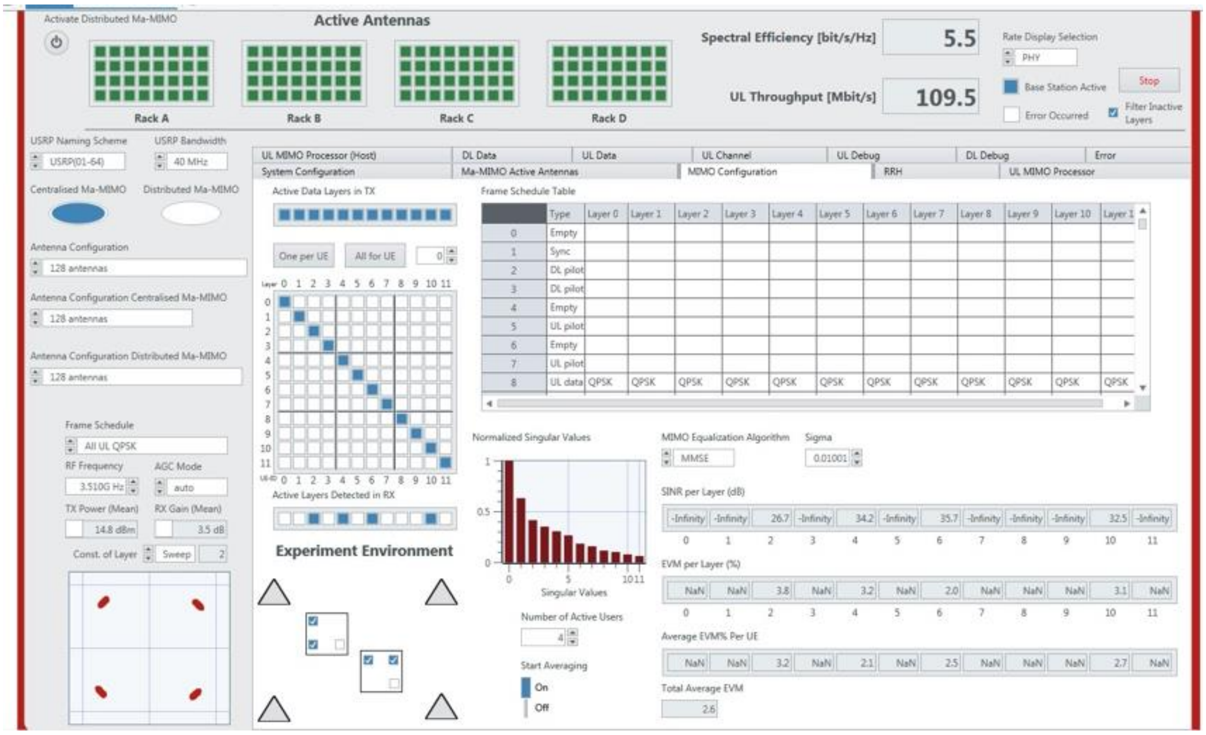


Figure 5-63: Centralised Massive MIMO configuration with 128 antennas at BS

5.11.2.3 Distributed (x4) Massive MIMO

In this configuration, the four racks were distributed at four corners as shown in **Figure 5-64**. A maximum number of six users were deployed and grouped into two clusters. Different number of users and antennas were tested as described in the following scenarios:

<u>Distributed Massive MIMO with 32 antennas and 5UEs</u>

In this scenario, at each one of the four racks, 8 antennas (in one row), were activated, resulting in 32 antennas at the BS end. Four users were deployed, two groups of two users each, as employing six users (three users per group) resulting in failure due to two users in each group being in a straight line, and thus blocking two users. In this scenario, as shown in ***Figure 5-65*** a), the achieved SE was 5.5 bit/s/Hz and the UL throughput 109.6 Mbit/s.

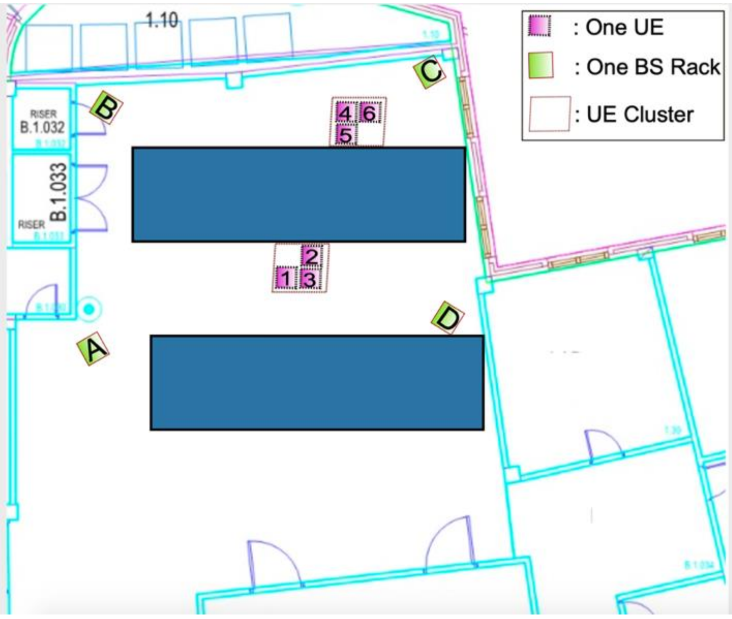
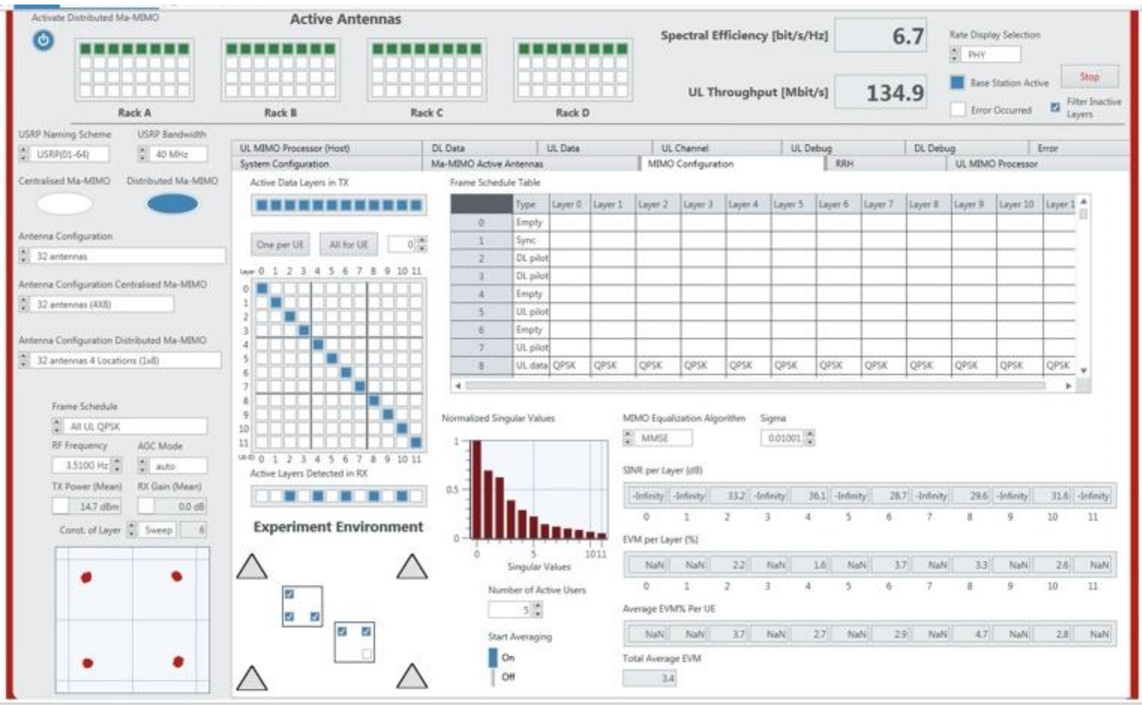
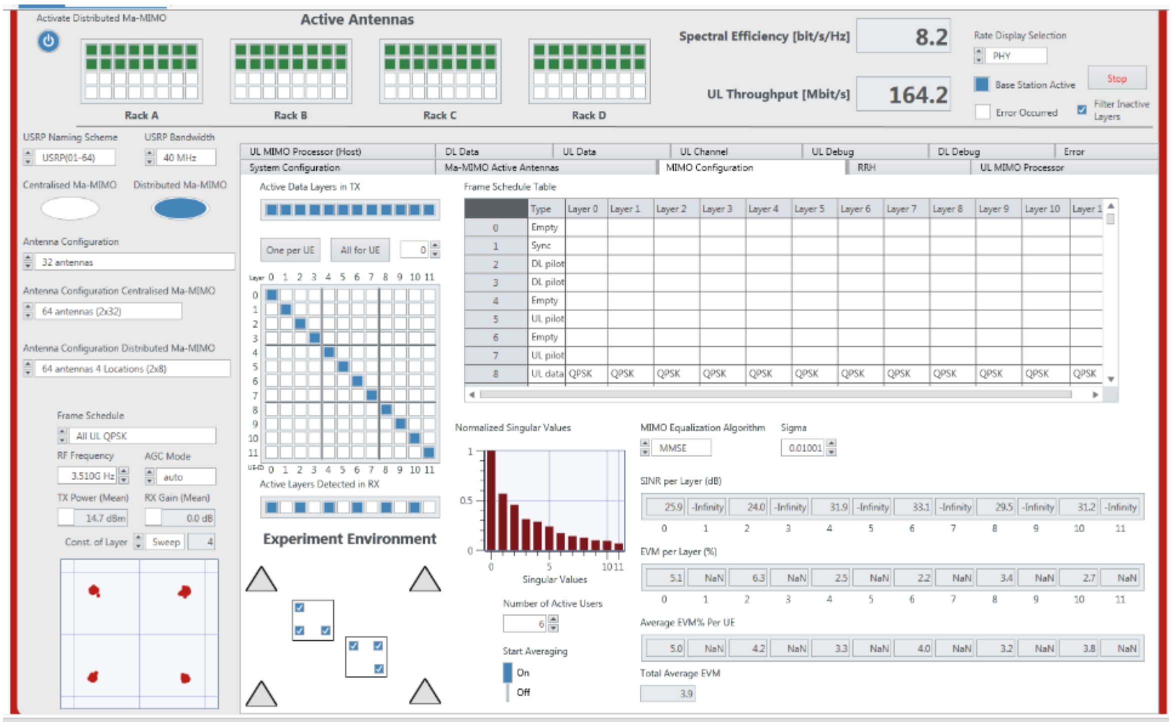


Figure 5-64: Distributed (x4) Massive MIMO testbed deployment at CSN



a)



b)

Figure 5-65: a) Distributed (x4) Massive MIMO configuration with 32 antennas at BS, b) Distributed (x4) Massive MIMO configuration with 32 antennas at BS

<u>Distributed Massive MIMO with 64 antennas and 6 UEs</u>

In this scenario, at each one of the four racks, 8 antennas (in one row), were activated, resulting in 32 antennas at the BS end. Six users were deployed, two groups of three users each. Due to the fact that two rows were activated at each antenna arrays, the issue with users being in line and thus blocked, was resolved. In this scenario, as shown in ***Figure 5-65*** b), the achieved SE was 5.5 bit/s/Hz and the UL throughput 109.6 Mbit/s.

5.11.2.4 Distributed (x2) Massive MIMO

In this configuration, two racks were placed at one side (AB) and two racks at the opposite side (CD) as shown in ***Figure 5-66***. A maximum number of six users were deployed, grouped into two clusters. Two scenarios were tested with different number of antennas at the BS and number of users

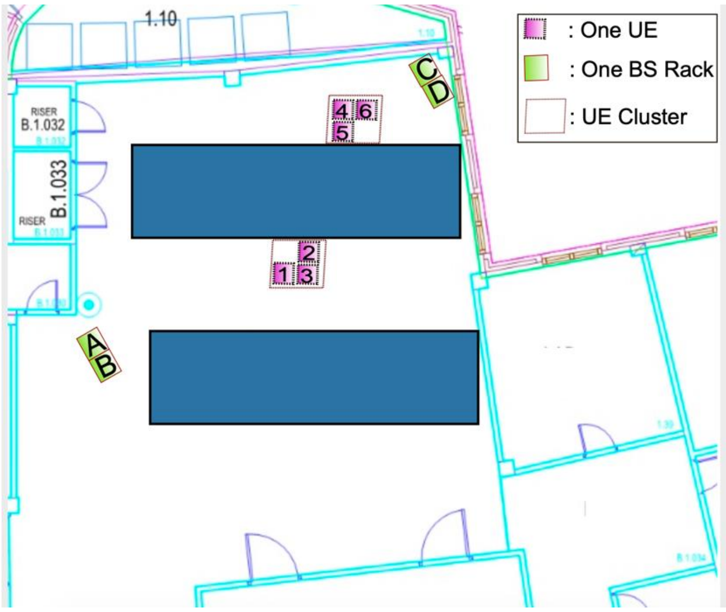
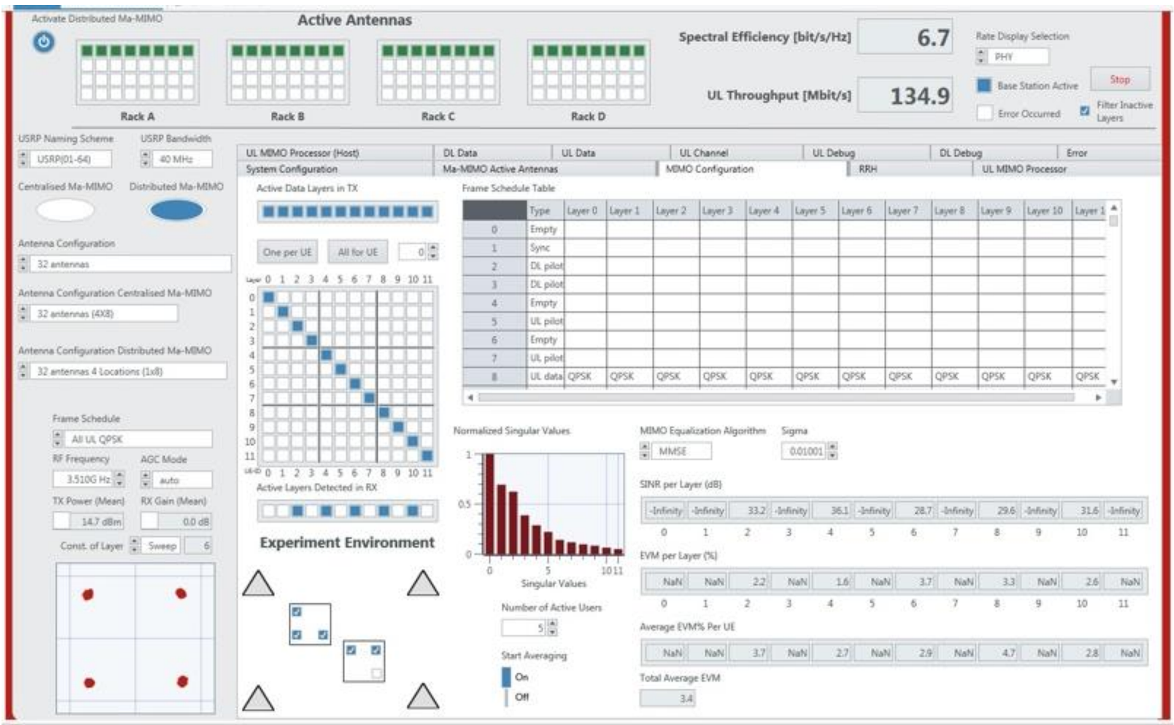


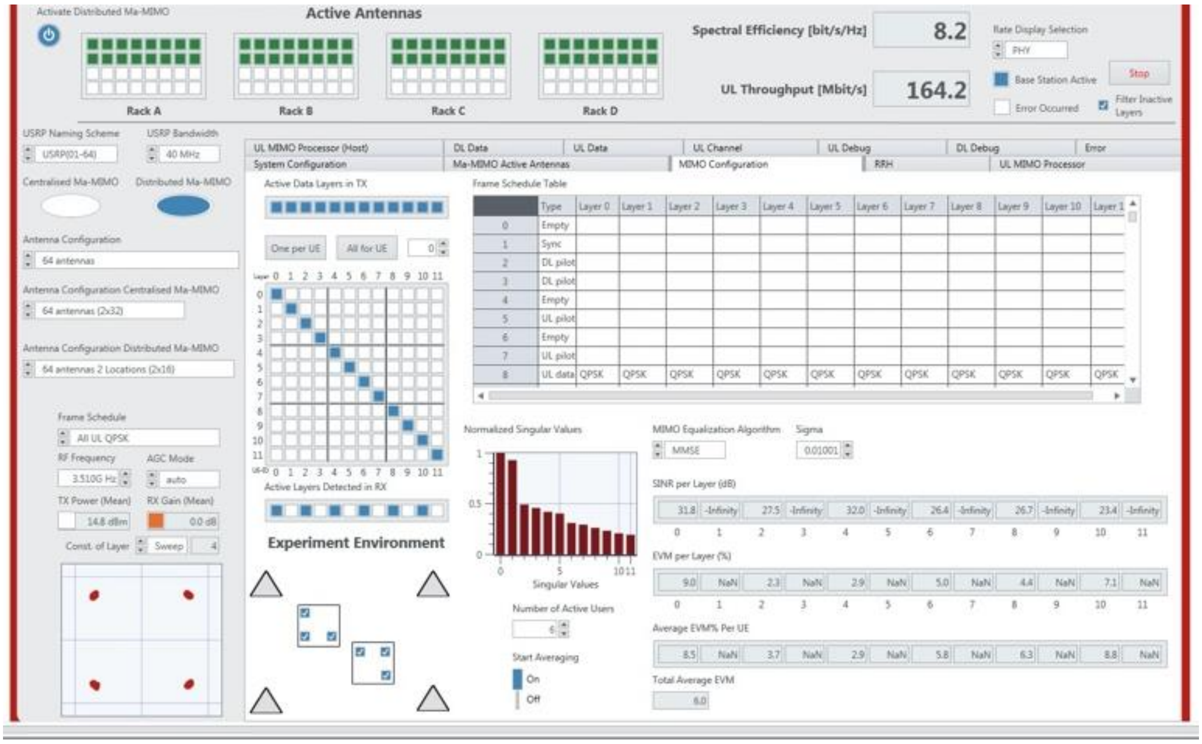
Figure 5-66: Distributed (x2) Massive MIMO testbed deployment at CSN

32 antennas Massive MIMO and 5 users

In this scenario, at each one of the four racks, 8 antennas (one row), were activated, resulting in 32 antennas in total at the BS end. Five users were deployed into two groups (one group of two users and one group of three users). The UL throughput achieved was 134.9 Mbit/s and the SE was 6.7 bit/s/Hz, as shown in ***Figure 5-67*** a).



a)



b)

Figure 5-67: a) Distributed (x2) Massive MIMO configuration with 32 antennas at BS, b) Distributed (x4) Massive MIMO configuration with 64 antennas at BS

64 antennas Massive MIMO and 6 UEs

In this scenario, at each one of the four racks, 16 antennas (two rows), were activated, resulting in 64 antennas in total at the BS end. Six users were deployed into two groups). In this scenario, as described before, we are working in elevation as well as the azimuth. As a result, we can serve six users without a compromise on the overall performance. ***Figure 5-67*** b) depicts the results of the test, with a SE of 8.2 bit/s/Hz and UL throughput 164.2 Mbit/s.

