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

5G-CLARITY Deliverable D5.2

Integration of Solutions and Validation

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List of Acronyms

3GPP	3rd Generation Partnership Project
5GC	5G Core
5GNR	5G New Radio
5GSA	5G Standalone Architecture
ADC	Analog to Digital Converter
AFE	Analog Front End
AI	Artificial intelligence
AGV	Automated Guided Vehicle
AMBR	Aggregate Maximum Bit Rate
AMF	Access and Mobility Management Function
AN	Anchor Node
AP	Access Point
AT3S / ATSSS	Access Traffic Steering, Switching, and Splitting
AUSF	Authentication Server Function
AWS	Amazon Web Services
AZ	Availability Zones
BBU	Baseband Unit
BRF	Bayesian Recursive Filter
CDF	Cumulative Distribution Function
COTS	Commercial-of-the-shelf
CPE	Customer Premises Equipment
CU-CP	Central Unit Control Plane
CUPS	Control and User Plane Separation
CU-UP	Central Unit User Plane
DAC	Digital to Analog Converter
DL	Downlink
DNN	Data Network Name
DoW	Description of Work
DU	Distributed Unit
e2e	End-to-end
eAT3S / eATSSS	enhanced Access Traffic Steering, Switching, and Splitting
EIRP	Effective Isotropic Radiated Power
eMBB	Enhanced Mobile Broadband
E2E	End-to-End
ETSI	European Telecommunications Standards Institute
FPGA	Field-Programmable Gate Array
GBR	Guaranteed Bit Rate
gNB	gNodeB
GPIO	General-Purpose Input/Output
GPRS	General Packet Radio Service
GSps	GigaSamples per second
GTP	GPRS Tunnelling Protocol
GW	Gateway
HW	Hardware
IHP	Innovations for High Performance
IoT	Internet of Things
ISM	Industrial, Scientific, and Medical
IMSI	International Mobile Subscriber Identity
IR	Infrared Radiation
KPI	Key Performance Indicator
LAN	Local Area Network

LiFi	Light Fidelity
LoS	Line of Sight
L2VPN	Layer 2 Virtual Private Network
MANO	Management and Orchestration
MBR	Maximum Bit Rate
MES	Manufacturing Execution Server
MF	Management Function
MIMO	Multiple-Input and Multiple-Output
ML	Machine Learning
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
MPTCP	Multipath Transmission Control Protocol
multi-WAT	Multiple Wireless Access Technology
Near-RT	Near Real Time
NFV	Network Function Virtualization
NFVIaaS	Network Function Virtualization Infrastructure as a Service
NFVO	Network Function Virtualization Orchestrator
NGAP	NG Application Protocol
NIC	Network Interface Card
NLLSQ	Non-Linear Least SQuare
NLP	Natural Language Processing
NNSF	Network Node Selection Function
NPN	Non-Public Network
NRF	Network Function Repository Function
NSA	Non-Standalone Architecture
NSSF	Network Slice Selection Function
OCC	Optical Camera Communications
ORAN	Open Radio Access Network
OSM	Open Source MANO
PCB	Printed-Circuit Board
PCC	Policy and Charging Control
PCF	Policy Control Function
PDN	Public Data Network
PGW-c	PDN Gateway Control plane function
PLC	Programmable Logic Controller
PLMN	Public Land Mobile Network
PLMNID	Public Land Mobile Network ID
PNF	Physical Network Function
PNI	Public-Network Integrated
QAM	Quadrature Amplitude Modulation
QCI	QoS Class Identifier
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radiofrequency
RIC	RAN Intelligent Controller
RRM	Radio Resource Management
RSRP	Reference Signal Received Power
RSS	Received Signal Strength
RTT	Round Trip Time
RU	Radio Unit
SA	Standalone Architecture
SBC	Single Board Computer
SDN	Software Defined Network
SDR	Software-Defined Radio

SFP+	Small Form-Factor Pluggable Plus
SIM	Subscriber Identity Module
SlaaS	Slice as a Service
SMF	Session Management Function
SNPN	Standalone Non-Public Network
SNR	Signal-to-Noise Ratio
S-NSSAI	Single - Network Slice Selection Assistance Information
SoC	System-On-Chip
SRTT	Smooth Round Trip Time
SSID	Service Set Identifier
TAC	Tracking Area Code
TCP	Transport Control Protocol
TDD	Time Division Duplex
ToA	Time of Arrival
ToF	Time of Flight
TRL	Technology Readiness Level
TWR	Two Way Ranging
UC	Use Case
UDM	Unified Data Management
UDP	User Datagram Protocol
UDR	Unified Data Repository
UE	User Equipment
UL	Uplink
UDP	User Datagram Protocol
UPF	User Plane Function
URSP	UE Route Selection Policy
VAF	Virtualised Application Functions
VDC	Volt Direct Current
VIM	Virtual Infrastructure Manager
VLAN	Virtual Local Area Network
VLP	Visible Light Positioning
VNF	Virtual Network Function
VPN	Virtual Private Network
VXLAN	Virtual Extensible Local Area Network
WAT	Wireless Access Technology
WR	White Rabbit

Executive Summary

This document presents the details of the integration of the primary 5G-CLARITY architecture components that will be used in the pilots' demonstrations at the Bosch factory in Aranjuez and at the M-Shed museum in Bristol. To that end, we will discuss how the proposals from WP2, WP3 and WP4 have been incorporated into each pilot in order to deploy the core 5G-CLARITY technology. In order to clearly define their relationships, we will first present a mapping of the various defined components to the strata of the reference 5G-CLARITY architecture proposed in D2.2 [1]. This mapping will be also discussed for each UC. We will also demonstrate how the essential technologies and components are implemented for each defined scenario, evidencing how the reference architecture's components may be combined to meet the needs of various scenarios.

In D5.2 we provide the in-lab validation of the KPIs defined for the use cases by fusing the technologies from multiple partners and the equipment that will be placed at the pilots' venues. Finally, we will detail the venue setup information that will be used for the 5G-CLARITY architecture's overall KPI validations and demonstrations.

In brief, D5.2 provides performance evaluations, implementation details, and adjustments for the venues for 5G-CLARITY enablers listed below:

- **5G-CLARITY**'s **CPEs:** In this document we provide the design and implementation of the 5G-CLARITY CPE which integrates MPTCP to execute eAT3S functionality for the various wireless technologies chosen—LiFi, Wi-Fi, and 5GNR—. In addition, we present three distinct CPE implementations in detail, illustrating various hardware options.
- **Multi-access based multi-connectivity:** the validation and the performance evaluation of the aggregation of the different wireless technologies is provided by testing the CPE and proxy within the Accelerant and Pure LiFi hardware at University of Bristol's lab, integrating the CPE with the RAN Cluster.
- **Multi-domain network slicing for private networks**: UC1 lab setup uses VNFs and multi-WAT to demonstrate the guide robot functional validation.
- **Service and slice management subsystem:** The functional validation at i2CAT's lab of multi-slice support is presented in this document. This subsystem is integrated to the CPE.
- **Edge Cluster:** This component is evaluated at the installation of University of Bristol by benchmarking the guide robot and smart tourism of UC1 related VNFs' performance.
- **SNPN 5G Core (5GC):** The Open5gs for SNPN case is tested within the multi-slicing functional validation.
- **AI-vision ML algorithm:** In this deliverable, we benchmark related KPIs such as the accuracy and response time of the obstacle detection algorithm.
- **PNI-NPN 5GC:** The obstacle detection validation tests are used to validate 5GC functioning in 5TONIC facilities.
- **RAN Cluster:** We use the dRAX and Prometheus server at the University of Bristol to obtain 5GNR, Wi-Fi and LiFi telemetry to provide the throughput and delay performance KPIs of the multi-connectivity framework.
- **Intent Engine:** The Intent Engine provides an abstract interface for the communication of operations in both UC1 and UC2.2.

1 Introduction

This deliverable reports the integration of solutions developed in 5G-CLARITY WP3 and 5G-CLARITY WP4, and the evaluation of the integrated setup performance. This deliverable will be used, together as 5G-CLARITY D5.1 [2], to inform the UC1, UC2.1 and UC2.2 demos regarding the setup and deployment of the developed components in the testbeds and cases sites and to report integrated setup validation tests.

1.1 Scope of the document

5G-CLARITY D5.2 takes the technology and innovation components of the project as inputs from 5G-CLARITY WP3 and WP4. The output of 5G-CLARITY D5.2 will be the basis for tasks T5.3 and T5.4, in which 5G-CLARITY final demonstrations will be deployed and tested at the venues of the use cases. The project's T5.2 follows T5.1, and it is responsible for the integration of the individual solutions for the control and user plane, and management plane, developed in WP3 and WP4. Additionally, it is responsible for the validation of the integrated platform according to the architecture and plan formulated in T5.1. The output of T5.2 will be used as the basis for final demonstrations of UC1, UC2.1 and UC2.2 as part of tasks T5.3 and T5.4.

