Beyond 5G Multi-Tenant Private Networks Integrating Cellular, Wi-Fi, and LiFi, Powered by Artificial Intelligence and Intent Based Policy

5G-CLARITY Deliverable D5.3

5G-CLARITY Use Cases: Demonstrations and Evaluations

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List of Acronyms

3GPP	3rd Generation Partnership Project
5GNR	5G New Radio
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AP	Access Point
B5G	Beyond 5G
CAPEX	CApital EXpenditures
CDF	Cumulative Distribution Function
CPE	Customer Premises Equipment
DoW	Description of Work
eCDF	Empirical Cumulative Distribution Function
GUI	Graphical User Interface
IE	Intent Engine
KPI	Key Performance Indicator
LiFi	Light Fidelity
LTE	Long Term Evolution
MES	Manufacturing Execution System
ML	Machine Learning
MNO	Mobile Network Operator
MPTCP	Multipath TCP
Multi-WAT	Multiple Wireless Access Technology
NFV	Network Function Virtualization
NS	Network Service
OCC	Optical Camera Communications
OPEX	OPerational EXpenditures
OSM	Open Source Mano
RIC	Radio Intelligent Controller
RRM	Radio Resource Management
RRT	Round Trip Time
RSS	Received Signal Strength
SDN	Software Defined Networking
SLA	Service Level Agreement
TCO	Total Cost of Ownership
UC	Use Case
VM	Virtual Machine
WAT	Wireless Access Technology
WP	Work Package

Executive Summary

This document corresponds to 5G-CLARITY deliverable D5.3 that reports on the integration of the 5G-CLARITY technologies developed in WP2, WP3 and WP4 into two pilots: i) a smart tourism pilot held in the M Shed museum in Bristol, and ii) an Industry 4.0 pilot held in a factory provided by BOSCH in Aranjuez, Madrid.

These pilots constitute two real implementations of the 5G-CLARITY architecture for private networks proposed in the project. The main technical innovations integrated in the two pilots are: i) the multi-connectivity framework based on Multipath TCP (MPTCP), ii) a set of positioning technologies integrated on Sub-6, 60GHz and Li-Fi radios, iii) a service and slice provisioning subsystem used to provision network slices, and iv) the intent and AI engines that can be used to simplify network operations.

The methodology that we follow to evaluate the 5G-CLARITY technologies in our two pilots is the following. First, we define a set of service specific KPIs, related to the services featured in each pilot, and a set of transversal KPIs. Second, we deploy the 5G-CLARITY system in each site to validate the service KPIs, and then execute a measurement campaign that allows us to measure the transversal KPIs in the museum and factory environments. Then, we use the results of our measurement campaign to derive a set of deployment models that could be used to address the service KPIs. Finally, we compare the different deployment models in terms of Total Cost of Ownership (TCO) to understand the performance/business trade-offs. We try to maximize the impact of our results by reporting on the KPI performance of each technology in isolation, as well as on the resulting performance when using the 5G-CLARITY mechanisms. In this way, researchers interested only on the performance of the individual technologies can also benefit from our results.

Next, we summarize the main results that we extract from our two pilots, where the BOSCH pilot is split in two use cases, i.e. UC2.1 production line connectivity and UC2.2 about AGV positioning.

The goal of the smart tourism pilot executed in the M Shed museum in Bristol is to integrate a robot that interacts with visitors providing tips and information. The main challenge in integrating this robot is providing connectivity for a 360-degree camera mounted on the robot, which requires a dedicated UL capacity of 120 Mbps across the museum space. A second goal of the museum use case is to demonstrate how the 5G-CLARITY intent engine can be used by the private network IT administrator to quickly redirect the stream of the 360-degree camera to the handheld device of a public safety officer that requests to tap on this stream for security reasons. The main findings of this pilot are that neither Wi-Fi alone nor 5G alone are enough to provision the necessary UL capacity across the museum. Wi-Fi has a very high capacity when close to the AP, but the throughput quickly degrades with distance. In addition, deploying multiple Wi-Fi APs has the drawback of introducing significant interruptions due to handovers that impact the quality of the transmitted stream. Using only 5G, where we have a 100 MHz carrier, we can guarantee a 100 Mbps in UL across the museum area, which is slightly below the required capacity. Our recommended deployment in this case is to cover the museum with a single 5G cell combined with a single AP in each floor of the museum, which fulfils the required service KPIs, and results in only a moderate cost increase with respect to a Wi-Fi only solution. Regarding the integration of the 5G-CLARITY intent engine, this pilot demonstrates how the 5G-CLARITY system allows to use a simple trigger in natural language, to execute a complex networking pipeline that involves provisioning a new network function that captures the stream from the 360-degree camera in the robot and redirects it to the device of the public safety officer.

The goal of the production line connectivity use case in BOSCH Aranjuez was to demonstrate the feasibility and the benefits of connecting production lines in a factory using wireless technologies, instead of Ethernet as it is being done today. The critical network KPI in this service is the round-trip latency between the PLC and the Manufacturing Execution System (MES) service, which impacts the minimum cycle time that can be sustained by the manufacturing process. For this service we use the 5G-CLARITY redundant scheduler to measure the achievable round-trip delays under different interference conditions, and for each technology separately and combined. Based on our field measurements we conclude that the best deployment consists of a single 5G cell that provides coverage throughout the factory complemented with 6 Wi-Fi APs, which results in the latency required to sustain cycle times as low as one second. When performing a cost analysis, we conclude that our recommended 5G + Wi-Fi deployment is comparable in cost to the current Ethernet deployments, where cabling accounts for a significant portion of the cost. An important conclusion of our costs analysis is that there is a significant room for cost reduction in 5G networks if the core network is simplified, e.g. by adopting open source implementations.

The goal of the AGV positioning use pilot in BOSCH Aranjuez was to demonstrate how the three 5G-CLARITY Wireless Access Technologies (WATs), namely Wi-Fi and 5G New Radio (5GNR) operating below 6 GHz, 5GNR operating at mm-wave and Li-Fi, can be enhanced with positioning capabilities. The positioning capabilities developed in the project are applied to track in real-time the position of a moving AGV, which is used for internal logistics in the factory. We demonstrate how our positioning mechanisms deliver sub-meter accuracy in the case of Sub6 radios, cm-level accuracy in the case of mm-wave radios, and accuracy below 5 meters in the case of Li-Fi.

Based on the results of the two pilots reported in this document we conclude that the 5G-CLARITY project objectives have been accomplished[1].

[1] A detailed analysis of the objectives reported in the DoA is included in section 7.

1 Introduction

1.1 Objective and scope of this document

5G-CLARITY D5.3 describes the demonstrations carried out in the M Shed museum in Bristol and the BOSCH factory in Aranjuez. These demonstrations illustrate the benefits provided by the technologies developed in WP3 and WP4 in two relevant scenarios for private 5G networks. This deliverable collects the outputs of Task 5.3 and Task 5.4, which were dedicated to the demonstration of UC-1 and UC-2 respectively.

Being the last technical deliverable of the project, the main objective of this report is to highlight the benefits of the 5G-CLARITY technologies in our target museum and factory environments. To this end, the following technologies are demonstrated:

i. The 5G-CLARITY multi-connectivity framework developed in WP3. It is used to guarantee an UL performance of 140 Mbps across the museum environment for UC-1. In UC2.1 the multi-connectivity framework is used simultaneously for two different applications. First, a mobile Customer Premises Equipment (CPE) uses the multi-connectivity framework in aggregation mode to enjoy DL capacities between 200 Mbps and 500 Mbps throughout the factory. Second, a production line connected to the 5G-CLARITY network uses the redundant mode of the multi-connectivity framework to communicate with a MES server obtaining round trip latencies below 10 ms.

ii. The Service and Slice provisioning subsystem developed in WP4 is used to demonstrate how we can setup a network slice dynamically to serve the AGV use case in the BOSCH factory. The slice provisioning time is measured to be of three minutes.

iii. The multi-WAT localisation mechanisms developed in WP3 are used in UC2.2 to position a moving AGV in real-time in the BOSCH factory with sub meter localisation accuracies.

iv. The Intent Engine developed in WP4 is used in UC-1 to demonstrate how a public safety office can express an intent in natural language that results in a surveillance video stream being redirected to the officer's mobile device.

A second objective of this report is to perform an exhaustive KPI analysis in the two use case environments used in the project, i.e. the museum and the factory. This exhaustive KPI analysis is then used to feed three custom cost models that allow us to compare the TCO of 5G-CLARITY networks as compared to the cost of the current Wi-Fi and Ethernet networks being currently used in museum and factory environments.

1.2 Document structure

The deliverable is structured into the following sections:

Section 2 presents the transversal KPIs that are measured in the M Shed and BOSCH locations. Our considered transversal KPIs include throughput over distance, latency under interference, inter-WAT mobility and localization related KPIs. For each KPI we present a measurement methodology and provide links to the tools developed to measure the KPIs which have been open sourced.

Section 3 presents the details of the M Shed use case in Bristol. The section first describes the mapping of the 5G-CLARITY architecture to this use case. Second, it presents the use case objectives. Third, it documents the validation of the service KPIs that took part in the museum. Finally, it reports the results of a measurement campaign carried out to collect the transversal KPIs introduced in Section 2.

Section 4 presents the details of the UC2.1 use case in BOSCH Aranjuez. The section first describes the mapping of the 5G-CLARITY architecture to this use case. Second, it presents the use case objectives. Third, it documents the validation of the service KPIs that took part in the factory. Finally, it reports the results of a measurement campaign carried out to collect the transversal KPIs introduced in Section 2.

Section 5 reports on the AGV positioning use case demonstrated in BOSCH Aranjuez. The section describes the deployment and demonstrations carried out in BOSCH, and then presents the results of an exhaustive measurement campaign that characterize the positioning performance for all three WATs in terms of precision and accuracy.

Section 6 presents three custom cost models for UC1 and UC2.1. The cost models have been developed considering the transversal KPI measurements reported respectively for each use case in sections 3 and 4.

Finally, section 7 summarizes and concludes this report.

2 Definition and test methodology of transversal and UC specific KPIs

In this section we introduce the target network configurations and transversal KPIs that will be evaluated in the BOSCH and museum sites.

Between the BOSCH and museum use cases we will consider a set of 3 network configurations, introduced in Section 2.1, and four different transversal KPIs including:

- Throughput over distance, in Section 2.2, which measures how the throughput in UL and DL delivered by each WAT is affected by distance in the respective environments of each site.
- Latency under interference, in Section 2.3, which measures the latency delivered by each WAT under different levels of interference.
- Inter/Intra-WAT mobility, in Section 2.4, which measures reconnection time across and between WATs using the 5G-CLARITY multi-connectivity framework.
- Localisation precision and accuracy in Section 2.5.

To gather the different transversal KPIs we have elaborated a measurement toolkit that has been published open source here: https://bitbucket.i2cat.net/users/ferran_canellas/repos/mptcp_tester/browse.

2.1 Target network configurations

Considering the capabilities of the 5G and Wi-Fi equipment available in the BOSCH Aranjuez site and in the Bristol M Shed museum site we consider 3 different network configurations, where two of them are tested in the BOSCH site, and the other one in the M Shed site. These 3 configurations are described in Table 2-1.

Table 2-1. Considered network configurations in BOSCH and M Shed sites.

Configurations	5GNR	Wi-Fi	LiFi
BOSCH-Default	BW: 40 MHz TDD: 5 ms, 6 DL, 3 UL Vendor: Amarisoft + AW2S	80 MHz Vendor: Custom	DL in visible light: Blue LED (~450 nm) with phosphor coating UL in IR: LED (850 nm) BW: 16 MHz DL & UL
BOSCH – UL	BW: 40 MHz TDD: 5 ms, 3 DL, 6 UL Vendor: Amarisoft + AW2S	80 MHz Vendor: Custom	DL in visible light: Blue LED (~450 nm) with phosphor coating UL in IR: LED (850 nm) BW: 16 MHz DL & UL
MSHED-Default	BW: 100 MHz TDD: 7 DL 4UL Vendor: NOKIA	160 MHz Vendor: Ruckus	DL in visible light: Blue LED (~450 nm) with phosphor coating UL in IR: LED (850 nm) BW: 16 MHz DL & UL

Notice that the default configurations have higher bandwidth for 5G in the downlink, which is the common case in public networks, whereas the UL configurations allocate a larger number of slots to the uplink. In addition, larger carrier bandwidths for 5G and Wi-Fi are considered in the M Shed configurations due to a 100 MHz 5G license being available and the availability of 160 MHz capable WiFi6 APs.

2.2 Throughput over distance

The goal of this KPI is to characterize the throughput delivered in UL and DL for each different WAT, and for the 5G-CLARITY multi-connectivity framework when using a round-robin scheduler [1]. To obtain this KPI the following methodology is proposed:

- In each site we deploy the three WATs, 5G, WiFi6 and LiFi, colocated around an initial position which we refer to as Pos-A.
- We then identify a set of measurement positions, {Pos-B, …, Pos-X} with a growing distance from "Pos-A".
- In each of our target positions we deploy the 5G-CLARITY CPE and execute repeated throughput tests using our measurement toolkit, where we evaluate the UL and DL performance of each technology, as well as the performance in aggregated mode using the MPTCP round-robin scheduler.
- We repeat the tests for the different configurations described in each site in Table 2-1.

The results of this KPI for the M Shed site are reported in Section 3.4.2 and in the BOSCH site are reported in Section 4.4.1.

2.3 Latency under interference

Figure 2-1 depicts the setup proposed to measure latency under interference. The goal of this KPI is to understand how the different wireless access technologies (WATs), as well as the 5G-CLARITY multi-connectivity framework using the redundant scheduler, behave when there is interference. To this end, we need two 5G-CLARITY CPEs. The first CPE is used to measure latency using the lagscope (https://github.com/microsoft/lagscope) measurement tool that allows to measure latency for TCP traffic. The interferer CPE is used to generate different amounts of interference in the network.

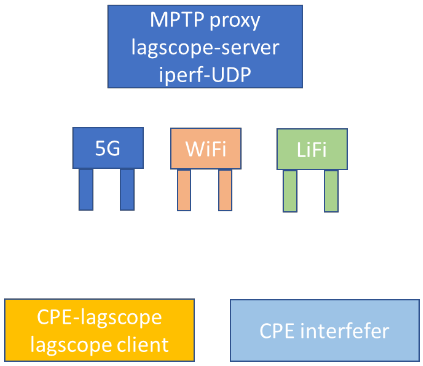

Figure 2-1. Proposed test setup to measure latency under interference.

The following methodology is proposed to measure this KPI:

- The two CPEs (lagscope and interferer) are co-located in a location where the different WATs can be accessed simultaneously.
- A level of interference X% is generated by the interfering CPE for each technology, where X increases from 0% to 80%. We note here that X represents an equivalent level of interference for each considered WAT. The concept of equivalent level of interference is required because the considered WATs have very different capacities. For example LiFi offers 10 Mbps in DL and Wi-Fi 300 Mbps, thus introducing a 5 Mbps interferer will have a very different impact in the two WATs. Instead our methodology consists in empirically determining a nominal capacity for each WAT, and then introducing an equivalent interference of X% for each WAT, derived from the determined nominal capacity.

- Repeat our experiments when considering UL and DL interference, i.e. the direction between the CPE interferer and the iperf server in Figure 2-1 .
- Repeat each experiment for multiple runs, collect all the latency samples delivered by lagscope, and plot the resulting distribution using a boxplot.

The results for this KPI corresponding to the M Shed site are presented in Section 3.4.2. The results for the BOSCH site are presented in Section 4.4.2.

2.4 Inter/Intra-WAT mobility

The 5G-CLARITY multi-connectivity framework offers the advantage of utilizing multiple WATs to deliver a high throughput and dependable connectivity experience to end users through the 5G-CLARITY CPE. However, given the mobility of the CPE as it is mounted on a mobile robot, it is possible that one or all of the links may become inaccessible due to the loss of signal as the CPE moves outside of the coverage area. In such a scenario, it becomes crucial to determine the optimal location for access points to ensure adequate overlap between different access technologies and provide seamless connectivity. This requires consideration of the time required for the disconnected link to be re-established and fully functional by the CPE. A longer link re-establishment time necessitates greater overlap, while a shorter recovery time requires less. The speed of the robot around the museum, determines that of the rate of CPE's mobility.

The KPI for measuring the duration of both LiFi and WiFi-6 is expressed in microseconds. We however do not explicitly measure reconnection time for 5G because 5G has inherent support for handover, which is not the case in the other two component WATs used in 5G-CLARITY.

We have developed scripts that enable measurement of the time it takes to re-establish flow over MPTCP in microseconds, which are available here: https://github.com/hpn-bristol/5gclarity-kpi-measurement. The scripts log events based on the client's state on the CPE for each individual access technology, and timestamp them with microsecond precision. By post-processing the logs, it is possible to determine the overall time taken between being within coverage and re-establishing the flow over MPTCP. To ensure accuracy, these measurements and tests have been conducted at least 10 times per access technology. Both LiFi and Wi-Fi have corresponding events, which are described as follows.

LiFi connection re-establishment sequence:

Sequence	Event name	reported by	Type	Description
1	SME: TRYING TO AUTHENTICATE	wpa_supplicant	Timestamp	Triggers when the LiFi client receive signal from the AP by being in the coverage of LiFi AP
2	GAINED CARRIER	networkd	Timestamp	Layer2 communication is established between Client and AP
3	DHCPv4 ADDRESS	networkd	Timestamp	L3 established and the client get IP from the DHCP server. at this stage the interface on the CPE has the IP address and can start / restart TCP/IP communication
4	MPTCP JOIN ID	tcpdump	Timestamp	MPTCP subflow has been established re-established over the MPTCP. At this stage the link utilized by the MPTCP while using Round Robin as a scheduler

Wi-Fi connection re-establishment sequence:

Sequence	Event name	reported by	Type	Description
1	SME: TRYING TO AUTHENTICATE	wpa_supplicant	Timestamp	Triggers when the Wi-Fi client receive signal from the AP by being in the coverage of Wi-Fi AP
2	GAINED CARRIER	networkd	Timestamp	Layer2 communication is established between Client and AP
3	DHCPv4 ADDRESS	networkd	Timestamp	L3 established and the client get IP from the DHCP server. at this stage the interface on the CPE has the IP address and can start / restart TCP/IP communication
4	MPTCP JOIN ID	tcpdump	Timestamp	MPTCP subflow has been established re-established over the MPTCP. At this stage the link utilized by the MPTCP while using Round Robin as a scheduler

The results for this KPI are provided for the M Shed site in Section 3.4.2. This KPI is not collected in the BOSCH site because only one Wi-Fi AP was available in the site and the high ceilings used to mount the LiFi APs artifically limited the coverage of LiFi in this scenario.

2.5 Localisation precision and accuracy

The results for this KPI are reported for the BOSCH site in Section 5.3. Corresponding results for the M Shed site are not available because the multi-WAT localization technology was only available in UC2.2.

The goal of this KPI is to evaluate the precision and the accuracy of the developed positioning systems in a realistic environment, i.e. in this case BOSCH factory in Aranjuez, Spain. A total of 3 positioning systems were deployed in the BOSCH factory in Aranjuez. These include: Sub-6 GHz, mmWave and LiFi positioning system.

The following KPIs were evaluated in the BOSCH factory:

1. Static precision/accuracy of the Sub-6 GHz system.
2. Dynamic precision/accuracy of the Sub-6 GHz system.
3. Static precision/accuracy of the mmWave system.
4. Functionality of the LiFi system.
5. Position estimation latency and frequency.

To test the static precision/accuracy of the Sub-6 GHz system, a few points with known coordinates were established. The positioning equipment was moved to these points and left there for a given period of time, long enough to acquire a few hundred of position estimates. Further, the accuracy with respect to the referent point and the precision were calculated.

For estimating the dynamic precision/accuracy of the Sub-6 GHz system, the positioning UE was placed on a cart and moved along a straight-line with a constant speed. This way, knowing the starting and the ending point, as well as the speed it is possible to predict the ground truth. The precision/accuracy of the Sub-6 GHz system is further calculated based on this ground truth. This is performed in this way, because no other, high-precision positioning system was available as a reference.

For the mmWave system only static tests were performed due to the limited length of the synchronization cables between the APs and the UE. The tests were performed by choosing a few different points with known positions, i.e. ground truth, and the UE was places on these points. For each point a few hundred estimates were acquired. The main problem in this case was to estimate the accuracy, since it is expected to be in the sub-centimetre range. Positioning the UE, which is on a movable cart with sub-centimetre position is not an easy task, and therefore, it is expected that the obtained results for the accuracy are positively biased.

Regarding the LiFi positioning system, due to the large mounting height, the RSSI indicator was always showing the minimum value. Therefore, it would be only possible to estimate the coverage area and that to be used as a measure for position of the UE.

The latency and the frequency of the position estimation for the Sub-6 GHz and the mmWave position systems were also estimated. The latency is mainly due to the computation time needed for position estimation. The frequency of the position estimates is finite due to the computational time as well as the time needed for acquiring the samples and transferring them to the computer for further processing.

The obtained results are presented in Section 5.3.

3 Bristol UC: Demonstration and KPI evaluation

In this section we present the results of the 5G-CLARITY field trial at the Bristol M Shed Museum for UC-1 "Enabling Enhanced Human-Robot Interaction (Smart Tourism)".

3.1 Use Case objectives and execution plan

The Bristol UC-1 demonstration shows the benefits of the 5G-CLARITY framework in enabling public and private 5G networks, as well as multiple wireless access technologies, to support guide robot services associated with Smart Tourism. The demonstration of this use case has the following goals:

- Goal 1: To provide validation for the 5G-CLARITY multi-connectivity framework through the deployment of Smart Tourism App for visitors' assistance in a museum environment.
- Goal 2: To validate the deployment of public safety service using the 5G-CLARITY Intent Engine (IE) developed in WP4 [2].

To achieve these objectives, we execute the following plans:

- Implement the Smart Tourism Application by mapping the 5G-CLARITY system architecture to the application elements and show how the architecture maps to physical deployment at M Shed and Smart Internet Lab.
- Provide validation for the 5G-CLARITY UC-1 KPIs in a real deployment environment.
- Record a video of the 5G-CLARITY museum demonstration that is available here: https://gigasysone.sharepoint.com/:v:/s/5G-CLARITY/EVPSs5mVa89No0mQLTRTr40BQ3fxyST2MJIT1VMi9x7pVg?e=DM9AnU

To accomplish the aforementioned objectives, multiple visits were made to the Bristol M Shed museum, which served as the location for the UC-1 final demonstration.

- November 24th, 2022: Final assessment of UC-1 demo venue, identification of equipment installation positions, cabling requirements and connection points.
- December 5th, 2022: Deployment of basic infrastructure in support of the virtualized RAN functions.
- February 6th, 2023: 5G-CLARITY UC-1 infrastructure deployed on demo site.
  - Multi-connectivity infrastructure (5GNR RUs, WiFi-6 and LiFi APs) installed.
  - Guide robot and 5G-CLARITY CPE deployed and integrated with the multi-connectivity framework.
  - The guide robot management applications up and running.
  - Fixed and 360-degree cameras installed and tested.
  - KPI measurements performed. UL and DL throughput aggregation and human-robot interaction tested.
- February 20th, 2023: Final demonstration and KPI evaluation of 5G-CLARITY multi-connectivity framework
  - Deployment of Smart Tourism App for visitors' assistance in a museum environment.
  - Validate the deployment of public safety service using the 5G-CLARITY Intent Engine.
  - 5G, WiFi-6 and LiFi performance test.
  - Validation of throughput and latency related KPIs.
- February 27th, 2023:
  - Measurement and validation of mobility related KPI.

3.2 Network infrastructure deployment and architecture

This section covers the network infrastructure that links the M Shed museum and Smart Internet Lab sites, where the RAN and Edge clusters for the UC-1 demonstration are hosted. The 5G-CLARITY system architecture is illustrated in Figure 3-1 highlighting in red ticks the various components implemented in UC-1.

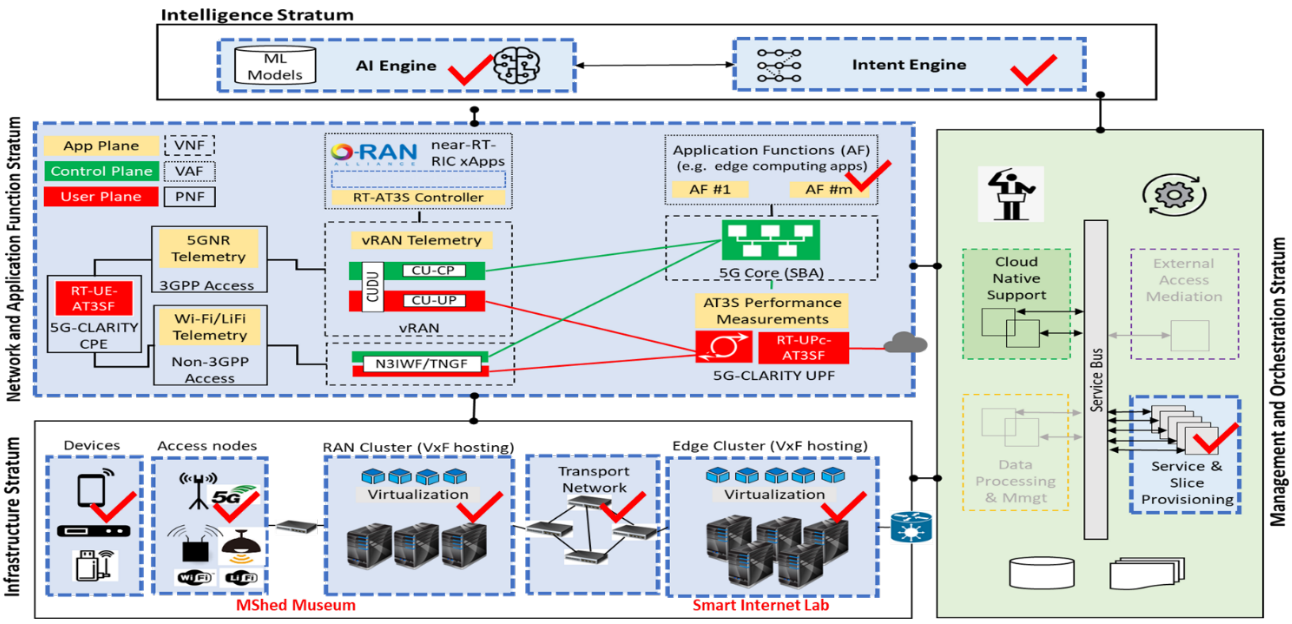

Figure 3-1 The 5G-CLARITY system architecture with elements (in red ticks) deployed in UC-1 and their locations.

In Figure 3-2, we can see an aerial view showing two locations in Bristol: The Smart Internet Lab site, which houses the Edge cluster; and the Bristol M Shed Museum, which hosts the RAN cluster. The figure also indicates the network elements in the two locations.

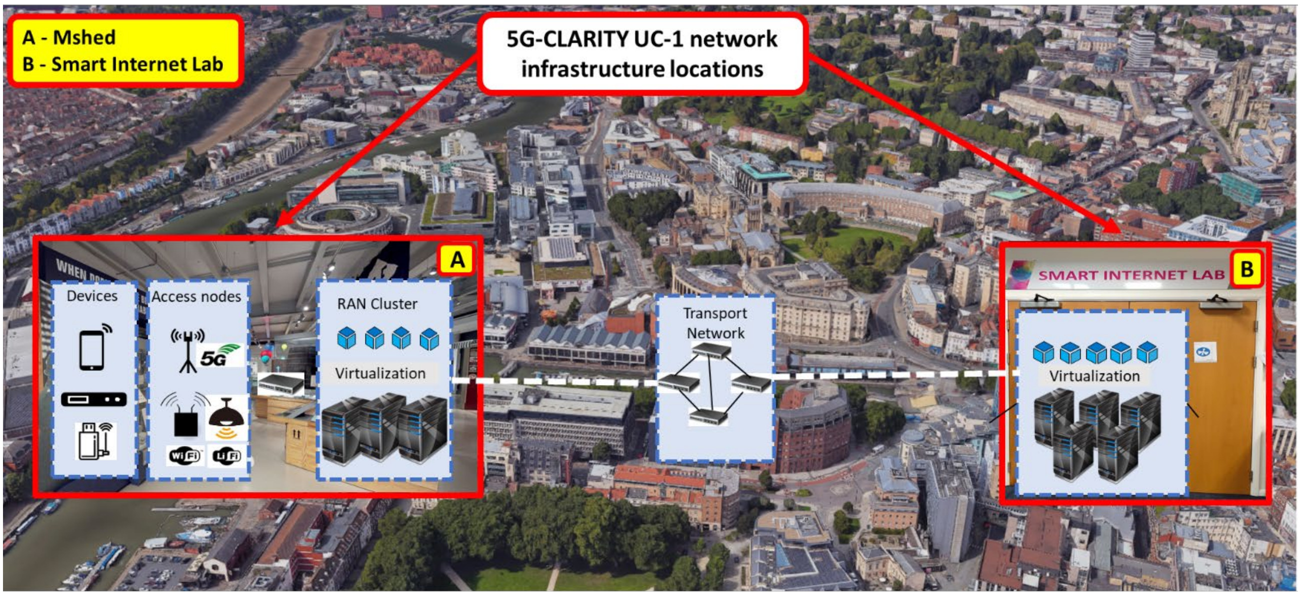

Figure 3-2 Deployment of UC-1 infrastructure across Bristol city at Mshed and Smart Internet Lab.

In the following section, the infrastructure requirements for UC-1 are outlined, encompassing both the RAN and Edge clusters. This includes a description of the equipment and their respective specifications.

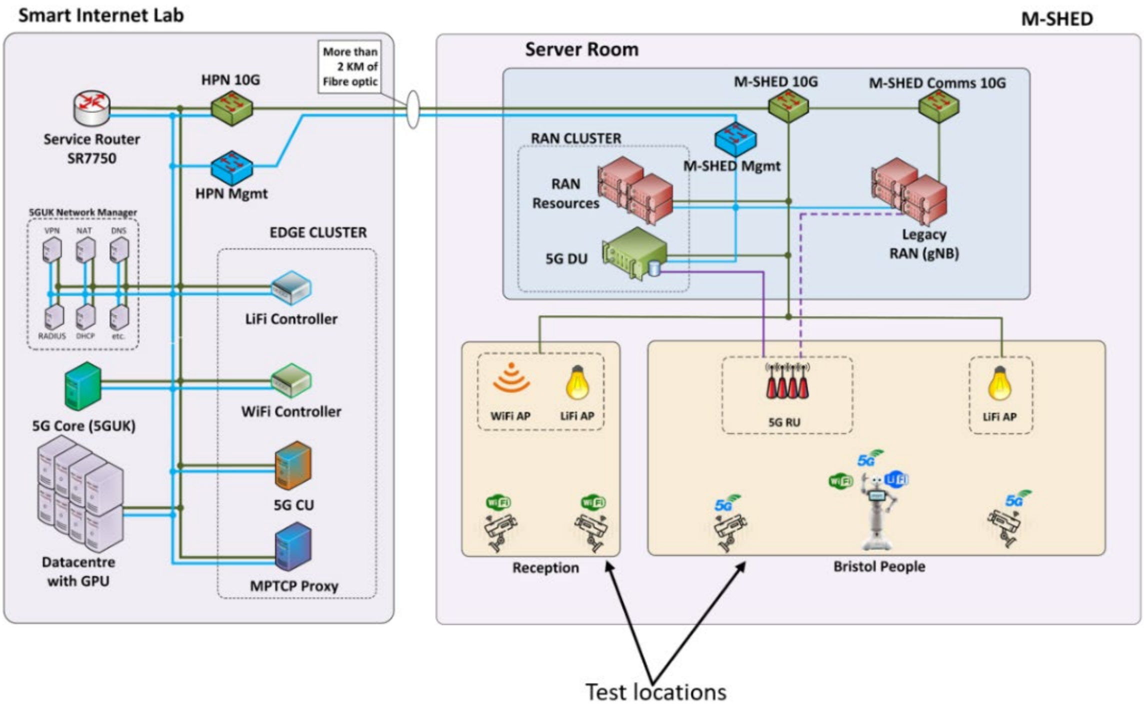

Figure 3-3 Connections between UC-1 Edge and RAN clusters.

The test location is defined as the RAN cluster. It provides an NFV infrastructure environment for the execution of the virtualized functions and applications from the 5G-CLARITY framework. The RAN cluster host 5G, WiFi-6 and LiFi access nodes, gNB-CU, DU and Radio Intelligent Controller (RIC). The controller node and several compute nodes are part of the implementation setup, and they are dispersed throughout the UC-1 testbed [3] . Figure 3-3 describes the actual test location at M Shed with connections between the Edge and the RAN clusters.

3.2.1 Infrastructure requirements

We outline the essential infrastructure components required for the implementation of the Smart Tourism use case. Table 3-1 presents a listing of the main equipment utilized in UC-1 demonstration.

Table 3-1 A list of the primary equipment used in UC-1 implementation.