5.11.3 Results Discussion

Overall, we have performed a wide range of different network configurations based on centralized and distributed Massive MIMO. For all our experiments, we have used QPSK in order to establish and maintain reliable connectivity. In addition, no error correction was used during all the Massive MIMO testbed real-time evaluations.

Table 5-3 summarises the main results from all our experiments. In particular, average EVM (%), the UL throughput and the spectral efficiency for the maximum number of users employed are given for every scenario.

In general, we can observe that deploying a distributed the Massive MIMO system results in higher UL throughput and SE. For example, “Centralised 32 – 4UEs” results in worse throughput (109.6 Mbit/s) compared to “Distributed 32x4 – 5UEs” (134.9 Mbit/s) where we have split the BS into four different locations.

In addition, as we increase the number of antennas, once again the throughput and SE increase as well. For instance, “Distributed 32x4 – 5UEs” achieves a lower SE (6.7 b/Hz) compared to “Distributed 64x4 – 6UEs” (8.2 b/Hz).

Table 5-3: Real-Time Results from the massive MIMO demo in the CSN lab (no error corrections)

Scenario	Average EVM%	UL Throughput [Mbit/s]	SE [bits/Hz]
Centralised 32 – 4UEs	4%	109.6	5.5
Centralised 64 – 5UEs	4.4%	136.7	6.8
Centralised 128 – 5UEs	3.8%	138	6.8
Distributed 32x4 – 5UEs	3.8%	134.9	6.7
Distributed 64x4 – 6UEs	3.9%	164.2	8.2
Distributed 32x2 – 5UEs	5.4%	136.9	6.8
Distributed 64x2 – 6UEs	6%	164.2	8.2

Table 5-4: Results from post-processing the massive MIMO demo results (3/4 rate LDPC code)

Scenario	Max UL Throughput for Max UEs [Mbit/s]	Max SE for Max UEs [bits/Hz]
Centralised 32 – 4UEs	255.3	12.7
Centralised 64 – 5UEs	310	15.5
Centralised 128 – 5UEs	310	15.5
Distributed 32x4 – 5UEs	328.3	16.4
Distributed 64x4 – 6UEs	364.8	18.2
Distributed 32x2 – 5UEs	291.8	14.5
Distributed 64x2 – 6UEs	310	15.5

It has been also shown that if more than one row (in the antenna array is activated), then the performance could be improved. In scenarios "Distributed 64x4 – 6UEs" and "Distributed 64x2 – 6UEs" we had two rows at the antenna array activated and we managed to employ six users in the network.

In general, the lower the EVM value, the better performance we can get. Regarding the EVM results, one might argue that in the "Centralised 32 – 4UEs" scenario the average EVM (4%) is lower than in the case of "Distributed 64x2 – 6UEs" (6%). That is correct, however there is a very good reason for why that happens. In the former scenario we employ four users, however in the latter we have six users, which imposes additional interference due to adjacent users.

All the results acquired from the Massive MIMO trial were later post-processed in our Massive MIMO simulator in order to employ LDPC code (3/4 rate) and higher modulation schemes (16-256 QAM), and observe resulting improvement in the performance. ***Table 5-4*** summarises the main results for all the scenarios. In particular, the maximum UL throughput and spectral efficiency for the maximum number of users employed in each scenario are given.

Overall, we can observe that distributing our Massive MIMO BS into four racks achieves the best results. In particular, having a total of 32 antennas split into four locations ("Distributed 32x4 – 5UEs") achieved higher maximum UL throughput (328.3 Mbit/s) compared to having a total of 64 antennas but split them into two locations ("Distributed 64x2 – 6UEs") (310 Mbit/s).

In general, the post processing results show that real-time throughput and spectral efficiency achieved at the massive MIMO demo can be increased by 100% when higher modulation schemes are used, ie.256-QAM.

5.12 Lessons Learned of the Stadium demo

In order facilitate development between geographically diverse partners, it was necessary to build a distributed development platform so that all the components operated over a single Layer-2 network. For this, we used L2 OpenVPN tunnels between the respective partner sites. We encountered a number of problems in creating a truly Layer-2 network over a Layer 3 network through firewalls. Nevertheless, we were, ultimately, able to resolve these problems by building a common development platform. Note, this was only any issue for development, for the actual demonstration, all the components from each partner would be in a single geographical location and Layer-2 tunnels would be unnecessary.

Nevertheless, these early challenges required close cooperation between partners in order to coordinate the configuration and setup network components. This spirit of close partner collaboration proved beneficial for the actual demonstration. The project demonstration coincided with the escalation of COVID-19 infections throughout Europe. Partners either avoided travelling, or if they had travelled to the UK for the demonstration, returned, home. This left the UK partner, Zeetta Networks, to carry out the physical installation and setup. However, as we had done in the development stages of the project, we continued to work together remotely. Partners that returned home provided support via video conference throughout the demonstration setup and execution.

Other lessons learned include an appreciation of the added complexity when one does not have complete control of the environment. Given that AGS's network was a production network, nothing we did could impact the network's operation. We were, therefore, reliant on the Stadium's internal IT staff and MSP for even small network configuration changes (such as adding VLANs). Sometimes "misinformation" would result as messages were passed from the partner, to internal IT staff and finally to the MSP. At times, policy decisions were made based on our ability to acquire control of the situation. Sometimes, this control was not possible and we had to rely on Stadium staff and their MSP. In such cases we would endeavor to plan ahead and give the Stadium as much notice of our requirements as possible.

6. Additional demonstrations

6.1 Synchronization harmonizer demonstration

In the 5G-PICTURE deliverable D4.3 [36], several different algorithm approaches for the synchronization harmonizer were discussed. This section provides the demonstration results for one of the possible application scenarios of the synchronization harmonizer, where a mmWave transport network is considered.

The goal of demonstrator is to obtain a relative performance comparison between the multiple synchronization paths from different Grandmaster Clocks (GC) to the Ordinary Clock (OC). Particularly, the focus of the investigation is the impact of using mmWave nodes that are not equipped with IEEE1588v2 Transparent Clock (TC) capability to the synchronization accuracy, i.e. observable clock offset. As the multitude of mmWave nodes used in transport network are typically not IEEE1588v2 TC compliant, the goal is to evaluate if the proposed synchronization harmonizer could be applied for such scenarios.

6.1.1 Measurement Setup and Procedures

In order to evaluate the functionality of the synchronization harmonizer, a demonstrator setup is constructed. The setup consists of two Microsemi TP4100 devices configured as Operator and Tenant Grandmaster Clocks (GC1, GC2) and one TP4100 configured as an Ordinary Clock (OC). Furthermore, in order to obtain a baseline for the clock offset estimation by the OC, the two GCs are synchronized between each other through the PPS/10MHz inputs/outputs, respectively. The OC is connected to GC1/GC2 through two wireless paths respectively, using the wireless nodes (WN1, WN2 and WN3), as depicted in ***Figure 6-1***. In this setup, the 60 GHz Mikrotik wAP 60Gx3 WNs are used, which are non-IEEE1588v2 TC compliant. Due to the bulk of the demonstrator hardware, the setup is arranged in an indoor office environment at a short link range of 3.64 m for both synchronization paths, as shown in **Figure 6-2**.

The TP4100 devices are configured with the Telecom-2008 PTP profile that provides a message rate of 64 hardware-timestamped messages per second in both directions, i.e. from GC1/GC2 to OC and vice versa. These messages contain both the ingress and egress timestamps of the respective transmission, which are then analysed in the post-processing. In order to obtain statistical confidence in the results, the measurements are conducted for an interval of 30 minutes, thus collecting a total of 230.4K data points (timestamps). Finally, the extracted timestamps are fed as input to the synchronization harmonizer algorithm in order to determine the best GC in terms of the most stable clock offset and skew. The latter step is performed offline for convenience, since real-time implementation of the synchronization harmonizer would require significant efforts and low-level access to the device PTP modules.

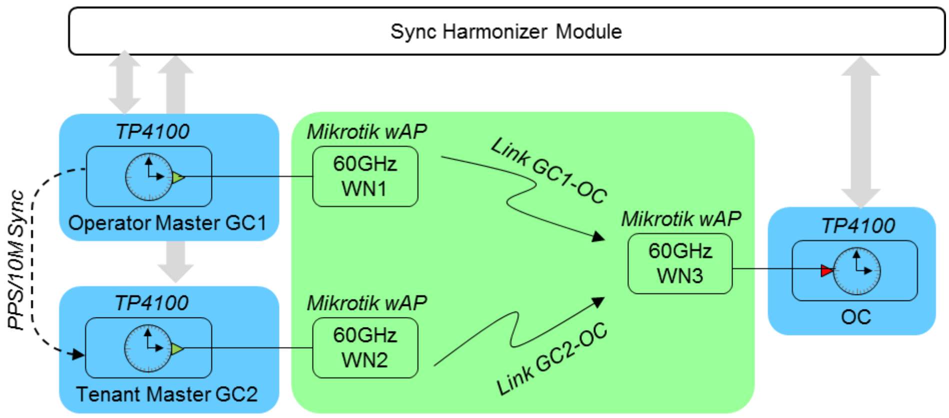


Figure 6-1: Synchronization Harmonizer Demo Setup

Figure 6-2: Measurement Scenario, showing: a) 60 GHz Wireless Link Setup, b) Enclosure with Microsemi TP4100 Clocks

6.1.2 Synchronization Harmonizer Algorithm

Equipping the network with multiple synchronization algorithms has been suggested in D4.3, [37] [38] under the concept of synchronization harmonizer. In deliverable D4.3 we comprehensively explained two main approaches adopted in the literature to tackle the problem of synchronization. Ideally, we should be able to divide a large-scale network and apply each of those algorithms where they suit the most. Nevertheless, since preparing a large-scale network in practice needs a huge amount of effort and preparation, we, in this deliverable, focus on implementing the pairwise synchronization algorithm introduced in D4.3 [37]. In particular, on one hand, we focus on estimating clock offset and skew with the aid of Kalman Filter (KF) fed by measured time-stamps. On the other hand, we rely on those estimations to determine the best synchronization path. To this end, we firstly obtain the information about the uncertainty of time-stamping from each node, namely the variance of time-stamping error σ^2. This information along with recorded time-stamps c_{ij}^{k} are then fed into the KF to obtain an estimation of clock offset. The process is depicted in ***Figure 6-3***.

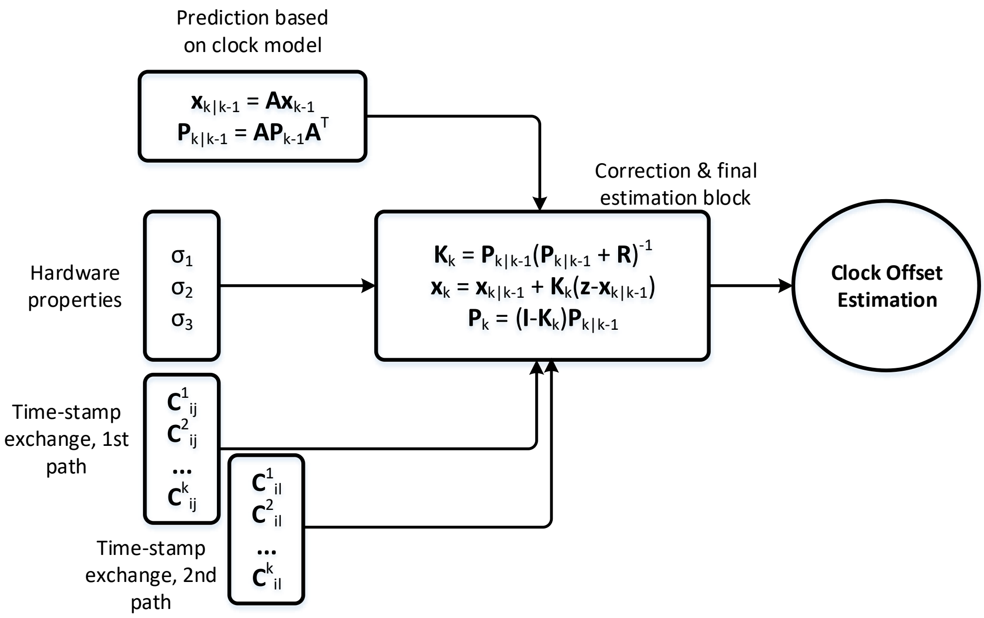
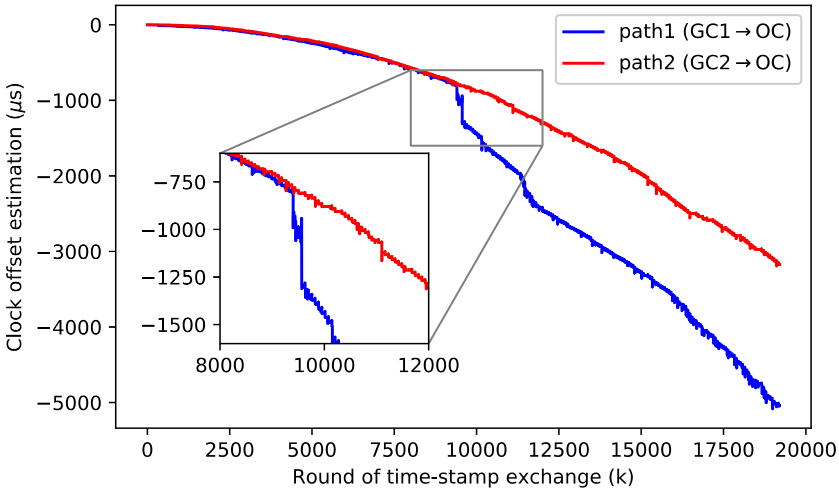


Figure 6-3: Clock Offset Estimation Approach

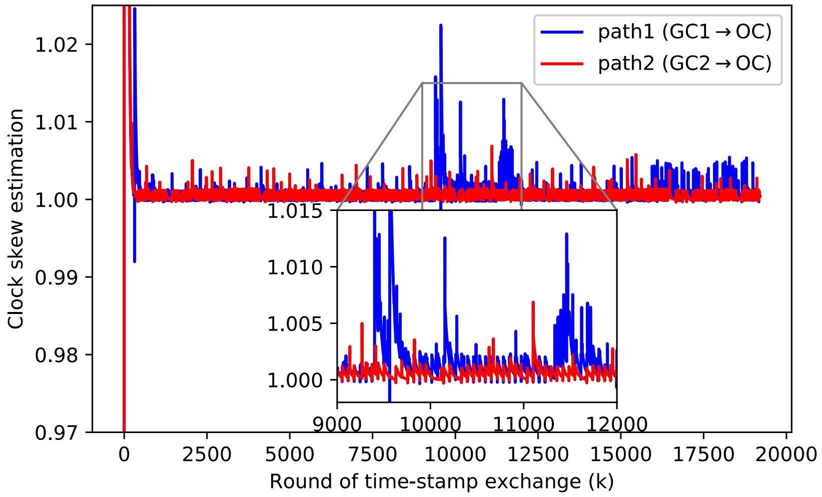
6.1.3 Demonstrator Results and Discussion

In the scenario shown in ***Figure 6-1***, both synchronization paths are using identical hardware devices. To analyze the performance of the harmonizer, as illustrated in deliverable D4.3, one possible method is to predefine the clock offset at the slave and then compare the predefined offset with the offset estimated by harmonizer.