Hence the focus of D5.2 is on the validation of the specific requirements and KPIs of the proposed use cases, whereas 5G-CLARITY D5.3, to be reported later towards the end of the project, will provide the validation of the transversal KPIs as well as the UC specific ones at the pilot's venues. Moreover, the combination of the different wireless technologies will be fully tested in D5.3. It is notable that in D3.3 and D4.3, the initial assessment of the key elements that will be implemented in the pilots are reported by utilising network hardware different from that which would be utilised in the final use cases setup. The evaluation of the technology integration that will be used by pilots is provided in 5G-CLARITY D5.2, the current document. Before taking the integrated setups to the use case demo venues, the integration of other partner's technologies is validated in the facilities and laboratories of the pertinent partner, ensuring their proper operation and performance.

1.2 Project objectives

The integrations and experimental validations carried out in Task 5.2 aim at satisfying project objectives formulated in the 5G-CLARITY description of work (DoW) as listed below:

- **OBJ-TECH-1**: Design and validation of a multi-tenant private wireless access network architecture, integrating 5G/Wi-Fi/LiFi, compute resources and machine learning (ML)-based network management.
- **OBJ-TECH-3**: Design and development of a multi-connectivity framework integrating 5G/Wi-Fi/LiFi evolving 3GPP Release 16 capabilities.
- **OBJ-TECH-5**: Simultaneous support of synchronization and positioning services over the proposed 5G/Wi-Fi/LiFi infrastructure.
    - Positioning to a peak accuracy < 1 cm, and availability of < 1 meter accuracy 99% of the time.
    - Synchronization to the ns-level via wireless transport of clock distribution protocols.
- **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 third-party 5G connectivity services in less than 5 minutes, while providing security and isolation to infrastructure and service slices.
- **OBJ-TECH-7**: Development of management enablers to deploy an E2E 5G slice integrating compute

and transport resources of a mobile network operator (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

- **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 two relevant use cases.

1.3 Mapping 5G-CLARITY technology developments to WP5 demonstrations

5G-CLARITY features two pilots and three use cases, namely the Smart Tourism pilot, to be implemented in M-Shed museum in Bristol as UC1: "*Enabling Enhanced Human-Robot interaction*", and the Smart Factory pilot to be implemented and demonstrated in the Bosch factory in Aranjuez as UC2.1: "*5G-CLARITY infrastructure slicing supporting Industry 4.0 services*", and UC2.2: "*Enhanced AGV positioning for intralogistics*". The main goal of demonstrated use cases is to validate as many technological developments carried out in 5G-CLARITY technical WPs (WP2, WP3 and WP4) as possible. However, due to obvious practical limitations in real world scenarios, not all technical developments in WP2, WP3, and WP4 can be directly demonstrated in the project UC demos. Hence, the following criteria was adapted to select the 5G-CLARITY technical innovations for UC demonstrators:

i. The selected technology development can be used to demonstrate some of the 5G-CLARITY technical design principles, e.g., multi-connectivity, localization, slicing, etc.

ii. The selected technology development has achieved a sufficient TRL in WP2, WP3 or WP4 to be integrated in the Smart Factory pilot or in the Smart Tourism pilot. The target is to showcase demos at TRL6.

iii. The selected technology development can be used to address some of the business needs presented in each UC.

iv. There is enough availability of the required HW, e.g., number of access points, to support the UC.

Applying these criteria, we have selected the following 5G-CLARITY technical features to be demonstrated in the Smart Tourism and the Smart Factory pilots:

- [WP2] 5G-CLARITY architecture: A 5G-CLARITY platform, composed of the four different stratums of the 5G-CLARITY architecture, will be demonstrated both in the Smart Tourism and the Smart Factory pilots, showcasing how the 5G-CLARITY architecture can address the needs of different verticals. A common implementation of the platform components will be used in both pilots, unless otherwise stated. Section 2 describes the implementation of the 5G-CLARITY platform carried out in WP5, based on the proposed architecture in WP2.

- [WP3] Multi-connectivity framework: This is the main technical feature that allows a 5G-CLARITY CPE to connect simultaneously through the various wireless access networks. Being this a fundamental capability, it will be demonstrated both in the Smart Tourism and the Smart Factory pilots. In addition, having this capability available on both sites will allow to compare the performance of the 5G-CLARITY multi-connectivity framework in two different operational settings.

- [WP3] Multi-WAT positioning: Multi-WAT positioning refers to the 5G-CLARITY capability of achieving cm-level accuracy through the combination of multiple wireless access technologies (WATs). This capability requires dedicated HW and will be demonstrated only in the Smart Factory pilot (UC2.2), since this was a capability required in for this UC.

- [WP4] Service and slice provisioning subsystem: The Service and Slice Provisioning subsystem is the key technical feature of 5G-CLARITY to enable the provisioning of 5G-CLARITY slices. This technology will be demonstrated both in both Smart Tourism and the Smart Factory pilots, where the type of slice will be adapted to support the requirements of each UC. This is described in detail in Sections 3.5.1.1 and 3.5.2.1 for UC1, and 4.1.1, 4.1.2, and 4.3.2 for UC2.1.

- [WP4] Intent and AI engines: These two components constitute the Intelligence stratum of the 5G-CLARITY architecture developed in WP4. These will be instantiated both in the Smart Tourism and the Smart Factory pilots. In each pilot though, the components will be customized to address specific requirements, e.g., the ML models in the AI engine or the south-bound provider integrations in the Intent Engine may differ for each UC. This is explained in Sections 3.5.1.2 and 3.5.2.2 for UC1, and Section 5.2 for UC2.2.

Figure 1-1 summarizes the mapping of key 5G-CLARITY technologies to the three project use cases executed in the Smart Tourism and the Smart Factory pilots. The role of each technology in each use case will be explained in detail in the subsequent sections.

UC1: Enabling Enhanced Human-Robot Interaction	UC2.1: 5G-CLARITY infrastructure slicing supporting Industry 4.0 services	UC2.2: Enhanced AGV Positioning for Intralogistics
WP2: 5G-CLARITY architecture	**WP2: 5G-CLARITY architecture**	**WP2: 5G-CLARITY architecture**
WP3: Multi-Connectivity framework	**WP3: Multi-Connectivity framework**	**WP3: Multi-Connectivity framework**
WP4: Service and Slice provisioning	**WP4: Intent based Service and Slice provisioning**	**WP3: Multi-WAT localisation**
WP4: Intent Engine + Service delivery models	**WP4: Private-Public interworking**	**WP4: AI Engine + ML NLoS detection**

Figure 1-1. Mapping of key 5G-CLARITY technologies to use cases

1.4 On the fulfilment of 5G-CLARITY requirements and KPIs

Figure 1-2 depicts the KPI assessment methodology that we have adopted in 5G-CLARITY, where we distinguish among two types of KPIs:

- 5G-CLARITY transversal KPIs: These were defined in the DoW as OBJ-TECH-X.
- Use Case specific requirements and KPIs: These were additional requirements and KPIs identified during the use case definition in D2.1 [3] and D5.1 [2].

Our approach to validate the previous set of KPIs is as follows:

- 5G-CLARITY transversal KPIs: They are related to the technology developments and have been evaluated in laboratory conditions in WP3 and WP4, c.f. D3.3 [4] and D4.3 [5]. In addition, transversal KPIs will be evaluated in operational conditions in the Smart Tourism and the Smart Factory pilots venues, i.e., in M-Shed museum in Bristol and in the Bosch plant in Aranjuez. The result of the operational evaluation will be reported in the future deliverable 5G-CLARITY D5.3 [6]. These common KPIs will provide comparable results at the different pilots, such as the aggregated throughput achievable versus the distance to the WAT sources, or the effect of interference on the aggregate multi-WAT traffic.
- Use case specific requirements and KPIs: These are first evaluated in laboratory conditions and are

reported in this deliverable. Later, use case specific KPIs will also be evaluated in operational conditions in the Smart Tourism and the Smart Factory pilots sites and will be reported in D5.3.

Figure 1-2 highlights the two-phase KPI evaluation methodology, where transversal and use case specific KPIs are first evaluated in the lab environment, and then in the vertical sites considered for the pilots demos.