Equipment type	Quantity/Description	Status
5G-CLARITY CPE	1x MPTCP enabled Linux kernel	Fully developed
LiFi	2x PureLiFi APs, 1x USB dongle	Deployed
WiFi-6	1x Rukus R850	Deployed
5G Radio	1x Nokia and Accelleran solutions	Deployed
Robot	1x Pepper	Deployed
Fixed cameras	2x	Deployed
360-degree camera	1x	Deployed
MPTCP platform	Setup	Integrated

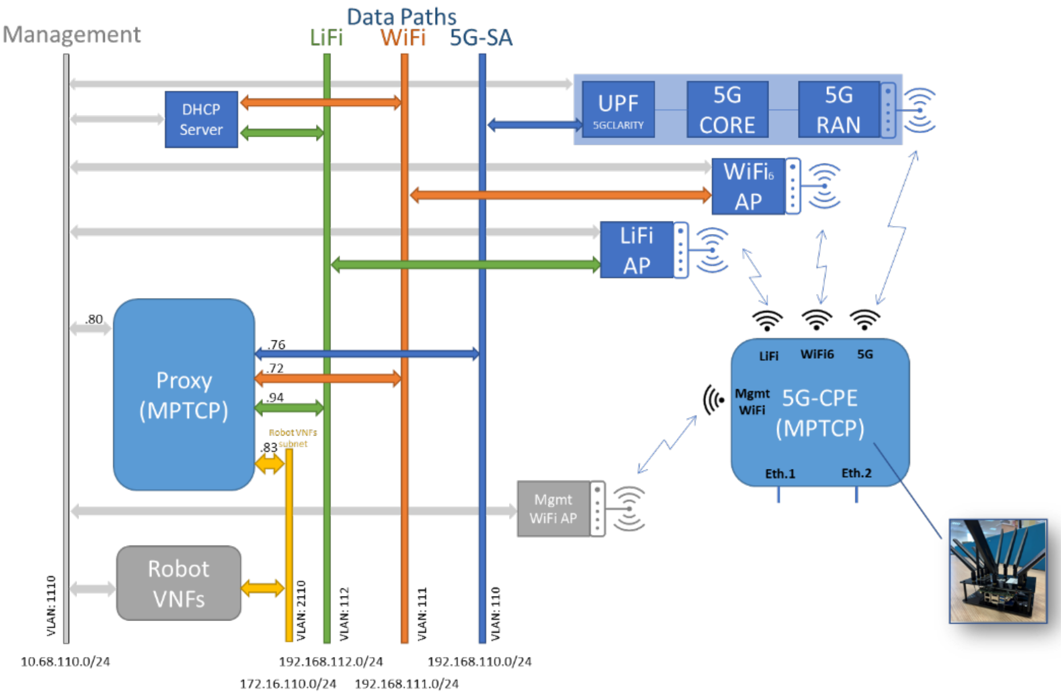

Figure 3-4 Architecture of 5G-CLARITY MPTCP enabled multi-connectivity framework.

The 5G-CLARITY multi-connectivity framework is embodied by this set of equipment, which involves hardware configurations, deployment of network services and the CPE integration with MPTCP. The integration of these components enable the aggregation of traffic parameters such as throughput. The 5G-CLARITY multi-connectivity framework has been reported in detail in [1]. Below, we provide detailed description of each of the components. Figure 3-5 depicts the MPTCP platform, demonstrating how the CPE with MPTCP capabilities connects to an MPTCP proxy, which in turn connects to robot VNFs via 5G, WiFi-6, and LiFi links. This representation showcases the concept of 5G-CLARITY multi-connectivity framework.

Figure 3-5 presents the hardware configuration of the CPE, which includes a Pentium processor, 8GB of memory, multiple antennas for 5G, Wi-Fi, and GPS, as well as a variety of ports for Ethernet, USB, HDMI, GPIO, and power input.

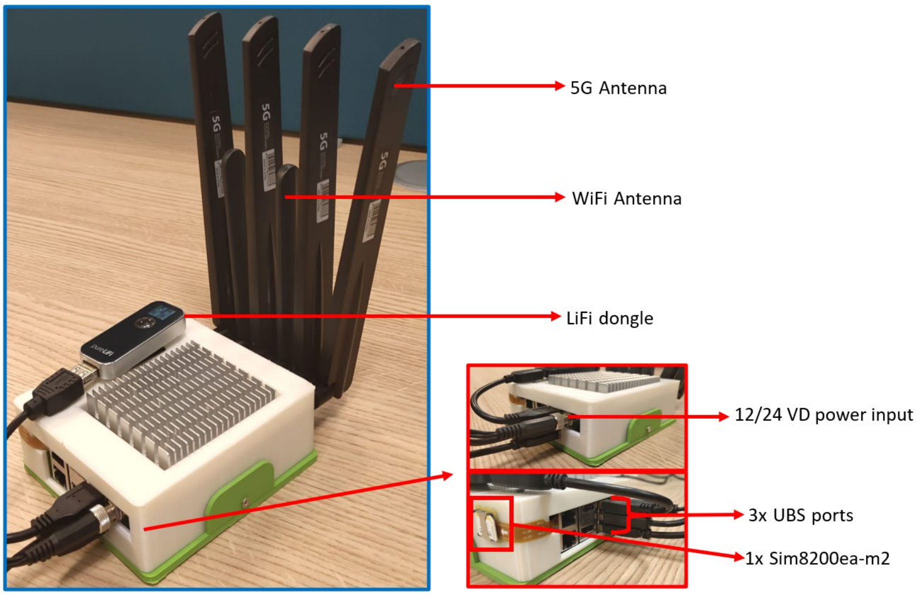

Figure 3-5 MPTCP supported CPE.

Table 3-2 presents the configuration details of the 5G NR, WiFi-6, and LiFi access technologies used in the use case implementation. For the 5GNR configuration, the Nokia AWHQM radio access network (RAN) is utilized, operating on Band 77 with a 100 MHz bandwidth, and employing 4x2 MIMO. The subcarrier spacing is set to 30 kHz, and the frame structure type is semi-static. The guard period length is 2 symbols, and the TDD configuration follows a 7DS2U pattern (7/4 Nokia configuration).

The WiFi-6 configuration includes a Ruckus R850 access point (AP) operating at a frequency of 5.180 GHz and a signal strength of -40 dBm. The SSID for the network is '5G-CLARITY WiFi-6'. The receive and transmit bitrates are both set to 1200.9 Mbps with 160 MHz bandwidth and HE-MCS 11, HE-NSS 2, HE-GI 0, and HE-DCM 0 settings.

In the LiFi configuration, a pureLiFi-X access point is used along with a pureLiFi USB dongle as the client. This setup highlights the distinct characteristics and performance capabilities of each communication technology in the context of 5G-CLARITY UC-1.

Table 3-2 multi-WAT configurations details used in UC-1.

Specification	Description
5G NR	
RAN: Nokia	AWHQM
Band 77	100 MHz BW
MIMO	4 x 2
Subcarrier spacing	30 KHz
Frame structure type	Semi Static
Guard Period length	2 Symbols
Frequency	3.8 GHz
Channel width	100 MHz
Throughput	100 Mbps
TDD configuration	7DS2U (7/4 Nokia configuration)
Wi-Fi-6	
WiFi-6 AP	Ruckus R850
SSID	5G-CLARITY WiFi-6
Frequency	5.180 GHz
Bandwidth	160 MHz
Throughput	600 Mbps
Signal strength	-40 dBm
RX bitrate	1200.9 MBit/s 160 MHz HE-MCS 11 HE-NSS 2 HE-GI 0 HE-DCM 0
TX bitrate	1200.9 MBit/s 160 MHz HE-MCS 11 HE-NSS 2 HE-GI 0 HE-DCM 0
LiFi	
Throughput	10 Mbps
LiFi AP	pureLiFi-X
LiFi Client	pureLiFi USB dongle

Figure 3-6 and Figure 3-7 display the 5G radio units, WiFi-6, and LiFi access points featuring the previously mentioned specifications. These units were initially utilized in the Smart Internet Lab Bristol for initial 5G-CLARITY KPI validation in a laboratory environment. Subsequently, the equipment was deployed at the M Shed Museum in Bristol for the UC-1 demonstration.

Figure 3-6 5G Radio Units at the Smart Internet Lab.

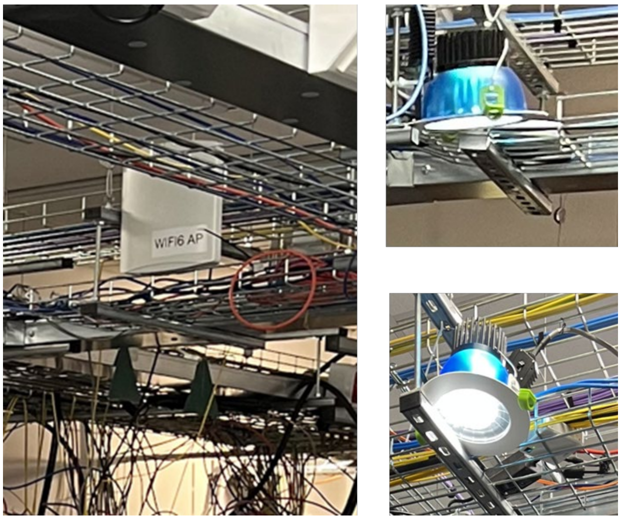

Figure 3-7 WiFi-6 and LiFi APs at the Smart Internet Lab.

3.2.2 Smart Internet Lab

The University of Bristol's Smart Internet Lab location host the Edge cluster for virtualized core network and application functions for the 5G-CLARITY UC-1 demonstration. The Smart Internet Lab site hold the following infrastructure:

- Virtualization Infrastructure
- Compute Resources
- Fibre network

3.2.2.1 Virtualization Infrastructure

To create the cloud infrastructure that houses the Virtual Network Functions (VNFs), the University of Bristol is using the OpenStack Wallaby version of the Virtualized Infrastructure Manager (VIM). This consists of a collection of OpenStack compute nodes that are installed on servers that have GPUs in the datacenter, which is housed in the server room of the Smart Internet Laboratory. It houses virtual machines (VMs) and virtual/physical network functions (VNFs/PNFs) running the 5G-CLARITY infrastructure (such as slice manager, NFVO, dashboards, and monitoring tools). Figure 3-8 pictures the rack in red frame holding the OpenStack deployment at the Smart Internet Lab.

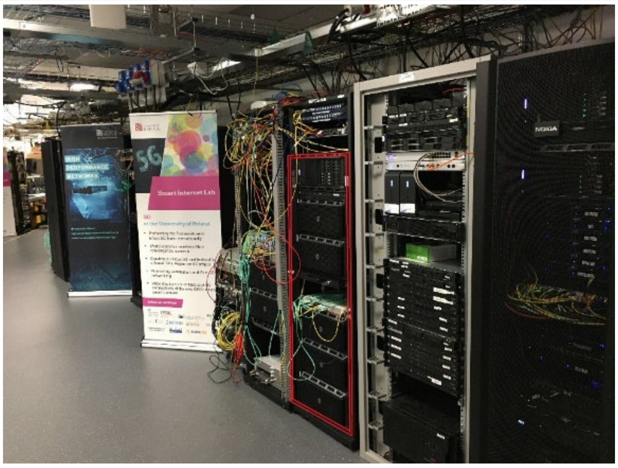

Figure 3-8 Dell server deployment of OpenStack at the Smart Internet Lab

3.2.2.2 Fibre Link

A high-speed, low-latency fiber-optic connection has been established between the Smart Internet Lab (the UC-1 Edge cluster) and the M Shed Museum (the UC-1 RAN cluster).

3.2.3 M Shed museum

The M Shed building is the location of the Bristol M Shed Museum and host of the 5G-CLARITY Smart Tourism demonstration UC-1. The building is a key location within the Bristol city centre hosting some of the University of Bristol 5GUK test network infrastructure. The site provides an NFV infrastructure environment for the execution of the virtualized functions and applications from the various 5G-CLARITY system strata in addition to hosting them. 5G access nodes such as gNB-CU, DU, and RIC are hosted by the RAN cluster. In relation to UC1, the RAN cluster will host the virtualized RAN functions that are installed at the M Shed museum in Bristol. Figure 3-9 presents the layout of network connectivity at the location.

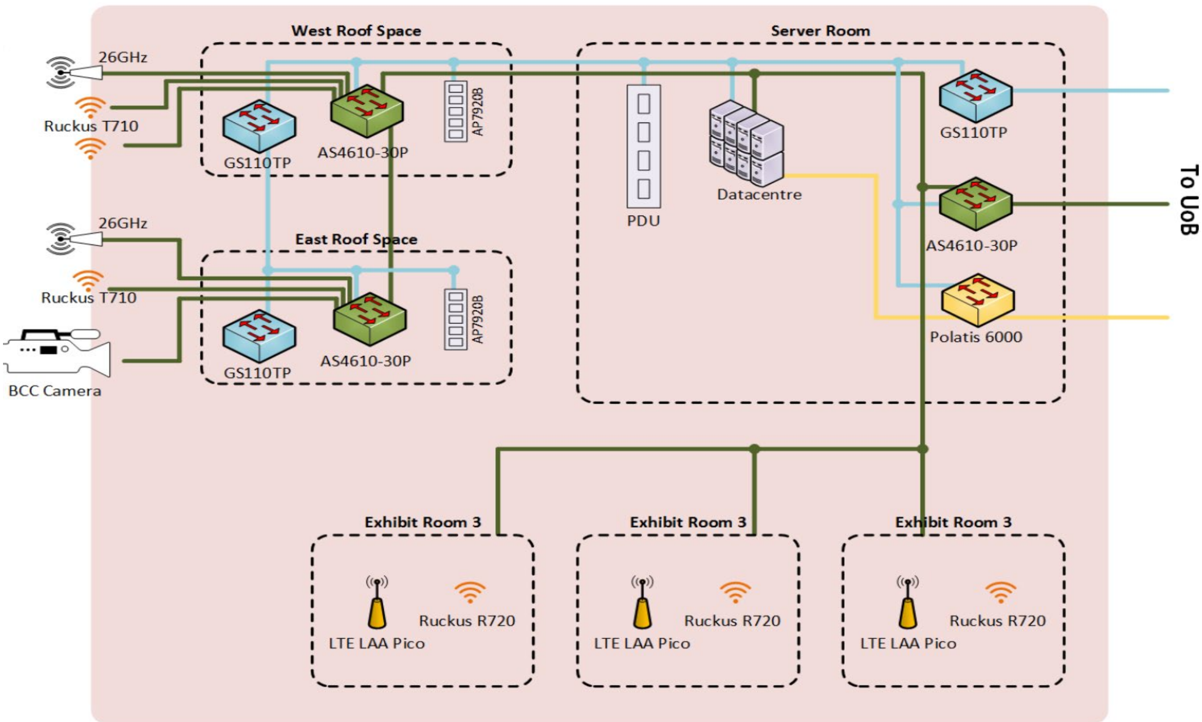

Figure 3-9 Network connectivity in support of UC-1 at M Shed.

3.3 Use Case implementation and scenario definition

In this section we describe the process of translating the 5G-CLARITY UC-1 into a functional system by defining the specific steps and interactions between the user and the use case. To show the use case implementation and define the scenario we have organised this section in the following steps:

- Use case analysis: Here we analyse 5G-CLARITY UC-1 and the main goals.
- Scenario definition: We define the specific situations in which the use case was executed.

3.3.1 Smart Tourism Use case analysis

As mentioned earlier, the Smart Tourism demonstration aims as follows:

i. To provide validation for the 5G-CLARITY multi-connectivity framework through the deployment of Smart Tourism App for visitors' assistance in a museum environment, and

ii. to validate the deployment of public safety service using 5G-CLARITY Intent Engine developed in WP4.

3.3.1.1 Validating 5G-CLARITY multi-connectivity framework for smart tourism and public safety deployment with intent engine

The museum management aims to introduce smart tourism by utilizing robot services as part of their strategy to improve visitor experiences. To accommodate the increased number of visitors this initiative is expected to attract, the management plans to enhance public safety within the museum space by equipping these robots with sensors, such as 360-degree cameras, to provide additional safety surveillance.

The objectives of this use case are to design, implement, validate, and demonstrate the following scenarios:

1. The 5G-CLARITY multi-connectivity framework within a private network setup, which enables intelligent, resilient, and pervasive interactions between a robot (serving as a tour guide) and humans visiting a museum.
2. The validation of public safety video service deployment using the intent engine. This involves the remote, on-demand deployment of video service from a 360-degree surveillance camera by a safety officer. In this context, the 5G-CLARITY UC-1 is utilized to demonstrate the advantages of the 5G-CLARITY framework and infrastructure in enhancing tourism and entertainment sectors in public spaces, while also supporting emergency and surveillance services for public safety.

To achieve these objectives, fixed wireless cameras equipped with motion-sensitive and obstacle detection capabilities are utilized to support the robot, enhancing its self-awareness. A 360-degree camera is mounted on the robot, and a multi-connectivity compatible CPE is attached to ensure network coverage for both the camera and the robot from 5G NR, WiFi-6, and LiFi access points. Furthermore, a safety officer can remotely deploy video service from the 360-degree camera through intent engine on a monitoring device.

The UL capacity requirement for each of the devices are given below, while the architecture for the multi-connectivity support for the 5G-CLARITY Smart Tourism application, KPIs and surveillance video are presented in Figure 3-10. From the architecture, the following communication flows can be observed:

1. The two fixed wireless cameras transmit raw feeds for processing to support the robot's obstacle detection. This requires an uplink data rate of up to 12 Mbps (2 x 6 Mbps), while the control system needs 1 Mbps.
2. From the 360-degree camera, an UL data rate of up to 126 Mbps is required to transmit the feeds to a forwarding unit provisioned at the museum's edge. The forwarding unit then delivers the feeds to a monitoring device, while the control system requires additional 1 Mbps.

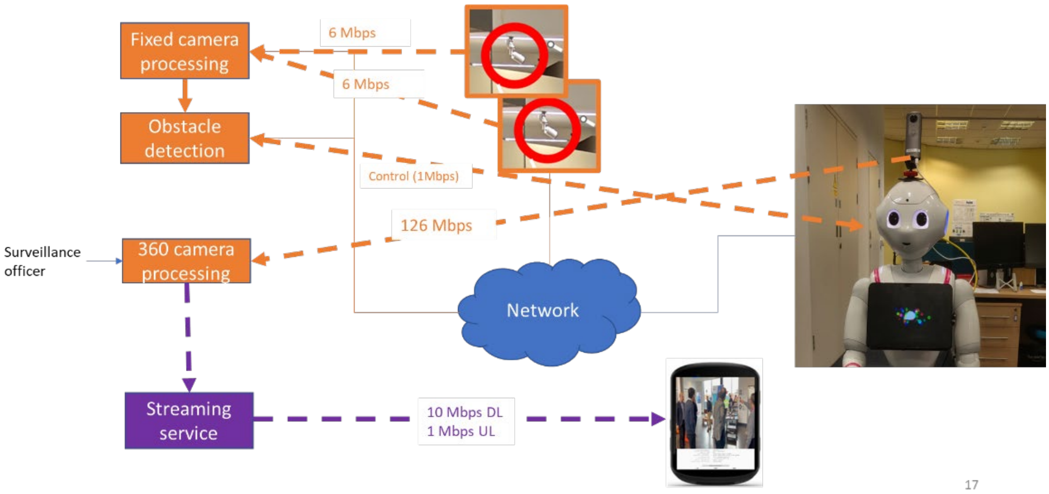

Figure 3-10 Architecture of Smart Tourism App and service KPIs

Figure 3-11 A snapshot from one of the motion sensitive cameras.

The fixed wireless cameras enhance the robot's self-awareness capabilities by detecting movements and converting the positions of movable objects into a map that indicates obstacle locations. This information guides the robot along a path free of obstructions. An example of this can be seen in Figure 3-11, which displays a perspective captured by one of the fixed cameras, with the frames highlighting the motion sensitive obstacles.

The metrics for the robot and camera for the UC-1 scenarios are as follows:

Fixed camera UL capacity requirement:	2x [3 – 6] Mbps	= 12 Mbps
360-degree camera:	1x [100 – 126] Mbps	= 126 Mbps
Safety officer monitoring device	1x [1 - 1] Mbps	= 1 Mbps
Control	1x [1 – 1] Mbps	= 1 Mbps
Camera processing delay:	0.03s - 0.3s,	
Detection precision:	0.1 - 0.2m	
Robot's mobility (speed):	0.25m/s	

Total range of UL requirement = [**108 – 140**] Mbps

Considering the upper limit of 140 Mbps uplink requirement, it is challenging for a single WAT to provide consistent and reliable connectivity for these devices across the entire coverage area of the museum. Hence, we aim to determine the most effective way to deliver adequate wireless capacity in support of the museum's smart tourism initiative by implementing the 5G-CLARITY multi-connectivity framework. This involves identifying the optimal combination of access networks, the appropriate number of access points, and the most advantageous access point locations to ensure optimal coverage and capacity.

3.3.1.2 Scenario definition

While the previous section derives an aggregate UL requirement in the range of 108 Mbps – 140 Mbps throughput in the museum, which justifies the need for the 5G-CLARITY multi-connectivity framework. In this section, we describe a scenario that demonstrates the implementation of the intent engine for the 5G-CLARITY Smart Tourism use case.

- A museum safety officer remotely requests specific surveillance footage from the 360-degree camera to be streamed to a monitoring device.
- To achieve this, a streaming server is required for the monitoring device to connect to.
- As the safety officer may not possess technical expertise in managing and orchestrating virtualized network functions and services, the 5G-CLARITY intent engine streamlines this network management process for them.
- By utilizing the intent engine, the safety officer can send an intent request to display video service from the 360-degree camera using natural language processing.
- The safety officer then sends the intent request: "*Display 360-degree video*".
- The service for the intent request is instantiated by description.

To deploy this service, a virtual media forwarding unit is set up at the edge within the museum, which is depicted in purple in Figure 3-10. This unit is responsible for transmitting the robot's camera feed to the safety officer monitoring device resulting in a DL data flow of 10 Mbps.

3.3.2 Smart Tourism Demo setup

In this section we present the different technologies and equipment deployed in the Smart Tourism use case demonstration. Based on the defined scenarios we describe the design specifications and interfaces used in implementing the use case. Finally, in section 3.4 we present test measurements and validated results meeting the use case requirements.

3.3.2.1 Equipment and infrastructure deployment

The 5G Nokia radio, WiFi-6 connectivity via Ruckus AP and LiFi via PureLiFi APs were all installed at the museum demonstration area. Fixed cameras were mounted to track the robot for navigation and positioning purposes. Figure 3-12 5G radio, and WiFi-6 and LiFi APs deployed inside the museum. Figure 3-13 shows pepper robot fitted with 360-degree camera and 5G-CLARITY CPE.

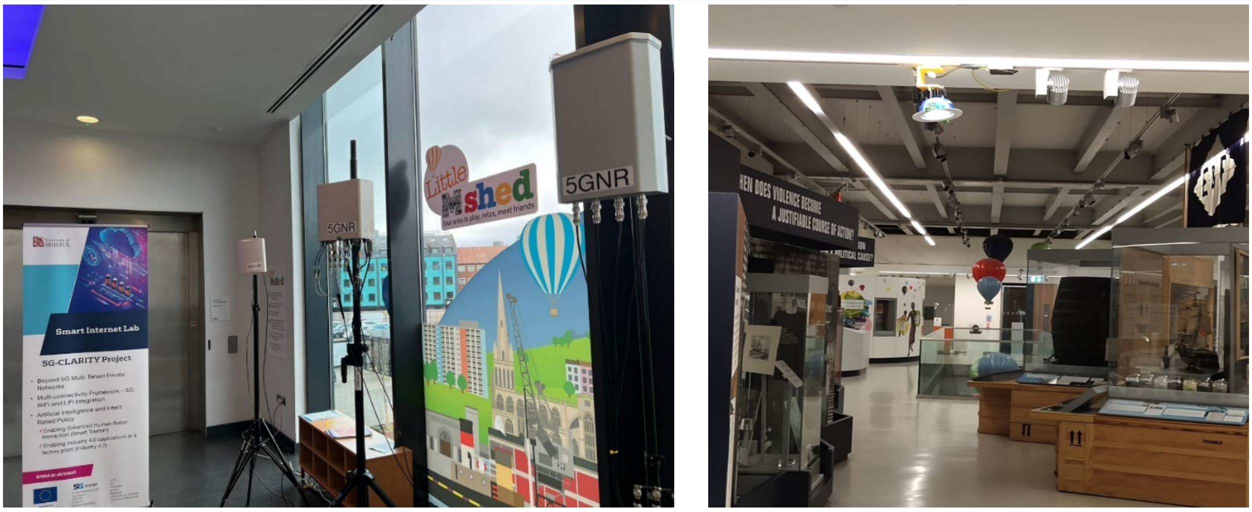

Figure 3-12 5G RUs, WiFi-6 and LiFi APs in demo area.

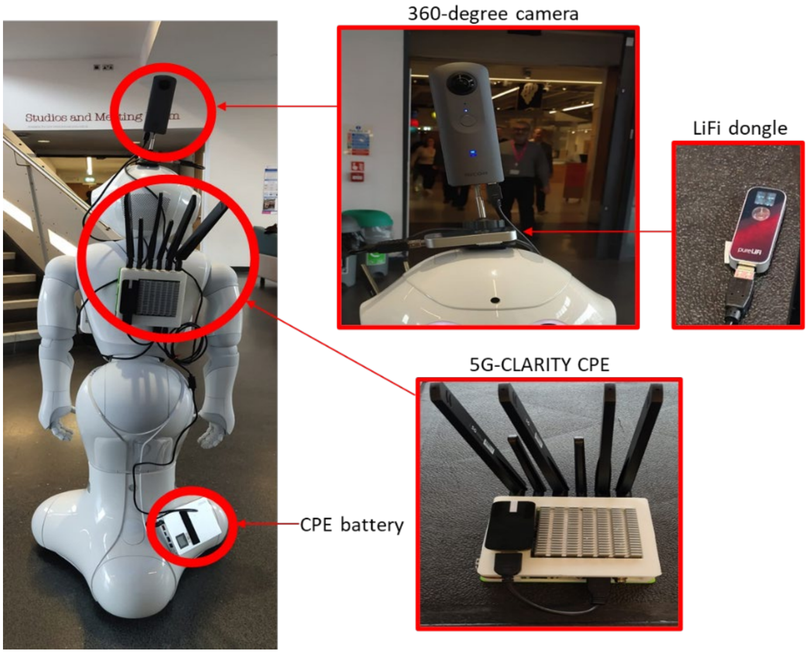

Figure 3-13 Robot with 360-degree camera and CPE.

3.3.3 Use Case specific KPIs

In this section we report the functional validation executed in the museum demonstrating the two main goals of the use case:

i. The target requirement of providing an aggregate UL data rate, enough to support up to 140 Mbps throughout the museum.

ii. The intent engine deployment in support of on-demand 360-degree video services requested by a public safety officer. This deployment will be demonstrated as an example of a management enabler, using the intent engine to facilitate the fulfilment of user requests.

3.3.3.1 Validating aggregate UL capacity

We conducted a minimum of 10 rounds of measurements within the demonstration area to verify the key performance indicators that are specific to the 5G-CLARITY smart tourism use case.

The aggregated UL traffic performance is illustrated in Figure 3-14. The figure displays the combined throughput performance results of LiFi, WiFi-6, and 5GNR along the robot's path across the coverage area in the museum. The result shows a combined UL traffic of around 140 Mbps. Throughout the demonstration area, the aggregated link had enough UL capacity to support the range of 108 Mbps to 140 Mbps required for the use case, despite the signal drop towards the end of the coverage area.

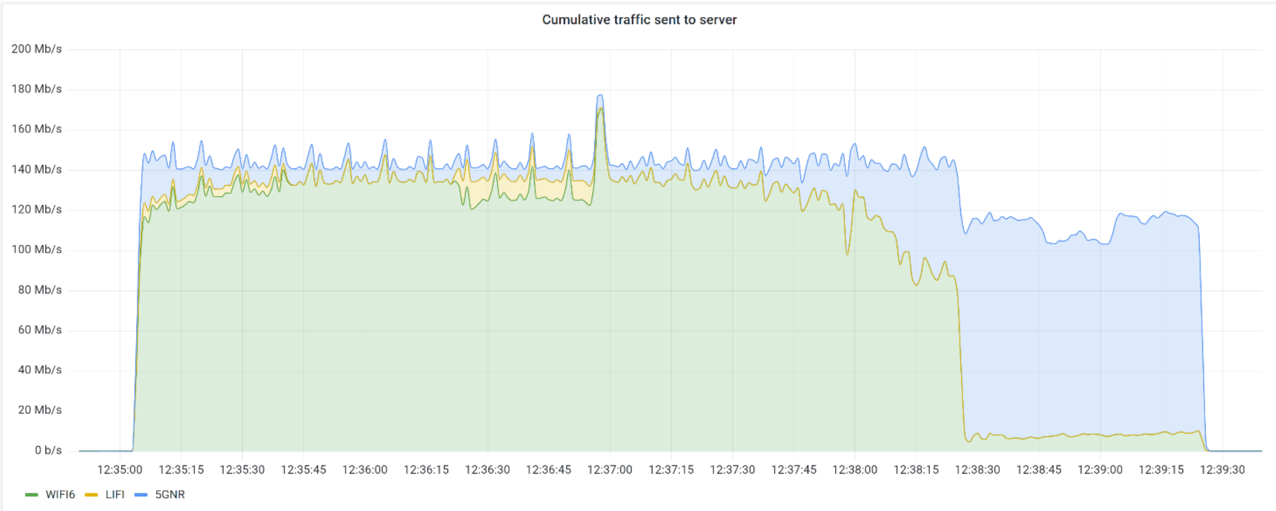

Figure 3-14 Aggregated UL Traffic to the server for UC-1 specific KPI.

Figure 3-15 shows the aggregated UL traffic, with 5G complementing WiFi-6 degrading performance. This finding is particularly significant because it demonstrates how MPTCP distributes resources to ensure adequate capacity provisioning based on requirements. The figure illustrates that as WiFi-6 performance declines, 5G capacity increases. This additional capacity allows 5G to supplement the WiFi-6 signals effectively, thereby maintaining the enough UL capacity for the use case.

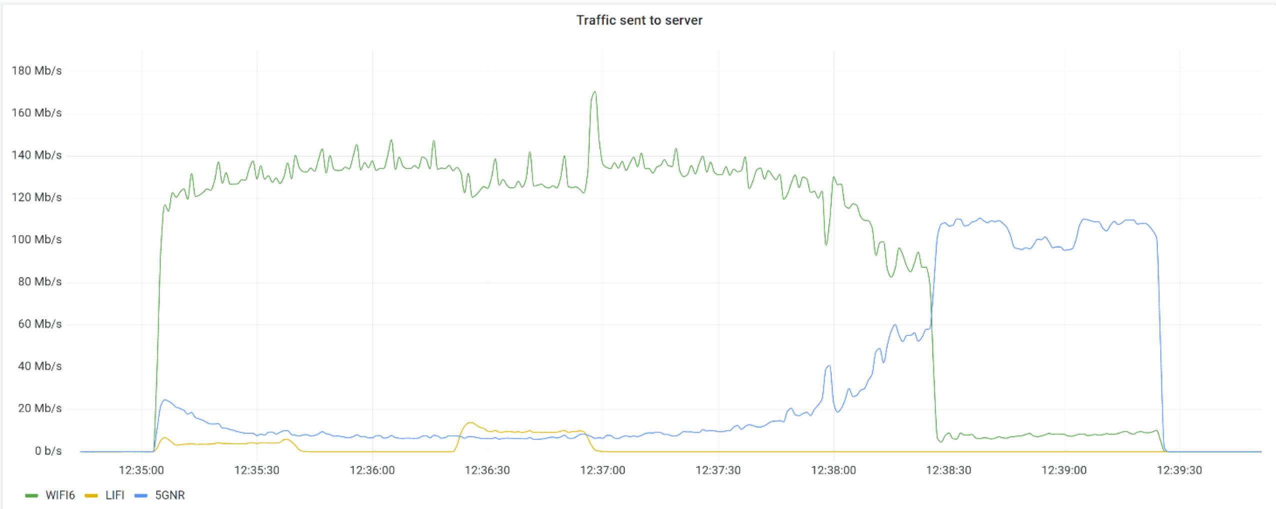

Figure 3-15 Aggregated UL Traffic with 5G complementing WiFi-6 degrading performance.

3.3.3.2 Functional demonstration of Intent Engine operation

This section presents the implementation of the 5G-CLARITY intent engine platform, which is based on a Natural Language Processing (NLP) interface. The platform simplifies network operations in an intent-based video service deployment. It demonstrates how the 5G-CLARITY intent engine can be used by the museum safety officer as a management enabler to dynamically provision on-demand public safety video service.

To implement the deployment scenario, the museum safety officer utilizes a monitoring device to remotely issue an intent request using natural language, such as "360-degree camera service." This request prompts the intent engine to instantiate the service by providing a detailed description and requesting the NS (Network Service) catalogue from the OSM.

The intent engine then matches the intent description to the catalogue description and returns the identification of the appropriate NS. The entire process, including messaging transitions, is illustrated in Figure 3-16, in five different windows.