Unfortunately, our hardware is not capable of predefining the clock offset and therefore we resort to another method to indicate the accuracy of harmonizer estimation. In particular, since the Grandmaster Clock nodes (GCs) share the same clock, we expect that the clock offset estimated from the time-stamps of path GC1-OC is close to the estimation obtained using that of GC2-OC. If this does not occur and any of the paths diverges from another, one can conclude that the synchronization path is impaired.



a)



b)

Figure 6-4: Measurement results on: a) Clock Offset Estimation for the GC1-OC and GC2-OC sync.paths, and b) Clock Skew Estimation

Figure 6-4 indicates the estimation of clock offset and skew, respectively. Both parameters are estimated for two paths. As we can see, both paths show almost identical behaviour until one of the clocks, i.e. path 1, diverges. The divergence can be observed in both figures. In particular, instability in clock skew (***Figure 6-4*** b), marked section) leads to a sharp change in clock offset (***Figure 6-4*** a), marked section). Having observed these two parameters, at this point in time, the harmonizer can select path 2 to perform synchronization of the OC to the GC2, while continuing to observe the status of both paths. In this manner, if again any change/deterioration occurs in any of the paths, the harmonizer can immediately switch the synchronization path.

7. Conclusions

This deliverable concludes the work of Work Package 6 (**WP6**) that focused on the demonstration and evaluation of the main architectural functionalities and solutions developed in the project. The demonstration activities took place in three different project demo sites: i) a Rail deployment in Barcelona in the railway lines of FGC showcasing a multitenant high-performance 5G network model for supporting critical and business services, ii) the smart city 5GUK testbed in Bristol demonstrating safety and VR services over a variety of highly configurable wired/wireless technologies, integrated in a single transport solution, and iii) a 5G deployment at Ashton Gate Stadium in Bristol where features of the proposed 5G OS have been showcased focusing on dynamic network slicing creation supporting a crowd sourced video application. Moreover, extensions to the 5G OS to support AI/ML functions able to manage the network have been proposed.

The capabilities of the 5G-PICTURE technologies and short scale network deployment options have been assessed in the 5G-PICTURE demonstrators. Together with the evaluation of the technologies made in the 5G-PICTURE technical Work Packages (WP3, WP4 and WP5), many of these technologies have served in WP6 to support the different 5G-PICTURE demonstration activities. These activities focused on different vertical industries and associated services, each having very different requirements, customers/users/stakeholders' profiles and operational environments. As a result, in each demonstrator testing and evaluation activities focused on different KPIs.

This deliverable has described in detail the characteristics of the various technologies deployed and their integration together with commercial products. Results collected from the execution of carefully planned test scenarios defined in deliverables D6.1 and D6.2 for each demo UC are described and analysed proving the validity of the 5G-PICTURE proposed solutions in a different operational environments supporting emerging applications with diverse service level requirements. More specifically, conclusions from the experiences gained and result analysis from each demo are presented below.

Railway Demo

The 5G-PICTURE Railway demonstration is Europe's first 5G Rail deployment in an operational environment. The demo installation at **FGC** comprises approximately 1.5 km of track providing 1 Gbit/s throughput to a train running up to 90 km/h. The demo solution designed, developed and integrated during the project execution is based on a mmWave RAN providing vehicle to infrastructure connectivity and a wireless access solution inside train. This model implements the 5G-PICTURE architecture for railways, for a cost efficient and multitenant 5G implementation, to facilitate 5G deployment in this vertical.

The developed solution is based on (1) Blu Wireless Technology (**BWT**) self-directed mmWave beams between train and track poles, to provide multiple wireless train to track connections, (2) state of the art **ADVA**'s ITU-T G.698.4 agnostic passive optical connectivity between poles, integrated into project purpose designed outdoor cabinets from COMSA, a HW programmable mobility server solution from CNIT to preserve session continuity, (4) a 100GE aggregation/protection layer to provide connectivity to the railways core network, and (5) a TCN network design from **COMSA**.

The solution is designed to support multiple 1 Gbit/s throughput, end to end latency below 2 ms and the support of precise time synchronization with lowest possible cost. This solution is a clear contribution to the FRMCS vision for the implementation of a 3GPP based solution for all railway's telecom needs.

The project implementation had two phases. The first phase was the validation of the overall solution in a testbed implemented in the COMSA lab in Madrid. The second phase was the direct implementation of the solution in the FGC track. The project required optical and electrical cable deployment along the track and inside the train.

In terms of services 5G-PICTURE railways trial has demonstrated services from the three defined types by FRMCS: (1) forward-looking low latency critical video over a 5G railway experimental testbed, (2) HD video streaming with the high-throughput traffic originated by the Business services inside the train,(3) Emulated Performance services with different traffic patterns (bandwidth, latency, packet jitter, etc.) that can be access via internal Wi-Fi.

A large number of tests were completed for both scenarios: stationary train and moving train. The demo shows E2E performance up to 2 Gbit/s (DL+UL) to the moving train with average latencies of 2.35 ms and power consumption per km of 200W. Compliance to recent GDPR legal framework was met by video pixelation.

In terms of lessons learned, the project showed that building complete system testbeds prior to deployment on the field were key to project success. The acquisition of a license for demo purposes was challenging since the mmWave technology did not belong to any of the existing technical types set out in the National Frequency Attribution Table for common use. An important lesson learned is that a railway innovation project is very challenging and complex due to the strict safety requirements of the railway's environment, imposing very restricted working schedules and special machinery. The railways demo became a project on its own inside the complete 5G-PICTURE project due to this complexity.

The solution trialed is the basis for future multitenant deployments with moving radio access nodes inside trains owned by train operators or telecom operators, and infrastructure along the track owned by railways infra administrations or telecom operators. The remote data server for surveillance and streaming is an example of how cloud-based services can be enabled with strong 5G connectivity between train and track.

For all the above the demo is believed to be of key importance for the deployment of 5G networks in the railway domain and shows the potential of strong impact in the transportation domain.

Smart City Demo

The **UNIVBRIS** test network has been used for the 5G-PICTURE smart city UC demonstration (Section 4). The main objective of this demonstration has been to showcase the multitenancy capability of 5G-PICTURE disaggregated transport layer and, at the same time, its capability to meet the forthcoming 5G services' performance requirements. For this purpose, 5G-PICTURE equipment and its disaggregated transport solution was integrated within the 5GUK test network spread across three different physical locations, comprising (among other infrastructure) 5G NR, LTE-A and Wi-Fi nodes at the access network part, a 5G NSA/LTE core as well as MEC and cloud compute resources. **IHP** integrated three devices operating in the unlicensed 60 GHz band to the test network, serving as a backhaul mesh segment. **XDE** brought an active massive MIMO Antenna Proof-of-Concept platform Radio Unit (RU), along with a Central Unit (CU) server solution emulating the base band processing along with a spectrum analyser as receiver emulating a UE function, serving as fronthaul transport stream. All these backhaul and fronthaul transport streams have been integrated with TSON's technology developed by **UNIVBRIS** in the framework of 5G-PICTURE. This technology was employed to enable mapping of multitenant traffic across infrastructure domains.

The 5G-PICTURE smart city demonstration successfully showcased the capabilities of the aforementioned deployment using two UCs: smart city safety and virtual reality. The critical performance KPIs associated with these UCs are radio network node capacity, end-user throughout and latency; therefore the demo focused on the evaluation of these KPIs. The evaluation results reveal that the 5G-PICTURE solution successfully met the expected KPIs targets for these UCs and for 5G services in general. In addition to the UC, a mMIMO RU demonstration successfully validated the benefits both of Sub-6 GHz mMIMO, as well as the functional split 7.2 and corresponding fronthaul interface.

Stadium Demo

In Section 5, the UC for the 5G-PICTURE demonstration at the Ashton Gate Stadium, Bristol UK was presented. Ashton Gate Stadium features an internal high speed, SDN provided by **ZN**. The network supports a number of services for the Stadium's internal IT requirements plus public Wi-Fi for match days and events. The purpose of the project was to augment this production network to a 5G network and an implementation of the 5G OS architecture developed in WP5 in a complex production network environment.

The demonstration focused on addressing the following 5G themes for the mega-event/stadium vertical:

- Application aware, programmable network over heterogeneous hardware.
- Differentiated treatment of the application traffic using slices.
- Service resilience using slices in a multi-connectivity link scenario for Wi-Fi and high capacity wireless access technologies, such as Massive MIMO.

For the UC we employed Watchity, which is a real-time, crowd-sourced video production application. Watchity comprises an application for capturing and uploading video/audio from an end user device and a cloud hosted video production platform, which in our case, ran on Amazon Web Services. The demonstration successfully showed that how the 5G-PICTURE intelligent network autonomously detected and prioritised video traffic in order to maintain QoE.

The demonstrator also proved the deployment capability to:

- Achieve 20-25 Mbit/s per user.
- Slice provisioning time below 40 seconds (37.8 s).
- Slice instantiation and reconfiguration (HO) in the order of some seconds – less than 40 s (compared to hours required currently, as they require manual interaction).
- RTT of 40 ms even during the slice reconfiguration (HO) phase.
- Achieve low network service deployment and termination times – below 5-6 seconds for services consisting of 4 VNFs.
    - Service Termination time below 5-6 seconds.
    - Service Deployment time in Compute domain below 5-6 seconds.

Massive MIMO, due to spatial multiplexing, can increase the spectral efficiency significantly. Thus, it was considered as a solution to support the network of a live game in a Stadium. During our demo, we have investigated two main configurations: a) centralized, and b) distributed, with the latter providing higher spectral efficiency and UL throughput. Furthermore, the more antennas were employed at the BS side, the higher the UL throughput and SE were. A maximum number of six users were considered, clustered into two groups. The higher the number of users, the greater the interference among them was. During the demo, QPSK modulation was employed in order to maintain a stable and reliable connection. However, post-processing has been applied to the results, employing higher modulation schemes and also a ¾ rate LDPC code. The highest performance was given by distributing 64 antennas into 4 racks serving 6 users, with an UL throughput of 364.8 Mbit/s.

8. References

[1] 5G-PICTURE, deliverable D6.1, “Specification of Vertical Use cases and Experimentation plan”, 2017

[2] 5G-PICTURE, deliverable D2.3. “Vertical services, architecture and final evaluations”, November 2019

[3] 5G-PICTURE, deliverable D6.2 Vertical Demo and Testbed setup and initial validation results, July 2018.

[4] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022, Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.pdf

[5] 5G-PICTURE, Deliverable D2.2 System architecture and preliminary evaluations, 31st July 2018.

[6] 3GPP TS 22.261 V16.1.0 (2017-09) 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Service requirements for the 5G system; Stage 1 (R16)

[7] 3GPP, TR 22.861, "Feasibility Study on New Services and Markets Technology Enablers for massive Internet of Things; Stage 1"

[8] 3GPP, TR 22.862, "Feasibility study on new services and markets technology enablers for critical communications; Stage 1"

[9] 3GPP, TR 22.863, "Feasibility study on new services and markets technology enablers for enhanced mobile broad-band; Stage 1"

[10] 3GPP, TR 22.864, "Feasibility study on new services and markets technology enablers for network operation; Stage 1"

[11] 3GPP, TR 22.891, "Feasibility study on new services and markets technology enablers; Stage 1"

[12] Recommendation ITU-R M.2083-0 (09/2015): IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond.

[13] NGMN 5G Initiative Team, "A Deliverable by the NGMN Alliance", NGMN 5G White Paper, Feb.17, 2015 - https://www.ngmn.org/5g-white-paper/5g-white-paper.html

[14] Euro-To5G project, Deliverable D2.6, "Final report on programme progress and KPIs", https://5g-ppp.eu/wp-content/uploads/2017/10/Euro-5G-D2.6_Final-report-on-programme-progress-and-KPIs.pdf

[15] 5G PPP, 5G PPP phase II KPIs – Annex to Programme Management Report, August 2019.

[16] 5G empowering vertical industries, brochure available online at https://5g-ppp.eu/wp-content/uploads/2016/02/BROCHURE_5PPP_BAT2_PL.pdf

[17] 5G-PICTURE, deliverable D2.1 5G and Vertical services, use cases and requirements, January 2018.

[18] METRO-HAUL, deliverable D2.1, “Definition of Use Cases, Service Requirements and KPIs”, Feb 2018

[19] “5G-PICTURE deliverable D3.3, “Final report on Data Plane Programmability and infrastructure components,” 2020.

[20] “5G-PICTURE D3.2 Final report on Data Plane Programmability and infrastructure components,” 2019.

[21] M. Piz, Wideband OFDM System for Indoor Communication at 60 GHz. Phd, Brandenburgische Technische Universität Cottbus, 2010.

[22] E. Oejefors et al "A 57-71 GHz Beamforming SiGe Transceiver for 802.11ad-Based Fixed Wireless Access" in Proc. of IEEE Radio Frequency Integrated Circuits Symposium (RFIC 2018), Philadelphia, USA, 2018

[23] BFM6005 Product Brief, [Online:] https://www.siversima.com/product/bfm06005/

[24] D2.1 5G and Vertical Services, use cases and requirements

[25] D2.2 System architecture and preliminary evaluations

[26] D4.2 Complete Design and Initial Evaluation of Developed Functions

[27] D6.1 Specification of Vertical Use cases and Experimentation Plan

[28] FRMCS User Requirements specification 4.0. International Union of Railways (UIC)

[29] "Watchity" https://www.watchity.com/

[30] "Wireshark" https://www.wireshark.org/docs/man-pages/tshark.html

[31] "5G-PICTURE deliverable D5.2 Auto-adaptive hierarchies"

[32] "5G-PICTURE deliverable D5.4 Integrated prototype (across tasks and work packages)"

[33] "5G-PICTURE deliverable D5.1 Relationships between Orchestrators, Controllers, slicing systems"

[34] "Iperf", https://iperf.fr/

[35] "Prometheus", https://prometheus.io

[36] 5G-PICTURE deliverable D4.3

[37] EuCNC Meysam

[38] SDN Harmonizer

9. Acronyms

Acronym	Description
AGS	Ashton Gate Stadium
AI	Artificial Intelligence
AP	Access Point
API	Application Program Interface
ATC/P/O	Automatic Train Control/Protection/Operation.
AWS	Amazon Web Services
BSSID	Basic Service Set Identifier
CCTV	Closed-circuit television
COP	Control Orchestration Protocol
CoS	Class of Service
CSA	Channel Switch Announcement
Draisine	Auxiliary rail vehicle, equipped to transport crew and material necessary for the installations and maintenance of railway infrastructure.
DFS	Dynamic Frequency Selection
DRCS	Data Radio Communication System.
DWDM	Dense Wavelength Division Multiplexing, a technique of signal transmission through optical fiber.
ELP/ERP	Ethernet Link/Ring Protection protocol
EVM	Error Vector Magnitude
FRMCS	Future Railway Mobile Communication System. The next worldwide telecommunication system designed by UIC successor of GSM-R and a key enabler for rail transport digitization.
GC	Grandmaster Clock
GDPR	The General Data Protection Regulation (GDPR) is a legal framework that sets guidelines for the collection and processing of personal information from individuals who live in the European Union (EU).
HEE	Header End Equipment
FOV	Field of view
G.metro	ITU-T G.698.4. Multichannel bi-directional WDM applications with port agnostic single-channel optical interfaces.
HPU	Host Processor Unit
LAG	Link Aggregation Group
MmWave	Frequencies between 24 GHz and 86 GHz.
MDO	Multi Domain Orchestrator
MNO	Mobile Network Operator.
NetFPGA board	FPGA Based Prototype Board
OCC	Operation Control Centre.

POE	Power Over Ethernet
SFP	Small form-factor pluggable, a compact, hot-pluggable network interface module to equip the interface port with most suitable type of transceiver to need.
TAN	Track Access Network, the telecom network along the track.
TCN	Train Communication Network, the telecom network inside the train.
TETRA	Trans European Trunk Radio.
UIC	International Railways Union, the worldwide professional association representing the railway sector and promoting rail transport.
V2I	Vehicle to Infrastructure radio link.
WDM	Wavelenth Division Multiplexing.
DFS	Dynamic Frequency Selection
EVM	Error Vector Magnitude
HO	Handover
MAC	Media Access Control
MANO	Management and orchestration
MEC	Multi-access Edge Computing
MDO	Multi Domain Orchestrator
MIMO	Multiple-Input Multiple-Output
NFV	Network functions virtualization
OvS	Open vSwitch
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RSSI	Received Signal Strength Indicator
RTMP	Real-Time Messaging Protocol
RTT	Round-Trip Time
SDN	Software Defined Network
SINR	Signal-to-Interference-plus-Noise Ratio
SSID	Service Set Identifier
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
VLAN	Virtual Local Access Network
VNF	Virtual Network Function
WAP	Wireless Access Point

10. Annexes

Annex A: Additional Train equipment components' description

Wi-Fi Access Points

We had two different Access Points (AP) proposals from the manufacturers Hewlett Packard (Aruba) and Huawei. The two main differences of both solutions are the following:

Huawei AP complies with railway regulations, while the Aruba Access Point does not.