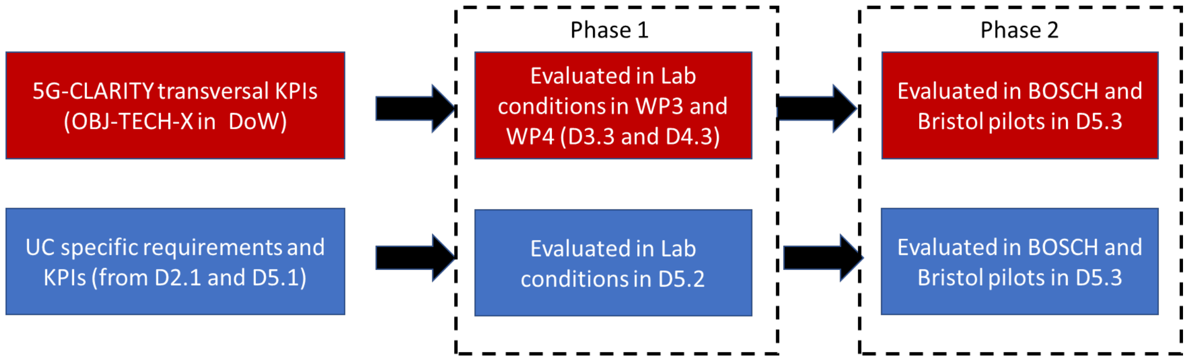


Figure 1-2. 5G-CLARITY KPI assessment methodology

A global context of how and where the requirements of the project identified in D2.1 [3] and D2.2 [1], as well as the measurement of the related KPIs, and their relationship to the work of WP3 and WP4 are presented in Table 1-1, where the focus is on the transversal requirements and KPIs. Details of the specific requirements and KPIs evaluation for UC1, UC2.1 and UC2.2 are provided in Sections 3, 4 and 5, respectively.

Table 1-1. 5G-CLARITY Transversal KPIs.

5G-CLARITY Transversal KPI	Description	Project KPI (D2.1)	Means of Validation
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.		The installation of the 5G-CLARITY platform in the Bosch factory and in the M-Shed museum in Bristol serves to validate this. The validation within D5.2 reporting is done in the labs of Bristol and I2CAT. The validation within D5.3 reporting is done in a vertical setting. Additionally, 5G-CLARITY D3.3, Sections 4.1 and 4.2, provide evaluation results of network-wide slicing of Wi-Fi networks with variable loads and autonomic LiFi attocellular network slicing, respectively.
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.		Since each pilot only takes into account one private network, this objective is not covered in WP5. However, the details of a co-existence and spectrum sharing architecture based on CBRS are presented in D3.3 Section 2, where disaggregated and cloud native CBRS client is implemented, and results are provided. D3.3 also presents how dRAX can host a spectrum related microservice and host xApps. D3.3 Sections 2, 3, and 4 provide details and evaluations on spectrum access, multi-access, and integrated Wi-Fi/LiFi network controller, respectively. The xApp deployment

			in the 5G-CLARITY RAN cluster is discussed in D3.3 Sections 2.4.2 and 3.1. Finally, the telemetry is demonstrated in D3.3 Section 3.1.
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.	5GC.KPI-1: UE downlink experienced data rates > 1 Gbps through interface aggregation. 5GC.KPI-2: Air interface latency < 1 ms for uplink and downlink through parallel access across various technologies. 5GC.KPI-3: Air interface reliability of at least six 9s (> 99.9999%) through smart interface selection. 5GC.KPI-4: Vertical handover between different WATs with handover times < 5 ms.	Since the final radio equipment was not yet ready due to COVID-19 delays, results were obtained using a non-ORAN 5G radio reported in D3.3. D5.2 presents the results using the ORAN radio that was taken into consideration for the project. These results, however, are more constrained than those reported in D3.3, because of the hardware constraints of the ORAN radio. We will keep improving the performance and we will present the outcomes obtained at the pilot venues, to be reported in D5.3. To that end, we will measure the throughput over the distance, the delay under interference, and the vertical handover at the selected venues. This assessment will serve to show the benefits of using 5G-CLARITY's MPTCP approach. D3.3, Sections 3.2.1, 3.2.2, 3.2.3, 3.2.4 provided the functional validation of default, redundant, round robin, and 5G-CLARITY MPTCP schedulers. Additionally, the evaluation results for the E2E latency achievable by the 5G-CLARITY multi-connectivity framework was provided in D3.3, Section 3.2.2. The reliability evaluation and further details were provided in D3.3 Section 3.2. D3.3 Section 3.2.3 provided further information and evaluation results for less than 5 ms vertical handover between wireless technologies. D5.3 will provide on site measurements.
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	5GC.KPI-5: Area capacity in dense private venues > 500 Mbps /m2 through RRM and SDN mechanisms fully exploiting combined multi-WAT capacity.	D3.3 Section 6.3.2 presents obtained link quality and performance results by means of simulation. Meaningful experiments with real hardware to empirically prove this goal in D5.2 and D5.3 is not possible due to the project's limited supply of UEs, radio, and LiFi devices.
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	5GC.KPI-8: Peak positioning accuracy < 1 cm, for an availability of sub-meter accuracy > 99% of the time.	D5.2 Section 5.4 reports the experimental performance evaluation of the localization system at IHP's laboratory with a fixed and a moving UE, by fusing the measures from with 8 APs of the selected technologies. We also provide details of the implementation of the localization server and a visualization tool developed.

	accuracy 99% of the time. ii. Synchronization to the ns-level via wireless transport of clock distribution protocols.		D3.3, Section 5, provided details and evaluations on the multi-WAT positioning framework. Specifically, mmWave based positioning interface details and implementation results were provided in Section 5.2, whereas LiFi positioning server implementation and related results were provided in Section 5.3. Synchronization results were demonstrated and reported in D2.4 Sections 5 and 6. Theoretical and simulation-based investigations and related results were provided in D3.3, Sections 3.2.3, 5.1, 5.2 and 5.3. D5.3 will provide on-site measurements for sub-6 GHz, mmWave and LiFi systems.
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.	5GC.KPI-12: Service deployment time < 5 min, for the provisioning of third-party 5G connectivity services inside the private venue.	D4.3, section 2.2, evaluated the time required to provision a 5G-CLARITY infrastructure slice in an experimental testbed. D5.2, Section 4.4.1, demonstrates the capability of setting up two simultaneous slices over the same 5G-CLARITY infrastructure stratum, whereas only one slice was provisioned in D4.3. This is a requirement for UC2.1. D5.3 will include a demonstration of the 5G-CLARITY slice functionality at the venue sites.
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.		D4.3, Section 2.3, provided the results of a public demonstration of the deployment of an E2E 5G slice between a public network (5TONIC) and a private one (i2CAT's labs) in less than 10 minutes. Following up on D4.3, D5.2 Section 4.4.3 benchmarks the application instantiated over the public slice, which is required in UC2.1. D5.3 will present the results of the private-public slice provisioning in the venue site.
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.		D4.3, Sections 6.2.1 and 6.2.2, demonstrated (by means of a functional validation) how the AI engine can reduce both manual and semi-automated intervention. D5.2 Sections 3.5.1 and 3.5.2 present the integration of the Intent engine and AI Engine for UC1. UC1, reported in D5.3, will provide additional onsite validations for the technology.

1.5 Document structure

The deliverable is structured into the following sections:

Section 2 describes the integrations performed and evaluated in T5.2 regarding their location in the 5G-CLARITY architecture defined in WP2, and describes the integration of common components that will be deployed in UC1, UC2.1 and UC2.2. To that end, after an overall description, the section is divided into four subsections, corresponding to the stratums defined for 5G-CLARITY architecture. Each subsection provides the implementation details of the shared pieces of the architecture that all the uses cases need.

Section 3 describes the specific integrations for UC1 *Enabling Enhanced Human-Robot Interaction (Smart Tourism)* and presents the resulting KPIs. To that end, we define the scope and objectives addressed in the use case. Then, we identify how the components of 5G-CLARITY are used in UC1, and we describe the setup for the final demonstration at the venue. After that, we describe the evaluation setup in Bristol laboratories, and the validation of KPIs with the integrated equipment. Finally, the updated risk management plan is provided.

Section 4 describes the specific integrations for UC2.1 *Infrastructure slicing to support Industry 4.0 services*, and presents the resulting KPIs. To do this, we define the scope and the objectives that will be validated in this UC. After that, we provide the details of the component integrations and its mapping to the reference 5G-CLARITY architecture. Then, provide the validation results obtained at i2CAT's laboratory. Finally, we present an updated list of risks and the corresponding mitigation plan.

Section 5 presents the specific integration and evaluation of components for the UC2.2: *Enhanced AGV Positioning for Intralogistics (Industry 4.0).* Following the general structure for each use case, we first present the scope and objectives involved in this UC. Then, we identify the 5G-CLARITY enablers and architecture components applied to this UC. After that, we describe the laboratory setup and evaluate the KPIs of the localization service. Finally, we provide an updated risk mitigation plan.

Section 6 provides the conclusions of the work, milestones achieved in T5.2, and next steps.