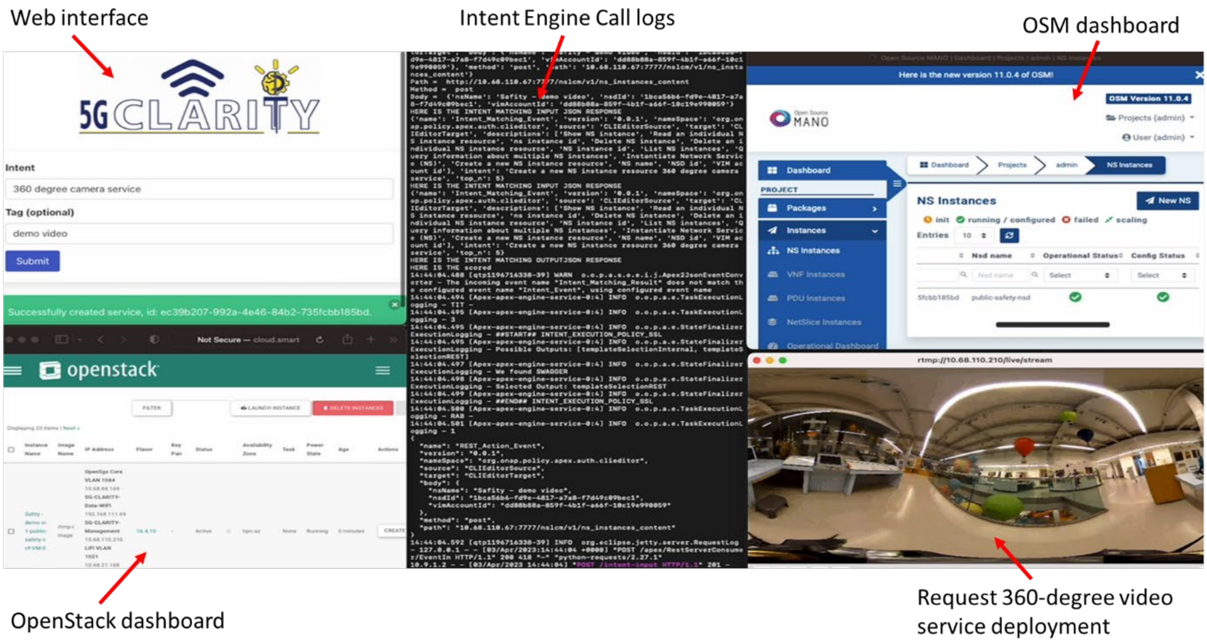

Figure 3-16 Snapshot of the intent engine web interface and interactions in the NFV orchestration process.

The display on the windows shows the process in which a safety officer, using a device, can remotely request the deployment of a 360-degree video. This action initiates a series of interactions in the NFV orchestration process, ultimately resulting in the deployment of the network service on the device.

The sequence of actions required for this process can be summarised as:

1. An intent request is made using natural language from the safety officer's device.
2. The 5G-CLARITY intent engine generates call logs and creates an instance of the network service.
3. In the OSM GUI dashboard, an orange tick confirms that the NS instance has been initialized.
4. The OpenStack GUI dashboard shows the VNFs are instantiated.
5. Then the OSM dashboard verifies that the NS instance has passed its instantiation and validation tests, and the ticks turn green to indicate that it is now running.
6. Finally, the requested 360-degree video service is deployed on the safety officer's device.

3.4 Transversal KPI evaluation

To complement the functional use case demonstration reported in the previous section, in this section, we present an exhaustive analysis of the Key Performance Indicators introduced in section 2.4 for the Bristol Smart Tourism demonstration, "Enabling Enhanced Human-Robot Interaction." The KPIs are identified, and the scenarios in which the measurements are validated are described. These KPIs will be used in section 6 to derive a cost model for the deployment of 5G-CLARITY technologies in museum environments.

3.4.1 Test Measurement Location

The KPI measurements are performed at the Bristol M Shed Museum, venue of the 5G-CLARITY UC-1 demonstration. The location offers a real deployment environment for measurements and KPI validations.

To perform the test measurements under a real deployment environment we have configured the different access networks to provide adequate coverage within the museum space for the purpose of our smart tourism showcase. The demonstration area consists of two main areas – reception and Bristol people, all within the first floor of the museum complex. The guide robot equipped with the CPE travels approximately 50 metres from the reception to the end of the Bristol people area. To evaluate the KPIs, measurements of 5G, WiFi-6, and LiFi coverage are taken.

3.4.1.1 Measurement considerations

As previously mentioned, we conducted a minimum of 10 rounds of measurements in all the key performance indicators verifications within the museum demonstration area.

For the KPIs each round involved moving the robot, which was equipped with the CPE, from point A to point D, covering a total distance of 50 metres.

As shown in Figure 3-17, the robot's starting position is in the museum's reception area under a LiFi AP, and within approximately 8 meters of a WiFi-6 AP, and a 5GNR radio. This means that at the starting position, the robot is within coverage area of all three access networks.

To provide further context, we will now describe the building's characteristics. The museum is spread across three floors and comprises predominantly of glass panels, metal, aluminium, concrete, and wooden walls. Figure 3-17 depicts a floor plan of the coverage area, which is representative of the other floors.

Each floor is divided into two main sections - the reception area and the Bristol people area. The reception area is mostly an open space, with a largely line-of-sight scenario, while the Bristol People area is densely packed with exhibition articles, creating various obstructions such as soft partitions, walls, glass showcases, metals, and frames between the transmitter and receiver, forming a non-line-of-sight scenario.

Figure 3-17 shows the middle floor of the multi-storied museum, highlighting the placement locations of the different access networks. These details provide a comprehensive picture of the indoor museum's layout and architecture, and how the different sections of the building may affect the network performance of the access networks deployed.

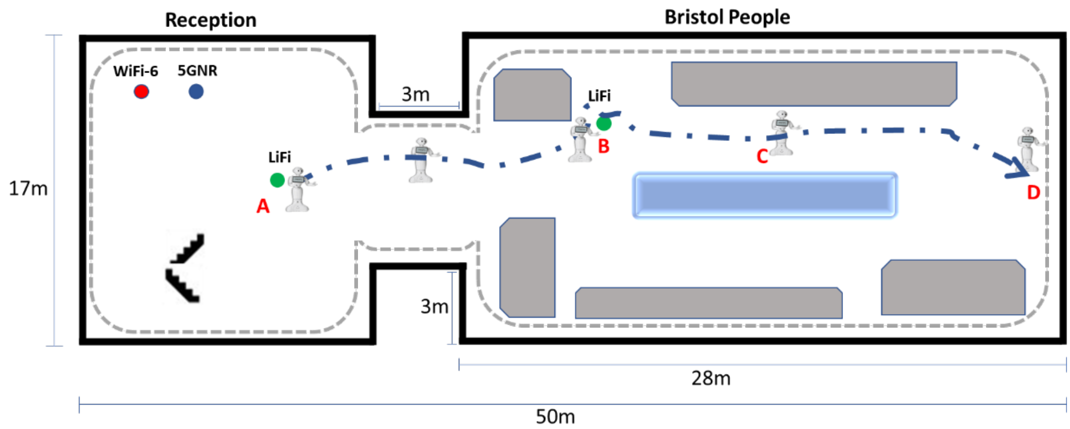

Figure 3-17 UC-1 demo area floor plan, robot path and APs placement.

3.4.2 Transversal KPIs descriptions

The Bristol UC-1 measures Throughput, Latency and Mobility related KPIs introduced in Section 2.4 using a CPE when deployed on a mobile robot. Initial laboratory validations of UC-1 transversal KPIs have been reported [1] and [3]. For the field trials at the Bristol M Shed Museum, measurements are collected at a range of distances from the access network as the robot travels with the CPE. Measurement parameters and scenarios for the mobility related KPI are described in the Table 3-3. The reference positions for these locations have been marked **A**, **B**, **C**, and **D**, in Figure 3-17.

All the measurements are specific to the scenarios described within the museum locations and results will be used for UL and DL comparison.

Table 3-3 Mobility related KPI measurement parameters.

Access Network	Measurement Device	Distance from AP (metres)	Obstacle presence / Interference level %	Measurement Positions
5GNR	CPE	0-5	None – very low 0-20%	**A**
Wi-Fi				
LiFi				
5GNR	CPE	13 – 15	Low 40%	**B**
Wi-Fi				
LiFi				
5GNR	CPE	35 – 36	High 60%	**C**
Wi-Fi				
LiFi				
5GNR	CPE	45-50	Higher 80%	**D**
Wi-Fi				
LiFi				

The chosen distances of 5 meters, 15-20 meters, and 45-50 meters in Table 3-3 provide a good range for comparison within the indoor environment and can be justified as follows:

1. **Position A: 0-5 meters from AP**:

   This distance represents a very close proximity to the access point, which is typical in scenarios where users are near the access point, without any impactful obstacles and hence constitute a line-of-sight scenario. Measuring performance at this distance provides insight into the best-case connectivity and potential maximum throughput that can be achieved in an indoor setting.

2. **Position B: 13-15 meters from AP**:

   This distance represents a close-range distance from the access point. By measuring at this distance, we evaluate how both 5G and WiFi-6 perform as the user moves further away from the access point. As there may be some low obstacles, it helps assess the stability and reliability of the connection in a more typical indoor usage scenario.

3. **Position C: 35-36 meters from AP**:

   This distance represents a far-range distance from the access point, approaching the edge of the coverage area for WiFi-6 and potentially pushing the limits of connectivity in indoor environments. Measuring performance at this distance allowed us to understand the limitations and degradation of signal quality as users move further away from the access point. It helps to recognise coverage gaps, identify areas where WiFi-6 performance degrades and the coverage strength of 5G across the demonstration area.

4. **Position D: 45-50 meters from AP**:

   This distance represents the farthest from the access point, reaching the boundary of the coverage area for WiFi-6 and further pushing the limits of connectivity in the museum scenario. Measuring performance at this distance allowed us to better understand the limitations and degradation of signal quality as users move further away from the access point. This analysis like the previous measurement also helps to recognise coverage gaps and identify spots with limited WiFi-6 coverage and the coverage strength of 5G across the demonstration area.

3.4.2.1 Throughput over distance measurements

This section outlines the results obtained from the measurement campaign conducted at the M Shed museum. We present the average throughput results from at least 10 performance evaluations conducted.

To begin with, we offer a graphical overview that highlights the individual UL contributions of the various access technologies, which illustrates the overall trends reflected in the aggregated UL results.

Figure 3-18 presents an UL traffic results for 5G, WiFi-6 and LiFi technologies. It shows their respective signal levels across the museum's coverage area. The graph shows that the WiFi-6 signal experiences significant fluctuations and its quality decreases as the distance from the AP increases. The signal starts at around 890 Mbps but deteriorates as the distance increases, eventually dropping to approximately 50 Mbps at location **D**.

Also, a difference in signal levels between the two LiFi APs can be observed, which can be attributed to the disparity in the height at which their respective APs are positioned. The access point installed at location A is elevated at a height of 4.2 metres, whereas the one at location B is positioned a lower height of 2.9 metres. This variation in APs heights at the two locations is a result of the museum building having different ceiling heights at both locations.

In terms of 5G, the performance of 5GNR remained consistent and strong throughout the coverage area, maintaining an average throughput of around 100 Mbps in all sections of the museum.

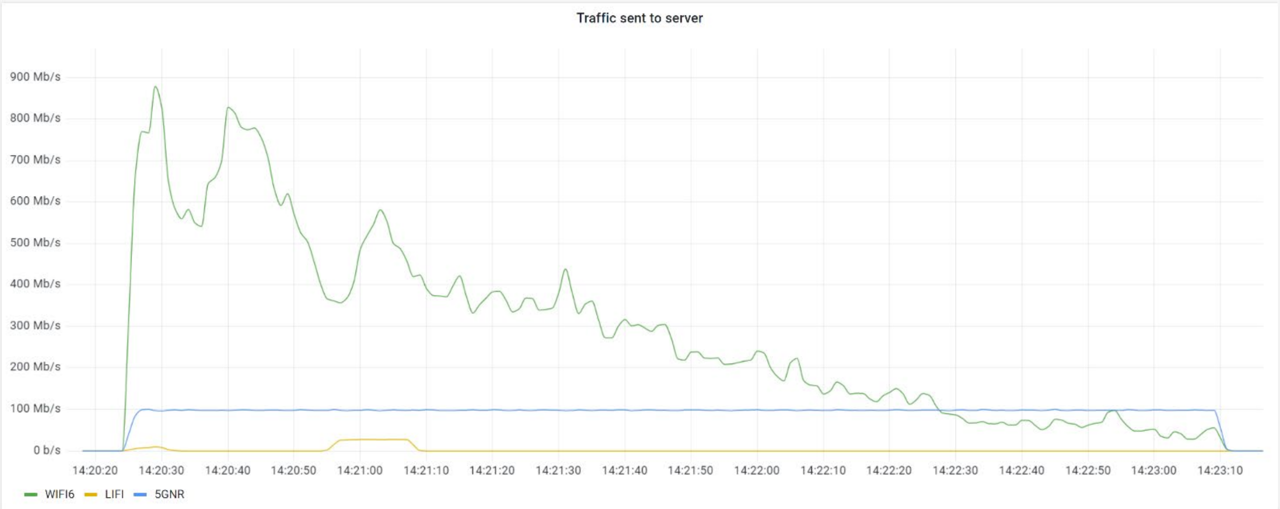

Figure 3-18 UL traffic 5GNR, WiFi-6 and LiFi access technologies.

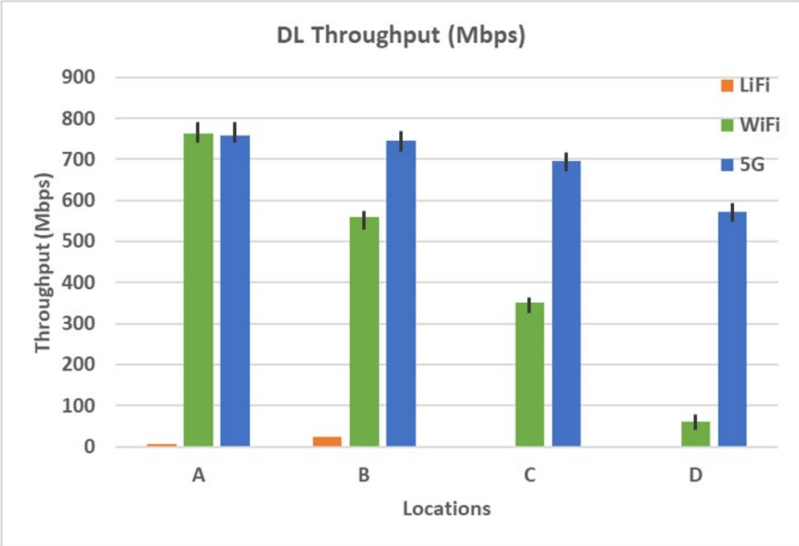

Figure 3-19 Average DL measurement for Radio Access Technologies.

The above description indicates that the combined links have enough capacity to meet the 140 Mbps uplink requirement, even though WiFi-6 performance dropped to approximately 50 Mbps, below that of 5G. This is possible due to the robustness exhibited by 5G in the uplink.

Figure 3-19 displays the average DL measurements for all three access technologies. It is noteworthy that WiFi-6 performance gradually deteriorates as the CPE moves further away from its starting position. On average, 5G exhibits a more consistent performance across various positions. The throughput performance of LiFi, on the other hand, differs between the two locations.

In Figure 3-20, the average UL measurement results for 5G, WiFi-6, and LiFi are presented. The results show that while WiFi-6 experiences significant performance degradation as the distance from the starting position increases, 5G maintains a stable 100 Mbps throughput across the entire coverage area, providing a valuable complement to WiFi-6 which averages around 50 Mbps at location **D**. The individual contributions to the overall throughput performance from each access technology can be seen. We can see that in location **D**, none of the technologies can individually provide the 140 Mbps that were required by the use case.

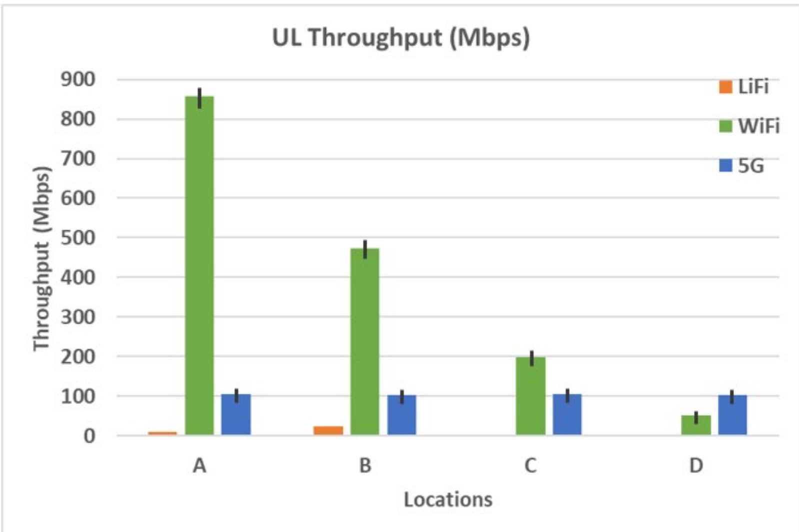

Figure 3-20 Average UL measurement for Radio Access Technologies.

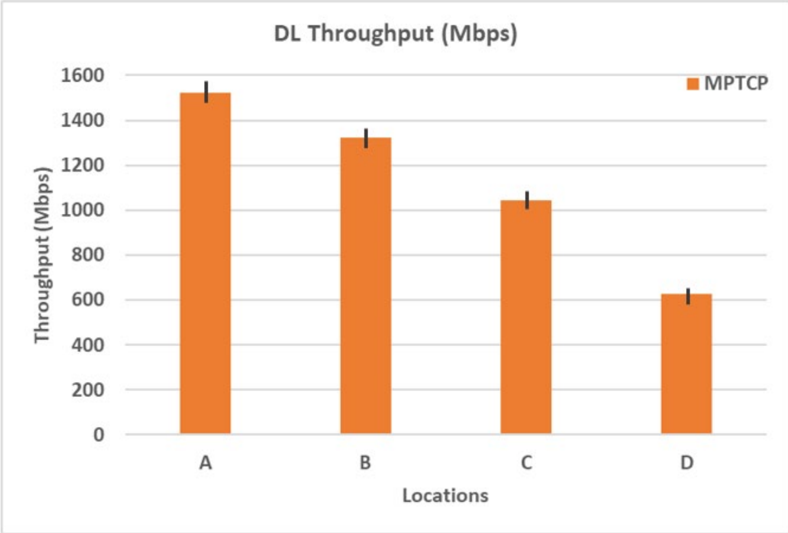

Figure 3-21 Average DL throughput with MPTCP in place.

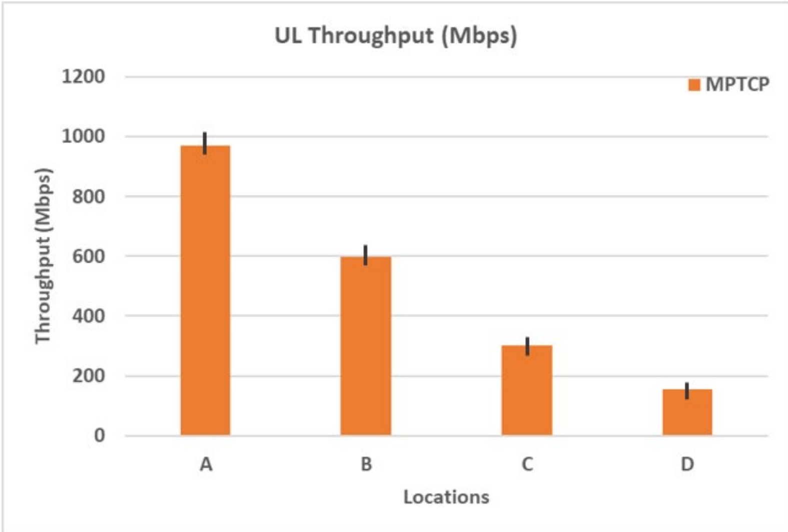

Figure 3-22 Average UL throughput measurement with MPTCP in place.

In Figure 3-21, the average DL throughput performance with MPTCP with round-robin scheduler is enabled is presented. The findings demonstrate the considerable performance improvement achieved through the implementation of MPTCP for link aggregation.

In Figure 3-22 the average UL throughput performance when MPTCP is in place is presented. From this and earlier results, it is evident that MPTCP enabled throughput aggregation brings great performance benefits, which demonstrates that the 5G-CLARITY multi-connectivity framework supports the UL requirements throughout the coverage area. We observe how thanks to the 5G-CLARITY multi-connectivity framework the 140 Mbps UL requirement is achieved in all tested locations.

3.4.2.2 Latency under interference Measurements

The latency measurements performed at the Bristol M Shed Museum are presented here. The KPI for measuring the duration of both LiFi and WiFi-6 Round Trip Time (RTT) latency is expressed in milliseconds. The aim of the latency measurements as a network KPI is to assess the responsiveness of the network in relation to the 5G-CLARITY multi-connectivity framework and the selected WATs behaviour under diverse interference conditions at varying distances from their respective APs. Table 3-4 has specified the nominal per-WAT data rates for the interference experiment conducted. According to the methodology described in

Section 2 we specify a nominal capacity for each tested WAT, from which 60% of interference is derived. The following table describes the configured interference.

Table 3-4. Nominal per-WAT data rates for interference experiment

	Nominal DL Rate (Mbps)	Nominal UL Rate (Mbps)	Example: 60% UL interference (Mbps)	Example: 60% DL interference (Mbps)
LiFi	8	8	4.8	4.8
WiFi	900	900	540	540
5G	900	100	540	60

To optimize latency performance, the 5G-CLARITY multi-connectivity framework is configured in redundant mode for these experiments. Figure 3-23 report results of UL and DL latency measurements at four different locations within the M Shed museum as experienced by the mobile CPE. Multiple runs were executed with varying levels of interference introduced at different reference points. All the sample obtained from the multiple runs were then aggregated using lagscope, from which the resulting latency distributions were plotted.

3.4.2.3 Result Analysis:

The results in Figure 3-23 depicts the outcomes of the latency measurements conducted under various interference level configurations for the different technologies, as outlined in Table 3-4.

These measurements were taken in a demonstration scenario that reflects the network topology, quality of service requirements, traffic size, and distance between the endpoints. The analysis presented below is based on the observation of the results.

1. Down Link vs Up Link:

Based on our examination, it reveals that the interference condition had a more significant impact on the DL latency than the UL latency at all locations measured. This could be explained by the application and usage patterns employed in the smart tourism use case traffic requirements, which predominantly involved video feeds and streaming services.

Across all four locations, the UL traffic experienced lower latency interference than the DL traffic. As expected, the latency tends to increase with distance for both traffic types.

2. Interference Level Configurations

Given the nominal per-WAT data rates configured for the different interference levels, there is higher disparity between the WiFi-6 and 5GNR configurations in the DL and UL. While the UL for both technologies have identical data rates the DL interference levels varies greatly. The data rates for 5G are higher in the UL compared to the DL, which may provide greater robustness for UL traffic. This potentially could account for the greater level of distorted latencies experienced in the DL.

However, it was our observation confirms that the RTT stayed under 20 ms for both the UL and DL traffic. This latency level is sufficient for the remote control and offloading operations, as it indicates that the network can effectively support these operations without significant delays or interference [4].

3. Location C observation

An interesting interference behaviour occurred at location **C**, where there was a spike in the observed latency levels. This spike can be attributed to the obscured corner of the location within the museum and the cluster of reflective exhibition items positioned around that location. Even though the location was a few metres closer to the APs compared to the final location **D**, the higher interference levels indicate the impacts of the exhibition items on the interference condition of the location. This location has the greatest degree of NLOS scenario among all four locations.

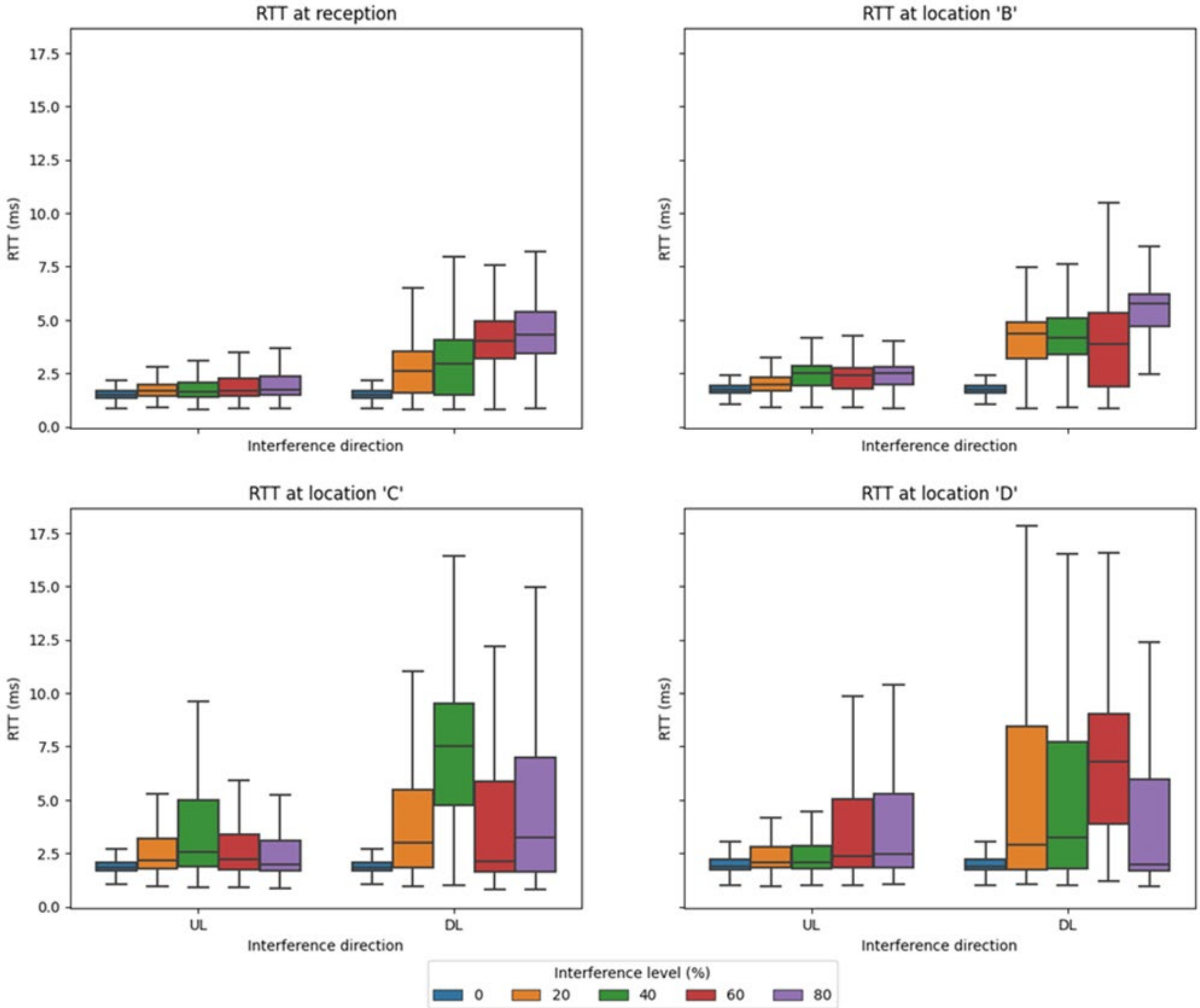

Figure 3-23 Round trip time latency measurements from four different reference positions.

3.4.2.4 Mobility related KPI

The mobility related KPI measurements are conducted for WiFi-6 and LiFi access technologies. 5GNR has not been measured using the same metric, given the higher level of reliability of 5GNR link as has been explained in Inter/Intra-WAT mobility. The objective of measuring mobility related KPIs is to ensure optimal access point placement, providing coverage overlap and continuous connectivity while taking reconnection time into account. This is important as links may become unavailable when the mobile robot carrying the CPE moves beyond the coverage area.

Figure 3-24 illustrates a detailed time sequence diagram for the re-establishment of a LiFi connection, based on four different events or connection re-establishment stages. The diagram begins with the event "SME: TRYING TO AUTHENTICATE" assumed to occur at time 0 and finishes in the "MPTCP JOIN" event, which represents the final stage in the sequence. Each event in the diagram is assigned a numerical value representing the elapsed time from the start of the sequence up to that particular event.

To provide an accurate overview of these times, three different series are presented: minimum, average, and maximum times of multiple retries. For instance, the maximum time taken from the first event to the last one, i.e., "MPTCP JOIN," is 556,920 microseconds, which is roughly 550 milliseconds.

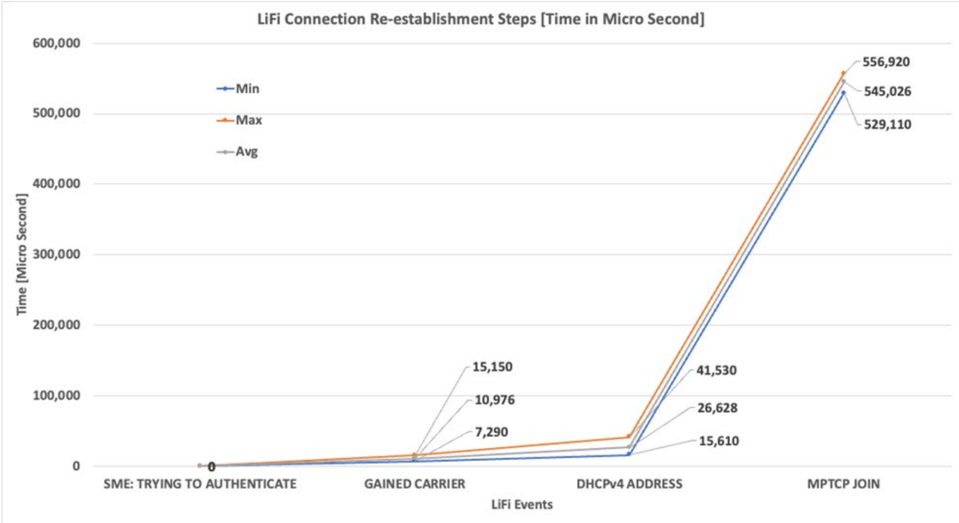

Figure 3-24 Mobility related KPI for LiFi reconnection steps.

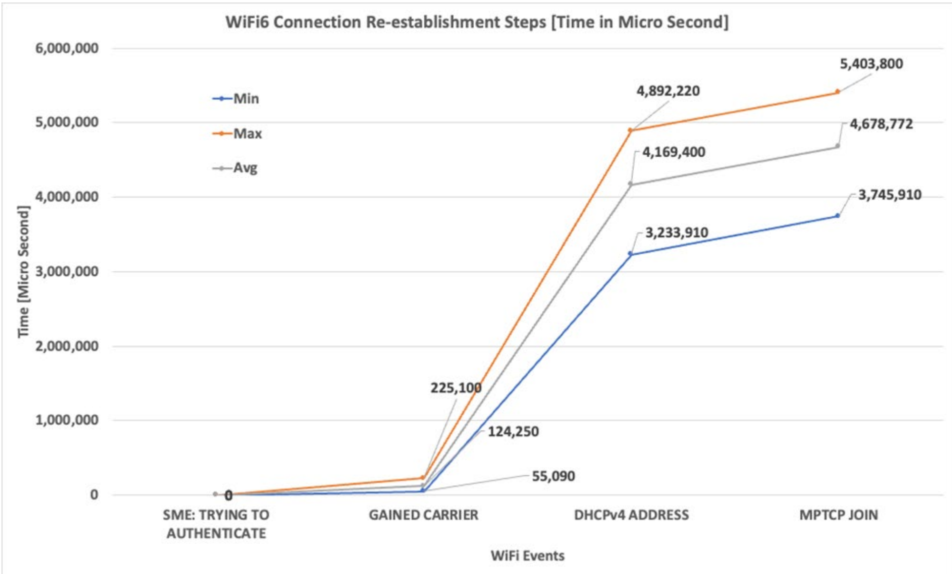

Figure 3-25 Mobility related KPI for WiFi-6 reconnection steps

The time sequence for re-establishment of a WiFi-6 connection is presented in Figure 3-25. Three different series are also presented to indicate the minimum, average and maximum times calculated from the multiple retries. The maximum time taken from the first event to the last one, i.e., "MPTCP JOIN," is 5,403,800 microseconds, which is about 5,400 milliseconds and on average requires 4,678,772 microseconds which translates to approximately 4700 milliseconds for the same series of event (first to last).

3.4.2.5 Conclusion

The goal of mobility related KPI measurements is to identify areas of the network that need improvement and take appropriate actions to improve the network's performance, reliability, and user experience, especially for the CPE device that rely on continuous connectivity.

Based on the results that it takes a maximum of approximately 4.7 seconds for the mobile CPE device traveling at a speed of 0.25m/s to establish reconnection with the WiFi-6 network, it indicates that there is need for coverage overlap of about 1.2m to ensure a seamless handover process between WiFi-6 access points in the network.

This means that the coverage areas of the access points should overlap by at least 1.2 m to allow for a smooth transition of the mobile device from one access point to another without experiencing a disconnection or significant delay in re-establishing a connection. Ensuring a seamless handover process is crucial for maintaining continuous connectivity and a high-quality user experience for mobile devices that rely on WiFi-6 networks.

For the LiFi with a maximum reconnection time of 0.5 seconds with device speed of 0.25 m/s, it suggests that the handover process is able to quickly establish a new connection even when the device is moving at a moderate speed. However, the conclusion from these results have wider implications for the general research community who may find relevant use and application of the results.

4 BOSCH UC2-1: Demonstration and KPI evaluation

In this section we describe the results of the 5G-CLARITY demonstration executed in BOSCH related to UC 2.1: "Infrastructure slicing to support Industry 4.0 services". The section is organized as follows:

- Section 4.1 briefly summarizes the main goals of this demonstrator and describes the different steps required to deploy the network infrastructure and execute the demonstration.
- Section 4.2 describes the 5G-CLARITY infrastructure and architecture deployed in the factory to support the use case.
- Section 4.3 describes the results of the use case specific KPIs that were measured during the execution of the demonstration.
- Section 4.4 describes the results of the transversal KPIs introduced in Section 2.