Aruba AP carries the antennas integrated in the housing of the equipment itself while Huawei AP has two separate modules (housing and antenna).

Option A: Aruba AP-345 (RW)

The Aruba 340 series access points provide the fastest 802.11ac gigabit data speeds and superb user experience for mobile devices and applications in a digital workplace.

Designed with an integrated, 802.3bz compliant, HPE Smart Rate multi-gig Ethernet port to eliminate wired bottlenecks, these APs offer unmatched wireless performance and capacity.

The unique and flexible dual-5GHz architecture of the 340 series offers a way to boost 5 GHz capacity where needed.

Figure 10-1: HP Access Point Aruba AP-345 (RW) Unified AP

Benefits of the Access Point of Aruba are the following:

- Antenna polarization diversity (fixed) for optimized RF performance. Antenna integrated in the equipment.
- It allows a simpler installation and a minor visual impact inside the train.
- Unified AP, deploy with or without WiFi controller.
- Dual Radio 4x4 802ac access point with Multi-User MIMO (wave 2).
- Supports up to 2,166 Mbit/s per radio in the 5 GHz band and up to 800 Mbit/s in the 2.4 GHz band.

Table 10-1: Aruba AP parameters and characteristics

PARAMETER	MAIN CHARACTERISTICS
Dimensions:	22.5 cm (W) x 22.4 cm (D) x 5.2 cm (H)
MTBF:	640khrs (73yrs) at +25C operating temperature

Power over Ethernet (PoE):	48 Vdc (nominal) 802.3af/802.3at compliant source
Direct DC source:	48Vdc nominal, +/- 5%
Operating temperature:	0ºC to +50ºC
Storage and transportation:	-40ºC to +70ºC

PART NUMBER	DESCRIPTION
JZ031A	Aruba AP-345 (RW) Unified AP
JW047A	AP-220-MNT-W1W Mt Basic White Kit

Option B: Huawei AP9131DN

The Access Point "AP9132DN" (shown in **Figure 10-2**) is an 802.11ac vehicle dual band (2.5 GHz and 5 GHz) AP that support 3 x 3 MIMO. They use industrial anti-vibration M12 interfaces, comply with EN50155 vehicle mounted electronic equipment standards, and support fast switchover, meeting train-ground backhaul network deployment and compartment coverage requirements.

Figure 10-2: HP Access Point Huawei AP9131DN & AP9132DN.

AP9131DN: HARDWARE SPECIFICATIONS

Table 10-2: Huawei specifications

	ITEM	DESCRIPTION
Technical specifications	Dimensions (H x W x D)	40 mm x 180 mm x 100 mm
	Weight	1.2 Kg
	Interface type	1 x 10/100/1000M self-adaptive Ethernet interface (M12, PoE) 1 x 100/1000M Ethernet optical interface (eSFP) 1 x Management console interface (RJ45)
Environmental specifications	Operating temperature	-40ºC to +65ºC
	Storage temperature	-40ºC to +70ºC
	Operating humidity	5% to 95% (non-condensing)
	Dustproof and waterproof grade	IP41
Power specifications	Power input	DC power supply: 48 V rated voltage; voltage range: 33.6 V to 60 V PoE power: –48 V DC (in compliance with IEEE 802.3at)-
	Maximum power consumption	Compartment coverage scenarios: 17.5W Trackside single-5G scenarios: 12.5W

		NOTE: The actual maximum power consumption depends on local laws and regulations.
Radio specifications	Antenna type	External antennas, 3 x QMA female connectors (2.4G/5G combined)
	Maximum number of VAPs for each radio	16
	Maximum number of users	<=256
	Maximum transmit power	2.4G : 25dBm (combined power) ; 5G : 25dBm (combined power)
	Channel rate	802.11a: 6, 9, 12, 18, 24, 36, 48, and 54 Mbit/s
		802.11b: 1, 2, 5.5, and 11 Mbit/s
		802.11g: 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, and 54 Mbit/s
		802.11n: 6.5 to 450 Mbit/s
		802.11ac: 6.5 to 1300 Mbit/s
Standards compliance	Vehicle-mounted electric equipment standards	EN 50155

The rejection sequence of the channels by train working at 2.4 GHz could be the typical C1 - C6 - C11 to give the guard of 3 channels that is usually recommended, but in order to avoid interference from other systems already installed and that they could degrade our signal.

As for working in the 5 GHz band, the number of available channels is much higher than those found in the 2.4 GHz band; 23 non-overlapping channels to easily avoid interference between them.

Figure 10-3: Indoor 2.4 GHz and 5 GHz Linear-Polarized Omnidirectional Antenna ref. “27012545”.

ANTDG0404D4SR: TECHNICAL SPECIFICATIONS:

Table 10-3: Wi-Fi Antenna specifications

ITEM	2.4 GHz	5 GHz
Frequency (MHz)	2400-2500 MHz	5150-5850 MHz
Gain	4 dBi	5 dBi
Horizontal lobe width (degrees)	360º	360º
Horizontal lobe width (degrees)	110º	110º
SWR	<=2	<=2
Polarization	Linear	

Connector	RP-SMA-J
Dimensions (mm)	H x W x D: 150 x 150 x 20
Weight (g)	450
Mounting mode	Ceiling mounting

Access Point installation

Two access points were installed in the train in the demo. One at the front and one on the rear wagon for simplicity purposes. Installing a third Access Point in the intermediate for coverage purposes would not add important value to the demo.

The AP and antenna assembly would have ideally been installed approximately in the middle of each car for coverage purposes. For the demo purposes the equipment was installed in an existing space inside the car.

Huawei option:

A special support is required to fix the body of the AP it to the structure of the train. The dimensions of the AP are 40 mm x 180 mm x 100 mm (H x W x D) and the weight is 1.2 Kg. The equipment can be supplied with a DC voltage of 48 rated voltage through a voltage converter (AC / DC) or a POE power (-48 VDC). The AP does not support AC power supply. The antenna can be mounted on a removable ceiling or a horizontal support (to define) with a hole of 23+/-0.5 mm (see **Figure 10-4**).

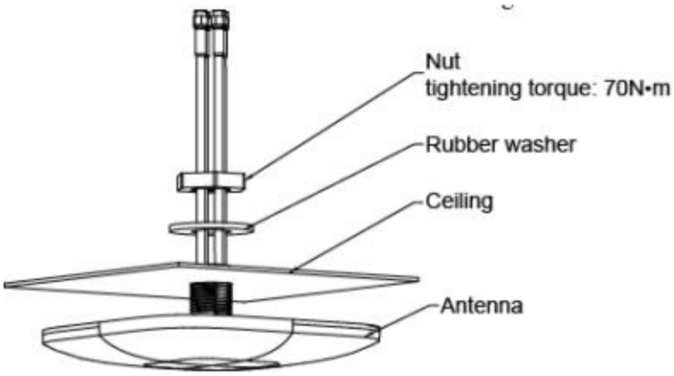


Figure 10-4. Installation of the antenna directly on the roof of the train.

The antenna has four 1 m feeder cables 50 Ohms delivered. Can be replaced with longer cables: 5 m, 10 m and 15 m with SMA-J/RP-SMA-J connectors. It is recommended that the AP and antenna are as close as possible to reduce cable losses.

Aruba option:

The antenna was integrated to the body of the AP. The decision was to install the Aruba Access Point based mainly on delivery times.

Figure 10-5: Final installation of Wi-Fi AP.

CCTV System

Current trains have a camera in the cabin that records traffic. It was decided to use a separate camera to avoid any interference into current operations.

Initially the possibility of using camera models of different resolutions was considered, but for reasons of robustness, a single model Dome Network Cameras 5 MP IR, reference "DS-2XM6756FWD-I", specific for railway environment was selected.

Two cameras were installed, one on the roof at the front of the train and one on the roof at rear, both recording the train track. The camera was installed on a metal plate above the roof of the train. A camera support is included to assure a good field of view without activating the zoom.

It was also necessary to clarify the way to pass the RJ-45 cable with data and feeding by injector POE to connect the cameras with the TCN switch.

Table 10-4: Elements of the CCTV system

UNITS	CCTV ELEMENTS	LOCATION
2	5 MP IR IP Mobile Dome Network Camera	On-board unit
2	Power converter (DC/DC or AC/DC)	On-board unit
1	CCTV video recorder."DS-7708NI-K4"	Martorell Enllaç station
1	Hard disk S-ATA, 4TB of capacity of DVRs	Martorell Enllaç station
1	Keyboard and mouse for the CCTV recorder	Martorell Enllaç station
1	49" LED Monitor format 16:9, speakers, VGA input, DVI, HDMI (4K)	Martorell Enllaç station
1	PC Workstation PT02: Core i7 6700 6Gen, 3,4GHz Quad	Martorell Enllaç station
1	32" LED Monitor format 16:9, speakers, BNC input, DVI, HDMI (1080p)	Martorell Enllaç station

The camera is wirelessly connected via the mmWave to a remote recorder, a workstation with a 49 "UHD LED monitor installed in Martorell. The system was specified to comply against the General Data Protection Regulation (GDPR).

GDPR is a Regulation by which the European Commission intends to strengthen and unify data protection for individuals within the European Union (EU). It also addresses the issue of distribution of personal data outside the EU.

Figure 10-6: Mobile Dome Network Camera 5MP IR.

The technical specifications of this on-board camera are the following:

Table 10-5: Technical specifications of 5MP IR camera

Camera	
Image Sensor	1/2.9″ Progressive Scan CMOS
Max. Resolution	3072 x 2048 @ 20fps
Min. Illumination	Color: 0.01 Lux @ (F1.2, AGC ON), 0.018 Lux @ (F1.6, AGC ON), 0 Lux with IR
Focal length	2.0/2.8/4/6/8 mm fixed lens
Audio / alarm	Audio and alarm (version S)
Streams	Three streams
Smart encoding	Low bit rate, low latency
WDR	120dB
IR	Range 30m, wavelength 850 nm
Compression Standard	H.265, H.265+
Video Bit Rate	32 Kbit/s to 16 Mbit/s
Smart Feature-set	4 behavior analyses and face detection
Lens	
Focal length	2.0/2.8/4/6/8 mm fixed lens
Aperture	F1.6
FOV	2.0 mm @ F1.6, horizontal FOV 119.5°, vertical FOV 69.8°, diagonal FOV 136° 2.8 mm @ F1.6, horizontal FOV 97.6°, vertical FOV 53.5°, diagonal FOV 113.6° 4 mm @ F1.6, horizontal FOV 73°, vertical FOV 40.3°, diagonal FOV 85.3° 6 mm @ F1.6, horizontal FOV 50.2°, vertical FOV 28°, diagonal FOV 57.7°

	8 mm @ F1.6, horizontal FOV 36°, vertical FOV 20°, diagonal FOV 41.6°
Lens Mount	M12
Network	
Network Storage	Micro SD/SDHC/SDXC card up to 128 GB, local storage and NAS (NFS, SMB/CIFS), ANR
Communication interface	1 RJ45 10M/100M Ethernet port
Protocols	TCP/IP, ICMP, HTTP, HTTPS, FTP, DHCP, DNS, DDNS, RTP, RTSP, RTCP, PPPoE, NTP, UPnP, SMTP, SNMP, IGMP, 802.1X, QoS, IPv6, UDP, Bonjour
API	ONVIF (PROFILE S, PROFILE G), ISAPI
Simultaneous Live View	Up to 6 channels
User/Host	Up to 32 users 3 levels: Administrator, Operator and User
Web Browser	IE8+, Chrome31.0-44, Firefox30.0-51, Safari8.0+
General	
Operating Conditions	-30ºC to 60ºC, humidity less than 95% or less (non-condensing)
Power Supply	-I, -IS: 12 VDC+/-25%, Coaxial power plug (Ø 5.5 mm) for DC input, -IM: 12 VDC+/-25%, Molex plug for DC input
Power Consumption and Current	12 VDC+/-25%, 0.5 A, max. 6W
Protection Level	IP67, IK08
Material	Metal
Dimensions	Camera: Ø 110 mm x 57.4 mm, with base: Ø 110 mm x 69.4 mm
Weight	Camera: Approx. 580g

As the lens rotates 360 degrees on the horizontal axis and from 0 to 80 degrees on the vertical, it can be mounted either on the ceiling or on the wall or surface parallel to the ground.

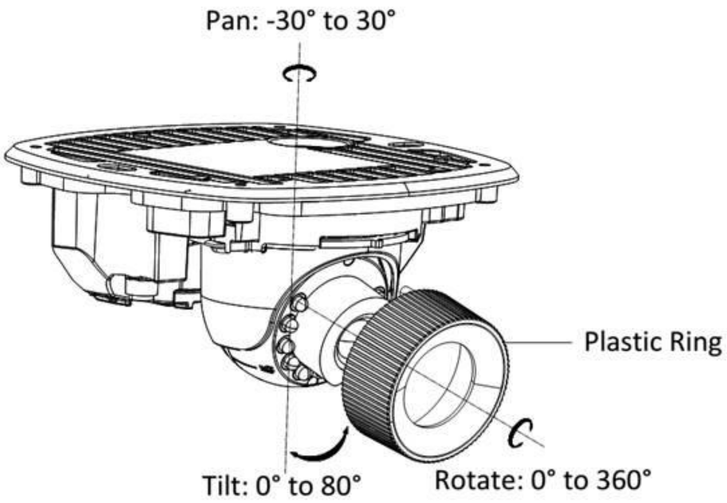


Figure 10-7: CCTV camera description.

Regarding the focal aperture will depend on the optics that it carries (varies the reference of the camera in this regard) as they can carry fixed lenses of 2, 2.8, 4, 6 and 8mm.

I detail below the opening of each optics:

- 2.0 mm @ F1.6, horizontal FOV 119.5 °, vertical FOV 69.8 °, diagonal FOV 136 °
- 2.8 mm @ F1.6, horizontal FOV 97.6 °, vertical FOV 53.5 °, diagonal FOV 113.6 °
- 4 mm @ F1.6, horizontal FOV 73 °, vertical FOV 40.3 °, diagonal FOV 85.3 °
- 6 mm @ F1.6, horizontal FOV 50.2 °, vertical FOV 28 °, diagonal FOV 57.7 °
- 8 mm @ F1.6, horizontal FOV 36 °, vertical FOV 20 °, diagonal FOV 41.6 °

In case of using the camera inside the passenger cabin, lens with large FOV would apply. In this case of track recording, lens with lower FOVs with a 2.0mm or 2.8 mm lens are appropriate.

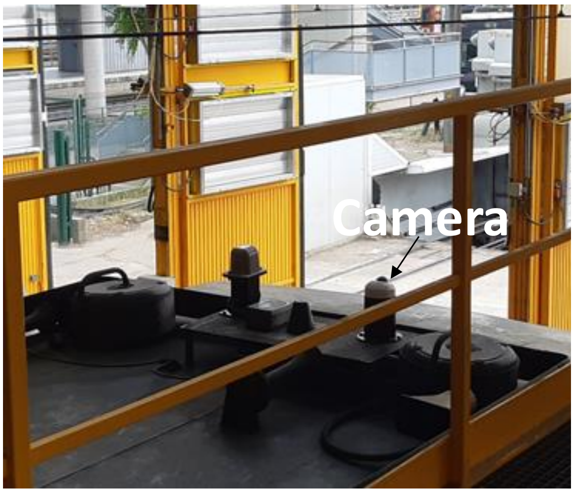


Figure 10-8: Final installation of the Camera on train roof.

Technical characteristics on-board wiring and connectors

On-board power requirements

There is 240V AC power in each of the three train cars. The equipment that is powered by 240V AC was connected directly to an AC socket, while the equipment fed in DC voltage needed an AC / DC converter.

Table 10-6 shows the maximum power supply requirements and the equipment requiring converter.

Table 10-6: Train equipment power requirements.

DEVICE		POWER SUPPLY	MAXIMUM POWER	CONVERTER
HOST PROCESOR MODULE	Front cabin	12 Vdc	50 Watts	AC/DC (240Vac / 12 Vdc)
HOST PROCESOR MODULE	Back cabin	12 Vdc	50 Watts	AC/DC (240Vac / 12 Vdc)
TCN Ethernet Switch	Front cabin	90 to 264 Vac	200 Watts	Direct 240 Vac
TCN Ethernet Switch	Intermediate cabin	90 to 264 Vac	200 Watts	Direct 240 Vac
TCN Ethernet Switch	Back cabin	90 to 264 Vac	200 Watts	Direct 240 Vac

Front Access Point	First train car	DC 48V (33.6V to 60V) PoE IEEE802.3at: -48 Vdc	17,5 Watts	AC/DC (240Vac / 48Vdc) or PoE direct
Intermediate Access Point	Intermediate train car	DC 48V (33.6V to 60V) PoE IEEE802.3at: -48 Vdc	17,5 Watts	AC/DC (240Vac / 48Vdc/) or PoE direct
Back Access Point	Back train car	DC 48V (33.6V to 60V) PoE IEEE802.3at: -48 Vdc	17,5 Watts	AC/DC (240Vac / 48Vdc) or PoE direct
Camera	Front train car	12 VDC +/-25%, 0.5A	6 Watts	AC/DC (240Vac / 12 Vcc)
Camera	Back train car	12 VDC +/-25%, 0.5A	6 Watts	AC/DC (240Vac / 12 Vcc)
TAN FlowBlazes	Front train car	12 VDC	25 Watts	AC/DC (240Vac / 12 Vdc)
		TOTAL:	789 Watts	

The following conclusions can be drawn from above table:

1) The maximum total consumption of on-board equipment is 764 Watts, distributed among the three train cars.
2) There are two devices that are powered by DC 12 Volts: The Host Processor Unit and the onboard cameras
3) The Wi-Fi Access Points have two power alternatives: either through a DC / DC converter, or through an Ethernet PoE port of the Switch or through a POE converter.
4) The Ethernet Switch TCN can be fed directly to 240 Vac.