2 5G-CLARITY platform integration

In this section we review the 5G-CLARITY platform architecture introduced in D2.2 [1] and describe the integration efforts carried out in WP5 to deliver a version of the 5G-CLARITY platform that can be demonstrated in the project use cases. Please note that both UCs refer to this common reference architecture. Sections 3.3, 4.3.1 and 5.2 will provide the details of how each UC makes use of the components from the reference 5G-CLARITY framework.

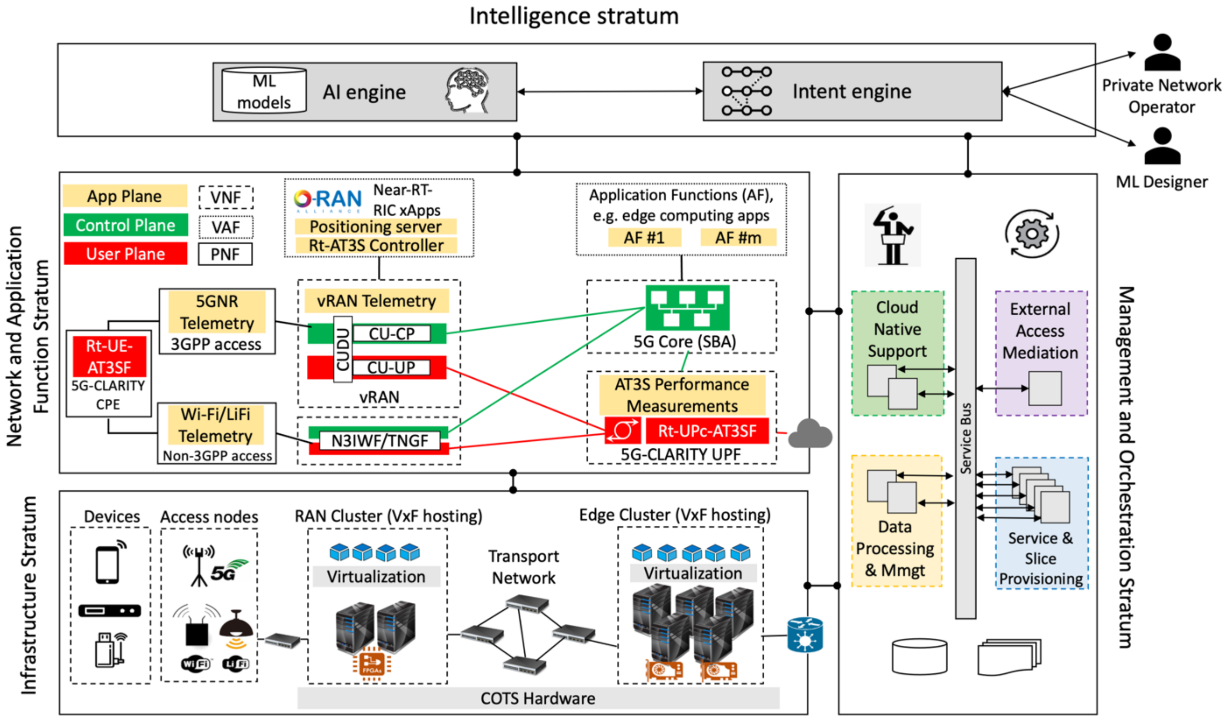


Figure 2-1. 5G-CLARITY architecture from D2.2.

Figure 2-1 depicts the 5G-CLARITY architecture that is composed of 4 different stratums, which we briefly summarize next:

- The **Infrastructure Stratum**, comprising the devices that connect to the network, the physical wireless access functions (gNBs, Wi-Fi and LiFi APs), a RAN cluster to host virtualised RAN functions, an Edge cluster to host virtualized core network and application functions and, finally, an Ethernet-based transport interconnecting all the infrastructure elements.
- The **Network and Application Function Stratum** consists of the virtual network and application functions that are deployed over the RAN and Edge clusters. Some of the relevant functions include a near-real Time RIC and Centralized Unit software in the RAN cluster, or a 5GSA core and the AT3S user plane function in the Edge cluster.
- The **Management and Orchestration Stratum** consisting of the Management Functions (MF) used to manage the physical and virtual network functions (VNFs) of the previous stratums. One of the main goals of the Management and Orchestration Stratum is to manage the lifecycle of 5G-CLARITY infrastructure slices and to mediate interactions of the 5G-CLARITY system with a public network.
- The **Intelligence Stratum**, which comprises the AI engine, hosting ML models; and the Intent Engine, offering a simplified interaction with the network.

In this section we review how we have implemented the integrated 5G-CLARITY platform in each of the two pilot sites, namely the M-Shed museum in Bristol and the BOSCH factory in Aranjuez. To describe our integrated implementation, we follow the different stratums of our architecture, and highlight for each stratum if the same implementation is used in the Bristol and Aranjuez pilots, or there are differences between both. In addition, we discuss in the subsequent chapters of this deliverable specific aspects of each use case.

To provide a complete description of how the architecture will be mapped to the use cases, we start providing a description of the infrastructure (mainly hardware) in Sect. 2.1, detailing the common and adapted parts of the 5G-CLARITY CPE for both UCs (Sect. 2.1.1), the physical wireless access functions (gNB RU, and WiFi6 and LiFi APs, Sect. 2.1.2), RAN and Edge clusters (Sect. 2.1.3 and 2.1.4 respectively).

After that, as described by the architecture of 5G-CLARITY, we explain the software components and their interactions that are situated in the various strata. More precisely, at the Network and Application Function Stratum, we describe near-RT RIC and xApps, and the centralized and distributed units running on the RAN cluster in Sect. 2.2.1, 2.2.2, and 2.2.3 respectively. The components running on the Edge Cluster (5G Core, AT3S User Plane and application Functions) are described in Sect. 2.2.4, 2.2.5 and 2.2.6, respectively.

At Management and Orchestration Stratum, we explain the NFVO, Multi-WA Non-Real Time RIC, the Slice Manager and the Telemetry Subsystem in Sect. 2.3.1, 2.3.2, 2.3.3 and 2.3.4, respectively.

Finally, components at the Intelligence Stratum, namely the AI and Intent engines are discussed in Sect. 2.4.1 and 2.4.2.

2.1 Infrastructure Stratum

We describe in this section the implementation of the 5G-CLARITY infrastructure stratum, introducing the following elements. First, the 5G-CLARITY CPE, which will be used to enable connectivity of end-devices to the 5G-CLARITY network in the different use cases. Here, we distinguish between the CPE that will be used in the Bristol use case and the CPE that will be used in the BOSCH factory. Second, we present the physical wireless access functions which consist of the radio elements provided by different project partners. Finally, we describe our implementations of the RAN and Edge clusters.

2.1.1 5G-CLARITY CPE

In this section we introduce the different modules implemented in the 5G-CLARITY CPE. We note that the CPE has been developed within WP3 and used to validate the multi-connectivity framework in D3.3 [4], where the 5G-CLARITY user and control plane KPIs are reported.

The 5G-CLARITY partners working in both Bristol and Aranjuez pilots have developed CPEs that support the aggregation of 5GNR, WiFi-6 and LiFi interfaces. The Bristol and BOSCH CPEs are built on Single Board Computer (SBC), with an MPTCP-enabled Linux kernel, running on Ubuntu 20.04.

The MPTCP application, which is deployed on the CPE, performs the selection, switching and throughput aggregation from the different WATs. MPTCP support the improvement of system reliability through multiple path traffic routing for the three selected radio access networks (RANs).

While the Bristol CPE was designed for UC1, the Aranjuez BOSCH CPE is built for UC2.2 and both have been used to test for and obtain initial validation results of transversal KPIs. We present a description of the component configurations implemented in the Bristol and Aranjuez BOSCH CPEs.

2.1.1.1 Bristol CPE Description

The Bristol 5G-CLARITY CPE is the UC1 CPE and consists of hardware and software components. It is designed with capability to measure signal reception of three different access technologies and to connect to the best available signal or switch between them. The design leading to the hardware selection and software implementation are aimed at validating the KPIs of the 5G-CLARITY multi-connectivity framework. Figure 2-2 presents a schematic view of the CPE internal hardware design.

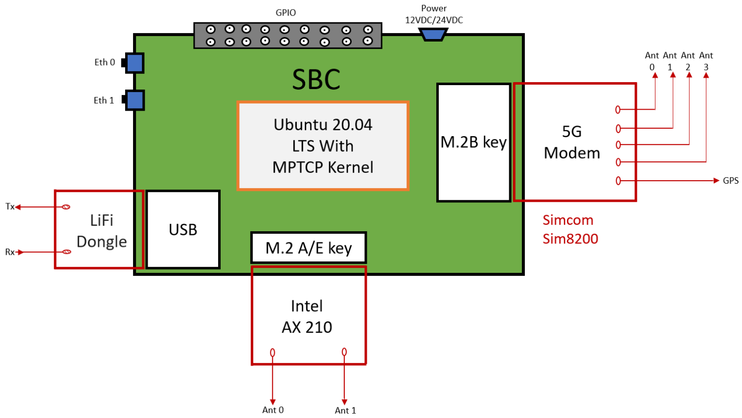


Figure 2-2. Schematic view of the 5G-CLARITY UC1 CPE internal hardware design.