4.1 Use Case objectives and execution plan

The execution of this use case has the following goals:

- Goal 1: Demonstrate the 5G-CLARITY infrastructure deployed in a manufacturing environment, benchmarking the capacity provided by the 5G-CLARITY multi-connectivity framework.
- Goal 2: Demonstrate the feasibility of connecting a production PLC to the 5G-CLARITY network and benchmark the latency in the communication between the PLC and a Manufacturing Execution Server (MES).
- Goal 3: Demonstrate the use of the 5G-CLARITY service and slice provisioning framework to manage the lifecycle of the 5G-CLARITY slices. In this case a slice to connect the AGV used in BOSCH UC 2-2 is used.
- Goal 4: Evaluate the transversal KPIs defined in Section 2 that will feed the 5G-CLARITY factory deployment model described in Section 6.

To execute the use case the following integration visits were required at the BOSCH factory:

- October 3rd – October 7th: The basic network infrastructure was deployed in the factory and a first coverage analysis was performed for each WAT. Feasibility of connecting a PLC was validated using a PLC emulation software running on a Windows machine.
- October 19th – October 21st: We validated a mobile CPE that allowed us to move throughout the factory while being connected to the different WATs. We also managed to connect the PLC of the production line, which differed from the original PLC planned in deliverable D5.2 [3].
- November 2nd – November 4th: We completed the infrastructure deployment installing two additional LiFi APs required to support the AGV use case. We validated the slice deployment for the AGV use case (UC2-2).
- November 7th – November 10th: Worked on stability and KPI measurements for the mobile CPE and the rack CPE, which was used to connect the PLC.
- November 21st – November 25th: Demonstration rehearsal and additional KPI measurements.
- January 23rd – January 25th: Additional measurement campaign to measure transversal KPIs.

4.2 Deployed network infrastructure and architecture

This section describes the network infrastructure required to support the use case, as well as their related configurations.

4.2.1 5G-CLARITY infrastructure in the factory

Figure 4-1 (left) depicts the factory layout, highlighting with a red start the point where the 5G-CLARITY portable rack, and associated antennas, were deployed. Figure 4-1 (right) depicts the portable rack, which was assembled at i2CAT before being shipped to the factory. In the upper part of the figure, we observe the three wireless access nodes: i) the 5G NR 3.9 GHz radio head, ii) the LiFi AP, and iii) the Wi-Fi 6 AP. The gNB software stack is provided by Amarisoft, the radio head by AW2S, the LiFi AP is provided by PureLiFi, and the Wi-Fi 6 AP is custom made based on the QCA6391 module and a Gateworks Venice GW7300 board. Table 4-1 describes the two network configurations evaluated in this use case, i.e. BOSCH-default, with a DL focused 5G configuration, and BOSCH-UL, with an UL focused 5G configuration.

The rack featured a supermicro server to host an Amarisoft based gNB, a DELL edge server with OpenStack Victoria featuring all the Virtual Network Functions (VNFs) required to support the two network slices described in the next section, a bare metal server hosting a mock-up MES function to connect the PLC, and an Edgecore Ethernet switch used to connect the different devices. Two additional LiFi APs, not visible in the picture, were also deployed along a corridor in the factory to support the AGV use case. Figure 4-1 (right) clearly illustrates the metallic environment existent in the factory, which creates a challenging radio propagation environment.

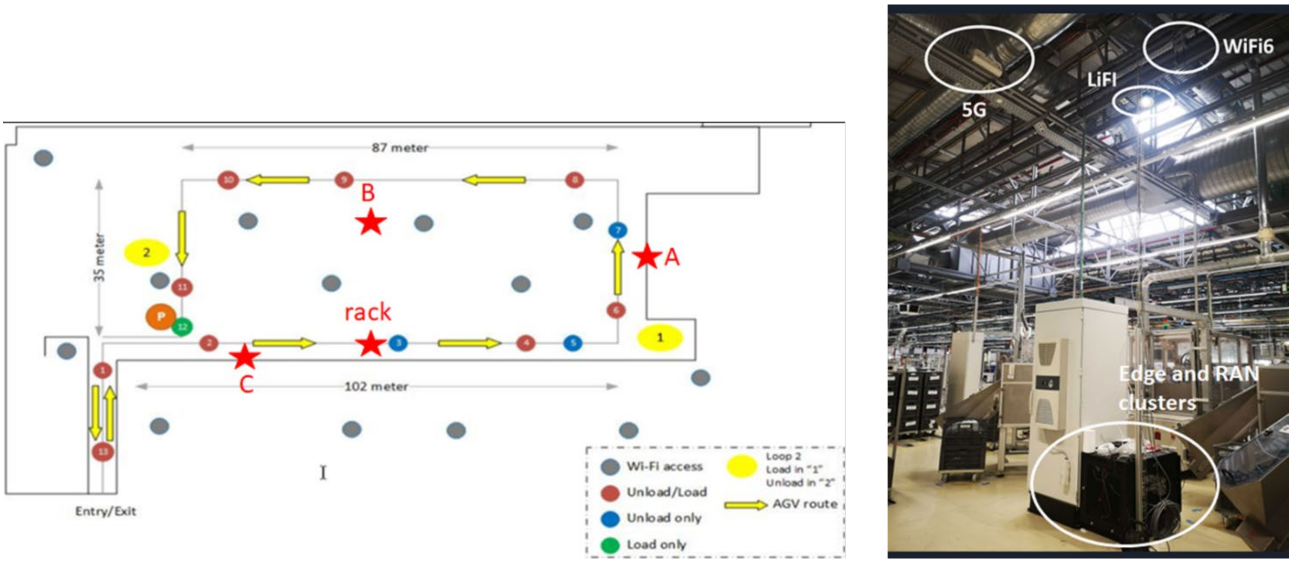

Figure 4-1. Factory layout (left). Deployed 5G-CLARITY infrastructure in the factory (right)

Table 4-1. Considered network configurations in BOSCH

Configurations	5GNR	Wi-Fi	LiFi
BOSCH-Default	Band: 3.9 GHz BW: 40 MHz TDD: 5 ms, 6 DL, 3 UL Vendor: Amarisoft + AW2S	Band: 5.8 GHz 80 MHz Vendor: Custom	Band: Blue LED (~450 nm) with phosphor coating DL; IR LED (850 nm) UL 16 MHz DL & UL
BOSCH – UL	Band: 3.9 GHz BW: 40 MHz TDD: 5 ms, 3 DL, 6 UL Vendor: Amarisoft + AW2S	Band: 5.8 GHz 80 MHz Vendor: Custom	Band: Blue LED (~450 nm) with phosphor coating DL; IR LED (850 nm) UL 16 MHz DL & UL

Regarding the deployed infrastructure, a deviation with respect to the original plan described in D5.2 [3] was to deploy an Amarisoft + AW2S 5GNR gNB, instead of the O-RAN-based Accelleran + Benetel solution that was being used in WP4. The reason for the change has been interoperability problems in the O-RAN based solution, which resulted in the system not being stable[2] enough to be used in the demonstration.

It is also relevant to note that the deployed infrastructure was completely isolated from the BOSCH IT systems. To this end, we deployed a commercial CPE, which connected to the public Vodafone mobile network. Through this CPE we provided Internet access to the different testbed devices, and we set up a remote management system to be able to access and monitor the infrastructure remotely.

In addition to the network infrastructure, we were forced to integrate three custom 5G-CLARITY CPEs to execute the use case. The reason is that a 5G-CLARITY CPE requires a custom linux kernel supporting MPTCP kernel 5.5[3]. The three CPEs are depicted in Figure 4-2. The rack CPE (left) and the AGV CPE (right), are based on a Gateworks Venice GW7300 board, with an Intel AX200 Wi-Fi 6 module, a USB powered Quectel RM500QGL 5G NR modem, and a USB LiFi dongle provided by PureLiFi. For the mobile CPE, we used a Dell Latitude 5420 laptop with the same wireless adapters as the other CPEs. The three CPEs are mapped to the use case goals in the following way:

- Rack CPE: Is used to demonstrate the connectivity of the PLC to the mock-up MES server (Goal 2).
- Mobile CPE: Is used to demonstrate coverage throughout the factory (Goals 1 and 4).
- AGV CPE: Is used to connect the AGV to the AGV slice deployed using the 5G-CLARITY service and slice provisioning framework (Goal 3).

Rack CPE *Mobile CPE* *AGV CPE*

Figure 4-2. 5G-CLARITY CPEs developed to support BOSCH demonstration.

4.2.2 5G-CLARITY architecture design

To support the execution of the use case we need to deploy two separate network slices. A "baseline slice", was pre-deployed during the demonstration and is used to connect the mobile CPE and the PLC. A second "AGV slice" was dynamically deployed during the demonstration and is used to connect the AGV CPE.

Figure 4-3 depicts the architecture of the baseline slice, where we can see the following three VNFs running inside the edge server: i) a 5GCore based on open5Gs dedicated to serving the PLMNID 00101 associated to this slice[4], ii) a MPTCP proxy in redundant mode that is used to connect the PLC, and iii) a MPTCP proxy in round-robin mode that is used to connect the mobile CPE.

[2] We experienced many problems related to the attachment procedure, where UEs were not able to synchronize with the network
[3] https://www.multipath-tcp.org/
[4] The interested reader is referred to the concept of PLMNID-based slicing introduced in deliverable D4.3 [2].

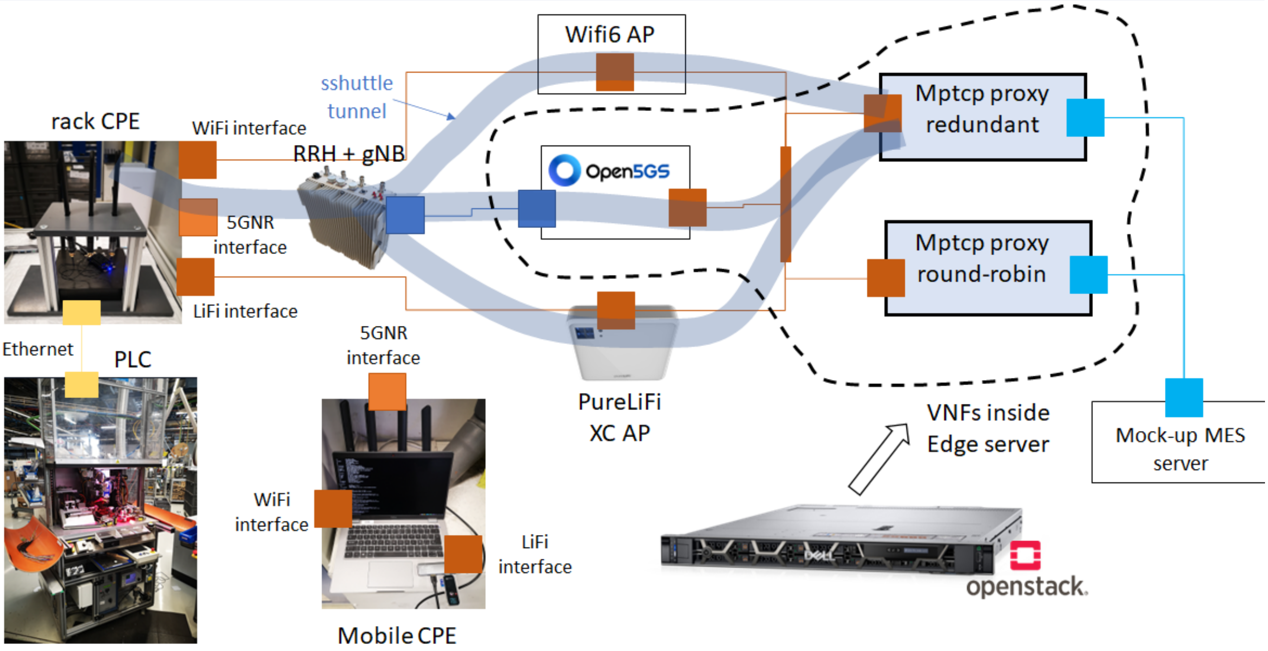

Figure 4-3. Baseline slice: Deployed network architecture for the baseline network slice used to connect the mobile CPE and the PLC

Note that the simultaneous use of multiple MPTCP proxies with a different scheduling behaviour is a feature of the 5G-CLARITY architecture that can be used to support different types of service. For example, the redundant proxy is used to connect the PLC because the critical KPI in this case is latency. Thus, by duplicating each packet generated by the PLC through each WAT and delivering to the MES the first arriving packet, the redundant scheduler minimizes the latency of this service. On the other hand, throughput is the critical KPI for the mobile CPE, for which the round-robin scheduler balances the load across the three WATs to deliver an aggregated data pipe.

Another important property of the 5G-CLARITY architecture validated in our setup is the ability to connect "native" 5G-CLARITY devices, e.g. the mobile CPE that has an MPTCP kernel, as well as legacy devices like the PLC, which is a Windows machine that does not support MPTCP. To support the connectivity of legacy devices, and SSH tunnel is established between the rack CPE and the MPTCP redundant proxy using the tool sshuttle[5] that maps the TCP connection from the PLC to an MPTCP connection between the rack CPE and the redundant proxy. This tunnelling technique was introduced and evaluated in deliverable D3.3 [1].

Parallel to the previous slice, Figure 4-4 depicts the architecture of the AGV slice. The goal of this slice is to connect the localization client deployed on the AGV to a localization server hosted in the edge server. Two additional VNFs are required to support this slice, namely: i) a new open5Gs based core associated to PLMNID 00103, and ii) a Linux based VM that includes the localization server software (developed in python). In addition to deploying these VNFs, provisioning the slice also requires reconfiguring the Amarisoft based gNB to start advertising PLMNID 00102 and connect to the newly deployed core network instance. The dynamic deployment of this slice is shown as part of the demonstration.

[5] https://github.com/sshuttle/sshuttle

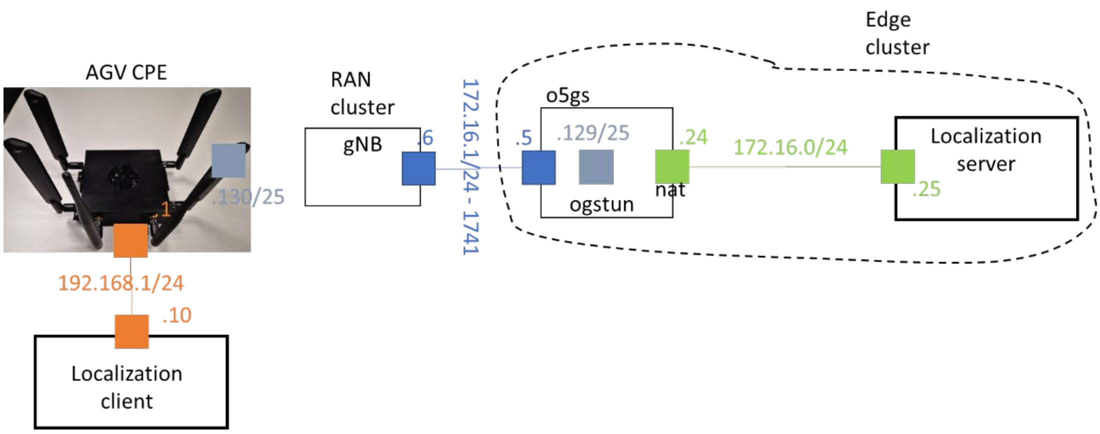

Figure 4-4. Slice 2: Used to support the AGV connection in UC-2.2

4.3 UC specific KPIs

In this section we describe the use case specific KPIs that were validated at BOSCH during the demonstration event held on November 24th 2022. We note that a more systematic KPI extraction aimed at developing the deployment model described in Section 6 was carried out after the demonstration and is reported in Section 4.4.

4.3.1 Mobile CPE

The main goal of the mobile CPE was to support KPI extraction related to the multi-connectivity framework at different locations in the factory. To this end, the Grafana dashboard depicted in Figure 4-5 was developed that depicted in real time the throughput (Mbps) received by the mobile CPE in through each WAT, as well as the aggregated throughput, both in DL and UL directions.

Figure 4-5. Grafana dashboard developed to measure mobile performance while moving across the factory

Armed with this tool we carried out several surveys walking around the factory. Figure 4-6 depicts a typical trace obtained in the factory walkout. To obtain these measurements an iperf3 TCP transmission with 15 TCP threads is started from the round-robin MPTCP proxy towards the mobile CPE. The tool measures the throughput delivered through each WAT, 5G in orange, LiFi in yellow and WiFi6 in grey, as well as the aggregated MPTCP throughput in blue. On the X-Axis we highlight different locations (**rack**, **A**, **B**, **C**, **D**) that are depicted in the factory layout shown in Figure 4-1 (left). The first aspect to highlight in Figure 4-6 is that the single 40 MHz 5G NR cell included in our setup delivers a uniform coverage of around 200 Mbps throughout the whole factory floor. Instead, the Wi-Fi 6 AP delivers a much choppier coverage, with peaks of up to 400 Mbps when moving slightly away from the rack but dropping very sharply at point **A** due to metallic structures blocking the AP line of sight and recovering performance again at point C when walking back towards the rack. This result illustrates how Wi-Fi 6 and 5G NR are complementary in factory environments, where Wi-Fi may enjoy higher peak data rates due to its greater carrier bandwidths but suffers from worse coverage. Indeed, our multi-connectivity framework delivers the sum of the Wi-Fi 6 and 5G NR capacities, delivering peaks of up to 600 Mbps when being close to the Wi-Fi 6 AP and a baseline performance of around 200 Mbps throughout the factory. Looking at LiFi, we can see that in terms of capacity its performance is severely limited due to its reduced carrier bandwidth, the lack of MIMO and the high ceilings available in the factory, delivering only around 10 Mbps in an area of 5 meters from the LiFi AP.

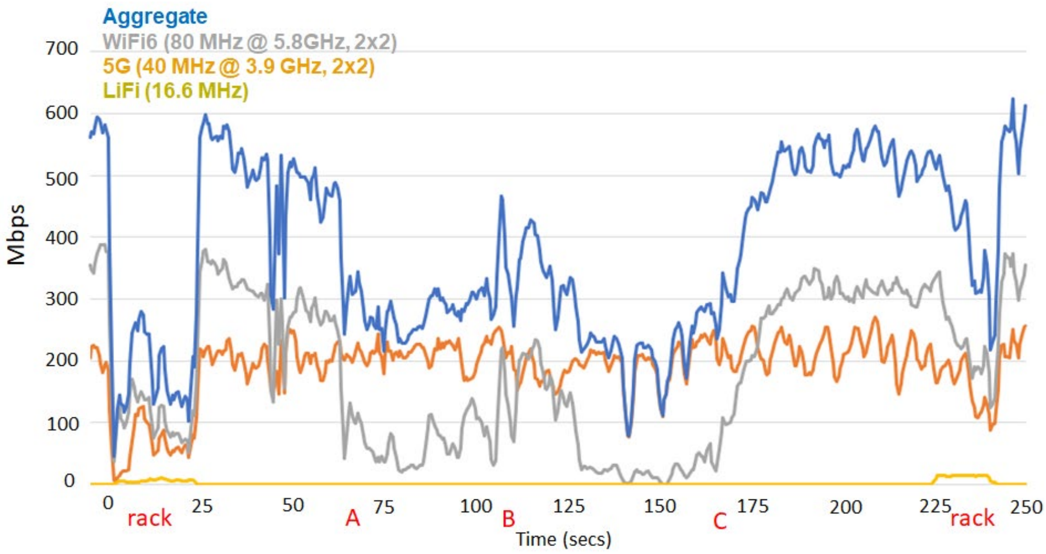

Figure 4-6. Functional validation of 5G-CLARITY multi-connectivity framework and DL coverage throughout the factory

Figure 4-7 shows another representative measurement trace this time focusing on the UL direction, where we can see similar trends. The 5G cell delivers a stable performance at around 40 Mbps, which is correct given the TDD pattern used in our demonstration corresponding to the BOSCH-default configuration in Table 4-1. WiFi6 offers higher data rates when being close to the AP, which abruptly decrease when moving away (note the reference points **rack**, **A**, **B** and **C** depicted in Figure 4-1). We note that the UL Wi-Fi performance is significantly lower than the DL one, i.e. 120 Mbps in UL and around 350 Mbps in DL. This is surprising because Wi-Fi is expected to have a symmetric performance, however we have consistently observed this behaviour in our testbed. We assume this is related to the intel based WiFi6 modem used in the CPE, which is different than the QCA modem used in the AP, but we have not been able to fully verify this assumption. The LiFi performance is similar than in the DL case, and much lower than the 5G and Wi-Fi ones. Overall, the multi-connectivity framework (blue line) can aggregate UL capacity resulting in a peak of 160 Mbps when being close to the AP and cells, and a baseline performance of 40 Mbps around the factory thanks to the consistent 5G performance.

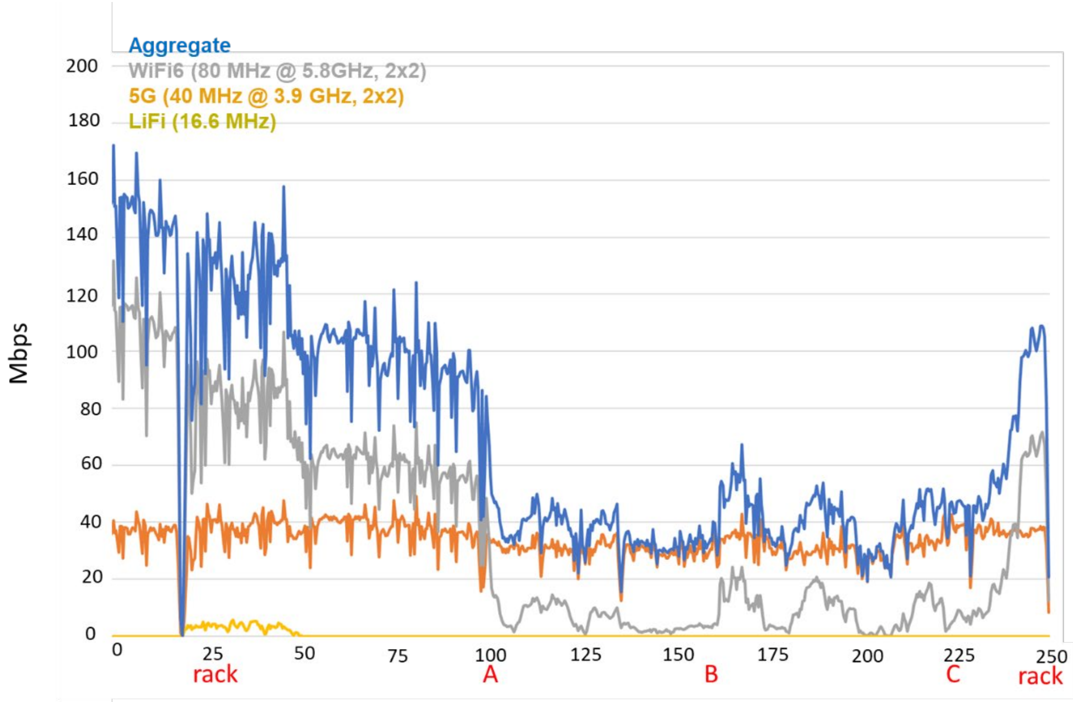

Figure 4-7. Functional validation of 5G-CLARITY multi-connectivity framework and UL coverage throughout the factory

Complementing the functional validation of the multi-connectivity framework described in this section, in Section 4.4 we provide a systematic capacity/coverage analysis of our factory setup.

4.3.2 Connected PLC

We evaluate the production line connectivity first by functionally validating that the packets generated by the PLC are duplicated at the rack CPE and transmitted in parallel through each WAT. Figure 4-8 (left) depicts a Wireshark capture at the redundant MPTCP proxy where we see highlighted in different colour the packets arriving from each WAT, i.e. light blue from LiFi, dark blue from Wi-Fi and orange from 5G. Looking at the Data Sequence Number of the Wireshark capture (right-most column), we see that the same packet is indeed transmitted through each WAT. Figure 4-8 (right) depicts the dashboard of the mock-up MES server successfully receiving messages over the 5G-CLARITY infrastructure for each produced part. We note that during the various tests performed in different days factory workers spent overall more than 3 hours producing parts while connected through the 5G-CLARITY network, without experiencing any disruption to their work.

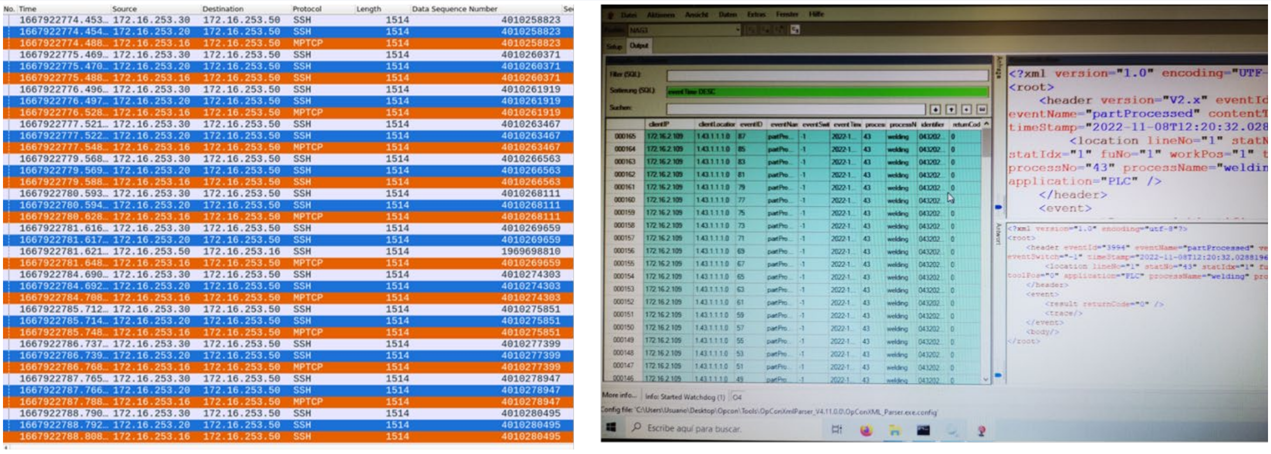

Figure 4-8. Wireshark capture depicting packets traversing each WAT with redundant scheduler (left). Dashboard of the mock-up MES server receiving packets from the PLC (right).

Figure 4-9. Developed latency dashboard from KPI measurement framework.

To measure the overall uplink latency experienced by the PLC packets when communicating with MES server, Figure 4-9 provides a snapshot of the latency measurement dashboard that we developed. This dashboard was used during the demonstration event to illustrate how latency was affected when switching between technologies. For example, we blocked the LiFi path with our hand and showed how data continued to flow through the Wi-Fi and 5G interfaces. We then further disabled Wi-Fi, by turning down the interface in the rack CPE, and showed how data continued to flow through 5G.

Finally, we use our measurement toolkit to extract a cumulative distribution function (CDF) of the latency between the PLC and the MES that is depicted in Figure 4-10 (left), showing a worst-case latency of 9 ms. To put this number in perspective, we also measured the resulting latency when connecting through a direct Ethernet resulting in a latency below 1 ms. It is expected that 5G-CLARITY cannot outperform Ethernet in terms of latency, however, achieving a below 10 ms latency through a wireless interconnect is enough to address the requirements of the cycle times used in the manufacturing processes available in BOSCH Aranjuez, and has the potential of saving complex Ethernet cable deployments. Figure 4-10 (right) complements the overall uplink latency measurements by depicting the uplink latency between the rack CPE and the redundant proxy experienced by each duplicated packet through the LiFi, Wi-Fi or 5G paths. We can observe that LiFi and Wi-Fi are significantly faster than 5G, due to several factors. First, these measurements are performed without congestion in any of the three WATs. Second, in our demonstration we used the

BOSCH-Default configuration that has a 5 ms TDD pattern and is optimised for DL throughput, which was important for the mobile CPE, but impacts UL latency. Finally, we suspect that the virtualized 5G core running in the edge node penalizes the 5G end-to-end latency, and that a latency optimized 5G deployment should feature a dedicated bare metal server for the core; however, we have not been able to experimentally validate this assumption.

To provide additional insights into the latency performance of our system, Section 4.3 presents a systematic analysis where latency performance has been studied under different interference conditions.

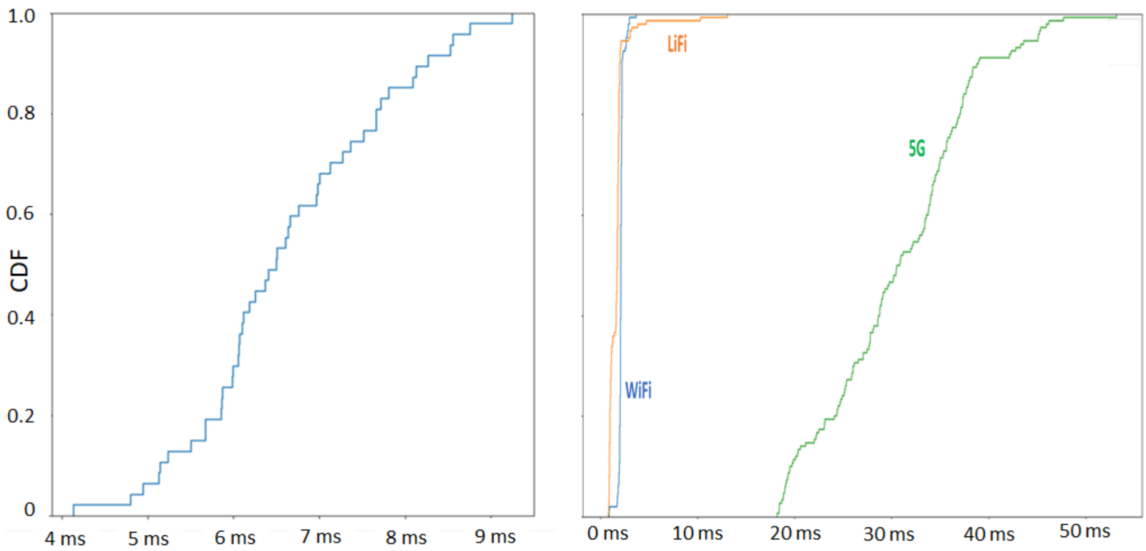

Figure 4-10. Measured PLC --> MES latency (left). Measured one way latency per WAT (right).

4.3.3 Slice deployment time

The last goal of the demonstration event at BOSCH Aranjuez was to demonstrate the dynamic deployment of the AGV slice illustrated in Figure 4-4. Deploying this slice required the 5G-CLARITY service and slice provisioning subsystem to execute the following steps:

- Deploy a new 5GCore VNF in the edge server, serving PLMNID 00102. This 5GCore already includes in the HSS the data associated to the SIM card used by the AGV CPE.
- Reconfigure the Amarisoft gNB to add the PLMNID 00102 associated to the new slice to the 5G cell, and to add a new AMF IP address so the gNB can connect to the new core.
- Deploy the localization server as a VNF connected to the data network that is accessible through the 5G Core.

Figure 4-11 depicts the interface used during the demonstration to trigger the provisioning of the AGV slice, which is based in POSTMAN. In the figure we can see how the PLMNID for the new slice is indicated, i.e. 00102, as well as the IMSI and allocated maximum bit rate parameters for the AGV SIM card.

To measure the slice provisioning time we executed 10 independent instantiations and computed the average. The average time was measured to be around 3 minutes with a very low variation across different tests. This time is reasonable considering the various steps required in provisioning the slice, i.e. booting VNFs, reconfiguring the gNB, etc.

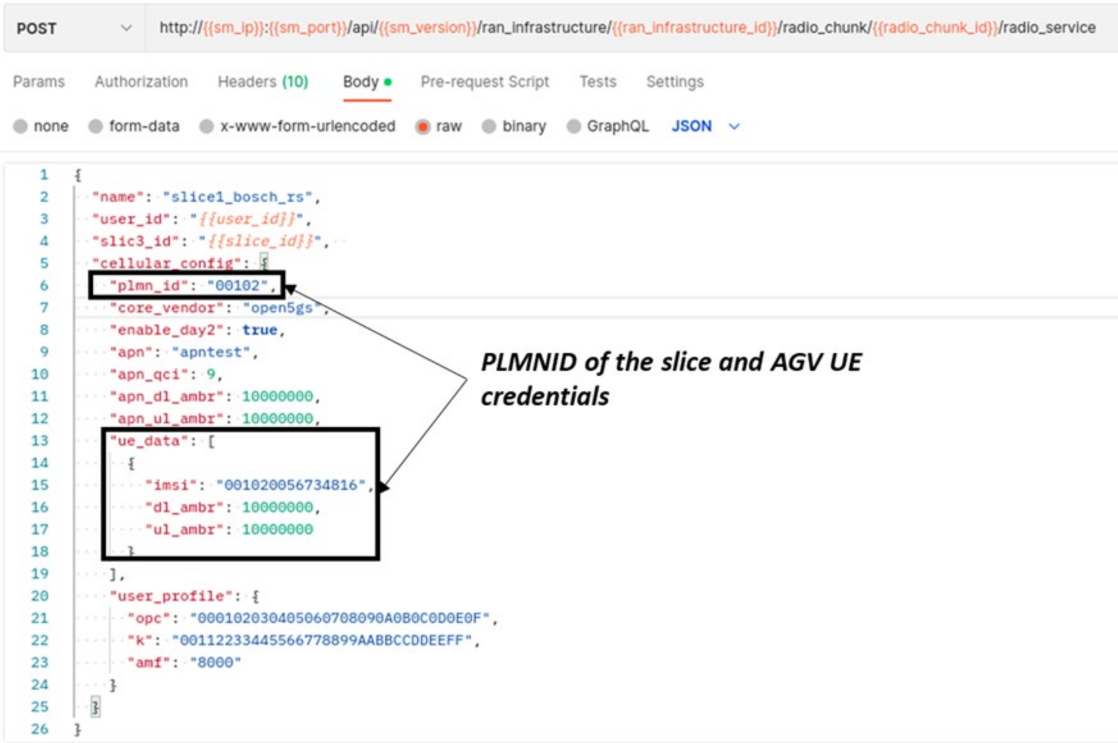

Figure 4-11. POSTMAN based front-end of slice provisioning framework

4.4 Transversal KPIs

In this section we evaluate the transversal KPIs introduced in section 2 for the BOSCH scenario. For our analysis we consider both the BOSCH-Default and the BOSCH-UL configurations.