Electric cabling

The proposed electric cable used by any equipment installed on the train was “FLAMEX 20 EN 50306-3 3x1.50 MM –S” with Nexans reference “2PH191”. The color of the sheath is black.

Strictly halogen free, these types of wire combine the advantages of small size, lightweight, high chemical resistance, high mechanical properties. They are recommended for installation in railway vehicles.

This cable complies with the following standards:

- International: EN 45545-2 (HL3); EN 50264-1; EN 50305; EN 50306
- National: NF C 32-070 / C1; NF C 32-070 / C2

The bending radius are the following (in accordance with “NF F 61-010” standard:

Dynamic use: 10 x outer diameter

Static use: 5 x outer diameter

A 125 ° C conductor temperature is allowed for a 20000 hours cumulative working time.

Table 10-7: Electric cable characteristics

Construction characteristics	
Halogen free	EN 50267-2-2
Dimensional characteristics	
Conductor cross-section	1.5 mm²
Conductor diameter	1.7 mm
Maximum outer diameter	6.4 mm
Approximate weight	75 kg/km
Number of cores	3

Electrical characteristics	
Max. DC resistance of the conductor at 20°C	13.7 Ohm/km
Usage characteristics	
Chemical resistance	Good
Fire retardant	EN 50266-2-4; EN 50266-2-5; EN 50305.9.1.2
Smoke density	EN/IEC 61034-2 & NFF 16101 & EN 45545-2
Operating temperature, range	-40. 90 °C
Electromagnetic interference resistance	Yes

TCN 10G fibre ring

For the on-board 10G support Single-Mode fibre was proposed.

The technical characteristics of the fibre optic cable are the following:

- GI-fibre 9/125 µm Single-Model
- Number of fibres: 4
- Meets railway standards EN-45545-2
- 4 x LC/PC fibre connectors to implement the fibre optic ring between switches.
- Complies with fire propagation regulations IEC 60332-1-2, IEC 60332-3-25 and UL1666.

Figure 10-9 represents a fibre optic breakout cable. A cable "break out" is a protection element to avoid large bends in fibre optic cables when the protection of the outer cable coatings is not available.

The breakout was designed to protect the fibres of the outer cables that come with 250 µm coating, this protection was used in our installation for the interconnection of the optical fibres between train cars.

The fibre goes directly from the connector on one end to the connector on the other end without intermediate fusions. As you can see in the next figure the cable is distributed in three sections (L2 + L1 + L3). The central section has a length L1 and allows us to channel the cable inside the train. The final sections (L2 and L3) allow the assembly of the fibre connectors to the connector. These lengths were defined by the manufacturer of the cables after a site survey carried out in the train unit.

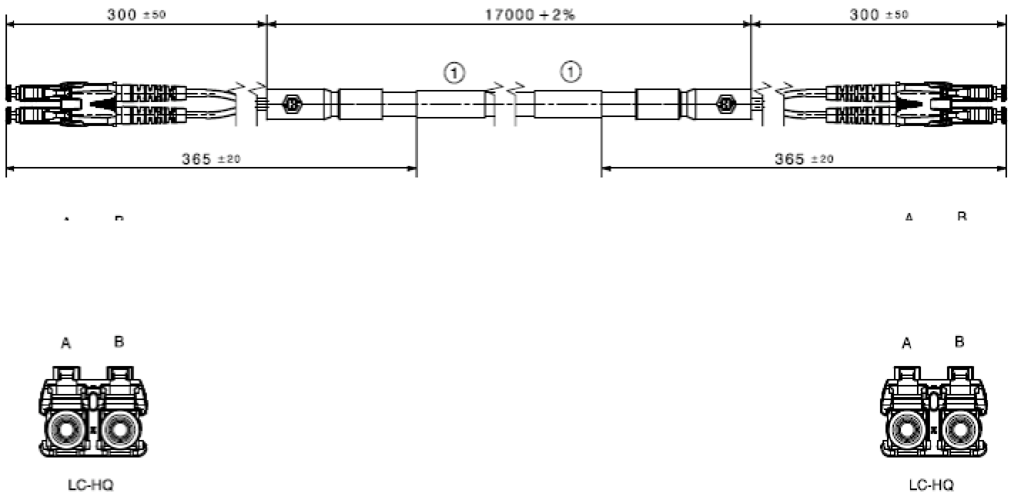


Figure 10-9: Diagram with the sections of the fibres that forms the 10G ring

There was also a shorter length of fibre cable between train vehicles. Therefore, to make the connection from cabin to three breakouts were required, one for each train car, and two pigtails to make the connections between vehicles.

At the intersection of each car it was necessary to have a free position for a module "Han LC module" of six LC connectors. Four of the six positions were used, two of them (Tx and Rx) to interconnect the switches between vehicles (front switch to intermediate switch, intermediate switch to back switch) and two additional (Tx and Rx) to implement ring redundancy (front switch to back switch).

Therefore, it was necessary to select a fibre optics cable with capacity for four single-mode optical fibres.

Data Sheet

FIBER OPTIC CABLE
Riser Cable

HUBER+SUHNER
Excellence in Connectivity Solutions

Description

02-../F(ZNG)H-...70

- Metal free indoor and outdoor cable
- Rodent-protected, glass-armoured
- Low smoke, halogen free and self-extinguishing

Available Types

Fiber count: 2 up to 2 Fibers

Type of Fiber

E9/125	according to IEC 60793-2-50 Typ B1.3 + ITU G.652.D
E9/125A1	according to IEC 60793-2-50 Typ B6_a1 + ITU G.657.A1
G50/125-OM2	according to IEC 60793-2-10 Typ A1a + ITU G.651
G62.5/125-OM1	according to IEC 60793-2-10 A1b

Standard Colours

Fiber:	E9, G50 and G62: transparent
Tube:	According to colour code
Jacket (outer):	Black

Technical Data

Construction

Description / Material	Size	Options / Notice
2 Optical fiber	245 / 400 µm	Fiber type, buffered
2 Tight tube	0.9 mm	Colour
Reinforcement / glass-roving		Swellable
Outer jacket	7 mm	Colour, inscription

Mechanical Data

Characteristics	Conditions	Tested acc. to	Values
Weight			55 kg/km
Tensile strength	During installation In service	IEC 60794-1-2 E1	1000 N 500 N
Minimal bending radius	During installation In service	IEC 60794-1-2 E11	105 mm 40 mm
Crush resistance	During installation In service	IEC 60794-1-2 E3	20000 N/dm 6000 N/dm
Impact resistance	Wp = 2.21 J	IEC 60794-1-2 E4	50 impacts

Environmental Data

Characteristics	Conditions	Tested acc. to	Values
Temperature range	During installation In service In storage	IEC 60794-1-2 F1	-25 °C up to +75°C -40 °C up to +75°C -40 °C up to +75°C
Fire load			1.2 MJ/m
Fire propagation	On a vertical single cable On a vertical cable bundle On a vertical cable bundle	IEC 60332-1-2 IEC 60332-3-25 UL1666	passed passed passed
2011/65/EU (RoHS)			compliant

Specification for singlemode at 1550nm, for multimode at 1300nm

Comment

Compliant to EN 45545 / hazard level 3
Optional:
OFNR UL listed - ordering code: 02-.../F(ZNG)H-...70-UR

Figure 10-10: On-board 10G ring fibre's datasheet

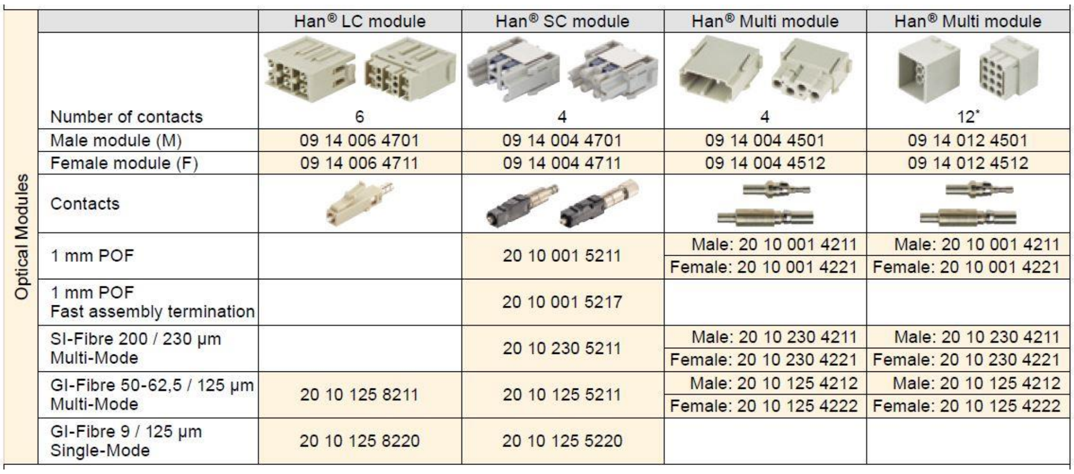
In **Figure 10-11** the connector "Han Modular" from the manufacturer Harting is depicted. It is commonly used by ALSTOM to mount in inter-vehicle for dynamic and outdoor environments.

This multi-connector is composed of different modules that are particularized according to the type of magnitude transmitted: power, signalling, data transmission, fibre optics, etc.

Figure 10-11: Intervehicle fibre connector

Harting has a set of connectors for different types of fibre optics used: Plastic fibre, HCS fibre, Multi-Mode and Single-Mode fibre glass. This project will use Single-Mode optical fibre to connect the switches through SFP+ optic transceivers with two LC connectors (confirmed by ADVA 07/03/2019).

In the following table we have all the options of fibre optic connectors available from the manufacturer Harting. The best alternative for making 10G Ethernet connections between switches is through single mode fibre with LC connectors.



Optical Modules	Han® LC module	Han® SC module	Han® Multi module	Han® Multi module
Number of contacts	6	4	4	12*
Male module (M)	09 14 006 4701	09 14 004 4701	09 14 004 4501	09 14 012 4501
Female module (F)	09 14 006 4711	09 14 004 4711	09 14 004 4512	09 14 012 4512
Contacts				
1 mm POF		20 10 001 5211	Male: 20 10 001 4211 Female: 20 10 001 4221	Male: 20 10 001 4211 Female: 20 10 001 4221
1 mm POF Fast assembly termination		20 10 001 5217		
SI-Fibre 200 / 230 µm Multi-Mode		20 10 230 5211	Male: 20 10 230 4211 Female: 20 10 230 4221	Male: 20 10 230 4211 Female: 20 10 230 4221
GI-Fibre 50-62,5 / 125 µm Multi-Mode	20 10 125 8211	20 10 125 5211	Male: 20 10 125 4212 Female: 20 10 125 4222	Male: 20 10 125 4212 Female: 20 10 125 4222
GI-Fibre 9 / 125 µm Single-Mode	20 10 125 8220	20 10 125 5220		

Figure 10-12: Options of fibre connectors

The reference for the single mode FO solution are included in ***Table 10-8***:

Table 10-8: FO Harting references

Description	HARTING Reference
GI-Fiber 9 / 125 µm Single-Mode	20 10 125 8220
Han LC modules: Male module (M)	09 14 006 4701
Han LC modules: Female module (F)	09 14 006 4711

The connectors have a capacity for six LC fibre optic connectors (contacts).

TCN Service Equipment Ethernet connections

Connections between the switches of both cabins were based on fibre optic cable to support 10 Gigabit.

Connections between a switch and a camera or Wi-Fi Access Point can be 1 Gigabit. These rates can be supported by copper cabling. The following figures provide the technical characteristics of the copper cable considered.

HARTING Ethernet cabling – cables and connectors, 8 wire

M12 system cable,
8-wire

Features

• Sheath material	Elastomer, electron beam cross-linked
• Category	7
• Number of wires	8
• Wire design	AWG 24/7
• Wire diameter	(8.1 ± 0.2) mm

Application

- For installation within and outside rail vehicles and buses

Benefits

- Transmission of Gigabit and 10 Gigabit Ethernet acc. IEEE 802.3 and multimedia services
- For installation within and outside rail vehicles and buses
- Fire protection acc. EN 45545-1, -2 and -5, flame retardant and heat resistant acc. DIN 5510 (1-4) and EN 50264-1
- UV resistant, RoHS conform, halogen free LSZH
- Designed to be compatible with products from HARTING like har-speed M12 Crimp and Han® GigaBit module.

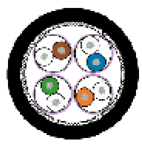
Technical characteristics

Cable structure	4 x 2, Twisted Pair, shielded, PIMF
Core structure	4 x 2 x AWG 24/7, tinned copper wire
Wire insulation	PE, Ø 1.55 mm
Sheath material	Elastomer, electron beam, cross-linked
Cable sheath diameter	(8.8 ± 0.2) mm
Transmission performance	Category 7 / Class D, E, E_A, F up to 600 MHz acc. to ISO/IEC 11801 and EN 50173-1
Transmission rate	1/10 Gbit/s
Shielding	Paired shielded with additional cable shield
Operating temperature range	-40 °C ... +85 °C
Supply lengths	100 m / 500 m / 1000 m
Colour	Black

Railway cords

Identification		Part number
Ha-VIS EtherRail® flexible data cable, PIMF 4x2xAWG 24/7, Cat. 7		
	10 m ring	09 45 600 0694
	50 m ring	09 45 600 0693
	100 m ring	09 45 600 0692
	500 m reel	09 45 600 0691
	1000 m reel	09 45 600 0690

Drawing — Dimensions in mm



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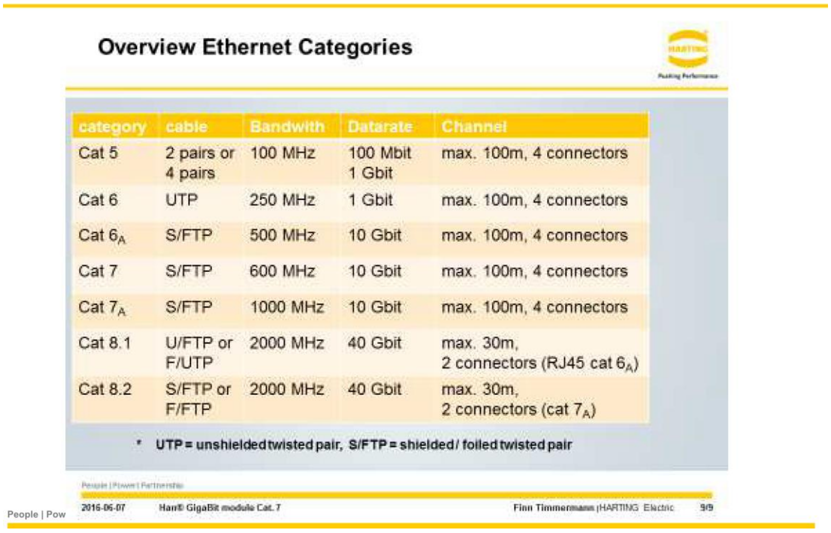
17

Figure 10-13: HARTING Ethernet cabling.

For connections at 1 Gigabit, specifically 10G, HARTING advises using the 8-pole “Ether Rail 4x2xAWG 24/7 Cat. 7” for Ethernet communication up to class 7 (600 MHz). On the next page we have the datasheet of this Ethernet cable.

In ***Figure 10-14*** we have identified the characteristics of the different cable categories:



Overview Ethernet Categories

category	cable	Bandwith	Datarate	Channel
Cat 5	2 pairs or 4 pairs	100 MHz	100 Mbit 1 Gbit	max. 100m, 4 connectors
Cat 6	UTP	250 MHz	1 Gbit	max. 100m, 4 connectors
Cat 6_A	S/FTP	500 MHz	10 Gbit	max. 100m, 4 connectors
Cat 7	S/FTP	600 MHz	10 Gbit	max. 100m, 4 connectors
Cat 7_A	S/FTP	1000 MHz	10 Gbit	max. 100m, 4 connectors
Cat 8.1	U/FTP or F/UTP	2000 MHz	40 Gbit	max. 30m, 2 connectors (RJ45 cat 6_A)
Cat 8.2	S/FTP or F/FTP	2000 MHz	40 Gbit	max. 30m, 2 connectors (cat 7_A)

* UTP = unshielded twisted pair, S/FTP = shielded / foiled twisted pair

2016-06-07 Han® GigaBit module Cat. 7 Finn Timmermann |HARTING Electric 9/9

Figure 10-14: Ethernet cable categories

The length of the Cat. 7A Ethernet copper cable can't exceed 100m. In case of not installing the central vehicle switch, as in the demo, it must not be exceeded the maximum length allowed by the copper Ethernet cable.