The 5G-CLARITY UC1 CPE has provision for two sims slots for 5GNR, a WiFi-6 modem, and multiple USB ports for LiFi dongle. Antennas are mounted on the CPE to boost 5GNR and WiFi-6 connectivity. External device connection is supported through the provision of two Ethernet interfaces, which multiplexes Ethernet traffic over the different access technologies.

To better understand how different versions of the UC1 CPE would perform in a similar scenario, we have designed, built, and tested a low power version of the CPE using Raspberry Pi. Figure 2-3 shows the two versions of the 5G-CLARITY UC1 CPEs developed at the Smart internet Lab, University of Bristol, which are the based on Single Board Computer (SBC) our main UC1 CPE and Raspberry Pi.

a) Main UC1 CPE based on Single Board Computer

b) CPE based on Raspberry Pi

Figure 2-3. Different versions of the 5G-CLARITY UC1 CPE

2.1.1.2 UC1 CPE deployment

The 5G-CLARITY UC1 CPE is deployed on a mobile guide robot. With the robot actively mobile in an indoor museum space, the CPE switches between 5GNR, WiFi-6 and/or LiFi wireless access networks or performs multi-WAT aggregation, based on the network availability or predefined scenarios. This supports the 5G-CLARITY multi-connectivity framework, enabling enhanced human-robot interaction for smart tourism and public safety.

A list of the key functions of the CPE are detailed as follows:

- Provides multi-access connectivity using 5GNR, WiFi and LiFi between the guide robot and the Edge Server.
- Performs multi-connectivity throughput aggregation using MPTCP.
- Conducts handover between the different access technologies.
- Monitors and measures key radio parameters and network KPIs.

2.1.1.2.1 Bristol CPE software components

To enable the key functionalities, a monitoring and measurement application was deployed in the UC1 CPE. This application monitors and measures radio parameters for network evaluation and 5G-CLARITY KPIs validation. It is designed to measure the objective network performance experience between the CPE on various air interfaces, such as 5GNR, WiFi-6, and LiFi. The monitored radio parameters include Reference Signal Received Power (RSRP), Signal-to-Noise Ratio (SNR), and network KPIs, namely Throughput, Latency, and Jitter.

2.1.1.2.2 Bristol CPE hardware configurations

The CPE is linked to the guide robot via one of the Ethernet ports and the other port to a 360º-surveillance camera. A 12/24 Volt Direct Current (VDC) power inlet is enabled and a General-Purpose Input/Output (GPIO).

The 5G-CLARITY UC1 CPEs, as illustrated in Figure 2-3, comprise of the following hardware configurations:

- UP-Squared Pro:
  This is our SBC design, based on Intel platform with 5G connectivity. The board’s industrial setup including 5G support, multiple serial ports and other features make it suitable for a variety of domains such as the 5G-CLARITY UC1.
  Figure 2-4 shows images of the UP-Squared Pro selected for use in our SBC design.

Figure 2-4. UP-Squared Pro Series.

- Raspberry Pi4 8GB:
  Our choice of Raspberry Pi4 model 4 offers capability of up to 1.5 GHz 64-bit quad core ARM Cortex-A72 processor, on-board 802.11ac Wi-Fi, Bluetooth 5, two USB 2.0 and 3.0 ports, 2-8 GB RAM.
  Figure 2-5 presents a photo of the Raspberry Pi4 8GB selected for use in our design.

Figure 2-5. Raspberry Pi4 8GB.

- 5G Modules:

  Two different 5G modems are deployed in the 5G-CLARITY CPE used in the UC1. The selected models are Quectel RM500Q and SIM8200EA-M2.

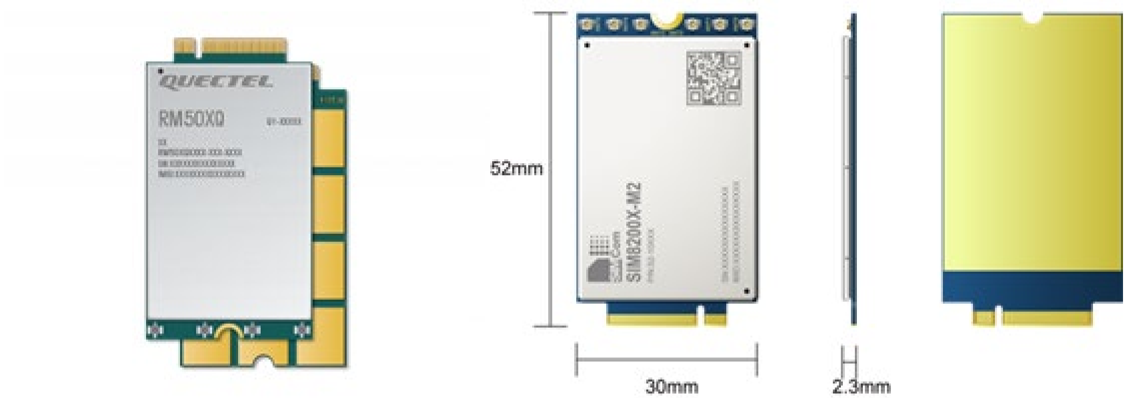
  - Quectel RM500Q

  This is a 5G sub-6GHz M.2 module. It measures 52.0mm × 30.0mm × 2.3mm in dimension and meets the 3GPP Release 15 specification, which is optimized for IoT and eMBB applications. It is compatible with both standalone (SA) and non-standalone (NSA) modes and capable of delivering maximum rates of 2.5 Gbps downlink and 900 Mbps uplink respectively. This is appropriate for testing the 5G-CLARITY KPI requirement within the multi-connectivity framework.

  - SIM8200EA-M2

  This is a multi-band 5GNR module with support for 5G NSA/SA and up to 4Gbps data transfer. Its design is particularly suited for applications with high throughput requirement for data communication in different radio propagation conditions. The module offers flexibility and integration for customer's applications suitable for the 5G-CLARITY CPE.

  Figure 2-6 shows the models of the two different 5G modems deployed in the CPE.



a) b)

Figure 2-6. Selected 5G modems: a) Quectel RM500Q, b) SIM8200EA-M2.

The specifications of other hardware components deployed in the 5G-CLARITY UC1 CPE based on the SBC are provided below:

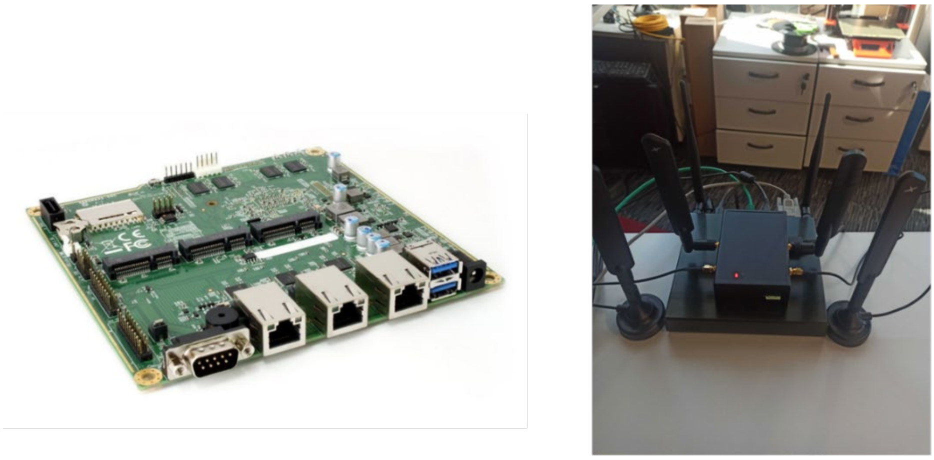
- Processor:
  - Pentium Quad Core
- Memory:
  - 8GB

- Ruckus WiFi-6 module

- PureLiFi dongle
- Antennas:
  - 8x 5G antennas (4 per modem)
  - 2x Wi-Fi antennas
  - 1x GPS antenna
- Ports:
  - 2x Gigabit Eth.
  - 3x USB3 Ports
  - 1x HDMI
  - 1x DP
  - RS232 and GPIO
- Power input: 12 or 24 VD

2.1.1.3 UC2 Aranjuez BOSCH CPE

The SBC chosen for this use case is the APU 2 board, a general purpose x86-64 board that features 2 miniPCIe and 2 USB-A 3.0 interfaces, making it suitable for integrating multiple kinds of wireless access technologies. Figure 2-7 depicts on the left the used SBC and on the right a picture of the BOSCH CPE prototype used for the lab validation reported in this deliverable.