4.4.1 Capacity measurements

Figure 4-12 depicts the selected locations in the factory floor to measure the throughput over distance KPI introduced in Section 2. In addition, to the rack location, depicted as "**A**" in the factory map shown in Figure 4-12 five additional locations are selected to get a representative understanding of the throughput coverage across the whole factory floor. Figure 4-12 also contains pictures of the mobile CPE deployed in each target location while executing the KPI measurements. Figure 4-13 depicts the per-WAT throughput in the different locations in the factory, computed as an average of 10 independent runs consisting of running iperf3 in the selected direction. The results confirm the instantaneous results obtained with the mobile CPE in Section 4.3 in Figure 4-6 and Figure 4-7. We can see how LiFi is only available at position **A** (the rack). Wi-Fi has a peak performance around the rack area slightly above of 300 Mbps in DL and of 90 Mbps in UL, but suffers significant degradation when moving away from the rack, i.e. positions C, D and E. Instead, 5G in both TDD63 (BOSCH-Default) and TDD36 (BOSCH-UL) configurations and in both DL and UL exhibits a very stable performance. It is interesting to note that 5G with TDD36 is the best performing technology in UL, providing 100 Mbps of UL capacity throughout the factory. Comparing the 5G TDD63 and TDD36 configurations, we see a slightly higher efficiency in TDD63 with an aggregate (DL+UL) throughput of approximately 230 Mbps versus the aggregate (DL+UL) throughput in TDD36 of approximately 200 Mbps. We posit that this efficiency differences are due to MIMO being used more often in DL than in UL.

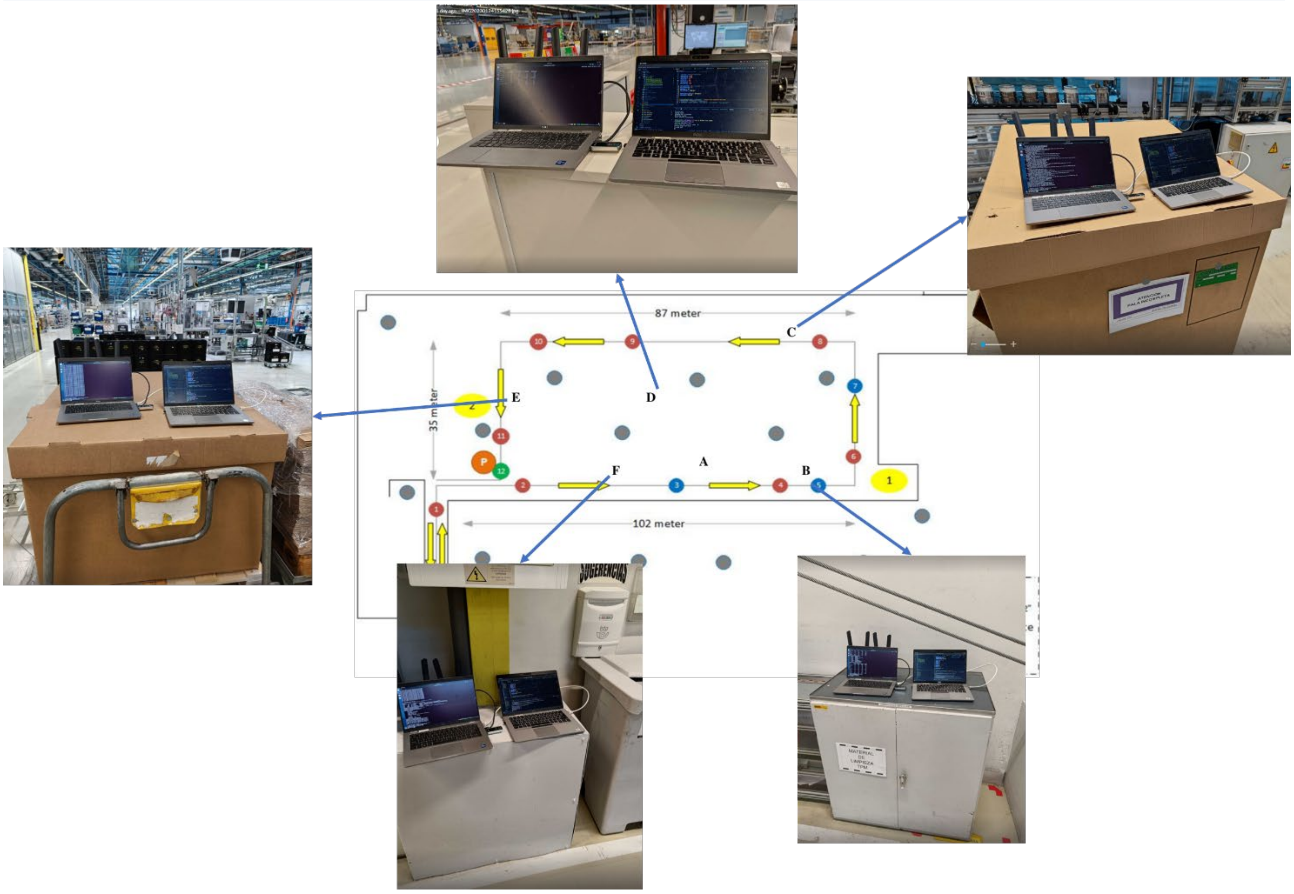

Figure 4-12. Selected locations to measure the capacity KPI in the factory floor.

Figure 4-14 depicts the corresponding results when using the 5G-CLARITY multi-connectivity framework aggregating capacities from all WATs with the round-robin scheduler. The graphs depict the resulting aggregated capacity both when using 5G TDD63 (BOSCH-Default) and 5G TDD36 (BOSCH-UL). We see that when using TDD63 we have a DL capacity between 500 Mbps in position **A** and 210 Mbps in position **E**, and an UL capacity between 150 Mbps in position **A** and around 50 Mbps in position **E**. When using 5G TDD36 we have a DL capacity between 410 Mbps in position **A** and 150 Mbps in position **E**, and an UL capacity between 200 Mbps in position **A** and slightly above 100 Mbps in position **E**.

In Section 6 we will use these KPI measurements to dimension the network used to connect a factory like the one available in BOSCH Aranjuez.

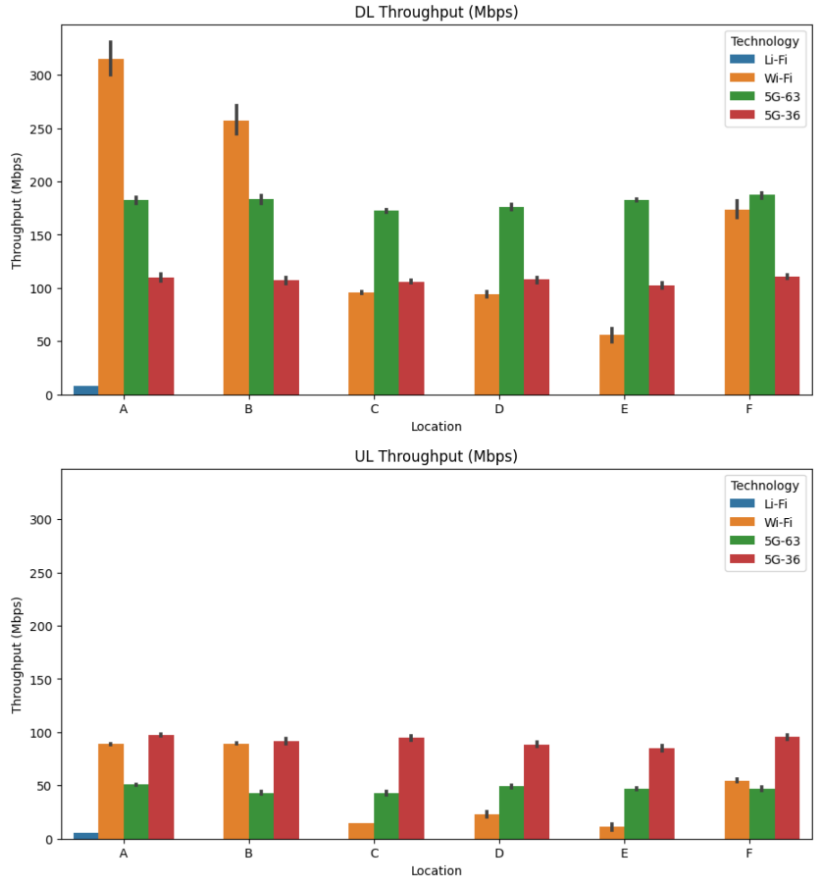

Figure 4-13. Per-WAT DL (upper) and UL (lower) throughput breakdown per position

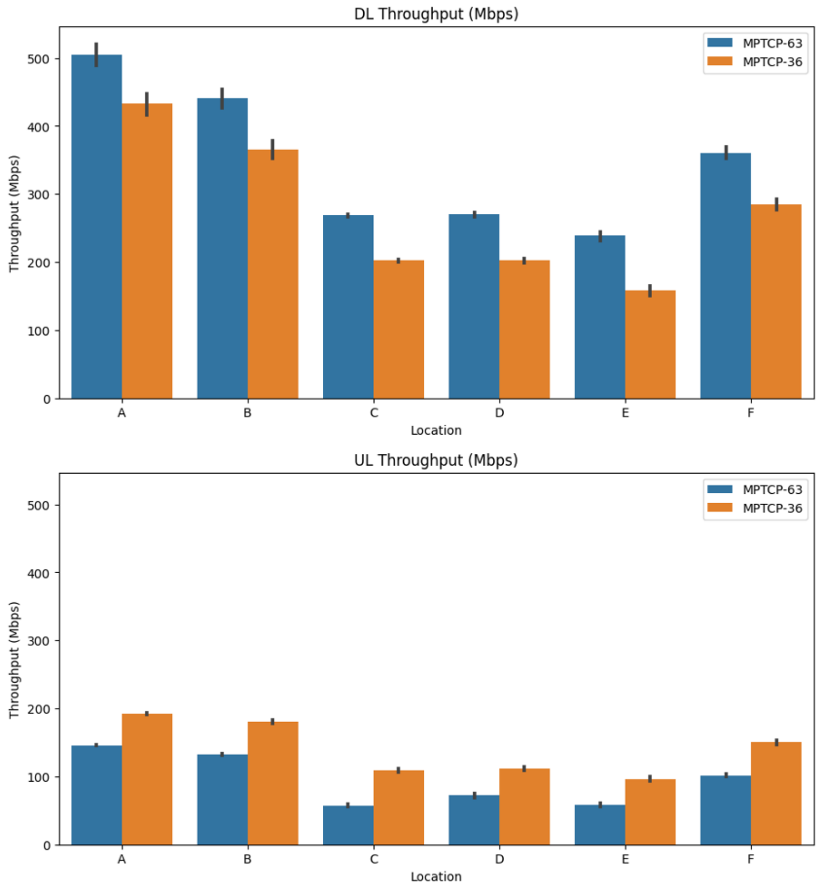

Figure 4-14. Aggregated DL (upper) and UL (lower) capacity when using 5G-CLARITY round-robin scheduler.

4.4.2 Latency measurements

4.4.2.1 Experiment setup and methodology

We present in this section the results of the latency benchmarking carried out in the BOSCH factory. The main goal of this benchmark is to understand how the latency delivered by the 5G-CLARITY multi-connectivity framework and by the different component WATs behave under different interference conditions. To this end we use the set up described in Figure 4-15, where we use our rack CPE (c.f. Section 4.2) as a device under test (DUT), generating lagscope traffic through the 5G-CLARITY network using an MPTCP redundant scheduler. Then, we use our mobile CPE (c.f. Section 4.2) to generate interfering load over the different WATs. Both the rack CPE and the mobile CPE are co-located, thus experiencing similar signal conditions.

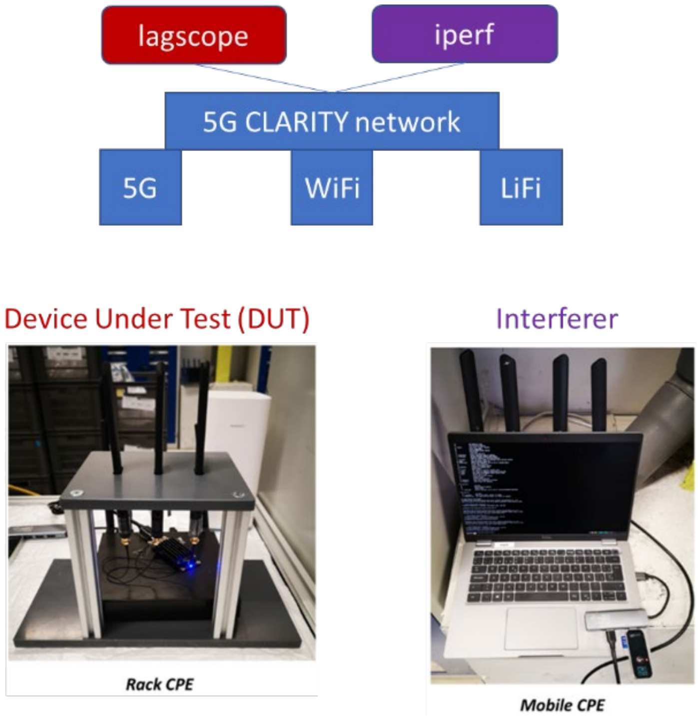

Figure 4-15. Set up for evaluating latency under interference.

Given that each component WAT is capable of very heterogeneous capacities, we normalize interference for each WAT to be able to compare how an equivalent level of interference affects each WAT. To this end, based on empirical observations in our deployment, we define a set of nominal UL and DL data rates per technology, which are defined in Table 4-2 for UL and DL. Then, we compare the latency experienced by the rack CPE when increasing the level of interference introduced by the mobile CPE between a 0% and an 80%, where the interference data rate is derived from the nominal data rates, as illustrated in the third and fourth columns of Table 4-2 for the case of a 60% interference level.

Table 4-2. Nominal per-WAT data rates for interference experiment

	Nominal UL Rate (Mbps)	Nominal DL Rate (Mbps)	Example: 60% UL interference (Mbps)	Example: 60% DL interference (Mbps)
LiFi	5	5	3	3
Wi-Fi	400	600	240	300
5G-TDD63	40	200	24	120
5G-TDD36	100	150	60	90

We carry out our evaluation focusing on two sets of KPIs, following the latency measurement methodology described in Section 2:

- Multi-WAT evaluation: We measure the round-trip latency performance obtained when the device under test is using the redundant scheduler through all WATs in parallel.
- Per-WAT evaluation: We measure the individual one-way latency performance experienced by the packets that traverse each of the component WATs in UL and DL. Note that this per-WAT results were not provided for the M Shed use case in section 3. The reason to provide this additional analysis here is that the per-WAT latency behaviour is required for the cost analysis for factory deployments carried out in Section 6.

To obtain our latency results we execute 10 different runs in our testbed lasting each run 20 seconds. In each of these runs the rack CPE is simultaneously transmitting lagscope traffic through the three WATs in redundant mode, and the mobile CPE introduces UL or DL interference according to the specified interference level. We then aggregate all latency samples obtained through lagscope in all our experiments and plot the resulting latency distributions using boxplots. We study separately the effect of introducing interference in UL or DL, and our experiments are repeated for the two 5G configurations under study, i.e. TDD36 and TDD63, which respectively have 3/6 DL slots and 6/3 UL slots for a total frame duration of 5 ms.

Figure 4-16 depicts the round-trip latency experienced by the rack CPE in redundant mode when the mobile CPE introduces UL interference (upper part), and DL interference (lower part). Figure 4-17 and Figure 4-18 depict respectively for the cases of UL and DL interference the one-way latency experienced by the rack CPE broken up per WAT. Notice that Figure 4-17 and Figure 4-18 depict one way delay, so for each WAT we show the UL one way delay (blue) and the DL one (orange). In addition to the UL and DL one way delay boxplots, Figure 4-17 and Figure 4-18 also contain a grey line that represents the packet delivery ratio (PDR) experienced through each WAT. We consider PDR a relevant metric because we observe in our measurement traces that not all WATs are able to deliver all packets under interference. For example, LiFi severely suffers from UL interference. When this happens, we may observe an UL packet in the packet trace captured in the rack CPE, but do not observe the corresponding packet arriving at the MPTCP proxy during the duration of our experiment. We consider this case a packet loss, which is represented in the figure with a PDR below 1.

Finally, we note that while Figure 4-16 represents round-trip latency and Figure 4-17 and Figure 4-18 one-way delay, the resulting distribution depicted in Figure 4-16 is not directly the sum of the one-way delay distributions depicted in Figure 4-17 and Figure 4-18. The reason is that the redundant scheduler delivers the first arriving packet regardless of the WAT, so the round-trip latency distribution in in Figure 4-16 corresponds to the minimum of the distributions depicted in Figure 4-17 and Figure 4-18.

4.4.2.2 Analysis of results

Looking at Figure 4-16 we can see how, as expected, in all cases the latency experienced by the rack CPE increases with the interference introduced by the mobile CPE. Worst-case latency though never gets above 16 ms in any of our experiments. To understand the results obtained in Figure 4-16 we need to look at the per-WAT dynamics depicted in Figure 4-17 and Figure 4-18.

Starting with the case of UL interference, which is broken up per WAT in Figure 4-17, we can see how the LiFi PDR quickly degrades for an UL interference of only a 20%, which is due to the lack of a robust multi-user MAC layer in the current generation of LiFi products. Wi-Fi is the dominant WAT in terms of low latency for interference levels below 60% but is significantly degraded when the interference reaches 80%. Very low latency when the network is not congested, and a sudden degradation when approaching congestion is a well-known behaviour in Wi-Fi. Instead, we see that 5G exhibits an almost flat latency performance for the two TDD configurations under study and for all levels of interference. Only in the case of the TDD63 configuration we observe a slight degradation in latency at a level of 80% interference, which does not appear in the case of the TDD36 configuration[6]. This is expected as the TDD36 configuration has more UL resources. Looking at PDR, for 5G we observe an almost perfect performance for all levels of interference, while for Wi-Fi there is a slight decrease (~5%) when the interference is at 80%.

Looking now at the experiments with DL interference, where aggregate performance is depicted in the lower part of Figure 4-16 and per-WAT performance is depicted in Figure 4-18, we observe that in this case LiFi and Wi-Fi exhibit a much better performance than in the case of UL interference. In the case of LiFi, the reason is that with DL interference we do not have a medium access problem, as in the UL case, because both the DL rack CPE and the DL mobile CPE traffic are delivered by the same LiFi transceiver, i.e. the LiFi AP, and UL and DL operate in different frequency bands. In the case of Wi-Fi, we also observe a better performance when the interference is DL which is because there are only two transmitters in this scenario (rack CPE and AP), versus three in the scenario with UL interference (rack CPE, mobile CPE and AP). In the case of 5G a similar performance than in the case of UL interference is observed. Overall, the better performance of LiFi and Wi-Fi under DL interference, explains the better performance exhibited by the 5G-CLARITY redundant mode in the lower part of Figure 4-16, where the worst-case delay is below 8 ms for all interference levels.

The main conclusion of our study is that Wi-Fi delivers an excellent latency when the network is not congested, whereas 5G delivers a more stable latency regardless of the network congestion[7]. Regarding LiFi, it cannot tolerate interference, and therefore needs to be considered as a point-to-point technology. Based on these results we conclude that combining the low latency of Wi-Fi coupled with the reliability of 5G could be beneficial in factory environments. In Section 6 we will study how these results can be used to derive a deployment model for wirelessly connected production lines.

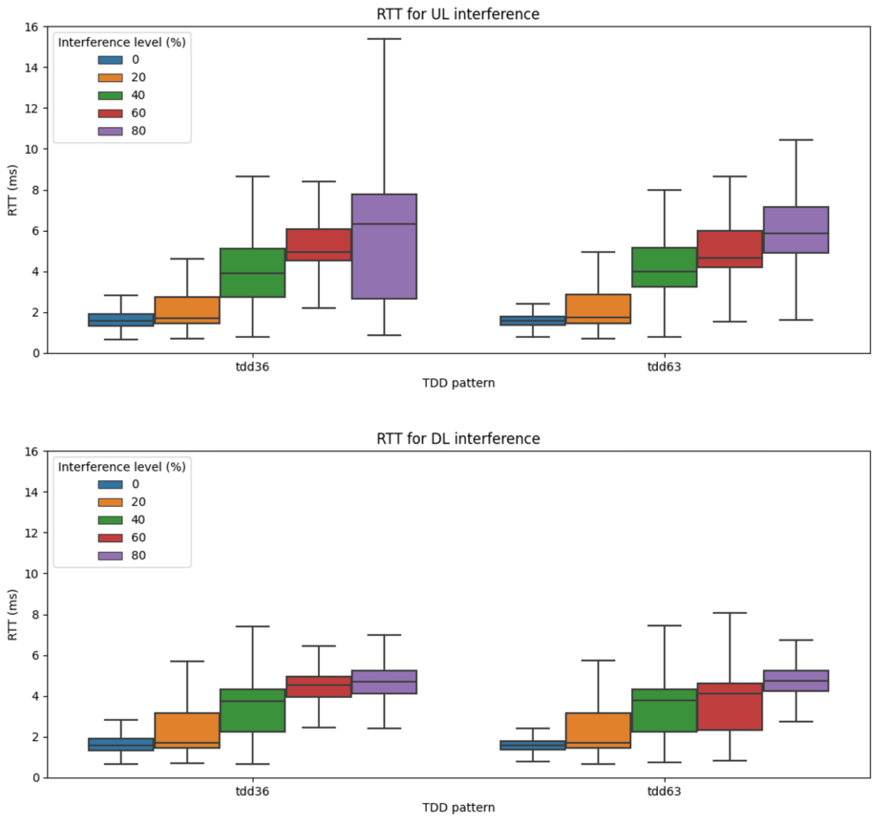

Figure 4-16. Round trip latency experienced by rack CPE when using redundant scheduler under different level of UL and DL interference. Experiments are repeated for two different 5G TDD patterns (TDD36 and TDD63)

[6] We note that comparison between the TDD63 and the TDD36 configurations is not immediate, as the nominal capacity in each case is different and thus the level of interference in UL and DL are also different.

[7] We have not been able to evaluate low latency 5G features defined for URLLC in Release 16 or 17.

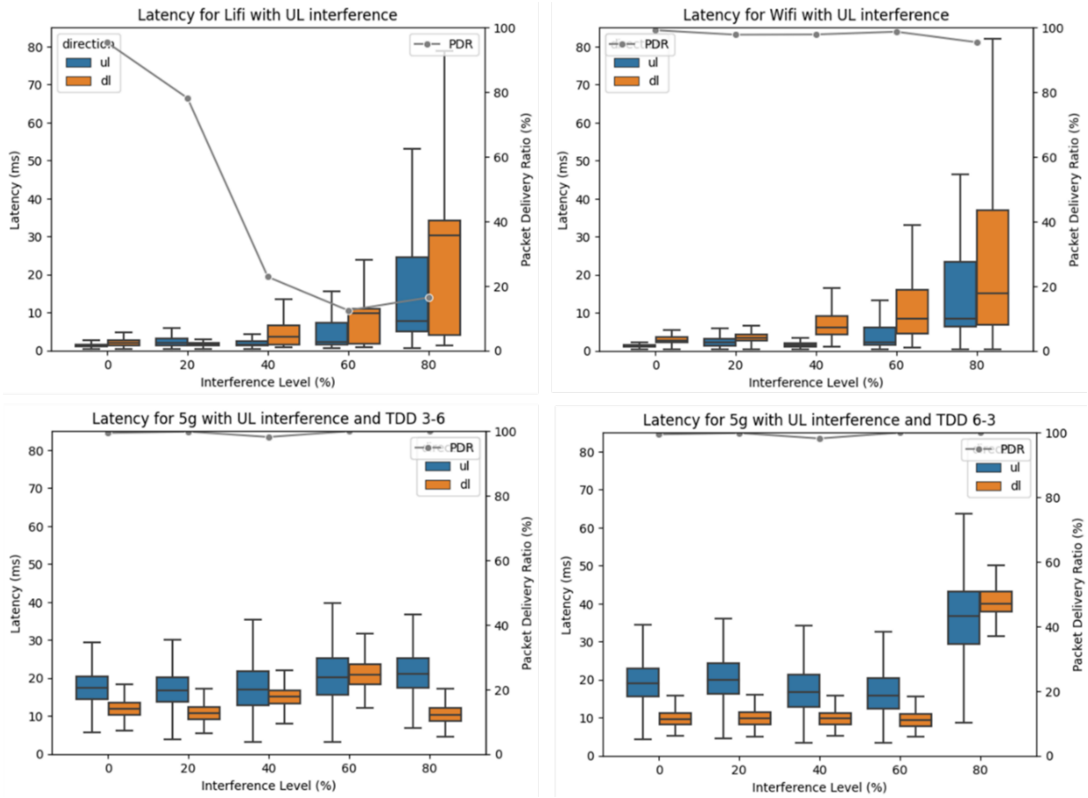

Figure 4-17. Results with UL interference

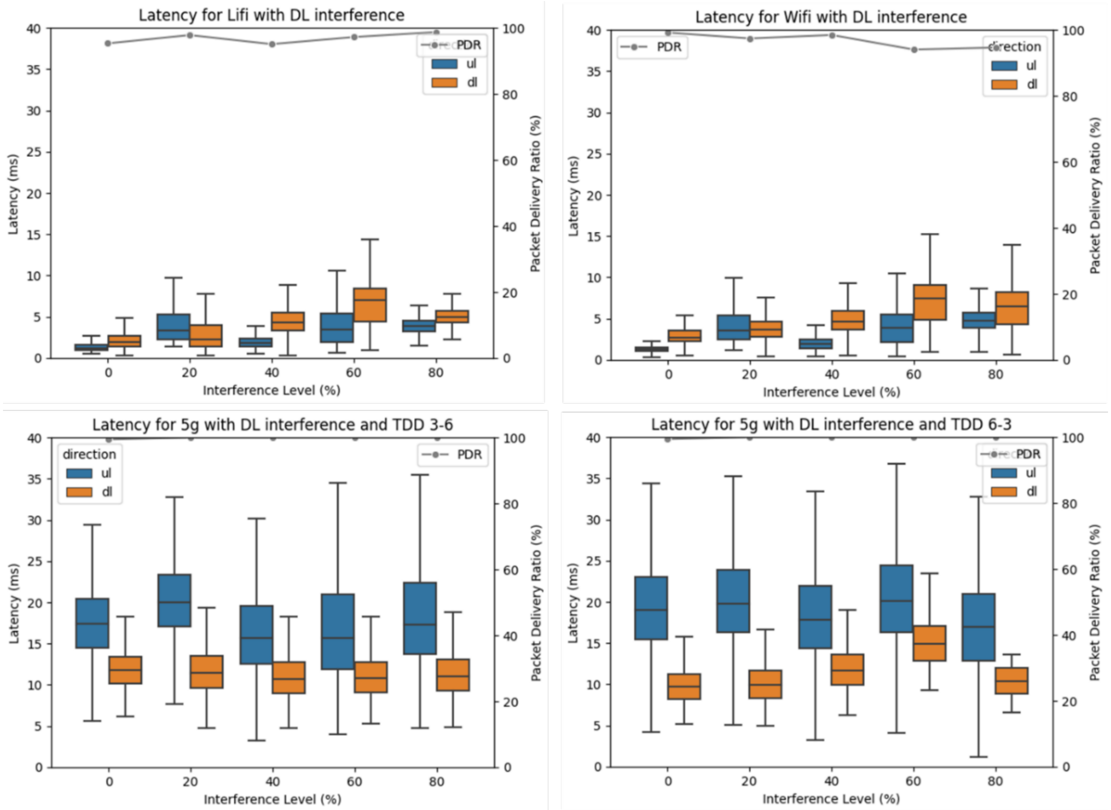

Figure 4-18. Results with DL interference

5 Industry 4.0 Pilot, UC2-2: Demonstration and KPI evaluation

The main objective in this use case is demonstration and evaluation of the developed indoor positioning technologies in an operational industrial environment, i.e. BOSCH factory in Aranjuez, Spain.

Within the 5G-CLARITY project a total of three indoor positioning technologies described in D3.3 [1] were developed. These technologies were demonstrated and evaluated within the UC2-2 demonstration. These include Sub-6 GHz system, mmWave system and a LiFi system.

Additionally, a localization server was developed within the 5G-CLARITY project. This localization server is used to control the developed positioning technologies and to acquire the localization data. At the same time, it is used to offer a technology independent interface towards the user for the positioning data. To support multiple positioning technologies, this server implements a positioning data fusion functionality, which collects the data from all the positioning technologies, merges the data together and offers a single position estimate to the end user. This approach enables the improvement of the position estimate when coverage from multiple technologies exists, and also enables roaming between areas covered by different technologies.

Regarding the evaluation of the developed positioning systems, the objective is to obtain the positioning system performance in a realistic environment such as a BOSCH factory. Initially, the proper functioning of the systems in a realistic environment was tested. The main accent of the demonstration is the evaluation of the precision of the deployed systems. The accuracy was also evaluated, but it can strongly depend on the environment and obtaining high accuracy is associated with optimal deployment of the access points for a given technology. This is out of the scope of this project and was therefore not analysed in detail.

Additionally, the proper functioning of the localization server was evaluated. A few different aspects were evaluated in this direction. First, we tested the suitable deployment of the server at the edge server of the 5G-CLARITY network deployed as part of UC2.1. Second, the connection of the positioning UE and the localization server through the deployed private network were tested using the CPE developed by I2CAT. Finally, the support of the localization server and the support for the different deployed positioning systems were tested.

5.1 Use Case objectives and execution plan

During the project, the developed positioning systems were tested and evaluated in laboratory conditions at the premises of the corresponding partners. These laboratories, however, do not fully represent the factory environment in which the final demonstration and evaluation of the positioning systems took place. Namely, a few different limitations were present in the laboratories or the factory that strongly affected the full deployment of the positioning systems. These limitations include, but are not limited to:

1. Deployment area: The area of deployment in a laboratory and a factory differ significantly. The laboratories that are available at the premises of the partners have an area of maximum 50-70 square meters. On the other hand, the production floor in the BOSCH factory has an area of 3000 meters squared (size of approximately 100 × 30 m^2). A network deployment across such a large area is not feasible from a number of reasons. First, the radio equipment used is a test equipment, e.g. software defined radios (SDRs), which is extremely expensive and has limited transmit power, well below the legal limits. This means that covering the whole factory area would require a high number of devices and will be quite over the project budget. Nevertheless, if these technologies are deployed within future commercial application-specific devices, a coverage of the area would be possible with lower number of cheaper devices.
2. Deployment height: The factory ceiling is usually higher than a typical office ceiling height. This was

also a main challenge for the light/optical positioning technologies. Namely, the developed light/optical technologies were intended mainly for deployment in offices, and their properties were tuned for these heights. Due to the deployment on higher ceiling in a factory, two main issues were observed. First, the received power from the light source was significantly lower, leading to lower RSS value, which leads to lower change of the RSS with distance. In our case the RSS value for the deployed LiFi system was always to the lowest level, strongly limiting the positioning precision/accuracy.

3. Lightning conditions: The lightning conditions within the factory include bright lights. Due to the bright lightning conditions, it is expected that the receiver of the LiFi UE might be saturated or brought in non-linear regime, which would affect its performance.
4. Logistics: This was probably the largest limitation encountered in this use case demonstration. Namely, in order to demonstrate the positioning technologies on an AGV, they would need a power supplied form a battery. The battery had to be supplied by IHP in order to power the IHP's equipment installed on the AGV. Nevertheless, as it was learned, shipping a battery is a major challenge since it is very strictly regulated. Another challenge was deployment of equipment in an operating factory. In order not to interfere with the production process, the deployment of the equipment is strictly limited. Namely, the access points cannot be placed anywhere, but only on places which are not being used at the moment. The cabling should be placed overhead, which requires services of a third-party company. Additionally, the situation in the factory changes with time. Even though some of the partners involved in UC2.2 visited the factory 5-6 months in advance, there were some changes in the factory layout when the deployment took place. The initially planned deployment area was not anymore the optimal place for deployment, because of the increase of ongoing activities in that area. Another area was a significantly better option. This led to inconsistency in the initial planning, i.e. even we initially planned to deploy all of the positioning systems in a way that they fully or partially have an overlapping coverage, this was not possible anymore given the new layout.
5. Technical: Also some technical risks that were predicted in the development stage have materialized, leading to some limitation in the demo an the evaluation process. Namely, there was a risk that we would not be able to synchronize the mmWave nodes wirelessly. Since this risk materialized, it was necessary to go to a fall back solution where the nodes are synchronized by a cable. This actually strongly limits the coverage area, since the cable has a limited length.
6. Ground truth: In order to evaluate the accuracy of the positioning systems, a reliable ground truth is necessary. This reliable ground truth requires a system that can be used for precise estimation of the position of the user equipment, i.e. mobile node. This precise estimate is to be used later to evaluate the accuracy of the positioning system. For this purpose, a few reference points were established and the position of the APs and user equipment were calculated based on the distance of the APs and the user equipment to these referent points. The distance to these reference points was measured using a laser distance meter model BOSCH GLM 80 Professional. Although the laser distance meter is calibrated and has a precision of ±1.5 mm, achieving this accuracy in the factory is practically not possible. The main reasons being that the instrument is held in hand, making aiming at the target at the referent point quite hard. This manual measurement would cause small errors in the measured distance, causing errors in the ground truth. This would affect the accuracy estimation. Additionally, in mobile scenarios, where the user equipment is moved along a straight line, it is not possible accurately to know the ground truth position of the user equipment. There are a few reasons, main being that moving the equipment along a straight line with a millimetre precision in a factory, without having special equipment for that, is not possible. Also, the speed of the user equipment is not constant, making it impossible to have high precision ground truth. Nevertheless, this would likely make the accuracy estimates slightly worse than they actually are. The precision, on

the other hand, would not be significantly affected since it measures the distribution of the position estimates around the mean value.