For a good operation at frequencies above 500 MHz, it was a must to ensure the connection of the screen of each pair and a good connection of the general cable screen. The connectors used allowed these screen connections.

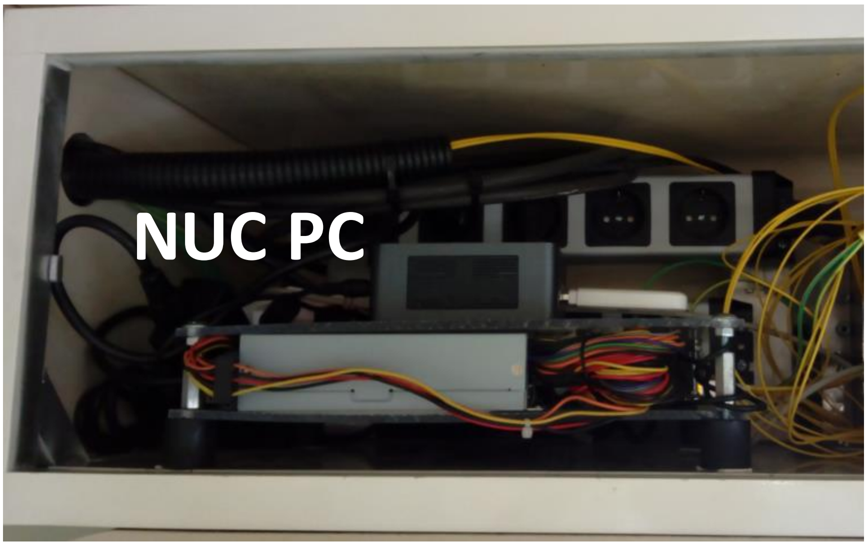


Figure 10-15: Final Installation NUC PC.

Annex B: Additional Track equipment components' description

Catenary pole bracket fixing

Figure 10-16 shows the special bracket for fixing the DN101LC AP to a circular lamppost. This support allows a fine adjustment of the orientation of the integrated antenna lobe.

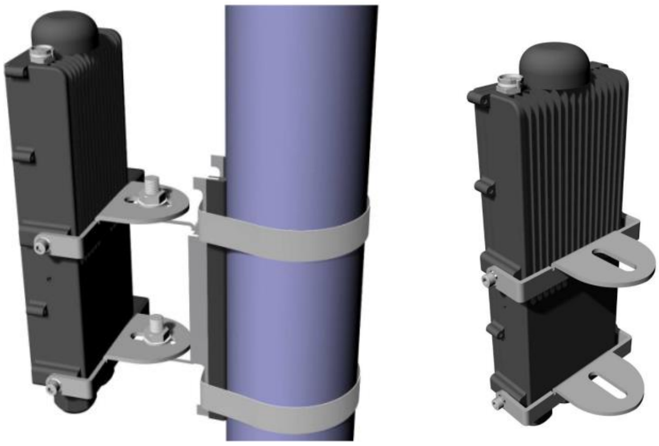


Figure 10-16. DN-101LC Lamppost bracket fixing.

The particularities of the installation of the two APs on the track section are the following:

1. Two DN101LC APs must be installed, one in each direction of the track. The radio beams must point parallel to the tracks in each direction of circulation.

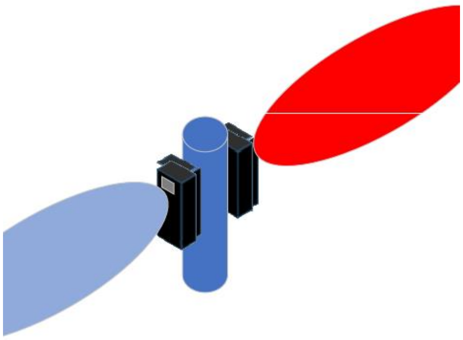


Figure 10-17: DN101LC APs radio beams.

2. Design of a new support for catenary pole composed of two metal plates joined by four studs. In each of the metal plates the special is fixed through two M8 screws, where the two vertical screws of M12 are welded to which it is fixed with the two special supports of the Access Point. In ***Figure 10-18*** illustrated the solution.

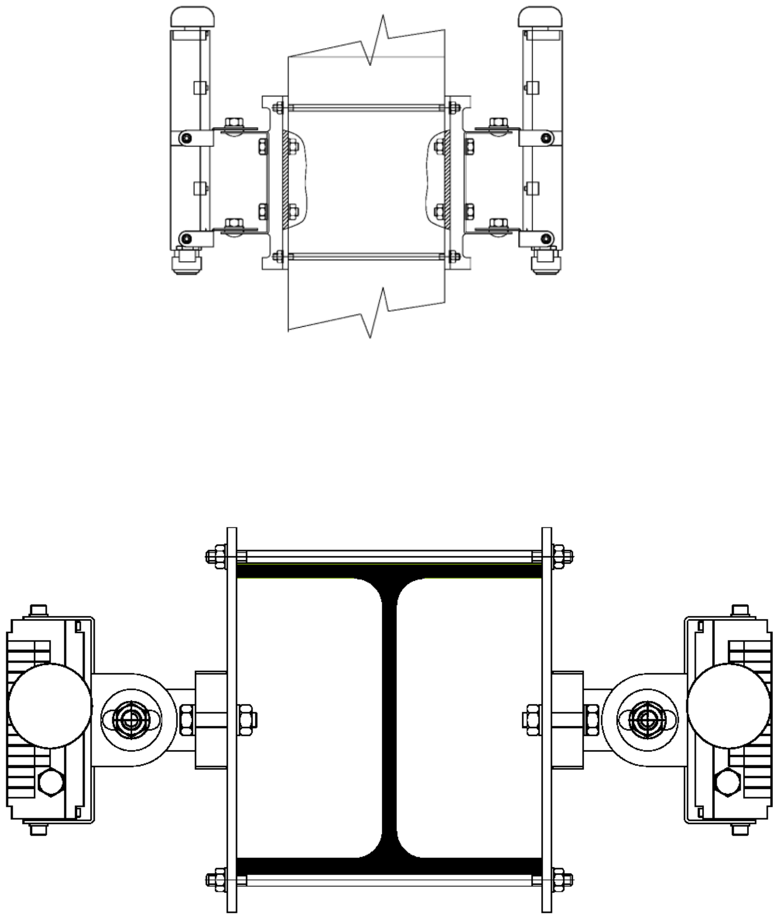


Figure 10-18. Catenary pole bracket fixing.

Stanchion Cabinet

The devices that make up the Stanchion Cabinet are integrated in a cabinet of measures 800 mm x 600 mm x 400 mm (Height x Width x Depth) reference "NSYCRNG86400" of the manufacturer Schneider. Compliance with a degree of protection IP66 and IK10 conforming to IEC 60529 and 62262.

A mounting plate has been designed to mount the various electrical components, designed with some additional requirements:

- It has free space to introduce elements to provide redundancy in power feed.
- It contains additional fibre length (to provide future operation over the fibres).
- All the components needed to provide fibre redundancy to the Passive WDM are contained in the ADVA Filter (Remote Node).
- The stanchion cabinet is water and dust proof.

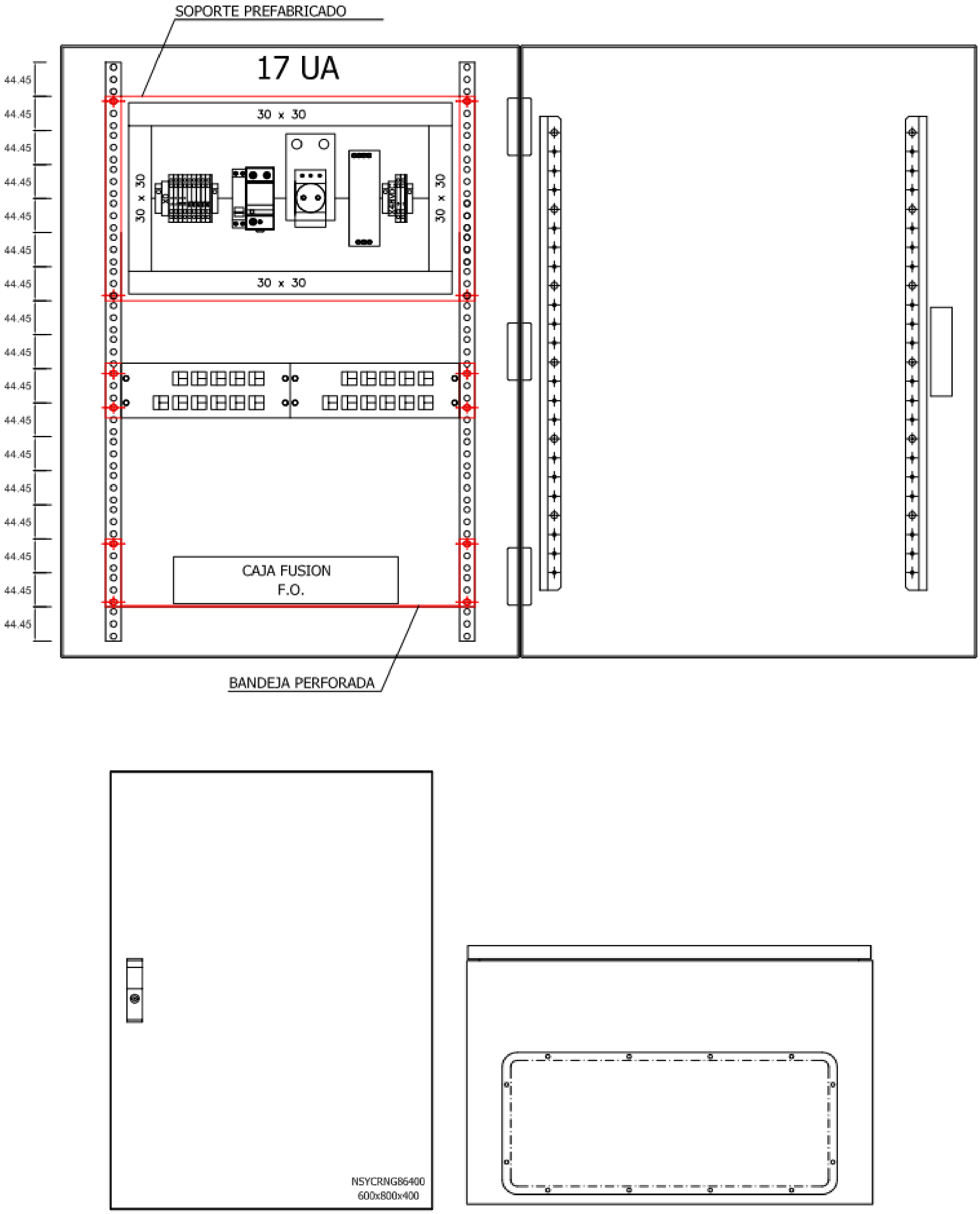


Figure 10-19: Stanchion Power Cabinet pre-design

Table 10-9: Stanchion cabinet components

Reference	Description	Manufacturer	Units
NSYCRNG86400	Spatial CRNG plain door w/o mount plate. H800xW600xD400 IP66 IK10 RAL7035	Schneider	1
A9A15310	DIN socket iPC – 2P+E – 16A – 250VAC – KEMA VDE 0620 – German std	Schneider	1

A9L16632	iPRF1 12.5r modular surge arrester - 1P + N - 350V - with remote transfer	Schneider	1
A9S60220	Switch Acti9 iSW - 2 poles - 20 A - 415V	Schneider	1
SC1-GSMV	GSM Power Switch Relay	KONLEN	1
NDR-120-48	120W Single Output Industrial DIN RAIL	MEAN WELL	1
	Prefabricated metal sheet 266.7 x 446 x 150 mm	COMSA	1

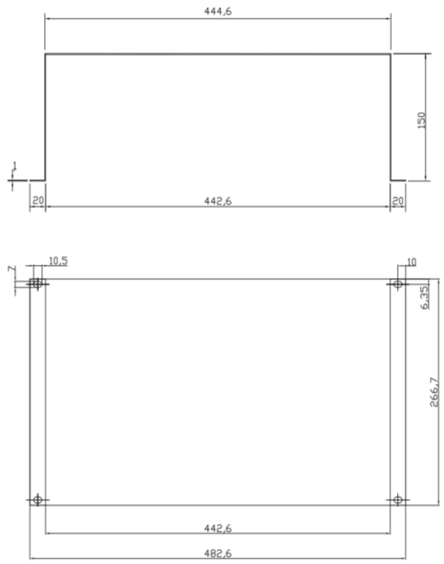


Figure 10-20: Prefabricated metal sheet 266.7 x 446 x 150 mm

AC/DC Single output power supply DIN RAIL

This is the AC/DC power converter contained in the Stanchion Cabinet:

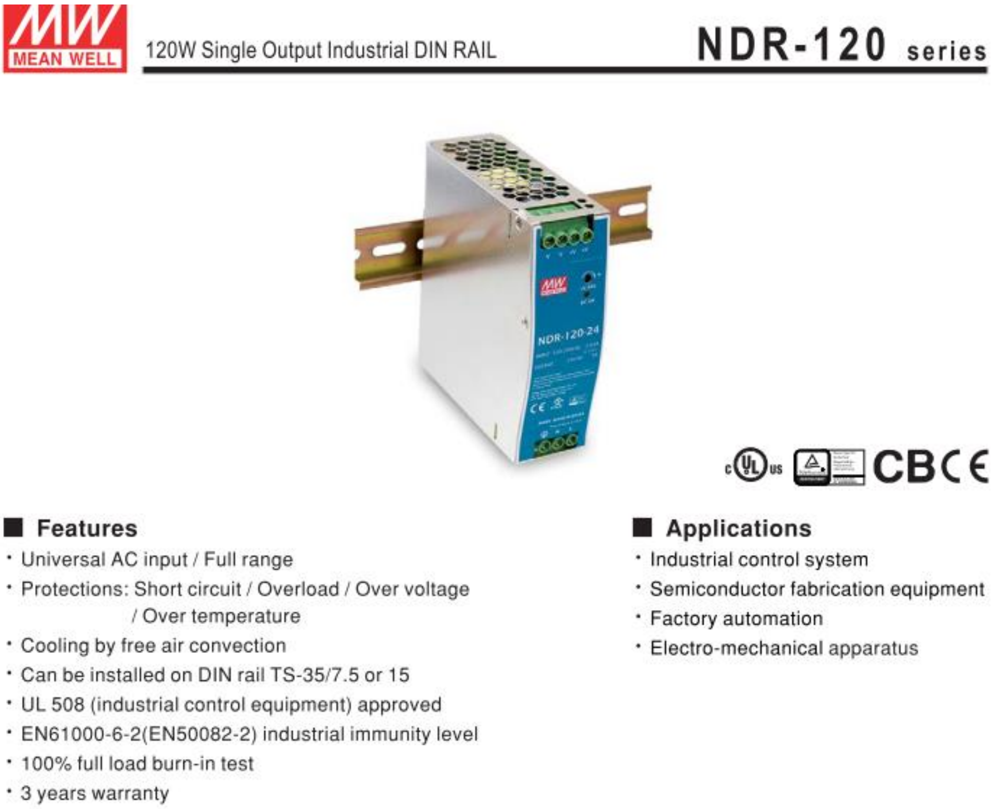


Figure 10-21: AC/DC Power Converter in the Bottom Cabinet

GSM Power Switch Relay

This component allows to reset the power corresponding to a couple of mmWave APS if necessary

Figure 10-22: Power Switch Relay (via SMS)

Specification:

- Communication: based on the GSM network
- GSM frequency: GSM850 / 900/1800/1900 MHz
- Nominal current: 16 A max. Nominal current: 16 A max.
- Rated power 3000 W Nominal power 3000 W
- Nominal voltage: 250 V to 110 V AC
- Dimensions: 113mm x 65mm x 77mm (4.44 inches x 2.55 inches x 3.03 inches)
- Operating humidity: less than 65%

- Working temperature: -10 to + 55 degrees Centi
- Socket and plug: European German standard
- 16A Max, compatible with the control of high-power appliances (light, air conditioning, heater, TV, stereos, etc.), and automatic door openers, AC motor, remote base station, PBX, TV pump, stereos, etc.), and automatic door openers, AC motor, remote base station, PBX, pump of water, server, etc. of water, server, etc.

Modular surge arrester

Space has been reserved inside the cabinet for the case of introducing redundancy in power feed. This functionality can be implemented introducing additional elements like the one shown in ***Figure 10-23***.

Product data sheet
Characteristics

A9L16632
iPRF1 12.5r modular surge arrester - 1P + N - 350V - with remote transfert

Main

Range of product	Acti 9
Product name	Acti 9 iPRF1
Product or component type	Surge arrester
Device short name	IPRF1 12.5r
Device application	Distribution
Poles description	1P + N
Remote signalling	With
Signal contacts composition	1 SD (1 C/O)
Surge arrester type	Electrical distribution network
Earthing system	TN-S TT

Figure 10-23: Module Surge Arrester

Cabinet support

In ***Figure 10-24*** the cabinet design at the stanchion is shown. It has been designed so that the cabinet does not invade the railway gauge of the train. The support materials would be made of hot galvanized steel.