(a) APU2 board from PCEngines (b) Prototype of BOSCH CPE

Figure 2-7. (a) SBC used for BOSCH CPE, (b) prototype used for lab validation

The complete set of specifications of the 5G-CLARITY CPE that will be deployed in the BOSCH pilot are the following:

- Processor: AMD Embedded GX-412TC at 1 GHz
- Memory: 4GB DDR3
- Power: 12V DC
- 2x USB-A 3.0 ports
- 1x Quectel RM500Q 5GNR modem (4x antennas)
- 1x PureLiFi dongle
- 2x miniPCIe ports
- 1x Intel AX200 Wi-Fi 6 module (2x antennas)
- 3x 1Gbps Ethernet ports

- 1x mSATA port
- 1x RS232 serial port

2.1.2 Physical wireless access functions

In this section we describe the physical wireless access functions provided by the project partners that will be deployed in the Bristol and Aranjuez use cases. These physical network functions include wireless access nodes, namely gNB Radio Unit, WiFi6 APs and LiFi APs, as well as localization specific network functions. The wireless access nodes will be deployed both at Bristol and Aranjuez, but the localisation specific nodes will only be deployed at the BOSCH factory in Aranjuez.

2.1.2.1 Accelleran gNB Radio Unit

As described in 5G-CLARITY D5.1 [7] and later described in the integration phases of 5G-CLARITY D2.4 [5], Accelleran dRAX™ (RIC, CU, xApp framework) is integrated end to end together with third-party DU based on Effnet/Phluido components and commercial third-party radios from Benetel. The final phase of the integration setup is shown in Figure 2-8.

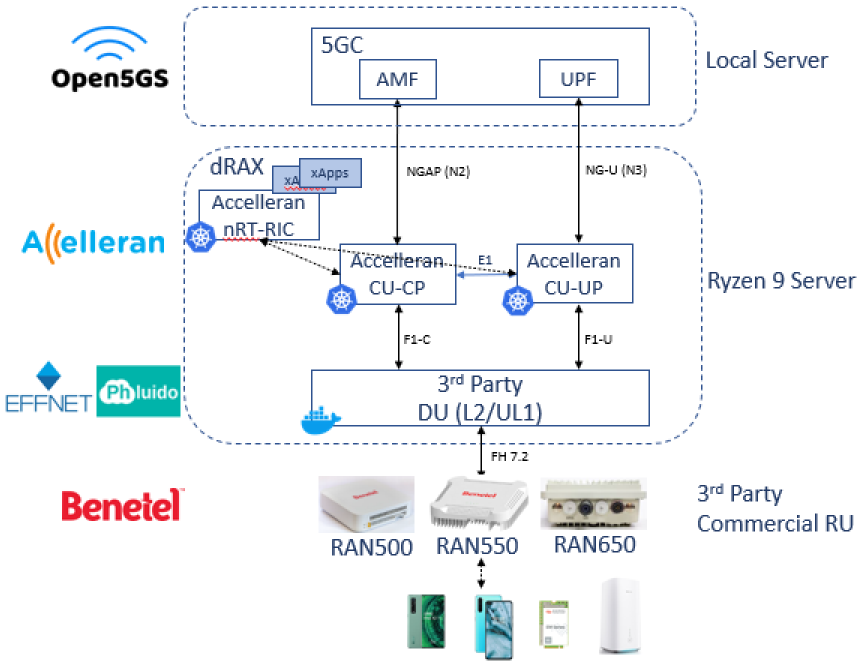


Figure 2-8. Final phase of integration with commercial Benetel RUs.

While the RAN500 was an engineering unit with reduced HW capabilities used for initial integration, the RAN550 and RAN650 were the commercial units integrated afterwards. These units are the ones to be deployed for the pilots in Bristol and Aranjuez.

Benetel RAN550 RU (Aranjuez pilot)

The Benetel RAN550 RU (Figure 2-9) is an indoor RU available in band N78. Since Telefónica will allow the use of their commercial N78 spectrum in the Aranjuez pilot, this RU was chosen for the pilot. The summary HW capabilities of the RAN550 are shown further below. Note that the end-to-end capabilities of the full CU/DU/RU can be different than the HW capabilities of the RU depending on the actual SW available for these third-party DU and RU together.

Figure 2-9. Benetel RU RAN550.

- Frequency: 3300-3800 MHz.
- Bandwidth: Up to 100 MHz.
- 4x4 MIMO HW capable.
- 4x Integrated antennas.
- SFP+ 10G Fibre.
- Max Tx 24 dBm/port (250 mW).
- 12 VDC.
- IP30.
- 235 x 235 x 56.5 mm (3.1 L).
- 2.5 Kgs.

Figure 2-10 shows a picture of the pre-integration lab setup in Accelleran lab premises with the Benetel RAN550.

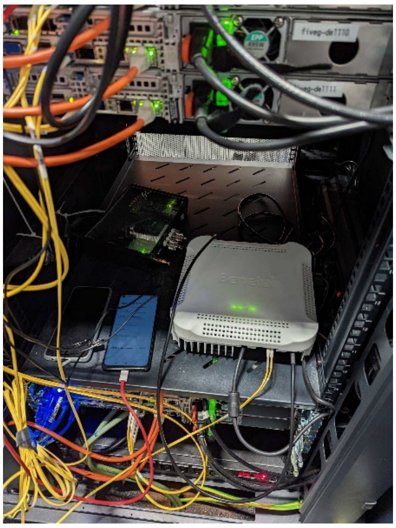


Figure 2-10. RAN550 pre-integration in Accelleran labs.

<u>Benetel RAN650 RU (Bristol pilot)</u>

The Benetel RAN650 RU (Figure 2-11) is an outdoor RU available in band N77u. Since University of Bristol has shared/local spectrum from Ofcom in this band this RU was chosen for the pilot. The summary HW capabilities of the RAN650 are shown further below. Note that the end-to-end capabilities of the full CU/DU/RU can be different than the HW capabilities of the RU depending on the actual SW available for these third-party DU and RU together.

Figure 2-11. Benetel RAN650 RU.

- Frequency: 3700-4200 MHz.
- Bandwidth: Up to 100 MHz.
- 4x4 MIMO HW capable.
- 4x External antenna ports (N-Type).
- SFP+ 10G Fibre.
- Max Tx 37 dBm/port (5 W).
- -48 VDC.
- IP67.
- 310 x 310 x 101.5 mm (9.8 L).
- 9 Kgs.

Figure 2-12 shows a picture of the pre-integration lab setup in Accelleran lab premises with the Benetel RAN550.

Figure 2-12. RAN650 pre-integration in Accelleran labs.

2.1.2.2 I2CAT WiFi6 AP

The WiFi6 AP is a Gateworks Venice GW7300-01 (see Figure 2-13), an ARM based industrial SBC with 3 miniPCIe ports. One of these ports is used, by means of an M.2 to miniPCIe adapter, by a Compex WLT639 Wi-Fi 6 module. It is based on QUALCOMM Atheros QCA6391, dual band and up to 2x2 MIMO.

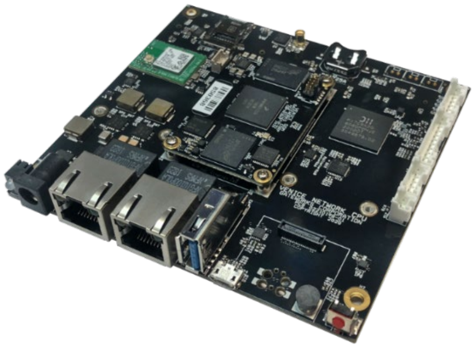


Figure 2-13. I2CAT's Gateworks Venice GW7300-01

The specifications of the other hardware components of the GW7300-01 are the following:

- Processor: i.MX8M Mini Quad Core @ 1.6 GHz.
- Memory: 4GB DDR4-2133 DRAM.
- Power: 8 to 60 VDC.
- 1x USB-A 3.0 ports.
- 2x 1Gbps Ethernet ports (with PoE+ support).

2.1.2.3 PLF LiFi AP

The LiFi AP has been described in 5G-CLARITY D5.1 [2]. To recall briefly, it contains:

- IEEE 802.11 OFDM PHY based physical layer, which was detailed in D3.1 [8],
- Digital-to-analogue and analogue-to-digital convertors for signal conversion in both downlink and uplink,
- A MAC layer interface between the PHY and the upper layers, with functions defined in IEEE 802.11.

In addition, an LED lamp and dedicated transmitter driver are included in the LiFi access node, to transmit wireless signals via light.

The LiFi AP has been enhanced within 5G-CLARITY for different purposes.

WP3 RSSI based LiFi localization. In addition to illumination and wireless data communication, the LiFi node has been developed for localization purpose. The algorithm is based on RSSI while the LiFi AP is utilised as the light signal source. The RSSI values will be read by the user device and then sent to the central localization server with known IP address via UDP.