5.2 Deployed positioning system infrastructure

The Sub-6 GHz system, the mmWave system and the LiFi were deployed in the BOSCH factory in Aranjuez, Spain. From those 3 systems only the sub-6 GHz system and the LiFi were deployed and tested simultaneously, i.e. used in a same scenario. The main reason is that the mmWave system needed cables for synchronization between the APs and the user equipment and special precautions had to be taken in order to avoid tripping some of the mmWave nodes. This strongly limited the mobility of the mmWave system, therefore it was tested and evaluated separately.

The sub-6 GHz system was deployed and tested together with the LiFi system. These two systems were also used to test the functionality of the localization server as well as the functionality of the fusion algorithm. The fusion algorithm was only partially tested, since it was not possible to overlap the coverage of the Sub-6 GHz system with the LiFi system.

5.2.1 Deployment of the sub-6 GHz system

In Figure 5-1 a sketch of the deployment scenario is given.

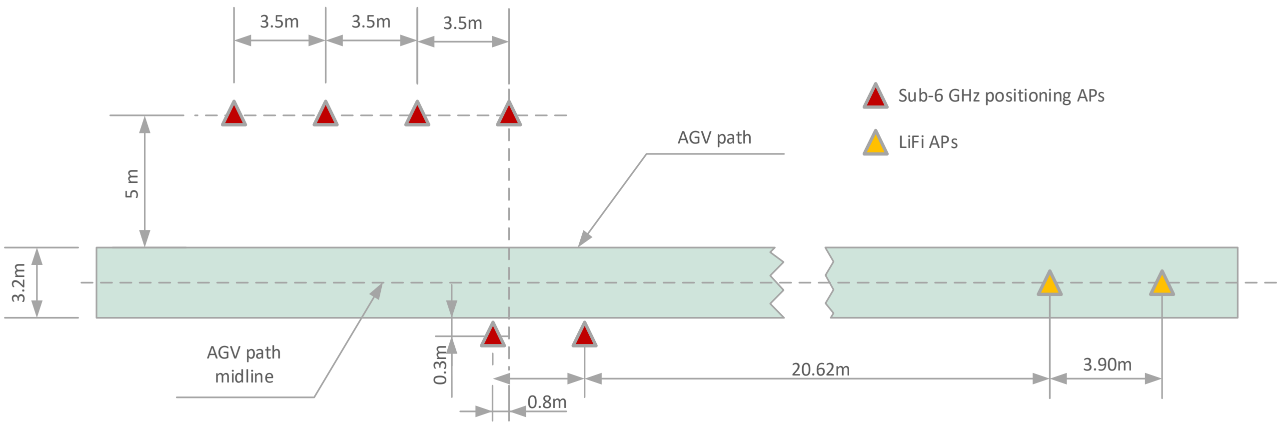

Figure 5-1 - Deployment scenario for the sub-6 GHz system

The light green track in the middle is the path where the AGV as well as the workers and other vehicles can move. On both sides of the track, there are machines and carts with raw materials or products.

The red triangles are the sub-6 GHz AP nodes. They are placed on the two sides of the track. The APs have a directional antenna, with a gain of 8 dBi in the 5 GHz band. The model of the antenna is LevelOne WAN-1160. A photo of the antenna is given in Figure 5-2. The antenna is mounted on a tripod that is 2.5 meters high. Since the antennas have relatively high gain of about 8 dBi, meaning that most of the energy is radiated forward, to achieve better coverage, they should be located further away from the area of interest, in this case the AGV path. Nevertheless, the antennas should not be too far away due to the limited link budget. As can be seen from Figure 5-1, placement of the Sub-6 GHz AP antennas away from the AGV path was possible on the top side. They are placed 2.4 meters from the edge of the AGV path. Unfortunately, on the other side of the AGV path, the bottom side in Figure 5-1, the antennas are placed next to the AGV path due to the existing machines which are 1-1.5 meters from the AGV path. This is not an optimal placement, which would lead to suboptimal results for positioning precision and accuracy. The reason for suboptimal placement is that this is only a temporary setup to be dismantled after the UC2.2 demo and, therefore, the needed large effort for placement of the APs on the ceiling construction is not justified. In case of a permanent installation, the nodes can be placed optimally, according to the available ceiling construction.

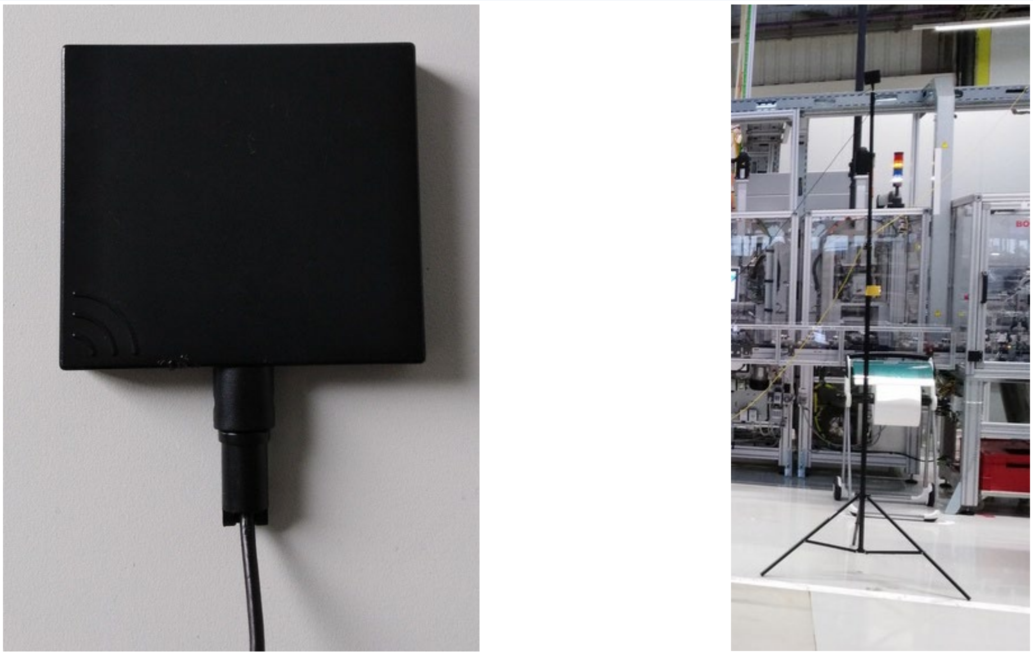

Figure 5-2 - Antennas used for the sub-6 GHz access points

A diagram of the deployed sub-6 GHz infrastructure needed for the positioning functionality is given in Figure 5-3.

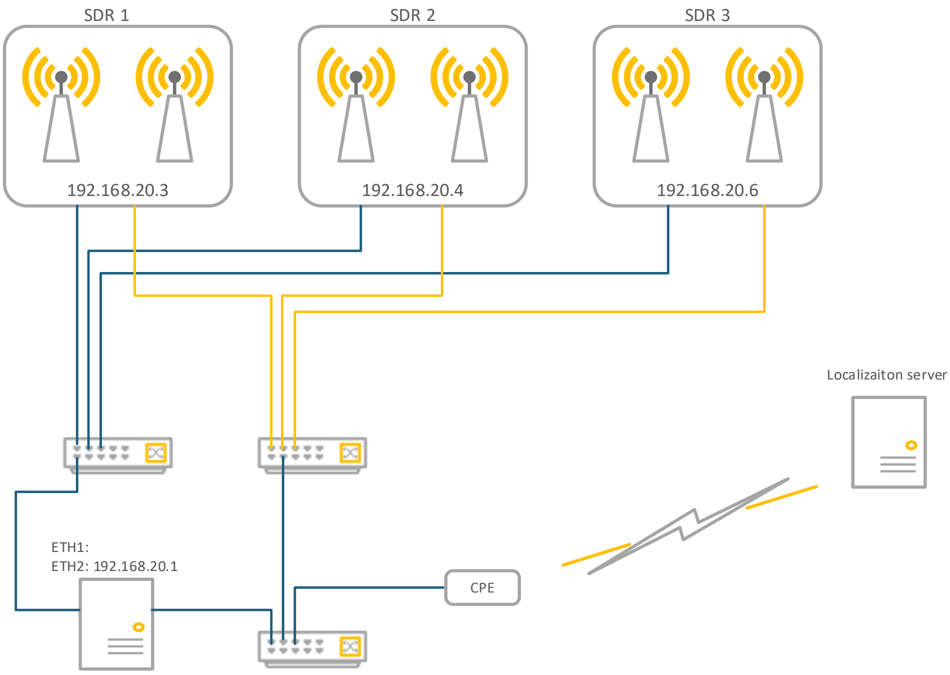

Figure 5-3 - Diagram of the sub-6 GHz positioning system

The sub-6 GHz localization setup comprises 3 SDRs of the model Ettus N321, one 10 Gbit Ethernet switch supporting fiber 10 Gbit adapters, a White Rabbit (WR) switch for synchronization, and a general-purpose personal computer (PC) running the developed software for controlling the localization system. Additionally, this PC is connected to a Gigabit switch on which the WR switch and possibly a CPE is connected. This is useful if a remote management of the WR switch and the sub-6 GHz architecture is needed.

Figure 5-4 depicts the sub-6 GHz system, where the antennas are mounted on tripods, and the radios are placed on the blue boxes. Each radio (SDR) has two independent units, which function as a separate radio. For localization purposes, it is important that these are physically separated, hence the two antennas are connected with longer coaxial cables to the SDR. This is not an optimal solution since the coax cables introduce additional attenuation of the RF signal, which, for these radios in the 5 GHz band, is anyways relatively low.

Figure 5-4 - sub-6 GHz localization system setup in BOSCH factory

Regarding the UE, the initial intention was to mount all necessary equipment onto the available AGV. Nevertheless, the used AGV had very limited space available for mounting the equipment. Therefore, in order to facilitate safe equipment mounting, a wagon which is used in the factory for transportation of raw materials and products, was used for deploying the equipment. This wagon can be connected to the AGV as a trailer and, therefore, can be used to carry equipment for localization of the AGV. Figure 5-5 shows the sub-6 GHz localization UE equipment installed on a wagon. The list of the installed equipment is given in

Table 5-1 - List of installed sub-6 GHz localization equipment

Equipment	Function
SDR Ettus N321	An SDR for reception of the localization frames
I2CAT CPE	Data connection to the private network installed in BOSCH, needed for access of the localization server
General purpose PC/Laptop	Needed for running of the localization software for processing of the received frames and estimation of the UE position
LiFi UE device	Enabling a LiFi functionality. In this case used for positioning based on the proximity to LiFi access point
mmWave 60 GHz node	Localization in the 60 GHz mmWave band
Gigabit Ethernet switch	Connection of all the devices on the UE side
Power station	A power station providing a 220 volts power, from internal batteries, for supplying the equipment while on the wagon

Figure 5-5 - AGV wagon (cart) with localization UE equipment installed on it

The diagram of the UE side equipment is given in Figure 5-6.

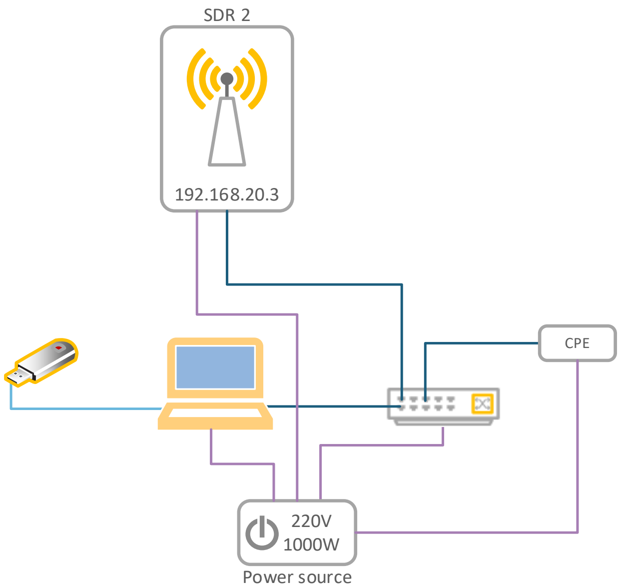

Figure 5-6 - UE connection diagram

5.2.2 Deployment of the mmWave positioning system

During the 5G-CLARITY project, a mmWave positioning system was developed and tested. This positioning system uses IHP's mmWave nodes (digiBackBoard SDR platform [5]) and a 60 GHz transceiver from Sivers Semiconductors [8]. For this demo, a setup with 2 anchor nodes (access points) and a single mobile node (or

[8] Sivers Semiconductors, https://www.sivers-semiconductors.com/

UE) was built. The distance between the two APs and the UE device is measured using two-way-ranging (TWR). These distances are later used to estimate the position of the UE. The position of the UE would be in the intersection of the circles described around the mmWave APs, the radius being the estimated distance between the AP and the UE. This approach will lead to two solutions for the UE position, since the described circles would intersect in 2 points. In order to avoid this issue, the mmWave APs can be placed in such an area that only one solution can be valid. Since one of the solutions is in front of the line passing through the both APs and the other is behind this line, constraining the area where the UEs can be, would exclude the other solution. Therefore, due to limitation of the number of mmWave APs, this solution was used.

The mmWave nodes from IHP have two different operation modes. In the first mode, the nodes can work as data transmission modems. This configuration cannot be used for localization. The other mode is so called the SDR mode. In this mode, all signal processing is performed in software running on a general-purpose PC. The data from and to the mmWave node is transferred using Gigabit Ethernet. For localization, i.e. implementation of TWR, the SDR mode of the mmWave nodes is used.

The main challenge faced during development of the TWR using the mmWave nodes is detection of the arrival of ranging frames. Normally, a preamble detector is used for this purpose. Nevertheless, the mmWave nodes have only 1 Gbps connection with the general-purpose computer, meaning they cannot transfer samples in real-time. This means that the preamble detection should be performed in hardware, which requires a relatively large effort and was not foreseen in this project. Therefore, a wired synchronization between the mmWave nodes was used. This, however, does not lead to loss of generality or to additional improvement of the measured localization precision or accuracy. The main reason is that the needed synchronization precision for the developed algorithm to function properly, is in the order of microseconds. This is easily achievable with the available preamble detectors. Additionally, the ranging algorithm is such that its precision/accuracy does not depend on the synchronization precision/accuracy.

The main disadvantage of this approach, where cabled synchronization is used for all mmWave nodes, is the mobility limitation. Due to the limited length of the synchronization cables, a precaution should be taken not to pull the equipment, which leads to an increased limitation of the mobility of the UE as well as the coverage. Nevertheless, since this system is extremely precise/accurate, even small changes in position of the UE can be easily estimated and, therefore, the system can be well evaluated.

A diagram and a photo of the mmWave system deployed in the BOSCH factory is given in Figure 5-7 and Figure 5-8 correspondingly.

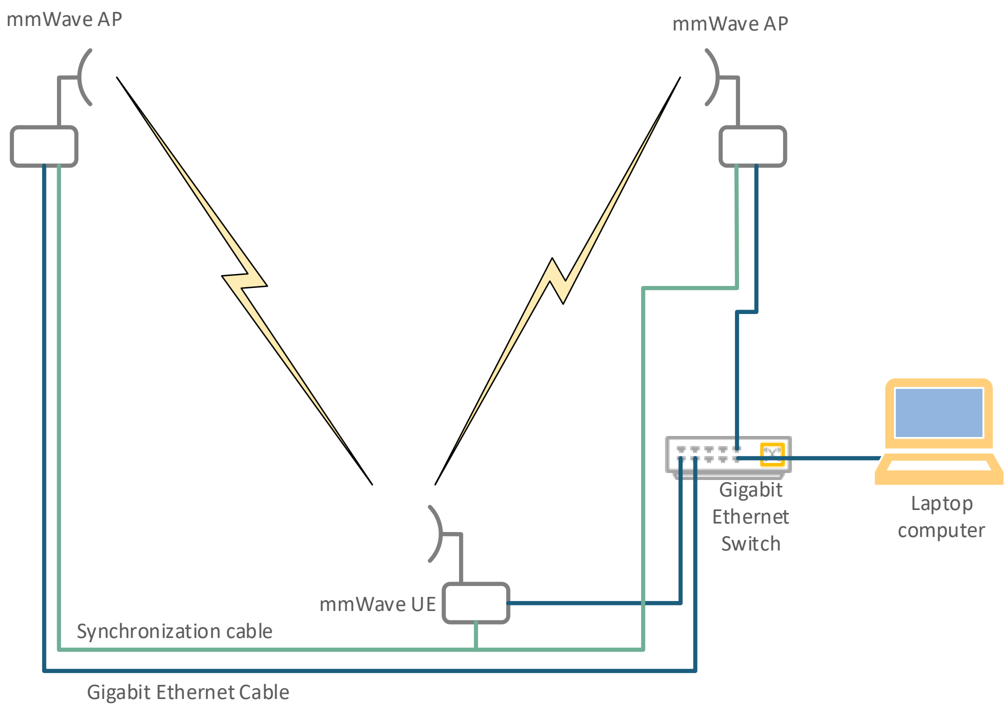

Figure 5-7 - Diagram of the deployed mmWave positioning system

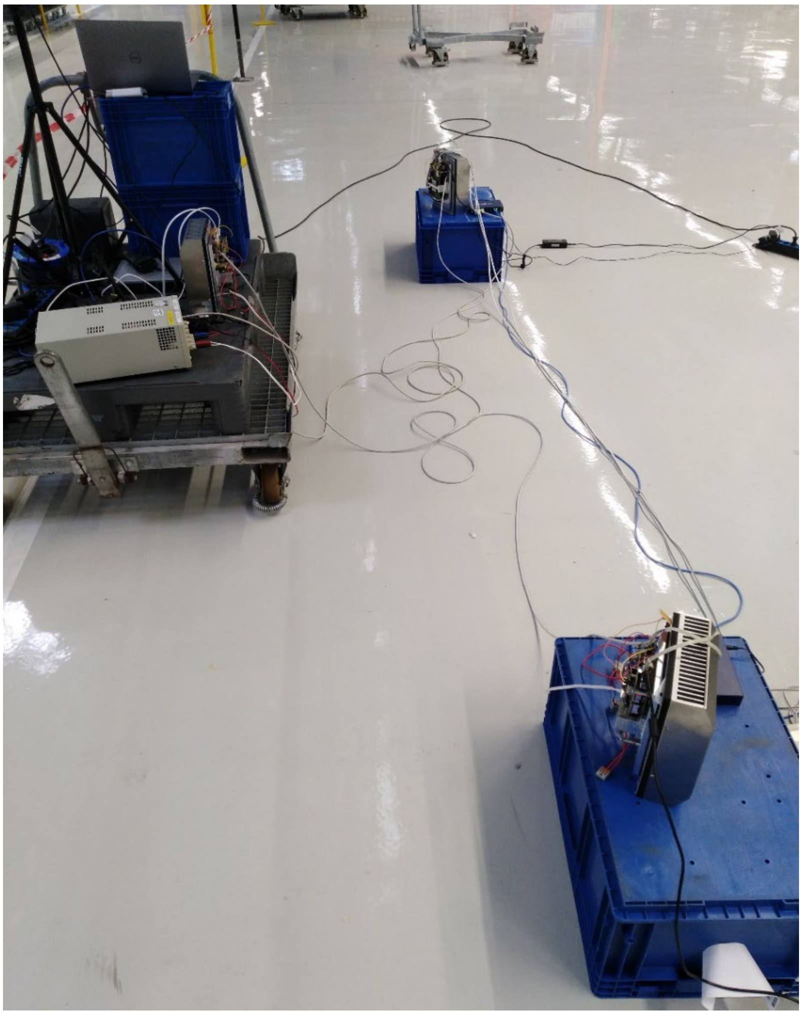

Figure 5-8 - Photo of the deployed mmWave positioning system

5.2.3 Deployment of the LiFi positioning system

For the LiFi positioning, a total of 2 LiFi APs in above the AGV path were deployed, as shown in Figure 5-9. The position of the installed LiFi access points is given in Figure 5-1. The initial approach for the LiFi system was to use RSS as measure for distance of the LiFi receiver to the LiFi AP. Unfortunately, this approach was not possible in the BOSCH factory and, therefore, a binary decision approach was used. Namely, the position of the UE was estimated based on the visibility of the LiFi APs. The defined areas were the first, the second or both APs can be seen. Based on the visibility of the LiFi APs, the position of the UE is assigned to one of these areas. This is not the optimal solution, but will anyway provide coverage to areas that do not require high precision/accuracy positioning.

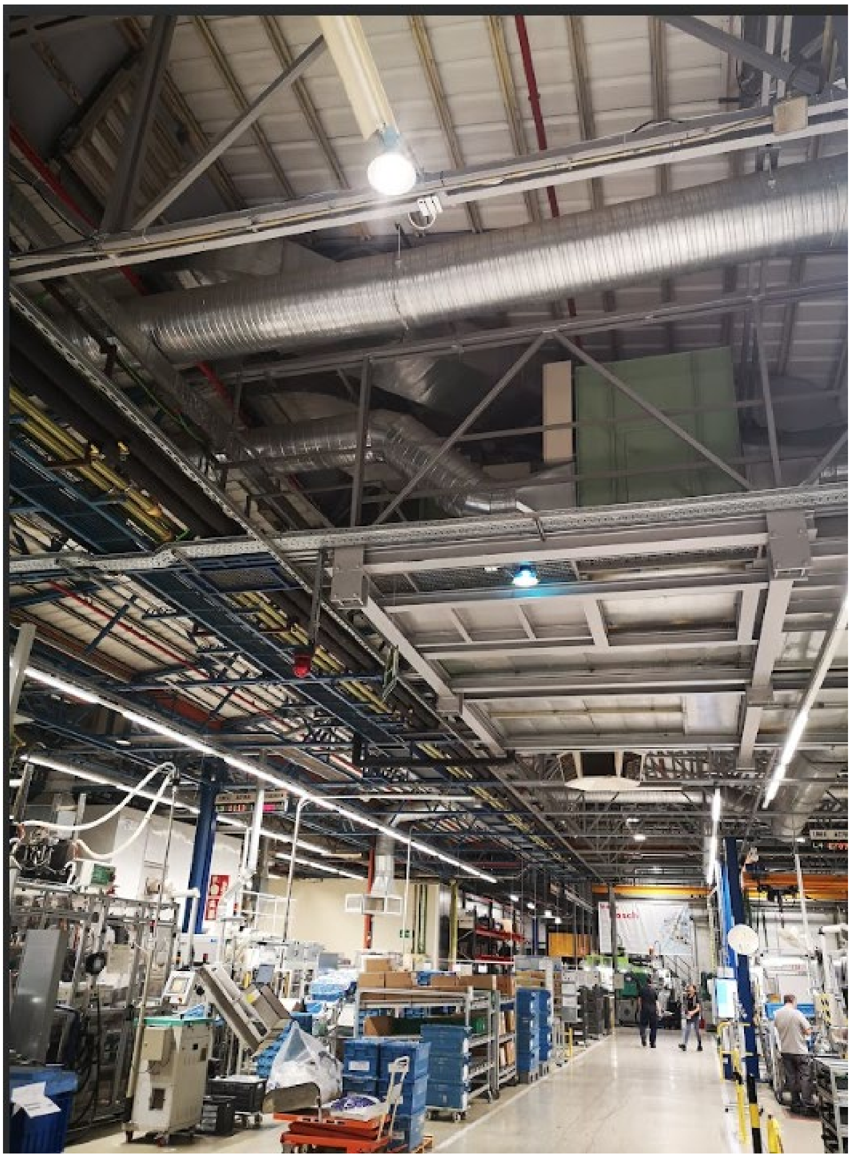

Figure 5-9 - LiFi access points mounted on top of the AGV path

5.2.4 Deployment of the localization server

The localization server [1] was written in Python and deployed on a separate server, running as a VM. The localization data is transmitted from the deployed positioning technologies to the server using the developed CPEs from I2CAT. In Figure 5-10, a dashboard of the localization server is shown. The localization server also runs data fusion algorithms that are used for fuse the positioning data from the different technologies.

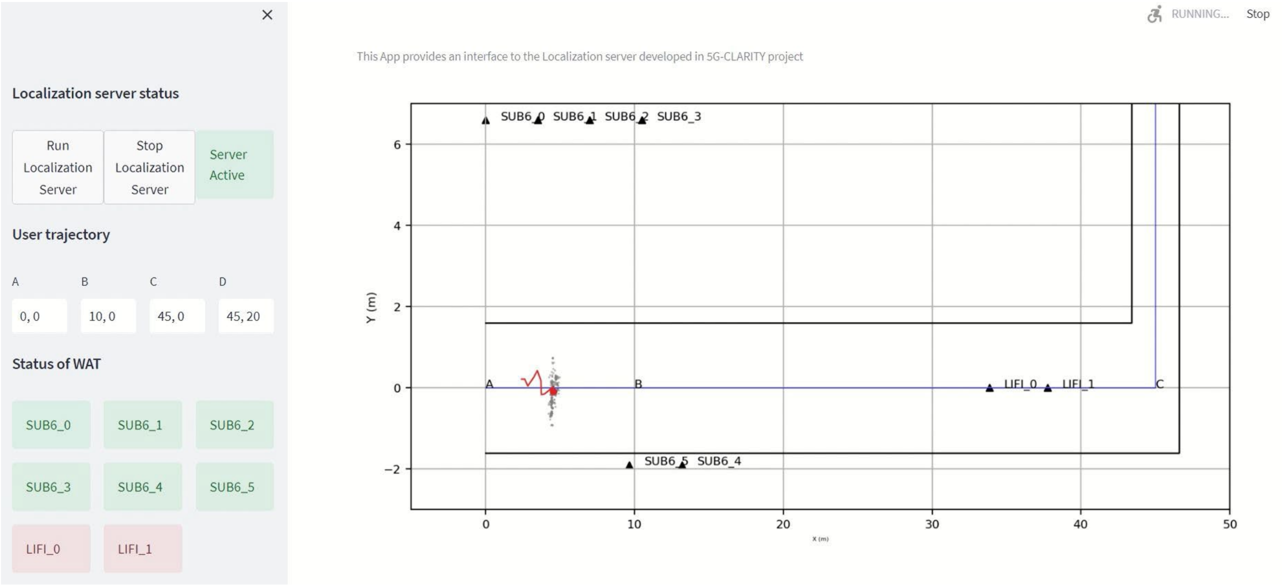

Figure 5-10 - Dashboard showing the position obtained from the localization server

5.3 Test scenarios for the localization system

To test the localization system deployed in the factory, a few different tests were performed. Initially, functionality tests were performed. These tests served to discover bugs in the algorithms and to correct them. After proper functioning of the system was established, two types of tests were performed. First, static tests were performed, which entail placing the UE devices at a given position and acquiring multiple position estimates. The static tests were performed for multiple positions. Further, dynamic tests were performed, by moving the UE along a straight line, as much as possible, and acquiring positions of the UE during this movement.

Two main properties of the system were evaluated during this demo, i.e. their accuracy and precision. The precision is easily assessable by collecting multiple position estimates. Since the precision is a measure of repeatability of a given estimate, the ground truth is not required. On the other hand, quantifying the accuracy requires a reference system for ground truth estimation. This system should have much higher precision in comparison to the one being evaluated. In the BOSCH factory, a laser distance meter was used, however, due to measurement errors, the obtained ground truth will not be satisfactory for the mmWave positioning system, where the positioning errors are in the millimetre order of magnitude.

Obtaining the ground truth for the mobile scenario is even a bigger challenge. In this case, a reference positioning system with an accuracy in the order of millimetre is required. This can be achieved in laboratory conditions where electro-mechanical systems can be used for positioning of the UE, but on a factory floor, with an active production process is almost impossible.

5.3.1 Sub-6 GHz test scenario

The test scenario for the sub-6 GHz system took place along the path intended for movement of the AGV and the workers in the factory. This path is highlighted with a green band in Figure 5-1. Two types of tests were performed, one being a static test and the other is a mobile test. In the static test, the wagon (Figure 5-5) was placed on a static position and a few hundred position estimates were performed. These measurements were used later for estimation of the empirical cumulative distribution function (eCDF) of the positioning error of the sub-6 GHz system. Additionally, a few mobile tests were performed, which include manual movement of the wagon on the track shown in Figure 5-1 and movement of the wagon using the AGV. In both cases, the intention was to move the wagon along a straight line.

5.3.2 LiFi test scenario

For the purpose of testing LiFi positioning, the LiFi USB stick is connected to the laptop computer used for running the software for both the sub-6 GHz positioning system and the mmWave positioning system. The wagon is moved from the area covered by the sub-6 GHz system towards the area covered by the LiFi. Unfortunately, it was not possible to overlap both areas due to limited choice for available place of installation. Nevertheless, this scenario was useful to test the possibility of transferring to different positioning technologies, transparent for the user. Namely, the localization server should provide position information to the user, regardless of the positioning technology that is available in a given area.

5.3.3 mmWave system test scenario

Regarding the mmWave system, as previously mentioned, a cable synchronization of the used mmWave SDRs in necessary. This greatly limits the area at which this system can be tested. Nevertheless, since this system is highly precise and accurate, even on relatively small areas of few square meters it can be tested and its precision and accuracy can be evaluated. The focus in these tests was on static scenarios, since the cables were greatly limiting the mobility of the UE.

5.4 UC specific KPIs

In this section the results from the 3 different localization systems are shown. Two main tests were performed during the test phase. The first is the static test where the UE is positioned on a known position, previously selected. This test is performed for multiple positions. During each of these tests multiple position estimates are acquired in order to estimate the precision and the accuracy of the system. The second test was a mobile test which was performed for the sub-6 GHz and the LiFi system. During this test an AGV was moving the wagon with the UE equipment and the position was continuously estimated.

5.4.1 Sub-6 GHz test results

For the sub-6 GHz positioning system, both the static and the mobile tests were performed. Initially, before the tests were performed, the system was calibrated.

In order to calibrate the system, the UE was positioned on a known location and the estimated time-difference-of-arrivals were compared to the expected ones. It was noticed that due to the different lengths of the cables leading from the SDR to the antennas, there was a small difference between the estimated and the expected TDoA. This can be compensated by knowing the cable length difference. Nevertheless, with this test it was confirmed that if the antenna cables have same electrical lengths, the rest of the system is relatively good synchronized and matched.

The initial test was performed by putting the wagon with the UE equipment on a few different positions. In order to estimate these positions, the distances from the UE Sub-6 GHz antenna to the AP antennas were measured using a laser distance meter (model BOSCH GLM 80 Professional). These distances are used to estimate the position, i.e. *x* and *y* coordinates of the UE position by triangulation. These positions are the ground truth.

The distance measurements from the laser distance meter have a millimeter precision. Nevertheless, Due to manual measurement of the distances form the UE to APs, a systematic measurement errors were made. This would introduce additional position estimate errors when the position estimates for the ground truth are made.

In Figure 5-11, the sub-6 GHz positioning scenario is shown. The red triangles are sub-6 GHz access points, the blue are the ground truth positions and the small dotted areas (clouds) are the position estimates for the corresponding ground truth positions. For each of the static positions of the UE, multiple (approx. 250) position estimates were performed. Due to the high positioning precision, the position estimates are tightly grouped and in Figure 5-11 cannot be seen as a separate position estimates. In Figure 5-12, a close-up of the estimated positions is shown. It can be seen that multiple positions are estimated for a given UE positions and they are grouped within a radius of 0.1-0.2 meters.

Finally, the eCDF of the positioning error is given in Figure 5-13. As can be noticed, for all of the static points, the positioning error is better than 12 centimetres.