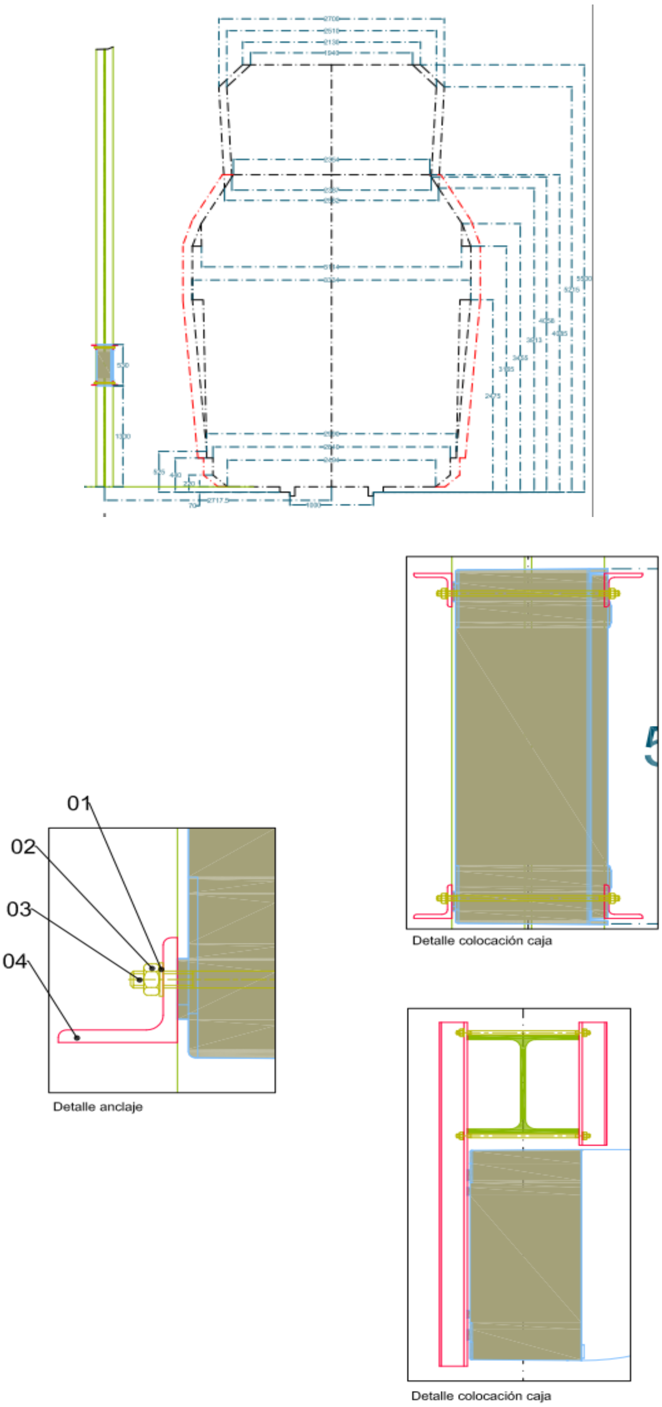


Figure 10-24: Cabinet support and railway gauge

Annex C: Additional components part of the stations

Martorell - CCTV video recorder

The basic elements of the CCTV system to install in Martorell station indicated in ***Table 10-10***:

Table 10-10: Martorell CCTV elements

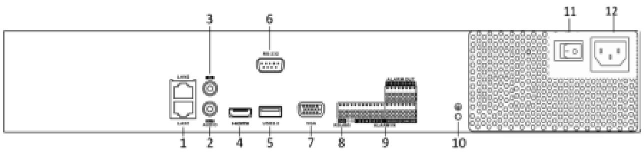
CCTV video recorder
49" LED Monitor format 16:9, speakers, VGA input, DVI, HDMI (4K)
32" LED Monitor format 16:9, speakers, BNC input, DVI, HDMI (1080p) as alternative
Keyboard and mouse for the CCTV recorder
PoE Injectors

Hikvision "DS-7708NI-K4" is a professional NVR with 8MP resolution recording. Capability, with 8x PoE ports making installation of IP cameras. 4K HDMI output enables connection to 4K HDMI output enables connection to 4K TV/Monitors. The technical specifications of the proposed CCTV recorder are:

Table 10-11: Technical specifications of the proposed CCTV recorder

Features & Functions	Descriptions
Professional and Reliable	Dual-OS design to ensure high reliability of system running ANR technology to enhance the storage reliability when the network is disconnected
HD Input	H.265/ H.264+/H.264/MPEG4 video formats Up to 32 IP cameras can be connected Recording at up to 8 MP resolution Supports live view, storage, and playback of the connected camera at up to 8 MP resolution
HD Video Output	HDMI and VGA independent outputs. HDMI Video output at up to 4K (3840 x 2160) resolution.
Decoding	Format H.265/ H.264+/H.264/MPEG4 Resolution: 8MP/6MP/5MP/4MP/3MP/1080p/UXGA/720p/VGA/4CIF/DCIF/ 2CIF/CIF/QCIF Capability: 2-ch @ 4K, or 8-ch @ 1080p
Storage and Playback	4 SATA interfaces for 4HDDs. A 4TB capacity HDD has been selected in this system.
Network protocols	Network protocols TCP/IP, DHCP, HIK Cloud P2P, DNS, DDNS, NTP, SADP, SMTP, NFS, iSCSI, UPnP™, HTTPS
Network interface	2 RJ-45 10/100/1000 Mbit/s self-adaptive Ethernet interfaces
Power supply	100 to 240 VAC
Power	<= 300 W max
POE Interface	IEEE 802.3 af/at
Working temperature	-10 to +55ºC
Working humidity	10 to 90%
Dimensions	19-inch rack, 1.5 chassis, 445 x 400 x 71 mm
Weight	<= 5 Kg

Physical Interfaces



Index	Description	Index	Description
1	LAN1 and LAN2 Network Interfaces	7	VGA Interface
2	AUDIO OUT	8	RS-485 Serial Interface
3	AUDIO IN	9	ALARM IN and ALARM OUT
4	HDMI Interface	10	GND
5	USB 3.0 Interface	11	100 to 240 VAC Power Input
6	RS-232 Serial Interface	12	Power Switch

Figure 10-25. CCTV recorder.

GDPR, a Regulation by which the European Commission intends to strengthen and unify data protection for individuals within the European Union (EU) is met by the installed CCTV system since the NVR integrates pixeling of faces.

Monitor 49” UHD LED

The main features of the monitor are the following:

- Type LED, screen Size 49”. Aspect Ratio 16:9
- Support up to 3,840 x 2,160 resolution
- Brightness 500cd/m
- High contrast ratio 4,700: 1
- Display Colour: 16.7 million
- Response time: 8ms
- Fast response time 8msAngle (H/V): 178” /178”
- Temperature sensor, 24/7 (50,000 hour), FHD 4 picture by picture support.

Table 10-12: Technical specifications of the proposed Monitor

GENERAL CHARACTERISTICS

ELECTRICAL	Input Voltage	100 ~ 240V AC (±10%) (50/60Hz)
	Power Consumption	100 (Typical), 140 (Rating), 154 (Max)
ENVIRONMENTAL	Operating Temperature	0 ~ +40°C
	Operating Humidity	10% ~ 80% (Non-condensing)
MECHANICAL	Dimensions with stand (WxHxD)	1195.0 x 721.0 x 177.0mm (47.05" x 28.39" x 6.97")
	Dimensions without stand (W x H x D)	1099.4 x 634.0 x 36.8mm (43.28" x 24.96" x 1.45")
	Bezel size	Top 11.0mm (0.43") / Side 11.0mm (0.43") / Bottom 12.0mm (0.47")
	Weight	13.4 Kg
	VESA Mounts interface	400 x 400mm. Rack mounts optional
DISPLAY	Dynamic C/R	Mega
	H-Scanning Frequency	30 ~ 81KHz
	V-scanning Frequency	48 ~ 75Hz
	Maximum pixel Frequency	148.5MHz
SOUND	Speaker Type	Built-in speaker (10W + 10W)
CONNECTIVITY	RGB input	DVI-I (D-Sub common), Display port 1.2 (2)
	Video input	HDMI (4)
	Audio input	Stereo mini jack
	USB input	USB (S/W update only)
	Audio Output	Stereo mini jack
	External Control	RS-232C (in / out), RJ-45
	External Sensor	IR

In ***Figure 10-26*** we indicated the physical measurements of the 49 "monitor as well as the measurements of the standard VESA mounting interface.

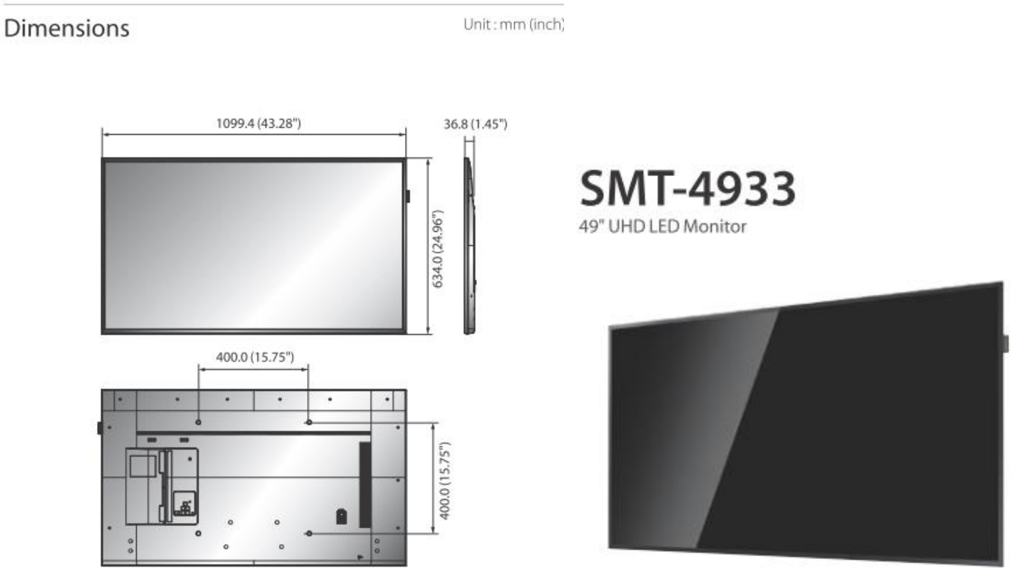


Figure 10-26. Monitor 49" UHD LED.

Annex D: Additional Components and frequency license

Micro Rain Radar (near track section in Olesa Station)

Two options were considered for the study of atmospheric impact.

MRR Option

One Micro Rain Radar (MRR) was planned to be installed close to the Olesa station. The MRR would have measured the vertical profile of rain rate, liquid content and drop size distribution. With the MRR we could have correlated weather conditions and performance tests results to check the behaviour of the mmWave links under adverse weather conditions. It was finally decided not to include the Micro Rain Radar since it was not possible to guarantee the system operative enough time to compare results across different atmospheric conditions.

Figure 10-27: Micro Rain Radar

Visibility measurement and Present Weather Identification

The sensor shown in ***Figure 10-28*** allows conditions and visibility to be monitored with great precision and reliability in a range of up to 75 km thanks to its modulated infrared light technology and digital filtering and averaging of the measurements. Current weather conditions are reported using the codes of the World Meteorological Organization (WMO).

To determine visibility, the sensor emits modulated infrared light from the transmitter and measures what percentage of it reaches the receiver according to the principle of forward scattering of light due to particles suspended in the air.

It can be connected to any conventional datalogger to carry out the storage of the data and its subsequent download and display on a computer. It has RS-232, RS-422 and RS-485 serial ports, an analogue output and 3 alarm outputs to relay.

Figure 10-28: Weather sensor

This solution includes a real-time data management module that allows remote access to them. This access is made through an integrated web server that can be accessed through the local network or the Internet if an external port is enabled in the network and the IP address of the module is NAT. The module also stores the data in an internal database and allows its export in CSV format (day to day or full month) to perform a treatment or subsequent analysis of them.

This solution includes the 220 VAC power system and an Ethernet output to connect to the ADVA switch

The range of the visibility sensor indicates between which values the level of visibility is determined. That is, the sensor determines the maximum distance at which an object could be sighted from the point where it is installed. For applications on roads or railway sections, the range is usually limited because there are no straight-line sections with such a long length. However, in aviation, the maximum sensor range is used.

The sensor can discriminate the states related in ***Table 10-13***. I does not only determines the type of precipitation but the intensity, suspended particles, etc.

Table 10-13: Precipitation codes

00 No significant weather observed
04 Haze or Smoke or Dust
11 Diamond Dust
20 Fog in last hour but not at time of observation
21 Precipitation in last hour but not at time of observation
22 Drizzle in last hour but not at time of observation

23 Rain in last hour but not at time of observation
24 Snow in last hour but not at time of observation
28 Blowing or drifting snow, visibility ≥ 1km
29 Blowing or drifting snow, visibility <1km
30 Fog
31 Fog in patches
32 Fog becoming thinner in last hour
33 Fog no appreciable change in last hour
34 Fog running or becoming thicker in last hour
35 Freezing Fog
40 Indeterminate Precipitation Type
51 Slight Drizzle
52 Moderate Drizzle
53 Heavy Drizzle
57 Slight Drizzle and Rain
58 Moderate or Heavy Drizzle and Rain
61 Slight Rain
62 Moderate Rain
63 Heavy Rain
67 Slight Rain and Snow
68 Moderate or Heavy Rain and Snow
71 Slight Snow
72 Moderate Snow
73 Heavy Snow
74 Slight Ice Pellets
75 Moderate Ice Pellets
76 Heavy Ice Pellets
77 Snow Grains
78 Ice Crystals
81 Slight Rain Showers
82 Moderate Rain Showers
83 Heavy Rain Showers
85 Slight Snow Showers
86 Moderate Snow Showers
87 Heavy Snow Showers
89 Hail or Small Hail (Graupel)

It was finally decided not to include the visibility measurements since it was not possible to guarantee the system operative enough time to compare results across different atmospheric conditions.

Process for obtaining the mmWave demo license

Legal and Regulatory Framework

The Spanish legal and regulatory framework in which a license has been obtained for the concept of experimental testing with 5G technologies is as follows:

- Law 9/2014, of May 9, General Telecommunications, which lays down the principles applicable to the administration of the spectrum whose ownership and administration correspond to the state.
- Royal Decree 123/2017 of 24 February approving the Regulation on the use of the radio public domain. The regulation concerns the development of Law 9/2014 of 9 May, General telecommunications (General Telecommunications Law), concerning the use of the public radio domain.

Royal Decree 123/2017

Royal Decree 123/2017 of 24 February provides in Articles 5 and 6:

- The use of the radio public domain shall be carried out in accordance with prior planning, delimiting, where appropriate, the bands and channels attributed to each of the services. This pre-planning is included in the National Frequency Attribution Table (CNAF)
- In order to achieve the coordinated and effective use of the radio public domain, the Ministry of Energy, Tourism and Digital Agenda shall adopt the National Frequency Allocation Table for the

different types of radiocommunication services, in accordance with the provisions of the European Union, the European Conference of Postal and Telecommunications Administrations (CEPT), and the Radio Regulations of the International Telecommunication Union (ITU). Among others, CNAF may establish bands,sub-bandsor frequencies that are considered to be commonly used in the radio public domain.

Royal Decree 123/2017 of 24 February provides in Article 10:

- The common use of the radio public domain shall not require any enabling title for the use of that domain, and shall be carried out in the frequency bands and with the technical characteristics established in the National Frequency Attribution Table.
- The special use of the radio public domain is that of the frequency bands enabled for operation in a shared manner, without limiting the number of operators or users, and under the technical conditions and for the services that are establish in each case.
- The private use of the radio public domain is that which is carried out through the exploitation, exclusively or by a limited number of users, of certain frequencies in the same physical scope.

Royal Decree 123/2017 of 24 February provides in Article 11:

- The use of the public radio domain will require the prior obtaining of an enabling title, except in cases of common use.
- Paragraph 3 of Annex I to May 9/2014, General Telecommunications, states:
- The reservation for private use or special use by operators of any frequency in the public radio domain in favour of one or more persons or entities shall be taxed at an annual fee.
- Article 87. Fee per reservation of the public domain radio of the BOE July 4, 2018, establishes the formula, coefficients and conditions for the calculation of the fee for obtaining licenses.

License spectrum grant process

Once the regulatory framework was understood. FGC proceeded with the obtaining of a spectrum license granted exceptionally under the special testing regime in the context of the 5G-PICTURE research project. This was agreed as the system installed for FGC/5G-PICTURE constitutes a private use of the public radio domain as it does not meet the technical characteristics set out in the National Frequency Attribution Table for common use.

Once the relevant applications had been processed by FGC with the Ministry of Economic Affairs and Digital Transformation, an enabling license for the private use of the radio public domain was obtained.