WP4 Netconf server integration for management purpose. The following features have been implemented:

- Support for Netconf interface using sysrepo, netopeer2-server, netopeer-cli and sysrepo-plugin.
- Netconf/Yang support is included in the build to support basic configurations in the LiFi AP system.
- Prometheus node exporter to export telemetry.

More detail has been reported in D3.3 [4] and D4.2 [9].

2.1.2.4 Sub-6 and mmWave localization specific network functions

The sub 6 GHz platform is a software-defined radio (SDR) from Ettus research, model USRP N321 (Figure 2-14). This is a high performance SDR that uses a unique RF design by Ettus Research to provide 2 RX and 2 TX channels in a half-wide RU form factor. Each channel provides up to 200 MHz of instantaneous bandwidth and covers an extended frequency range from 3 MHz to 6 GHz. The baseband processor uses the Xilinx Zynq-7100 SoC to deliver a large user programmable FPGA for real-time, low latency processing and a dual-core

ARM CPU for stand-alone operation. Support for 1 GbE, 10 GbE, and Aurora interfaces over two SFP+ ports and 1 QSFP+ port enables high throughput IQ streaming to a host PC or FPGA coprocessor. This USRP supports Ethernet-based synchronization using an open source protocol known as White Rabbit [10].

Figure 2-14. SDR model USRP N321 for the Sub 6 GHz platform.

The synchronization of the SDRs can be performed in two different ways. The first way is to use a 1 pulse per second (PPS) and 10 MHz reference clock sources supplied to each of the anchor nodes using a single source. This can be performed using a device called OctoClock [11], which can supply up to 8 synchronized PPS and 10 MHz signal for synchronisation of up to 8 devices. The main disadvantage of this approach is that 2 coaxial cables for each device are needed. Due to the limited drive capability of the outputs of the OctoClock, the maximal cable length is limited. This can be a limiting factor for demonstrating the capabilities in real scenarios where the distances between the OctoClock and the anchor nodes is larger than 10 meters. Nevertheless, the OctoClock was used in the initial laboratory experiments for developing and testing the localization approach. The used OctoClock is shown in Figure 2-15.

Figure 2-15. OctoClock - initially used for synchronization of the anchor nodes

To overcome the mentioned issues with the limited cable length, the WhiteRabbit solution is used in the later phase of the project. The time synchronization precision is about 100 ps and it uses fibre cables. The maximal length of these cables is limited to 10 km. The WhiteRabbit switch used in this experiment is given in Figure 2-16. The two bottom devices are WhiteRabbit switches and the upper device is a 10 gigabit Ethernet switch used for communication between the WhiteRabbit switch, the SDRs and the computers used for controlling the SDRs.

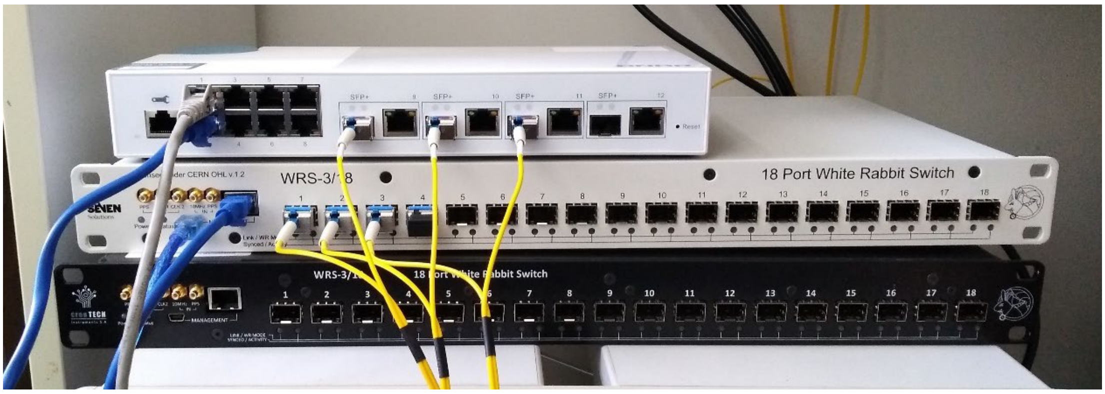


Figure 2-16. Top to bottom: a) 1/10 Gb Ethernet switch for communication with the SDRs, b) and c) WhiteRabbit switch for precise timing

For the 60 GHz system, we use a prototype mmWave modem developed at IHP. This prototype consists of a proprietary FPGA-based hardware platform, i.e., a motherboard called digibackBoard [12] with SDR capability and an adapter board that has been designed to be attached to the motherboard in order to host the commercial-of-the-shelf (COTS) 60 GHz transceiver module with phased array from SiversIMA (now Sivers Semiconductors) [13].

The baseband platform is a custom System-on-chip (SoC) SDR platform. A photo of the top side of the developed printed-circuit board (PCB) is shown in Figure 2-17. The PCB has a size of 155 × 100 mm. The platform consists of a SoC with a huge number of programmable logic resources as well as a high-performance dual-core ARM-based software processing system. The need of Gigasamples per second (GSps) data converters, which are not included in the SoC itself, are integrated as a separate chips on the PCB. The two analogue-to-digital converters (ADC) and two digital-to-analogue converters (DAC) channels with sampling rates up to 2.5 GSps are integrated on the same board, together with four Gigabit Ethernet interfaces and additional general-purpose input/output (GPIO) connectors. The SoC is of a Zynq 7000-series (for instance, Zynq 7045 or 7100). All GPIO extension connectors and the analogue interface are accessible on the top side, whereas mostly all active components like ADCs, DACs, SoC, and Ethernet PHYs are mounted on the bottom side to ensure proper cooling with a heatsink.

The used RF analogue front-end (AFE) is based on a 16-TX/16-RX 57-71-GHz RF transceiver from Sivers IMA. The transceiver comprises 16 TX + 16 RX channels in an RF-beamforming configuration with separate TX and TX antennas. The chip is mounted on a PCB (shown in Figure 2-17). Tx and Rx antennas are an array of 16 dual circular patch antenna elements. The chip has been designed for high transmit power and low phase noise in order to support 40 dBm EIRP and up to 64 QAM with 45 MHz reference signal.

To accommodate the RF AFE with the baseband platform an adapter-board has been designed. The adapter board acts as a “bridge” between the baseband board and the RF module. At the bottom are the connectors to take the baseband signal, reference, and control signals, which are routed further to a connector on top, to which the RF module will be attached. Furthermore, there are additional GPIO pins for debugging purposes, and an SFP+ cage for 10 Gbps Ethernet connection.

The integrated solution is shown in Figure 2-17 (right hand side).

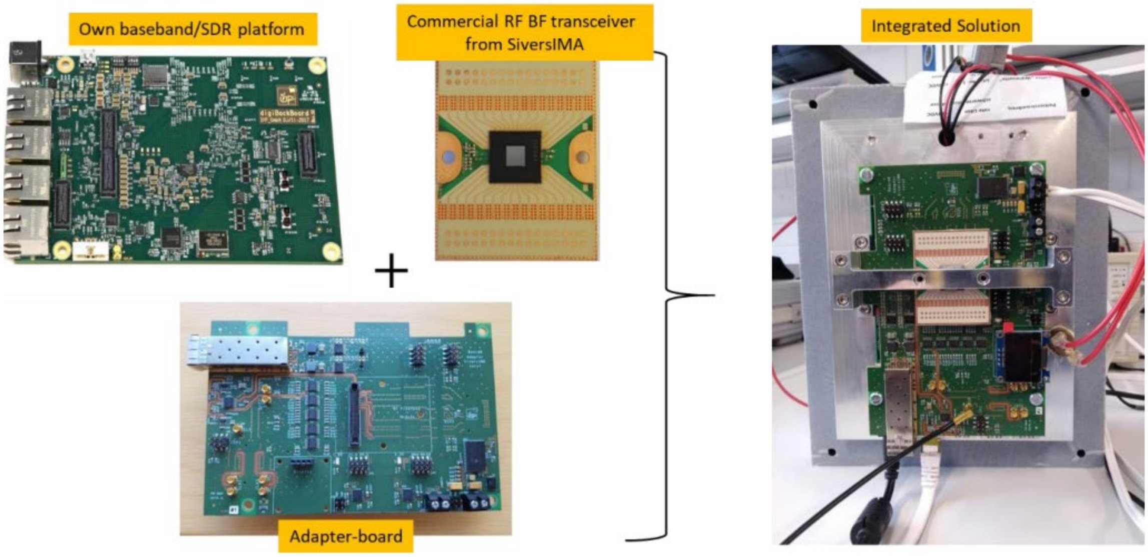


Figure 2-17. Sub-6 and mmWave localization integration.