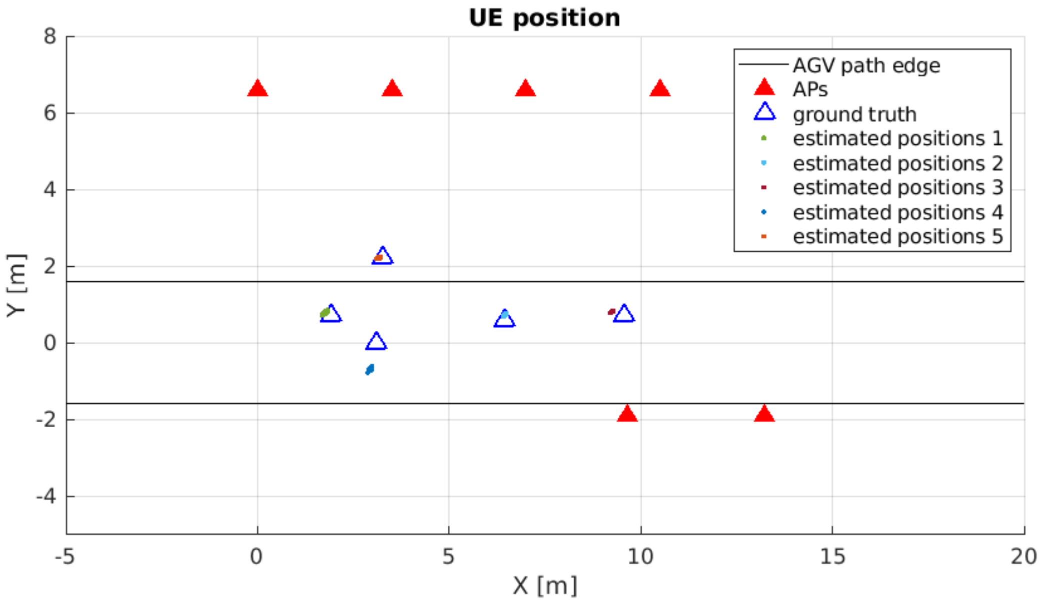

Figure 5-11 - Static test scenario and position estimates for the sub-6 GHz system

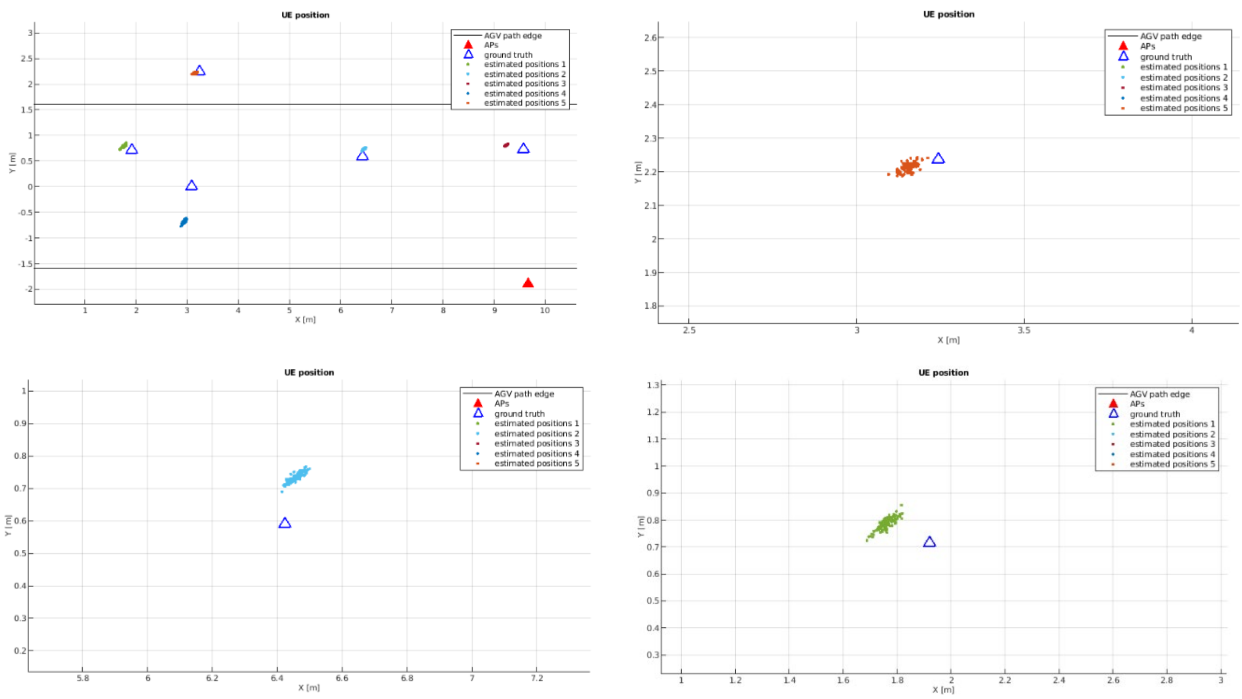

Figure 5-12 - Close-up of the position estimates

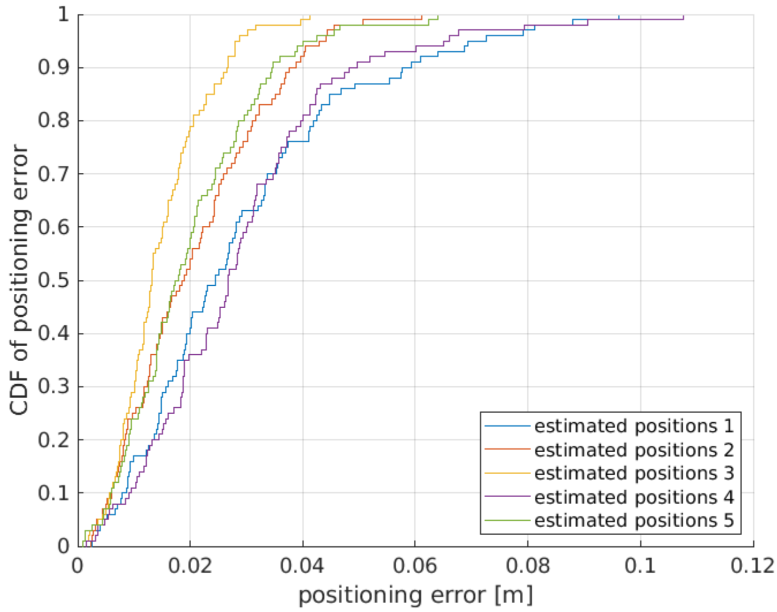

Figure 5-13 - Empirical CDF of the positioning error for the static scenario

Additionally, for the static scenario the accuracy of the position estimates was calculated. The accuracy for all of the points is given in Table 5-2. As can be noticed, for position 4 the accuracy is pretty low. This can be also noticed form the grouping of the position estimates in Figure 5-11 for this particular position. The source of this large error for this position is not known but it is assumed that one of the causes is the estimation of the ground truth. Probably an error in the manual measurement of distances between the UE and the APs was made, which caused an error in the ground truth.

Table 5-2 – Calculated accuracy for the static tests

	Ground truth		Mean estimated position		Error (accuracy)
Position No.	x_G [m]	y_G [m]	x_E [m]	y_E [m]	$\sqrt{(x_G - x_E)^2 + (y_G - y_E)^2}$ [m]
1	1.91	0.71	1.76	0.78	0.17
2	6.42	0.58	6.45	0.73	0.14
3	9.56	0.72	9.23	0.80	0.33
4	3.09	0.00	2.94	-0.68	0.69
5	3.24	2.23	3.15	2.21	0.09

Finally, a few different mobile tests were performed. The initial tests were performed by manually pushing the cart with the UE equipment on it, as in **Figure 5-5**. Nevertheless, it is not possible to push the cart along a straight line with this approach. Therefore, the final tests were performed with the wagon attached to an AGV since the AGV was able to move the wagon along a straight line. The results form 2 AGV runs are shown in **Figure 5-14**. During these runs, the AGV was moving near the centre line of the path. The red and the blue lines represent the reconstructed AGV paths obtained using the developed sub-6 GHz system. As can be noted, the highest precision is obtained when the AGV is near the APs. When the AGV moves out of this coverage area, the position estimates start to become less precise. This can be especially noticed on the left hand side in the **Figure 5-14**. In the middle area on the same figure, the both paths almost overlap. A bit of noise in the path position is to be see, but this is in the order of the previously estimated noise in static scenarios. Additional analysis were not performed, since these would require the ground truth of the AGV over time. Obtaining precise dynamic ground truth at that moment, with the available equipment, was not possible. Therefore, analysis of the precision and accuracy of this scenario was not possible. However, it can be assumed that the precision and the accuracy for the dynamic case are comparable to the static case, since the duration of the received frames needed for positioning is in to order of hundred microseconds, and the UE can be assumed to be static during this reception.

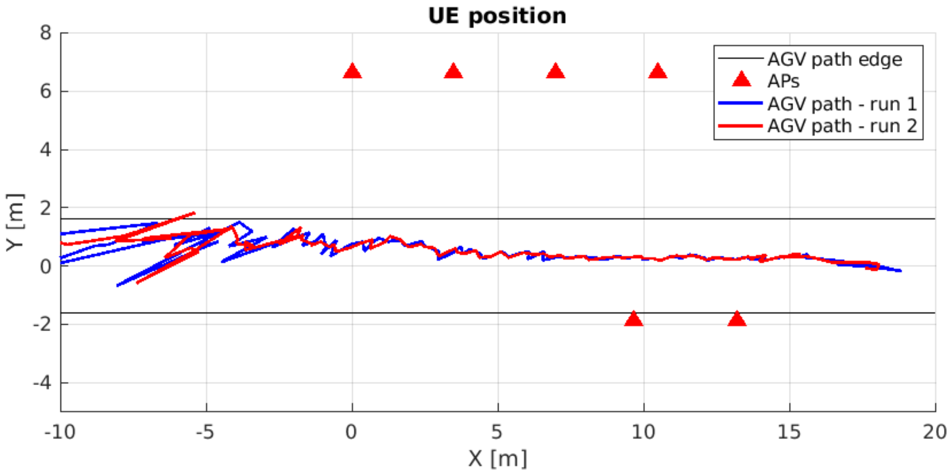

Figure 5-14 - Mobile test scenario for the sub-6 GHz positioning system. The estimated AGV path (blue and red) is from two separate runs.

5.4.2 LiFi test results

As mentioned previously, due to the high ceiling in the factory floor, the LiFi APs have to be placed relatively higher than their intended mounting height. This has as a consequence that the received RSSI level at the UE side is quite low and is actually on the lowest level whenever a LiFi AP is visible. This means that the positioning precision will be quite low, i.e. it would be possible to detect only if the UE is below a given LiFi AP or not. From the performed experiments, it was also notices that the coverage of the LiFi APs was a circle with a radius of approximately 2 meters. This means that the precision of this system, with this setup will be not better than 2 meters.

In Figure 5-15, the output of the iwscan command can be seen. In this case only a single LiFi AP is to be seen by the LiFi UE equipment. The RSSI value, market in red is -75 dBm, which is the minimum value.

```
BSS 70:b3:d5:95:8c:00(on wlx70b3d595881c)
        TSF: 0 usec (0d, 00:00:00)
        freq: 2417
        beacon interval: 100 TUs
        capability: ESS Privacy ShortPreamble ShortSlotTime (0x0431)
        signal: -75.00 dBm
        last seen: 2292 ms ago
        Information elements from Probe Response frame:
        SSID: LiFi-X
        Supported rates: 1.0* 2.0* 5.5* 11.0* 6.0 9.0 12.0 18.0
        DS Parameter set: channel 2
        ERP: <no flags>
        Extended supported rates: 24.0 36.0 48.0 54.0
        RSN:     * Version: 1
                 * Group cipher: CCMP
                 * Pairwise ciphers: CCMP
                 * Authentication suites: PSK
                 * Capabilities: 16-PTKSA-RC 1-GTKSA-RC (0x000c)
        BSS Load:
```

```
                * station count: 1
                * channel utilisation: 0/255
                * available admission capacity: 0 [*32us]
        Extended capabilities:
                * SSID List
                * Operating Mode Notification
        WMM:    * Parameter version 1
                * BE: CW 15-1023, AIFSN 3
                * BK: CW 15-1023, AIFSN 7
                * VI: CW 7-15, AIFSN 2, TXOP 3008 usec
                * VO: CW 3-7, AIFSN 2, TXOP 1504 usec.
```

Figure 5-15 - iwscan output when a single LiFi AP is visible

In Figure 5-16, the output of the iwscan command for two visible LiFi APs is to be seen. The RSSI levels are -75 dBm and -72 dBm and are marked in red. The value of -72 dBm in this case is the minimum value for the second LiFi AP.

```
BSS 70:b3:d5:95:8c:00(on wlx70b3d595881c)
        TSF: 0 usec (0d, 00:00:00)
        freq: 2417
        beacon interval: 100 TUs
        capability: ESS Privacy ShortPreamble ShortSlotTime (0x0431)
        signal: -75.00 dBm
        last seen: 3504 ms ago
        Information elements from Probe Response frame:
        SSID: LiFi-X
        Supported rates: 1.0* 2.0* 5.5* 11.0* 6.0 9.0 12.0 18.0
        DS Parameter set: channel 2
        ERP: <no flags>
        Extended supported rates: 24.0 36.0 48.0 54.0
        RSN:    * Version: 1
                * Group cipher: CCMP
                * Pairwise ciphers: CCMP
                * Authentication suites: PSK
                * Capabilities: 16-PTKSA-RC 1-GTKSA-RC (0x000c)
        BSS Load:
                * station count: 1
                * channel utilisation: 0/255
                * available admission capacity: 0 [*32us]
        Extended capabilities:
                * SSID List
                * Operating Mode Notification
        WMM:    * Parameter version 1
                * BE: CW 15-1023, AIFSN 3
                * BK: CW 15-1023, AIFSN 7
                * VI: CW 7-15, AIFSN 2, TXOP 3008 usec
                * VO: CW 3-7, AIFSN 2, TXOP 1504 usec
BSS 70:b3:d5:95:8b:8a(on wlx70b3d595881c)
        TSF: 0 usec (0d, 00:00:00)
```

```
freq: 2417
beacon interval: 100 TUs
capability: ESS Privacy ShortPreamble ShortSlotTime (0x0431)
signal: -72.00 dBm
last seen: 84 ms ago
SSID: LiFi-X
Supported rates: 1.0* 2.0* 5.5* 11.0* 6.0 9.0 12.0 18.0
DS Parameter set: channel 2
TIM: DTIM Count 0 DTIM Period 3 Bitmap Control 0x0 Bitmap[0] 0x0
ERP: <no flags>
Extended supported rates: 24.0 36.0 48.0 54.0
RSN:    * Version: 1
        * Group cipher: CCMP
        * Pairwise ciphers: CCMP
        * Authentication suites: PSK
        * Capabilities: 16-PTKSA-RC 1-GTKSA-RC (0x000c)
BSS Load:
        * station count: 1
        * channel utilisation: 0/255
        * available admission capacity: 0 [*32us]
Extended capabilities:
        * SSID List
        * Operating Mode Notification
WMM:    * Parameter version 1
        * BE: CW 15-1023, AIFSN 3
        * BK: CW 15-1023, AIFSN 7
        * VI: CW 7-15, AIFSN 2, TXOP 3008 usec
        * VO: CW 3-7, AIFSN 2, TXOP 1504 usec.
```

Figure 5-16 - iwscan output when two LiFi APs are visible

The data acquired using the iwscan command was automatically parsed and sent to the localization server. Unfortunately, due to the fixed value of the RSSI, further precision tests were not possible.

5.4.3 mmWave system test results

As mentioned previously, the mmWave system was tested as a standalone system in a relatively small area, due to the needed cables for synchronization. In Figure 5-17 the position of the anchor nodes as well as the position of the UE can be seen. The mmWave APs were positioned next to the path where the AGV travels, as can be shown in Figure 5-18. The UE equipment was placed on a wagon and moved to different static positions.

The ground truth positions of the UE is given in Table 5-3.

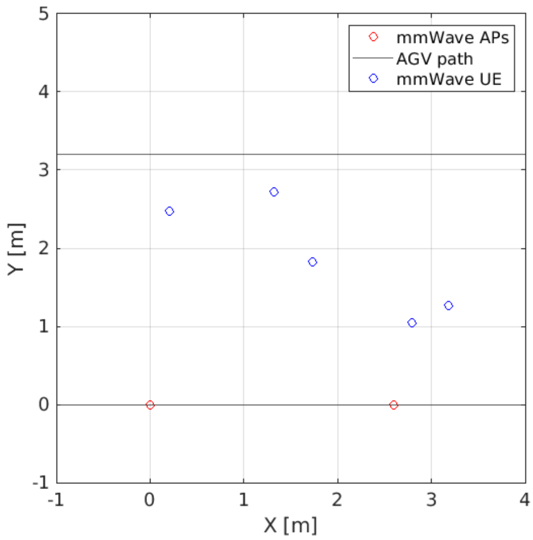

Figure 5-17 - Position of the APs and positions of the UE for the positioning tests

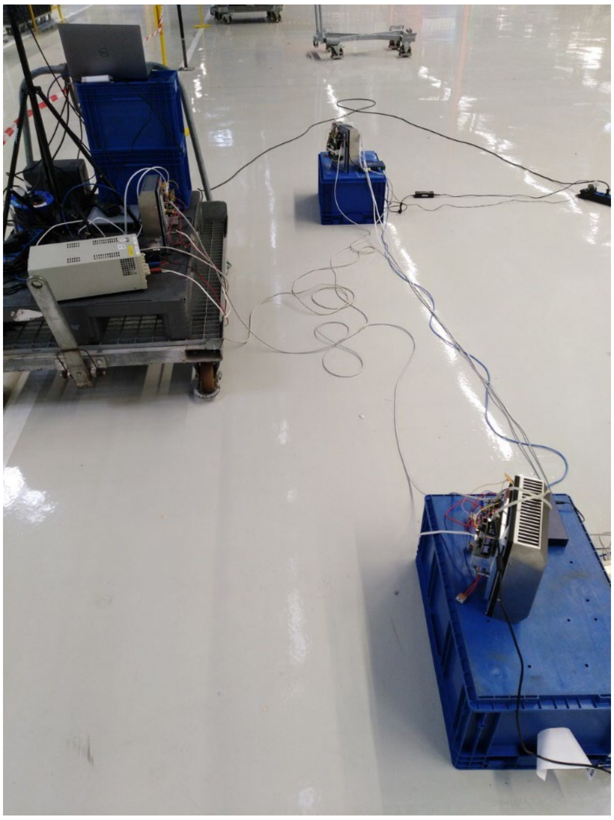

Figure 5-18 - Photo of the mmWave positioning system setup

Table 5-3 - Ground truth positions for the mmWave static positioning tests

Position No.	X [m]	Y [m]
1	0.21	2.48
2	1.32	2.72
3	2.79	1.04
4	3.18	1.27
5	1.73	1.82

It should be noted that errors in the order of a few centimetres in these ground truth positions are very likely. These positions were calculated based on the UE equipment distance to the mmWave anchor nodes (or APs). Since this is not a laboratory setup, a few sources of errors were identified. Due to the nature of the setup, it is not possible to completely avoid these errors. The first source of error is the manual measurement of the distances from the UE to the APs. These distances were measured using laser distance meter and due to movements of the hand, errors of a few centimetres are unavoidable. Further, the APs and the UE were not on a same height. Having only 2 APs, only 2D positioning can be performed, which means that all the devices must be in a same plane, i.e. height. In some positions, it can happen that small errors in distance measurement to the APs can cause large errors in position calculation. This is especially true if the UE is close to the Y axis. Of course, there are other sources of errors, but these are most significant.

Even there are some errors in the ground truth, and the accuracy of the system cannot be estimated significantly, the precision on the other hand can be relatively well estimated.

In Figure 5-19, the eCDF of the distance estimation error is given. This are the errors of the distance estimates between the AP1 and UE and AP2 and UE. Since a total of 5 different static positions are evaluated, a total of 10 eCDFs are shown in this figure.

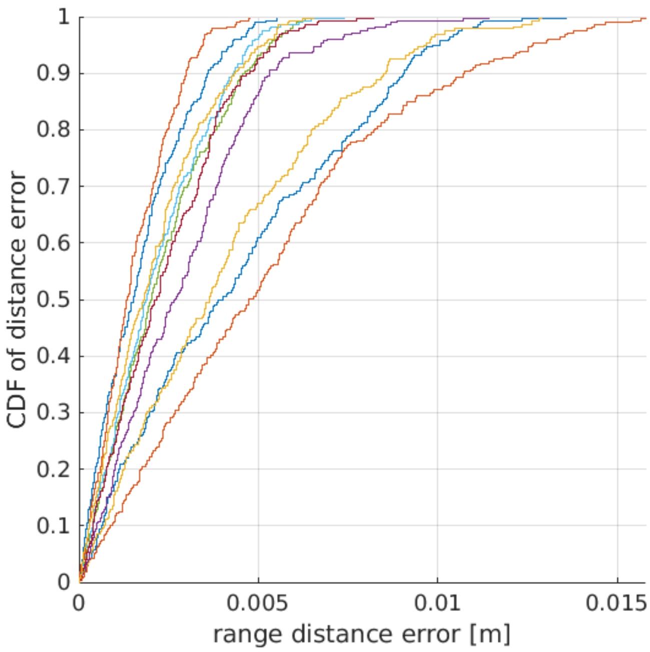

Figure 5-19 - Empirical CDF of the distance estimation error between UE and APs

In Figure 5-20, the eCDFs of the positioning error estimates are shown. A total of five curves are available, since a total of five positions were evaluated. As can be noticed, the positioning precision is better than 3 centimetres.

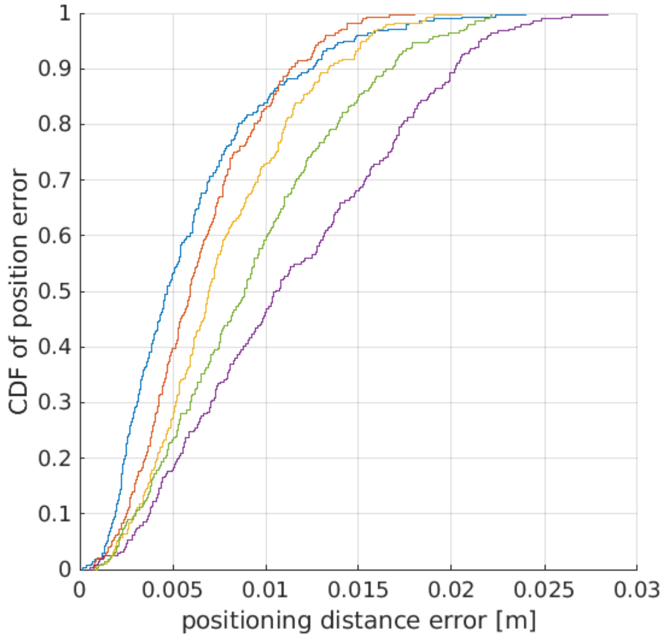

Figure 5-20 - Empirical CDF of the position estimation error

5.5 Transversal Specific KPIs

The transversal KPIs from Section 2.5 were evaluated and short summary is given in Table 5-4.

Table 5-4 - Transversal KPIs for UC2.2

KPI	Unit	Value	Comment
Static precision/accuracy of the Sub-6 GHz system	Meter	precision/accuracy 0.12/0.28	
Dynamic precision/accuracy of the Sub-6 GHz system	Meter	N/A	Not evaluated. Expected to be the same as in the static case. Not evaluated because no ground truth is available
Static precision/accuracy of the mmWave system	Meter	precision/accuracy 0.03/(N/A)	Accuracy was not evaluated since the ground truth cannot be precisely estimated
Functionality of the LiFi system		Functional	
Position estimation latency and frequency	second/Hz	latency/frequency 0.15/6.5	

6 5G-CLARITY deployment recommendations

6.1 Deployment recommendations in Museum environment from UC-1

In this section, we use the real measurements collected during the use case demonstration to develop a cost model that showcases the actual benefits of deploying the 5G-CLARITY multi-connectivity framework. To improve user experience and guarantee network reliability throughout the museum coverage area, we examine the uplink traffic capacity requirements. This examination helps us identify the minimum aggregate capacity needed across the multiple Radio Access Technologies. The analysis will provide valuable insights for decision-makers and stakeholders in the industry, enabling them to assess the financial feasibility, advantages, and potential return on investment when implementing this framework.

6.1.1 Traffic definition and requirements

To accomplish the goals outlined in the Smart Tourism use case (Section 3.3), the UL traffic capacity must satisfy certain requirements based on the various scenarios, considering the unique device configurations and their respective traffic conditions within the coverage area. The UL throughput requirements for different devices implemented in our setup are within the following range:

- Security surveillance
    - 360-degree camera = [100 - 126] Mbps
    - Monitoring device = [1 - 1] Mbps
    - Control for robot = [1 - 1] Mbps
- Multi-WAT support for robot obstacle detection
    - Fixed cameras = [3 - 6] Mbps
- Coverage area = 832 m^2

Section 3 has provided a description of the devices and their respective roles in the use case reported above. We have conducted calculations to determine the minimum and maximum UL data rate capacities for the respective throughput range. This analysis considers several factors, including traffic fluctuations based on different scenarios. For instance, we have deployed fixed cameras that use H.264 video compression to reduce the size of the video data generated by these cameras. The size of UL traffic sent to the server can vary depending on the number of people and movement captured by the cameras. H.264 encoding achieves compression by analysing each frame of the video and identifying areas of the image that remain constant, as well as other areas that change rapidly. This is particularly important in video surveillance applications implemented in private 5G network, where bandwidth and storage considerations are critical.

Therefore, by employing a link aggregation technique that combines 5G, WiFi-6, and LiFi using MPTCP, we can provide the UL bandwidth capacity needed to support the upper limits of our expected traffic throughout the museum's coverage area. This results in better connectivity, link reliability, enhanced user experience and improved productivity.

To determine the necessary throughput per device, we consider the uplink requirements and the expected number of devices connected to the 5G, WiFi-6, and LiFi access networks through the MPTCP-enabled multi-connectivity supported CPE, as well as their locations within the museum.

Next, we calculate the overall required throughput by multiplying the number of devices by the throughput for each device, which leads to the following calculation:

360-degree camera x 1

Monitoring device x 1

Robot control x 1

Fixed cameras x 2

Minimum UL capacity requirement = (1 x 100 Mbps) + (1 x 1 Mbps) + (1 x 1 Mbps) + (2 x 3 Mbps) = 108 Mbps

Maximum UL capacity requirement = (1 x 126 Mbps) + (1 x 1 Mbps) + (1 x 1 Mbps) + (2 x 6 Mbps) = 140 Mbps

To calculate the total capacity for the entire 3 floors of the museum building =

Total minimum UL capacity requirement = 108 Mbps x 3 = 324 Mbps

Total minimum UL capacity requirement = 140 Mbps x 3 = 420 Mbps

To ensure adequate network performance, we have determined the total UL traffic capacity needed for the entire museum building. This capacity requires provisioning, which involves allocating the necessary resources, to adequately support the expected data traffic. The expected UL traffic range between 324 Mbps and 420 Mbps.

6.1.2 Capacity and Coverage provisioning

To meet the anticipated traffic requirements for the entire museum building and to ensure the network performance is suitable for the Smart Tourism use case, we conducted several measurements of the individual access network KPIs, specifically focusing on 5G and WiFi-6. We compared the current state-of-the-art deployment model, which relies solely on Wi-Fi, to the 5G-CLARITY multi-connectivity framework model that combines WiFi-6 and 5G mainly.

We began by carrying out a performance analysis using a network performance model. This model predicts the performance of the selected access networks based on the signal quality and coverage measurements obtained. By quantifying the network KPIs, we can determine whether the deployment will achieve its performance goals.

Using the 5G, WiFi-6 and LiFi link aggregation via the MPTCP-enabled CPE, we conducted multiple iterations of measurements while adjusting the placement and settings of the access points. As a result, we were able to achieve an aggregated UL throughput that is enough to support the range of UL requirement as reported in section 3.4. This throughput capacity is sufficient to meet the maximum UL traffic requirement of 140 Mbps. Table 3-2 in section 3.2 details the configurations of the access points that we used to attain the aggregated UL and DL throughputs, as the results in Figure 3-18 shows. The figure presents the uplink traffic to the server. The measurements were taken between 14:20:20 and 14:23:10, and the results shows a peak throughput performance of 890 Mbps, while the minimum throughput performance was 150 Mbps. As the graph portrays, the performance of the network degraded as the distance between the CPE and the APs increased over time. The APs were located at the starting point of the measurement, and as the CPE moved away from them, the throughput reduced but still sufficient to support the maximum UL traffic capacity of 140 Mbps.

6.1.3 Extrapolation from measured KPIs to deployment recommendations

In this section, we utilise the extrapolation from the network KPI measurements to provide potential benefits for industry verticals with real recommendations for private 5G network deployment. We compare the outcomes of deploying only WiFi-6 versus deploying both WiFi-6 and 5G. Below is a description of the two scenarios.

6.1.3.1 Current state of the art deployment model – Scenario 1: Wi-Fi only deployment

Going by the networking performance three WiFi-6 access points are needed for each floor of the museum and a total of nine access points for the entire three floors of the museum building. This model was determined through a series of network KPI measurements reported in section 3.4, which presents WiFi-6 performance within the demonstration area. Though WiFi-6 had started out with high data rates of up to 890 Mbps, the signal experienced high fluctuations and degrades significantly to 50 Mbps with increased distance from the AP. Given this limitation of WiFi-6 in terms of its range and signal strength, for a WiFi-6 alone deployment three APs would be required to cover adequately each floor of the museum. Although in theory, two APs could suffice to meet the uplink requirements of each floor, the reality proves different due to various factors such as interference that obstruct WiFi-6 signals operating at a frequency of 5.180 GHz. These factors are primarily related to the nature and composition of the materials used in the museum's construction and exhibition areas, including dense concrete walls, glass, and metallic objects. With such an interference prone situation, over-provisioning would present a more pragmatic solution to achieve the level of network reliability necessary for the Smart Tourism use case.

6.1.3.2 5G-CLARITY multi-connectivity framework deployment model – Scenario 2: combined WiFi-6 and 5G deployment

Table 6-1 presents the total number of Wi-Fi 6 access points and 5G radio units needed for the entire museum building when deploying a combination of both wireless access networks to provide the required uplink traffic capacity.

Table 6-1 Combined WiFi-6 APs and 5G Radio Unit Deployment for Uplink Traffic Capacity.

Museum floor	No. WiFi-6 APs	No 5G radio unit
First floor	1	1
Second floor	1	
Third floor	1	
Total no. APs	**3**	**1**

Based on extrapolation, one 5G radio could cover the museum floors, to provide a more stable 5G coverage across all coverage areas. While this capacity may not be sufficient to fully address the uplink traffic requirements, it does allow for the use of only one WiFi-6 access point per floor as a complementary solution.

Compared to a Wi-Fi-only deployment strategy, the extent of over-provisioning is significantly reduced in this context. As a result, the 5G-CLARITY multi-connectivity solution becomes highly appealing due to the cost savings that accumulate over time.

6.1.4 Cost model analysis

In this section we analyse the cost elements for the two deployment scenarios described in sections 6.1.2.1 and 6.1.2.2.

To formulate the cost model based on the real indoor coverage measurements of 5G, WiFi-6, and LiFi, and to extrapolate deployment benefits we first identify all cost factors associated with 5G, WiFi-6 and LiFi deployment. These cost factors cut across the entire cost distribution, ranging from CApital EXpenditures (CAPEX) to OPerational EXpenditures (OPEX) and the Total Cost of Ownership (TCO). This would include such items as the cost of equipment, installation, maintenance. A detailed definition of all cost elements in CAPEX and OPEX are required to derive the TCO.

This cost model, using extrapolation from the network performance model optimizes the overall cost of deployment while maintaining the desired level of coverage and performance. The model integrates the

CAPEX and OPEX elements as well as the expected performance and coverage of the network. By quantifying the projected cost savings, industry verticals themselves could determine whether the optimization is likely to be profitable.

The Total Cost of Ownership equals the summation of the total cost of CAPEX and OPEX components, where

CAPEX = the capital expenditure, which refers to all one-off-investment cost used to acquire or upgrade physical assets or infrastructure such as equipment costs.

OPEX calculation = operational expenditure, which means the recurring or ongoing cost such as maintenance and power costs

$$TCO = \sum_{i=1}^{N_f} Capex + \left(\sum_{i=1}^{N_f} Opex \,.\, a_{infl}\right) Nyrs \qquad \text{--- (1)}$$

Where,

TCO = Total cost of network deployment.

CAPEX = Sum of capital expenditures, which include equipment cost and infrastructure cost.

OPEX = (Sum of operational expenditures x annual inflation) multiply by number of years, which include Energy consumption, Maintenance cost, Fault management/reparation cost.

N_f = number of museum floors.

Nyrs = number of years used for OPEX calculation.

Capex calculations:

$$CAPEX = \sum_{i=1}^{N} Cost_{Eq} + Cost_{Inst} + Cost_{Infra} + Cost_{Lfee} \quad \text{--- (2)}$$

Where,

$Cost_{Eq}$ = Cost equipment
$Cost_{Inst}$ = Cost of installation
$Cost_{Infra}$ = Cost of infrastructure
$Cost_{Lfee}$ = Cost of License fee
N = Number of cost item

OPEX calculations:

$$\text{OPEX} = N_D * \sum_{i=1}^{N} (CE * P_h) * N_{APs} + \sum_{i=1}^{Nm} C_M * C_F \quad \text{--- (3)}$$

N_D = Number of days
P_h = Power per hour
CE = Cost of one kWh of energy
N_{APs} = Number of Access Points
N_m = Number of maintenance
C_M = Cost of maintenance
C_F = Cost of fault reparation

The formulations for equations (1), (2), and (3) have been previously documented and elaborated in detail in references [6] and [7].

From Table 6-8 we have a list of assumed estimates for network costs components based on current commercial providers. To normalise the cost values to a common reference point, we give the cost distribution in percentages for 5G and WiFi-6. Table 6-2 and Table 6-3 present the CAPEX and OPEX cost breakdown for a greenfield 5G deployment scenario for one year. It shows the list CAPEX and OPEX cost components and their respective percentage cost estimate of the total CAPEX or OPEX cost. This way we can see the level cost contribution of the each of the various cost elements for 5G and WiFi-6 components (Table 6-4 and Table 6-5).