Annex E: TCN Detailed Scheme

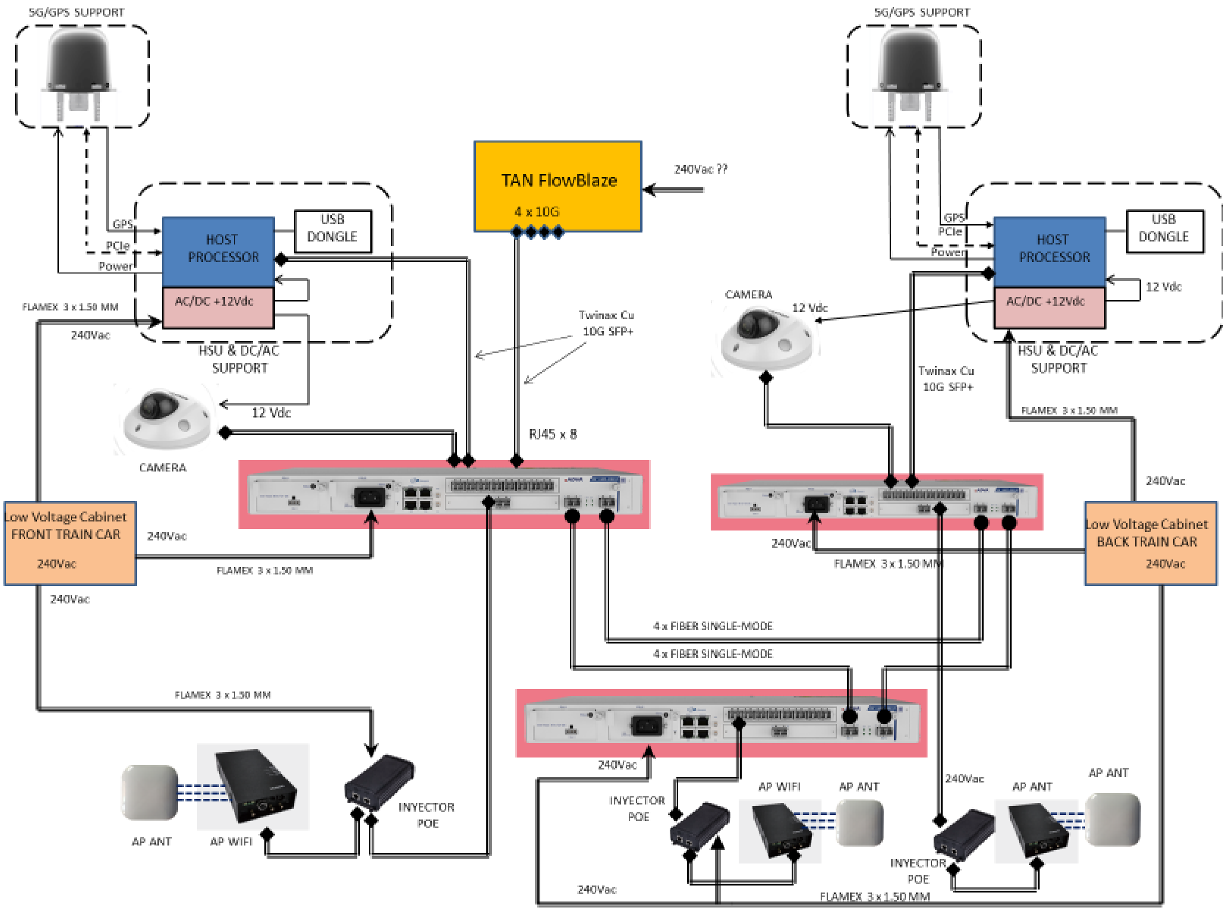
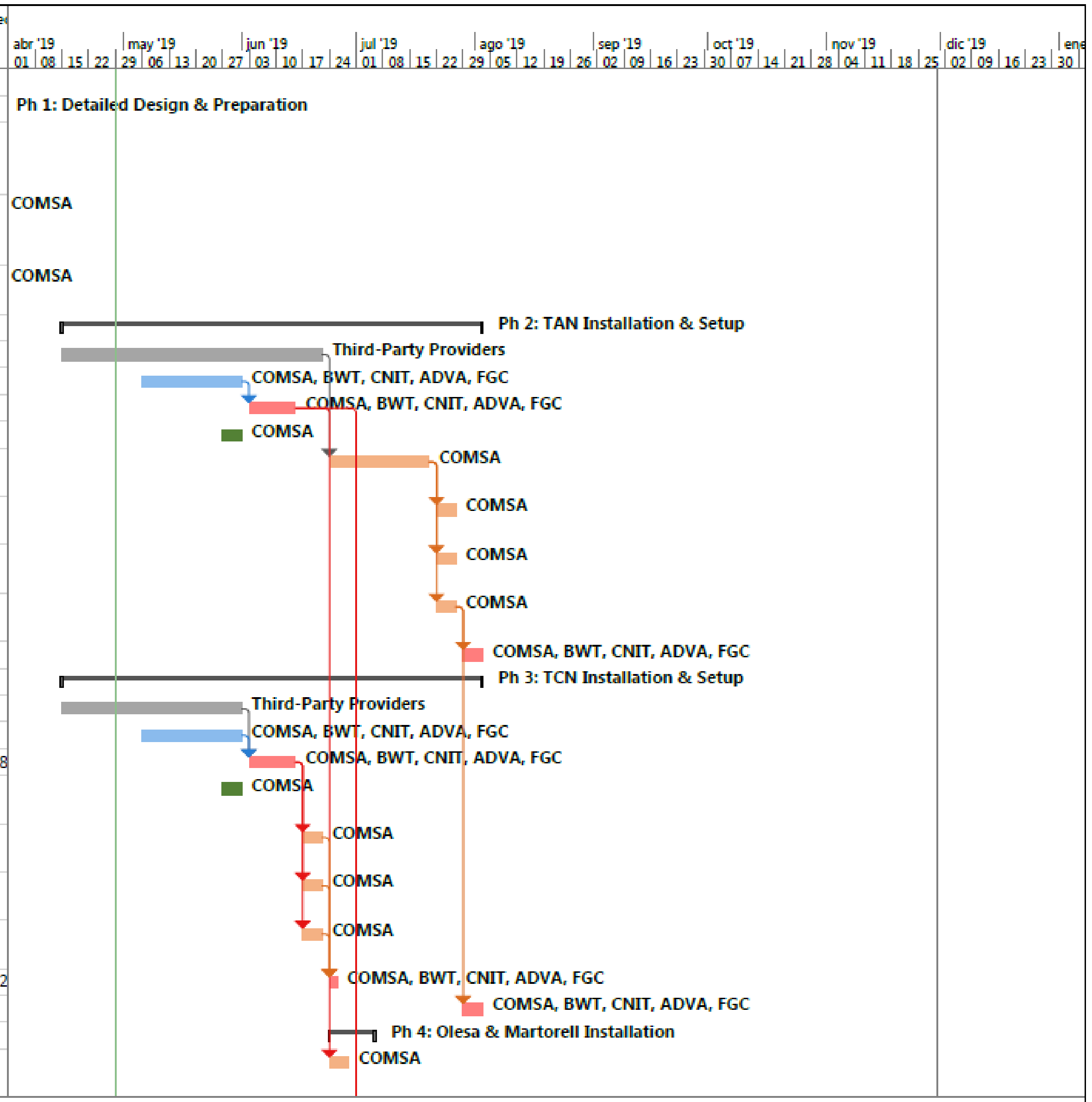


Figure 10-29: TCN Detailed Scheme

Annex F: Initial Work Plan

Id	Modo de tarea	Nombre de tarea	Duración	Comienzo	Fin	Predec
1		5GPicture Roll-out start	1 día	mar 01/01/19	mar 01/01/19	
2		Ph 1: Detailed Design & Preparation	12,8 sem.	mar 01/01/19	vie 29/03/19	
3		Track section inspection & ultimate decision for emplacements	4,6 sem.	mar 01/01/19	jue 31/01/19	
4		Constructive Project: detailed power installation & fibre connection project	8,2 sem.	vie 01/02/19	vie 29/03/19	3
5		Bottom stanchion cabinet design & production	12,8 sem.	mar 01/01/19	vie 29/03/19	
6		Ph 2: TAN Installation & Setup	16 sem.	lun 15/04/19	vie 02/08/19	
7		TAN Equipment & material supply	10 sem.	lun 15/04/19	vie 21/06/19	
8		TAN Testbed plan elaboration	4 sem.	lun 06/05/19	vie 31/05/19	
9		TAN Testbed	2 sem.	lun 03/06/19	vie 14/06/19	8
10		Stanchion's cabinets integration	1 sem	lun 27/05/19	vie 31/05/19	
11		Electrical & Fiber lines deployment/installation	4 sem.	lun 24/06/19	vie 19/07/19	7
12		Stanchion cabinets installation & connection	1 sem	lun 22/07/19	vie 26/07/19	11
13		DWDM-PON installation, connection & setup	1 sem	lun 22/07/19	vie 26/07/19	11
14		Typhoon nodes (T1&T2&T3&T4) installation, connection & setup	1 sem	lun 22/07/19	vie 26/07/19	11
15		TAN Final setup & testing	1 sem	lun 29/07/19	vie 02/08/19	14
16		Ph 3: TCN Installation & Setup	16 sem.	lun 15/04/19	vie 02/08/19	
17		TCN Equipment & material supply	7 sem.	lun 15/04/19	vie 31/05/19	
18		TCN Testbed plan elaboration	4 sem.	lun 06/05/19	vie 31/05/19	
19		TCN Testbed	2 sem.	lun 03/06/19	vie 14/06/19	17;18
20		10 G Ethernet ring line, wiring & mechanical installation	1 sem	lun 27/05/19	vie 31/05/19	
21		MM Wave on-board units, installation, connection & setup	1 sem	lun 17/06/19	vie 21/06/19	19
22		Wi-Fi Installation, connection & setup	1 sem	lun 17/06/19	vie 21/06/19	19
23		CCTV Installation, connection & setup	1 sem	lun 17/06/19	vie 21/06/19	19
24		TCN Partial setup & testing	0,4 sem.	lun 24/06/19	mar 25/06/19	21;22
25		TCN Final setup & testing	1 sem	lun 29/07/19	vie 02/08/19	14
26		Ph 4: Olesa & Martorell Installation	2 sem.	lun 24/06/19	vie 05/07/19	
27		Olesa's electrical & equipment installation (HEE+Agregator)	1 sem	lun 24/06/19	vie 28/06/19	9

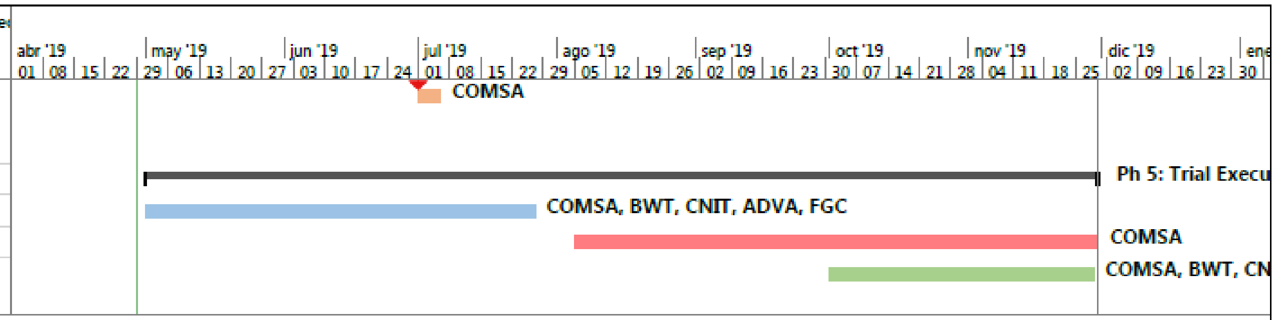


Proyecto: Plan de trabajos DSG
Fecha: lun 29/04/19

Tarea · División · Hito · Resumen · Resumen del proyecto · Tarea inactiva · Hito inactivo · Resumen inactivo · Tarea manual · solo duración · Informe de resumen manual · Resumen manual · solo el comienzo · solo fin · Tareas externas · Hito externo · Fecha límite · Progreso · Progreso manual

Página 1

Id		Modo de tarea	Nombre de tarea	Duración	Comienzo	Fin	Predec
28			Martorell's electrical & equipment installation (Agregator, CCTV & Recorder)	1 sem	lun 01/07/19	vie 05/07/19	9
29			Ph 5: Trial Execution	30,6 sem.	mié 01/05/19	vie 29/11/19	
30			Test plan elaboration	12,6 sem.	mié 01/05/19	vie 26/07/19	
31			Test plan execution	17 sem.	lun 05/08/19	vie 29/11/19	
32			Overall analysis of the trial results and D6.3 elaboration	8,6 sem.	mar 01/10/19	jue 28/11/19	



Proyecto: Plan de trabajos DSG
Fecha: lun 29/04/19

Tarea, División, Hito, Resumen, Resumen del proyecto, Tarea inactiva, Hito inactivo, Resumen inactivo, Tarea manual, solo duración, Informe de resumen manual, Resumen manual, solo el comienzo, solo fin, Tareas externas, Hito externo, Fecha límite, Progreso, Progreso manual

Página 2

Figure 10-30: Initial Work Plan

Annex G: Detailed final work plan sample (October November sample)

Month	October							October				
Week	41							42				
Day	7th Mon	8th Tue	9th Wed	10th Thu	11th Fri	12th Sat	13th Sun	14th Mon	15th Tue	16th Wed	17th Thu	18th Fri
Location 1		Martorell Taller	Martorell Taller	Olesa T2			Olesa TX	Olesa	Olesa	Olesa	Olesa	
Location 2			Olesa T2					Olesa TX	Olesa TX	Olesa TX	Olesa TX	
Location 3									Martorell Central	Martorell Central	Martorell Central	
Location 4												
Phase II Installation Activities in Barcelona												
TCN on-board antenna & equipment installation. Equipment cabling and connection via USB dongle.		8th Morning-Evening	9th Morning-Evening									
Testing items		Configuration of each device, remote management	Configuration of each device, remote management									
Equipment installation at Olesa & Martorell station.												
Testing items			Configuration of each device, remote management	Configuration of each device, remote management								
Stanchion Nº1 installation and adjustment.							13th Night-14th Dawn	14th Night-15th Dawn				
Testing items							Optical link check / link loss / power	Optical link check / link loss / power				
Stanchion Nº2 installation and adjustment.			9th Night-10th Dawn	10th Night-11th Dawn				14th Night-15th Dawn	15th Night-16th Dawn			
Testing items			Optical link check / link loss / power	Optical link check / link loss / power				Optical link check / link loss / power	Optical link check / link loss / power			
Stanchion Nº3 installation and adjustment.									15th Night-16th Dawn	16th Night-17th Dawn		
Testing items									Optical link check / link loss / power	Optical link check / link loss / power		
Stanchion Nº4 installation and adjustment.										16th Night-17th Dawn	17th Night-18th Dawn	
Testing items										Optical link check / link loss / power	Optical link check / link loss / power	
Train required to move and stop at each Stanchion										16th Night-17th Dawn	17th Night-18th Dawn	
Adva Equipment installation on track cabinets			9th Night-10th Dawn	10th Night-11th Dawn								
Test & measurements from Martorell station.				Remote management, VPN router, local link test				Remote management, VPN router, local link test	Remote access to Olesa and DNs, Iperf / TCP dumping between station FlowBlaze and DNs	Remote access to Olesa and DNs, Iperf / TCP dumping between station FlowBlaze and DNs		
Complete end to end connection from Martorell<->Train. Measurements and conclusions.										Connectivity test / e2e service check	Connectivity test / e2e service check	

Month	October							November				
Week	44							45				
Day	28th Mon	29th Tue	30th Wed	31st Thu	1st Fri	2nd Sat	3rd Sun	4th Mon	5th Tue	6th Wed	7th Thu	8th Fri
Location 1	Olesa	Olesa	Olesa	Olesa								
Location 2	Olesa TX	Olesa TX	Olesa TX	Olesa TX								
Location 3	Martorell Central	Martorell Central	Martorell Central	Martorell Central								
Location 4												
Phase III final preparation in Barcelona												
TCN on-board network	e2e service check, mobility optimization (i.e. handover), performance measurements	e2e service check, mobility optimization (i.e. handover), performance measurements	e2e service check, mobility optimization (i.e. handover), performance measurements	e2e service check, mobility optimization (i.e. handover), performance measurements								
Olesa station	Trouble-shooting	Trouble-shooting	Trouble-shooting	Trouble-shooting								
Martorell station	Trouble-shooting	Trouble-shooting	Trouble-shooting	Trouble-shooting								
Stanchion Nº1 installation and adjustment.												
Stanchion Nº2 installation and adjustment.												
Stanchion Nº3 installation and adjustment.												
Stanchion Nº4 installation and adjustment.												
Train required to move and stop at each Stanchion	28th Night - 29th Dawn	29th Night - 30th Dawn	30th Night - 31st Dawn	31st Night - 1st Dawn								
Adva Equipment installation on track cabinets												
Complete end to end connection from Martorell<-> Train. Measurements and conclusions.	e2e service check, mobility optimization (i.e. handover), performance measurements	e2e service check, mobility optimization (i.e. handover), performance measurements	e2e service check, mobility optimization (i.e. handover), performance measurements	e2e service check, mobility optimization (i.e. handover), performance measurements				Buffer placeholder for any unexpected issue				

Figure 10-31: Detailed final work plan sample (October November sample)