Table 6-2 Greenfield 5G deployment: CAPEX Cost Distribution.

Cost Category	Cost Description	Percentage of CAPEX Total Cost
Infrastructure	Network components setup Hardware / Software and integration fiber-optic, cables, antennas, etc.	40%
Equipment	Basic Equipment BBU, switches, routers, etc.	20%
Installation	System integration, labour	15%
Spectrum Licence fees	Regulatory permit	10%
Support services	Training and support	10%
Site preparation	Green field type deployment	5%

Table 6-3 Greenfield 5G deployment: OPEX Cost Distribution.

Cost Category	Cost Description	Percentage of Total OPEX Cost
Energy	Electricity bills	40%
Maintenance	Network monitoring, updates and upgrade, engineer/ technician salaries	30%
Software Licence renewal fees	Renewable software licences	20%
Fault management /reparation	Fault repairs	10%

Table 6-4 Greenfield WiFi-6 deployment: CAPEX Cost Distribution.

Cost Category	Percentage of Total Capex Cost
Access Point	45%
System Integration and installation	30%
Switching and cabling	15%
Design and planning	10%

Table 6-5 Greenfield WiFi-6 deployment: OPEX Cost Distribution.

Cost Category	Percentage of Total OPEX Cost
Maintenance and Support	50%
Energy consumption	25%
Upgrades and Expansions	15%
Network Monitoring and Management	10%

Figure 6-1 presents the CAPEX and OPEX results for WiFi-6 only versus WiFi-6 and 5G solutions. For the CAPEX comparison, the results reveal 27% Capex differential in favour of WiFi-6 only solution. This means that implementing the WiFi-6 only solution would require 27% less initial Capex investment or upfront costs compared to the WiF-6 and 5G combined solution.

Despite the 27% CAPEX differential, several qualitative advantages make the 5G-CLARITY multi-connectivity solution a more realistic choice for enterprise solution.

Figure 6-1 also provide OPEX result for both solutions. The result presents a 61% cost advantage for the Wi-Fi-6 only solution. Even as the OPEX percentage difference is higher than CAPEX, the OPEX real cost is much lower in comparison.

In the following section, we will conduct a cost-benefit analysis to highlight the advantages and limitations of each deployment model. It will compare both solutions against their network KPI performance and compare the benefits network performance brings to the cost difference between the two solutions.

The purpose of this analysis is to evaluate the trade-offs between network performance and cost, and to determine which deployment model provides the best overall value. This analysis supports decision-making for industry verticals to accurately weigh the benefits and costs of the different options before making a final decision for private 5G network adoption or not.

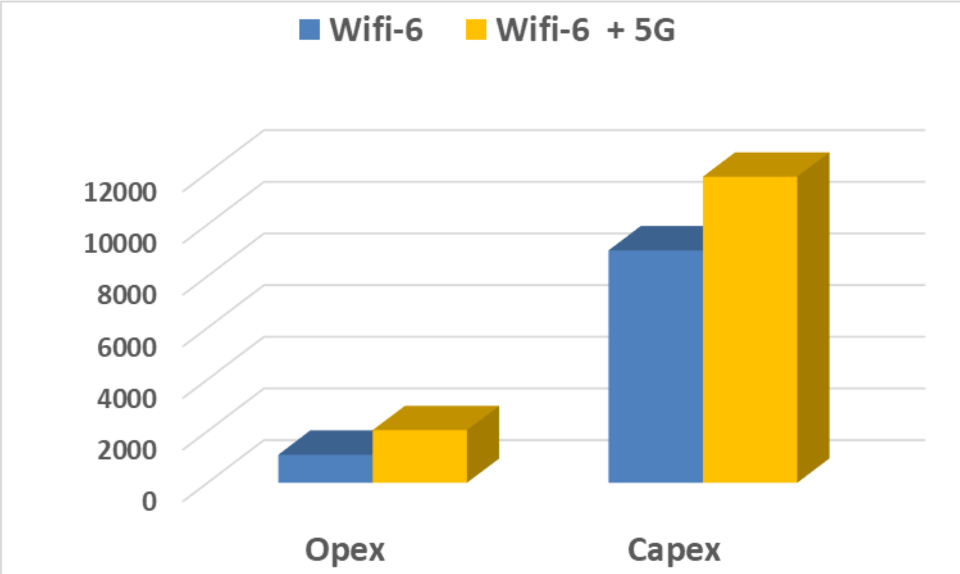

Figure 6-1 A comparison of Capital Expenditures (CAPEX) for WiFi-6 only versus a combined WiFi-6 and 5G solution.

6.1.5 Cost/benefit analysis

First, we analyse how WiFi-6 only deployment model vs WiFi-6 + 5G NR deployment model compares based on measurement results and cost calculations. Table 6-6 shows this comparison against the measured network performance.

Table 6-6 Wi-Fi-6 only deployment model vs WiFi-6 + 5G NR deployment model.

KPI measurements	WiFi-6 only deployment	WiFi-6 + 5G NR deployment
Coverage analysis	Walls and other materials impede signal penetration and hampers reliable connectivity.	Improve signal coverage and penetration, especially in areas with obstacles or interference that impede Wi-Fi signals, resulting in a reliable and consistent connection for users across the coverage area.

Network performance analysis	Throughput is over provisioned resulting to waste of valuable resources.	Offers improved network performance. In terms of reliability and latency, which QoS and QoE.
Mobility related performance analysis	WiFi-6 has a huge reconnection time of 4.7 seconds. This gap would result in a significant interruption to the video streaming service and consequently the poor user experience and reliability.	The mobility related interruption does not happen on the 5G link. This brings enormous benefits to the video stream services of the use case implementation.
Cost analysis	This solution is cheaper but at steep performance cost. The mobility KPI shows interruptions at 4.7 seconds which adversely affects the use case implementation.	Slightly pricier but at considerable performance advantage. Greater potential to accelerate return on investment. The interruption does not happen in 5G.
Scalability and future-proofing	Limited by the number of device connectivity. Scalability confined and restricted.	More scalable and better suited to handle the increasing number of connected devices and emerging enterprise applications. Robust and adaptable network infrastructure.
Flexibility and load balancing	Constraints by the limitations of Wi-Fi technology.	Leveraging the strengths of both technologies with capability to balance network load and optimize performance in different usage scenarios and environments.

6.2 Deployment recommendations for production line connectivity in factory environments – UC2.1

The goal of UC2.1 was to demonstrate the feasibility of connecting a production line through the 5G-CLARITY network, which was successfully shown in Section 4. The goal of this section is to extrapolate the measurements obtained through the UC2.1 demonstration to define a deployment model that can help us understand the advantages of connecting production lines through the 5G-CLARITY system, instead of connecting them through Ethernet, as it is being currently done. Our rationale to define this deployment model follows three steps:

- Step 1: Design a traffic model that we can use to set requirements on the network that will be deployed.
- Step 2: Based on the traffic requirements, and the measurements taken at BOSCH Aranjuez, dimension the type of 5G-CLARITY network that would have to be deployed.
- Step 3: Create a cost model for the network that we need to deploy, which can be compared to the cost required to deploy and maintain the current Ethernet network.

6.2.1 Definition of a traffic model for MES connected production lines

The first step to define a traffic model is to understand how much traffic is currently being generated by the production lines installed in the BOSCH factory at Aranjuez.

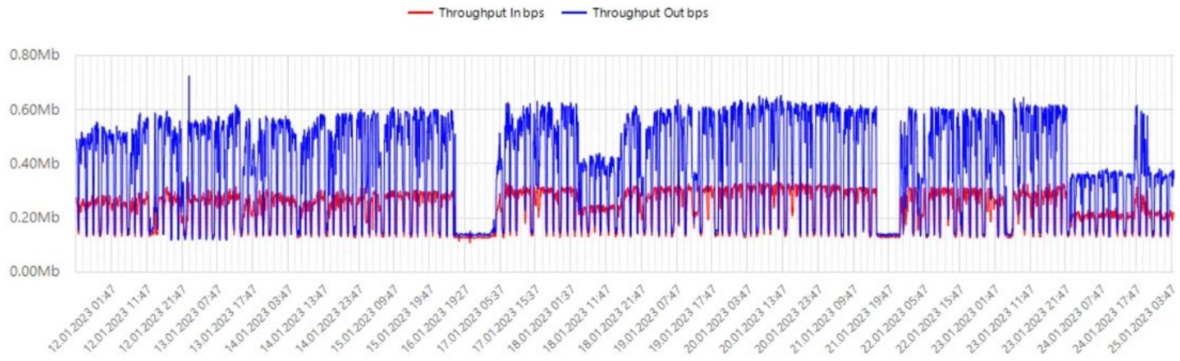

Figure 6-2. Aggregated UL throughput from all 6 lines in current BOSCH factory (1 month)

Figure 6-2 depicts a capture in one of the upstream switches that connects all the production lines in our target factory in BOSCH Aranjuez to their core router. The first observation is that traffic is surprisingly low, being around 0.6 Mbps in the uplink direction, i.e. PLC to MES, and around 0.25 Mbps in the downlink direction, i.e. MES to PLC. The reason why the traffic is low, is because most production lines in BOSCH Aranjuez have long cycle times, e.g. we have production lines with cycle times ranging from 5 seconds to 1 minute. Another relevant data from BOSCH Aranjuez, is that the traffic depicted in Figure 6-2 is generated by 6 production lines that are currently connected to the MES, but the factory is dimensioned to be able to host up to 15 production lines.

Given that the current BOSCH Aranjuez factory setup is only one example of the potential network requirements derived from a set of MES connected production lines, our goal is to generalize to other types of production lines, finding representative cases that can help us dimension the 5G-CLARITY network.

The key observation in the definition of the traffic model, is that the traffic generated by a production line is directly proportional to the cycle time of the manufacturing process. The reason is that there is a communication between the PLC and the MES at the end of each cycle. Thus, a production line with a 10x smaller cycle time will generate 10x more traffic. We define cycle time, **CT**, as a parameter of our traffic model that will help us dimension the network. We can now derive the UL and DL data rate generated by a typical factory floor as a function of the CT parameter.

Looking at the uplink direction, we have:

- Observed traffic at BOSCH Aranjuez: 0,6 Mbps
- Number of connected lines: 6
- UL Traffic per line: 0,1 Mbps
- Average cycle time: (5 + 60)/2 = 32,5 seconds

Thus, assuming a worst-case scenario where in the same space as the current BOSCH factory we deploy 15 production lines of we would have an overall uplink requirement of:

- UL_datarate = 0.1*15*(32.5/CT) = 48.75/CT Mbps

Following a similar analysis for the DL case, which we can see in Figure 6-2 to be around 0.25 Mbps, we derive a downlink data rate requirement of:

- DL_datarate = (0.25/6)*15*(32.5/CT) = 20.31/CT Mbps

The other key parameter in dimensioning the network is the maximum allowed round-trip latency with the MES server. Notice that the cycle time definition includes the communication with the MES server, as depicted in Figure 6-3. The larger the network latency, i.e. the round trip between the PLC and the MES, the shorter the time left for the mechanical process if we want to maintain the cycle time. Obviously, from an OT perspective the requirement is to make the network latency as small as possible to use most of the cycle time for the mechanical process. This is where current Ethernet networks excel. Thus, we define another parameter of our traffic model, namely the delay budget (DB) as a percentage of the cycle time, i.e. DB = MES_RT*CT, where MES_RT (MES Round Trip) is illustrated in Figure 6-3.

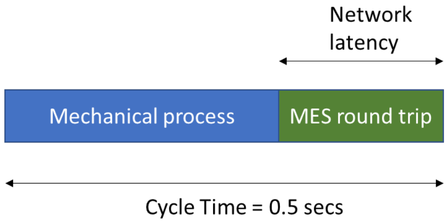

Figure 6-3. Cycle time definition for an example CT=0.5 ms

Based on our KPI measurement study in section 4, we know that the MES round trip delivered by the different WATs used in 5G-CLARITY is dependent on the amount of interfering load present in the channel. In addition, MES round trip needs to be defined from the perspective of every single production line connected to our network. Thus, assuming 15 production lines working at an average cycle time of CT, we can define the interference experienced by each line as the load introduced by the other 14 lines, i.e.:

- UL_interf_datarate = 0.1*14*(32.5/CT) = 45.5/CT Mbps
- DL_interf_datarate = (0.25/6)*14*(32.5/CT) = 18.98/CT Mbps

In the next section we will use the allowed UL and DL interference and the KPI analysis presented in Section 4.4.2 to dimension the network.

6.2.2 Network dimensioning

Our goal in this section is to come up with a network dimensioning strategy, i.e. to define the number of 5G cells, WiFi APs and LiFi APs, which are required to cover the factory as a function of the parameters that define the production process, i.e. CT and MES_RT. Looking at future manufacturing processes as the relevant ones to deploy 5G connected production lines, we consider cycle times below those used nowadays in BOSCH Aranjuez, namely we consider CT=0.5 seconds and 1 second, and maximum allowed round-trip times of MES_RT=5% and 10%.

Thus, we use the following network dimensioning strategy:

i. Fixing cycle time (CT) and MES_RT we have a limit on the maximum delay bound (DB=MES_RT*CT) that the network should deliver.

ii. Looking up the per-WAT latency results under interference derived in Section 4.4.2 we can see empirically what is the maximum level of interference that a given technology can sustain to deliver the target DB. Given that our application is mostly based on uplink traffic, we focus on the latency delivered under uplink interference (MAX_UL_INT) described in the upper part of Figure 4-16 in Section 4.4.2.

iii. Based on the maximum level of uplink interference MAX_UL_INT, and given the traffic generated for each production line that we know from the previous section, we can derive the overall UL network capacity that our deployment in the factory needs to support (NETWORK_CAPACITY).

iv. Finally, looking at the empirical UL throughput results obtained in the factory reported in Section 4.4.1, we can derive the throughput/coverage trade-off for each technology and propose a deployment, i.e. the number of required cells of a given technology that can fulfil the requirement.

Table 6-7 summarizes our analysis of feasible network deployments in the factory for different production line set ups, where the following aspects need to be considered:

- 5G and LiFi are FDD technologies, thus there is no interference between UL and DL. Therefore, to compute the interference generated by other production lines we only consider UL traffic, i.e. from our traffic model in the previous section *UL_interf_datarate = 45.5/CT Mbps*. In the case of WiFi though we can have UL/DL cross-interference, therefore we consider as interfering traffic from the other production lines *UL_interf_datarate + DL_interf_datarate = 64.48/CT Mbps*.
- As seen in Section 4.4.2, LiFi cannot tolerate UL interference. Considering that the factory dimensions are 100m*40m and that we have observed empirically approximately a 2.5m coverage radius for each LiFi AP, we would need 203 LiFi APs to cover the whole factory without interference. However, in practice we would only need to provide capacity in the place where each production line is installed. Thus, the real requirement is 15 LiFi APs corresponding to the 15 production lines that we assume in our factory. Note though that this means that if the production lines are reconfigured the LiFi APs would have to be reconfigured as well. This is a hidden cost that does not exist for the other WATs.

Table 6-7. Factory recommended network deployments.

WAT	CT (s)	MES_RT	DB (ms)	MAX_UL_INT (%)	NETWORK_CAPACITY (Mbps)	Area s.t UL capacity > NETWORK_CAPACITY (% factory floor)	#cells to cover 100*40 m
Wi-Fi	0.5	5%	25	40%	64.48/0.4 = 162	N/A: 1 AP 90 Mbps at 15m	6
	1	5%	50	60%	64.48/0.6 = 107.4	N/A: 1 AP 90 Mbps at 15m	6
		10%	100	60%	64.48/0.6 = 107.4	N/A: 1 AP 90 Mbps at 15m	6
LiFi	0.5	5%	25	0%	6,5	19,6%	203(15)
	1	5%	50	0%	3,25[9]	19,6%[10]	203(15)
		10%	100	0%	3,25	19,6%	203(15)
5G-TDD63	0.5	5%	25	N/A[11]	N/A	N/A	N/A
	1	5%	50	60%	45.5/0.8 = 75.8	N/A (max 50 Mbps)	2[12]
		10%	100	60%	45.5/0.8 = 75.8	N/A (max 50 Mbps)	2
5G-TDD36	0.5	5%	25	N/A	N/A	N/A	N/A
	1	5%	50	80%	45.5/0.8 = 56.8	100%	1
		10%	100	80%	45.5/0.8 = 56.8	100%	1

The conclusions from our network dimensioning study are:

[9] LiFi cannot tolerate interference, which means that we need to provision a dedicated LiFi AP for each production line. Thus, interference is avoided, and the overall UL capacity required for a production line at cycle time of 1 second is 3,25 Mbps and of 0,5 seconds is 6,5 Mbps.

[10] Assuming a 2,5m coverage radius, based on the empirical measurements in the factory.

[11] We observe worst-case latencies in UL above 25ms for all the tested 5G configurations. In our study though due to UE compatibility issues we were only able to test frame sizes of 5ms. It is possible that shorter frame sizes result in lower delays that address this scenario.

[12] We can deploy 2 cells at 40 MHz each, where each cell offers 40 Mbps in UL. Then we would split the production lines across the two cells, thus dividing the overall load. Note we do not consider the case of a 100 MHz carrier in a single cell, as it was not part of our experimental evaluation.

i. **With Wi-Fi we need 6 APs in different channels to cover the factory with enough performance**. Looking at the capacity KPIs in section 4.4.1 we can see that Wi-Fi can sustain around 90 Mbps in the UL for approximately 15 meters. Assuming this coverage radius we can cover the factory with 6 APs operating at orthogonal 80 MHz channels. These channels are indeed available in the 5GHz band, namely channels 42, 58, 106, 122, 138 and 155. This would provide an aggregate UL capacity of 90*6=540 Mbps across the factory, which would however have to be shared with other services making use of the Wi-Fi network, e.g. AGVs. Seeing in section 4.4.2how Wi-Fi latency is sensitive to interference, the problem in a Wi-Fi only deployment would be how to limit the interference generated by regular Wi-Fi users over the production line traffic. To the best of our knowledge there is no practical mechanism to guarantee this isolation in Wi-Fi. Thus, we consider that a Wi-Fi only deployment is not feasible.

ii. **Li-Fi can only address the requirements if a dedicated LiFi AP is provisioned for each production line**. However, given that the LiFi AP needs to be placed at a very short distance from the production line with line of sight, this is essentially no different from deploying a dedicated Ethernet cable for that line. Thus, there is no explicit benefit in using LiFi for this use case.

iii. **5G in TDD-36 mode with a single cell can address the two production line setups with cycle time equal to 1 second**. 5G is however still not able to address the cycle time of 0.5 seconds because of latency reasons. We note here that a single 5G cell with 100 MHz configuration may be able to address the case of cycle time of 0.5 seconds by itself, but we do not consider this case in our analysis because we have not been able to verify it empirically in the BOSCH setup. However, a combination of 5G and Wi-Fi using the 5G-CLARITY redundant scheduler would be able to address this use case, as shown in Figure 4-16, where we can see that when various WATs are used simultaneously a worst-case round-trip latency below 16 ms is obtained.

Based on our analysis we proceed to describe a cost analysis of connecting 15 production lines in the BOSCH factory using the following combination of technologies:

- _Ethernet only_: This is the baseline case used to connect production lines today. This is also the benchmark we need to use to model the cost of the wireless deployments.
- _5G-only deployment_: Consisting of a single 40 MHz cell in 5G-TDD36 configuration covering the whole factory.
- _5G+WiFi deployment_: Consisting of one 40 MHz 5G cell in TDD36 mode, along with 6 WiFi APs in the 5GHz band, occupying the available 80 MHz channels, namely channels 42, 58, 106, 122, 138 and 155.

6.2.3 Cost Analysis

In this section we present a cost model to compare the three target network deployments described in the previous section. This model is based on current market cost estimates depicted in Table [13].

Table 6-8. Assumed costs for our analysis based on current commercial providers.

Technology	Baseline[14]	Per connectivity	Cabling	OPEX per connected device (monthly)
Wi-Fi		460 USD / AP	215 USD / 30m	6,5 USD
Ethernet		3057 USD / switch	215 USD / 30m	3,5 USD

[13] For confidentiality reasons the actual providers declaring these costs are not identified.
[14] Baseline represents a fixed cost independent of the number of production lines to connect. An example is the core network in 5G.

5G	50K USD (core network + BBU)	500 USD / cell (assumed same price as AP)	215 USD / 30m	6,5 USD (assumed same as Wi-Fi)

Based on the previous table we analyze the TCO required for the three target deployments identified in the previous section, where we consider that we connect 15 production lines, where each production line has 20 PLCs, and that each PLC has integrated natively 5G and/or Wi-Fi so that CPEs are not required.

TCO Ethernet only

- CAPEX:
  - 15 production lines * switch cost = 45855 USD
  - Cabling:
    - Assumed average distance of 200m Ethernet to MES server → 215 * 200/30 = 1433 USD * 15 switches = 21500 USD
    - Assumed 10 meters on average from each PLC to the head of line switch → 20*15*215*10/30 = 21500 USD
  - TOTAL CAPEX Ethernet only = 88855 USD
- OPEX
  - 3,5 USD * 20 PLCs/production line * 15 production lines = 1050 USD monthly

TCO 5G only deployment

- CAPEX:
  - Baseline (core network plus BBU HW): 50K USD
  - 1 cell: 500 USD
  - Cabling: Assumed distance of 30 meters, since cell can be placed close to rack: 215 USD
  - TOTAL CAPEX 5G only = 50715 USD
- OPEX:
  - 6,5 USD * 20 PLCs/production line * 15 production lines = 1950 USD monthly
  - Spectrum fees: approx. 2000 USD/year based on German prices for Industry 4.0[15]

TCO 5G + Wi-Fi deployment

- CAPEX:
  - CAPEX 5G = 50715 USD
  - Wi-Fi APs = 460 * 6 = 2760 USD
  - Wi-Fi cabling (assumed 200m of Ethernet for each AP) = 215 * 200/30 = 1433 USD * 6 = 8600 USD
  - TOTAL CAPEX 5G + Wi-Fi = 62075 USD
- OPEX:
  - 6,5 USD * 20 PLCs/production line * 15 production lines = 1950 USD monthly
  - Spectrum fees: approx. 2000 USD/year based on German prices for Industry 4.0

[15] BundesNetzAgentur, Administrative rules for spectrum assignments for local spectrum usages in the 3700-3800 MHz band https://www.bundesnetzagentur.de/SharedDocs/Downloads/EN/Areas/Telecommunications/Companies/TelecomRegulation/FrequencyManagement/FrequencyAssignment/LocalBroadband3,7GHz.pdf?__blob=publicationFile&v=1

Table depicts the results of our TCO analysis for a 3-year period, where we extract the following conclusions:

i. There is a less than 10% difference in the 3-year TCO of the three types of deployments. In this sense, the flexibility provided by wireless connectivity comes at no penalty from a TCO perspective.

ii. Cabling has a significant cost in the case of an Ethernet-based deployment that is avoided in 5G.

iii. The main contributor to CAPEX in the case of 5G is the baseline cost of deploying the core network, with the required HW and SW licenses associated, where our cost estimate is based on current market prices that we have access to. Bringing down this cost is essential to kickstart the deployment of 5G private networks in production environments. In this sense commoditizing small core networks that can be used in private networks is a strategic move. For example, widely accepted open-source core network initiatives should be supported that can bring down the cost of this component. This is for example the vision of the private 5G group from the Telecom Infra Project (TIP)[16].

iv. Wi-Fi only adds a marginal cost on top of a 5G deployment. Thus, even though Wi-Fi cannot guarantee performance, it makes sense to combine it with 5G in a best-effort manner as enabled by the 5G-CLARITY multi-connectivity framework.

Table 6-9. Summary of projected TCO for each deployment type

Deployment type	CAPEX	OPEX (monthly)	TCO (3 year)
Ethernet only	88855 USD	1050 USD	126655 USD
5G only	50715 USD	2116 USD	126891 USD
5G + Wi-Fi	62075 USD	2116 USD	138251 USD

[16] https://telecominfraproject.com/5g-private-networks/

7 Summary and conclusions

This deliverable presents the integrations carried out in WP5 to demonstrate the 5G-CLARITY platform for private networks in a museum environment in Bristol and in a factory environment provided by BOSCH in Madrid.

Table 7-1 summarizes how the demonstrations described in this document, along with some of the technical developments performed in WP3 and WP4, contribute to the fulfilment of the 5G-CLARITY project-wide objectives. To achieve said objectives the pilots described in this document showcase the main technical innovations developed in 5G-CLARITY, including:

i. The multi-connectivity framework, based on MPTCP, which allows to achieve aggregated data rates above 1 Gbps, round trip latencies below 3 ms, and seamless vertical mobility between wireless access technologies.

ii. A set of positioning technologies, based on Sub6, 60 GHz or Li-Fi radios, which allow for concurrent localization and communication, and provide peak accuracies below 1 cm for 60 GHz and below 1 meter for Sub-6.

iii. A service and slice provisioning subsystem, which allows a private network to provision slices inside the private venue in less than 5 minutes, as well as to provision an end-to-end slice, connecting private network resources with external resources provided by an MNO, in less than 10 minutes.

iv. An Intent Engine and an AI engine, which simplify network management operations allowing the private network operator to interact with the management system using natural language.

In addition to addressing the 5G-CLARITY objectives, the work reported in deliverable D5.3 aims to generate a set of results that can be useful to the scientific and industrial community working on private 5G networks. To this end we contribute the following results:

- A set of transversal KPIs that are measured in operational conditions in the museum and factory environments. When possible, we have provided per-technology KPIs, i.e. KPIs for Wi-Fi, 5G and Li-Fi, as well as the aggregated KPI resulting from using the 5G-CLARITY multi-connectivity framework. We believe these results provide a realistic view of the performance of these technologies in operational environments, which is useful to researchers aiming to propose performance enhancements, and to vertical users interested in understanding if these technologies, individually or in combination, can address their service KPIs.
- A methodology that, using our transversal KPI measurements, allows us to derive a set of candidate deployment models that can address certain service KPIs. Then, a cost model is proposed to compare the candidate deployments in terms of TCO. The proposed methodology can be used to compare performance/business trade-offs for other types of services.

Table 7-1. Summary of 5G-CLARITY results

5G-CLARITY KPIs from DoA	Description
OBJ-TECH-1	Design and validation of a multi-tenant private wireless access network architecture, integrating 5G/Wi-Fi/LiFi, compute resources and ML based network management.
Project results	The 5G-CLARITY platform architecture featuring four different strata was defined in WP2. Individual components of these strata were developed and analysed in WP3 and WP4. In WP5 the developed elements have been integrated and demonstrated in the Bristol and BOSCH pilots described in D5.3.
OBJ-TECH-2	Design and validation of a multi-technology coexistence framework for private 5G/Wi-Fi/LiFi networks that enables efficient spectrum sharing between private and public networks operating in the same band.

Project results	We defined a coexistence framework based on integrating O-RAN enabled radios deployed in private networks with a CBRS-like regulation framework. The proposed mechanism allowed for example to negotiate power and TDD patterns across private networks. This mechanism was developed in WP3 where a lab-based prototype was showcased. The coexistence framework was not included in the WP5 trials, as each pilot featured only one private network.
OBJ-TECH-3	Design and development of a multi-connectivity framework integrating 5G/Wi-Fi/LiFi evolving 3GPP R16 capabilities by: i. Achieving downlink user experienced data rates > 1 Gbps through interface aggregation. ii. Reducing latency in the air interface < 1 ms for uplink and downlink through parallel access across various technologies. iii. Providing reliability of at least six 9s through smart interface selection. iv. Supporting vertical handover between wireless technologies with handover times < 5 ms.
Project results	The KPIs related to this objective have been benchmarked in the two project pilots with the following results: - <u>Data rates > 1 Gbps</u>. This is achieved in the Bristol use case where aggregated throughput exceed 1.4 Gbps (c.f. Figure 3-21) when using 100MHz 5GNR carrier and a 160MHz WiFi6 carrier. In the BOSCH pilot the maximum aggregated capacity is 600 Mbps since a 40MHz 5GNR and an 80MHZ WiFi6 carriers are used (c.f. Figure 4-14). - <u>Latency air-interface < 1ms</u>: Given the architecture of the 5G-CLARITY private network, our measurements on this KPI include not only the air interface, but also the core network segment. We have also focused on RTT measurements, instead of the one-way delay referred to in the target KPI. When no interference is considered we have found that using the 5G-CLARITY redundant mode and the three WATs in parallel we have measured an RTT latency below 2.5 ms in the Bristol pilot (position A in Figure 3-23) and an RTT latency below 3 ms in BOSCH (Figure 4-16). - <u>Reliability of at least six 9s</u>: This KPI is achieved by design because we use TCP as a transport mechanism that ensures reliable delivery. The drawback of using TCP is that retransmitted packets experience an increased delay. We have validated in our D5.3 that the latency experience by the services considered in our pilots was acceptable. - <u>Vertical handover time <5ms:</u> The pilots carried out in WP5 demonstrate that 5G excels in providing a ubiquitous coverage in factory and museum environments. Therefore, our recommended architecture consists in using 5G to provide blanket coverage, and then adding Wi-Fi or LiFi where additional capacity is needed. Using this approach, the MPTCP based multi-connectivity framework proposed in 5G-CLARITY allows the device to always be connected to 5G and add the additional WATs to the ongoing TCP connection as they appear. Thus, no vertical handover is required between technologies and the KPI is fulfilled by design.
OBJ-TECH-4	Demonstrate aggregate system area capacity in relevant indoor scenarios > 500 Mbps/m2 through smart RRM algorithms and SDN control frameworks that fully exploit the capacity of the combined 5G/Wi-Fi/LiFi access
Project results	Demonstrating the maximum aggregated area capacities achievable by the 5G-CLARITY system requires to deploy a high number of densely packets access points. Thus, this KPI was demonstrated by means of simulations in WP3.
OBJ-TECH-5	Simultaneous support of synchronization and positioning services over the proposed 5G/Wi-Fi/LiFi infrastructure: i. Positioning to a peak accuracy < 1 cm, and availability of < 1 meter accuracy 99% of the time. ii. Synchronization to the ns-level via wireless transport of clock distribution protocols.
Project results[17]	In UC2.2 we demonstrated that peak accuracies < 1 cm were achieved using 60 GHz radios (Figure 5-19). Sub-meter accuracies were also demonstrated with Sub6 radios (Table 5-2), which if

[17] The implementation and evaluation remain in the simulation as the cornerstone of the methods utilized here is the time-stamp exchange capability which is yet not available in all the devices

	appropriately deployed would enable the availability of < 1 meter 99% of the time. Regarding ns-level synchronization, the achieved results do not stem from the measurement campaign at BOSCH factory, but they have been extracted from the evaluation of joint synchronization and localization estimates as part of deliverable D2.4 [8]. These two problems are addressed and evaluated jointly, since they strongly overlap. From the results, ns-level synchronization has been proved to be achievable, below 2 ns (see results in deliverable D2. 4 [8]).
OBJ-TECH-6	Development and demonstration of a 5G/Wi-Fi/LiFi management platform and an intent-based policy language for venue operators, which allows to provision 3rd-party 5G connectivity services in less than 5 minutes, while providing security and isolation to infrastructure and service slices.
Project results	The service and slice provisioning subsystem developed in WP4 allows to provision slices inside the private venue. This development was demonstrated in BOSCH UC2.1, where the service and slice provisioning subsystem was used to deploy the network slice that was serving the AGV used for UC2.2. A slice provisioning time of 3 minutes was measured (c.f. Section 4.3.3).
OBJ-TECH-7	Development of management enablers to deploy an E2E 5G slice integrating compute and transport resources of an MNO, with a 5G/Wi-Fi/LiFi slice deployed inside the venue. The target deployment time of a minimal E2E 5G slice containing compute and network resources is 10 minutes.
Project results	The service and slice provisioning subsystem developed in WP4 was integrated with a multi-domain orchestration system developed by the 5G-ZORRO project. This resulted in a joint contribution to ETSI ZSM group where we demonstrated the provisioning of an end-to-end network slice composed of a private network slice, provided by the 5G-CLARITY system, and an MNO slice offering telco edge cloud resources. The total provisioning time of the end-to-end slice was below 10 minutes. A video of this demonstration is available[18].
OBJ-TECH-8	Development and demonstration of an AI-enabled engine translating high-level intent/policy into continuous network configuration. Demonstrate how AI can reduce both manual and semi-automated intervention in at least 2 relevant use cases.
Project results	We have proposed the 5G-CLARITY intelligence stratum that is composed of an AI engine and an Intent engine. A full implementation of this intelligence stratum has been demonstrated in the Bristol use case, where the Intent Engine is used to easily redirect the video stream of a 360-camera mounted on the mobile robot to the handheld device of a public safety office (c.f. Section 3.3.3.2). In addition, two more use cases have been demonstrated using the Intent Engine and the AI engine for which demo videos are available in the 5G-CLARITY YouTube channel. First, an intent-based slice provisioning use case[19], and second a NLoS positioning use case[20]. The three intent related use cases developed in the project have been disseminated in a joint publication[21].

[18] https://www.youtube.com/watch?v=heU_ceO315s&t=2s

[19] 5G-CLARITY Intent Based Slice Management Demonstration. Available at: https://www.youtube.com/watch?v=5Jsc2ds-etI&t=186s

[20] 5G CLARITY Intelligent Stratum Demo v02. Available at: https://www.youtube.com/watch?v=-FgdyJBPiJQ

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