2.1.3 RAN cluster

As described in 5G-CLARITY D5.1 [7], Accelleran dRAX™ is the cloud native and O-RAN aligned 5G standalone virtual RAN (VRAN) solution used in 5G-CLARITY pilots. It consists of a near-RT RIC, CU-CP, CU-UP and xApp SDK framework integrated E2E with third party DU and RU components from the disaggregated RAN ecosystem. The third-party RU is the only PNF of the end-to-end system and has been described in previous section.

The components deployed in the 5G-CLARITY pilots that are part of the RAN Cluster are:

- 1x dRAX™ component with near-RT RIC, CU and xApp framework delivered as a software component (VNF).
- 1x DU component delivered as a software component (VNF).

The components of the RAN cluster and their relation to Edge Cluster and Infrastructure are shown in Figure 2-18. In the Antwerp lab pre-integration setups with RAN550 and RAN650 shown in Figure 2-10 and Figure 2-12 respectively, the Open5GS 5GC, dRAX CU/nRT-RIC and xApp SDK on Kubernetes VM and DU on Docker bare metal where deployed on the same COTS server.

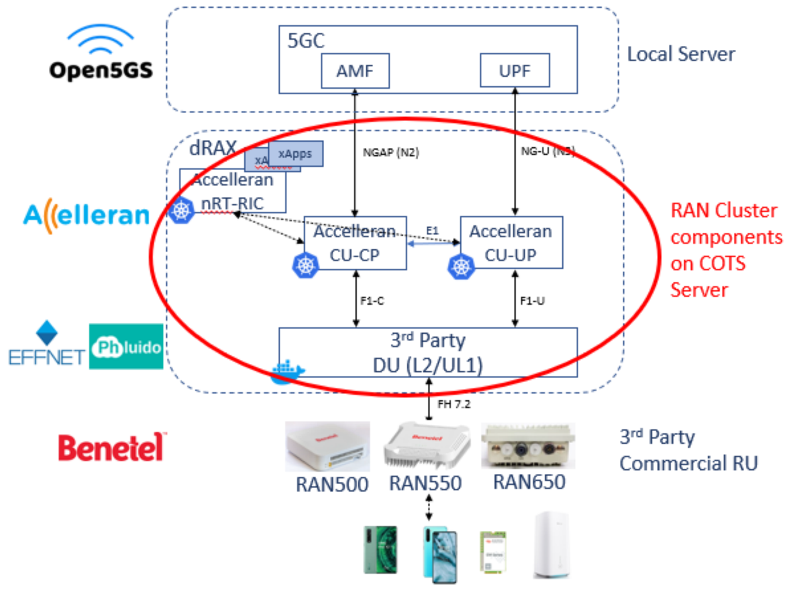


Figure 2-18. RAN cluster components.

While the current end to end integrated feature baseline for CU/DU/RU at the time of writing is based on a 40 MHz Bandwidth and 2x1 MIMO scheme (2 spatial streams in DL for 1 in UL), since the Benetel RU is HW capable of supporting up to 100 MHz bandwidth and 4x4 MIMO, as soon as SW Releases for RU and DU are available from the third-party partners with 100 MHz and higher order MIMO support, they will be updated accordingly to achieve better throughputs.

2.1.4 Edge cluster

In this section we describe our implementation of the 5G-CLARITY edge cluster in the two pilot sites. Given the pre-existent conditions of each pilot, e.g. a connection exists between the lab at the University of Bristol and the M-SHED museum but an isolated deployment is required at BOSCH in Aranjuez, a different edge cluster implementation is used for each site.

2.1.4.1 Bristol edge cluster

For the UC1 demonstration, the University of Bristol is using OpenStack Wallaby version as the Virtual Infrastructure Manager (VIM) to build the cloud infrastructure that host the VNFs.

The implementation setup includes the controller node and several compute nodes, placed on different locations within the UC1 testbed, which serves as the edges. The compute resources are categorized and grouped using the "host aggregate" definition in OpenStack. Three different Availability Zones (AZ) have been defined corresponding to each location. The two AZs which are related to this project are HPN-AZ and M-SHED-AZ.

HPN-AZ is pointing to the group of resources at Smart Internet Lab, while the M-SHED-AZ is pointing to the group of resources which are available in M-Shed edge.

The logic behind this design ensures the orchestrator, which in this case is the OSM 11, considers each AZ as an individual VIM and manages their resources individually. This way, the need to have multiple OpenStack implementations, one for each edge is avoided.

The rest of the network are configured and connected via the SDN fabric. Figure 2-19 shows the overall design of the network and cloud infrastructure described above and which the OpenStack Wallaby version supports.

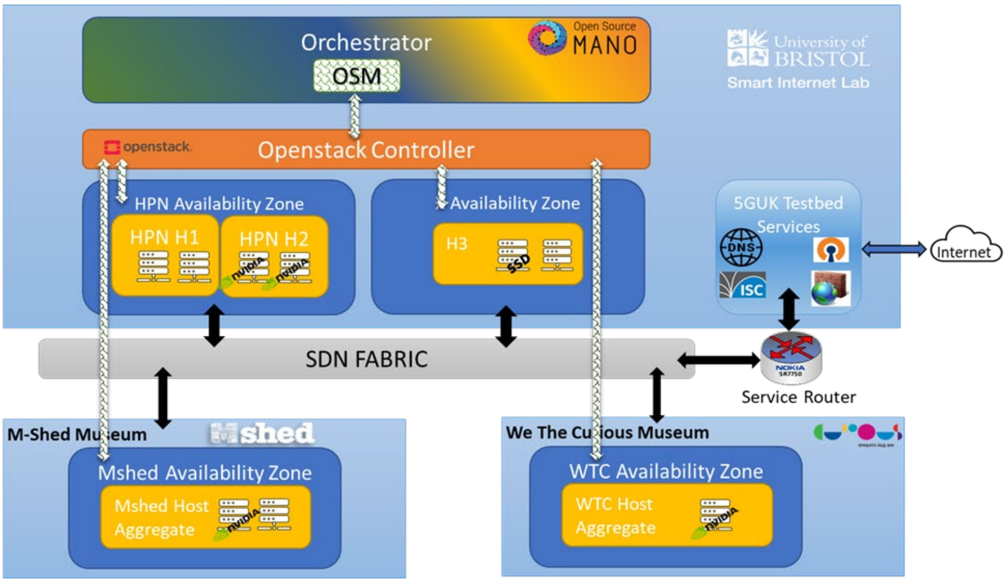


Figure 2-19. Overview of the cloud infrastructure and VIM implementation for UC1

In Figure 2-20 we present an overview of the compute resources including the vCPU, Memory, and number of allowed VMs allocated to 5G-CLARITY UC1 implementation and the usage of this resources in OpenStack.

In Figure 2-21 we show a description of the network topology deployed for VM inter-connection as well as integration of the technology solutions.

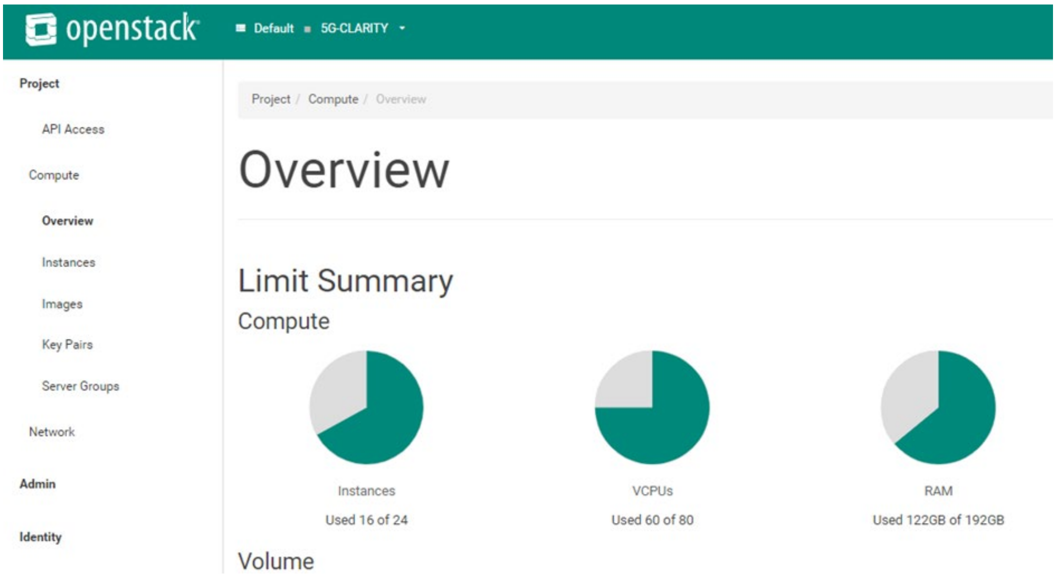


Figure 2-20. A sample summary of the allocated and used compute resources deployed in UC1

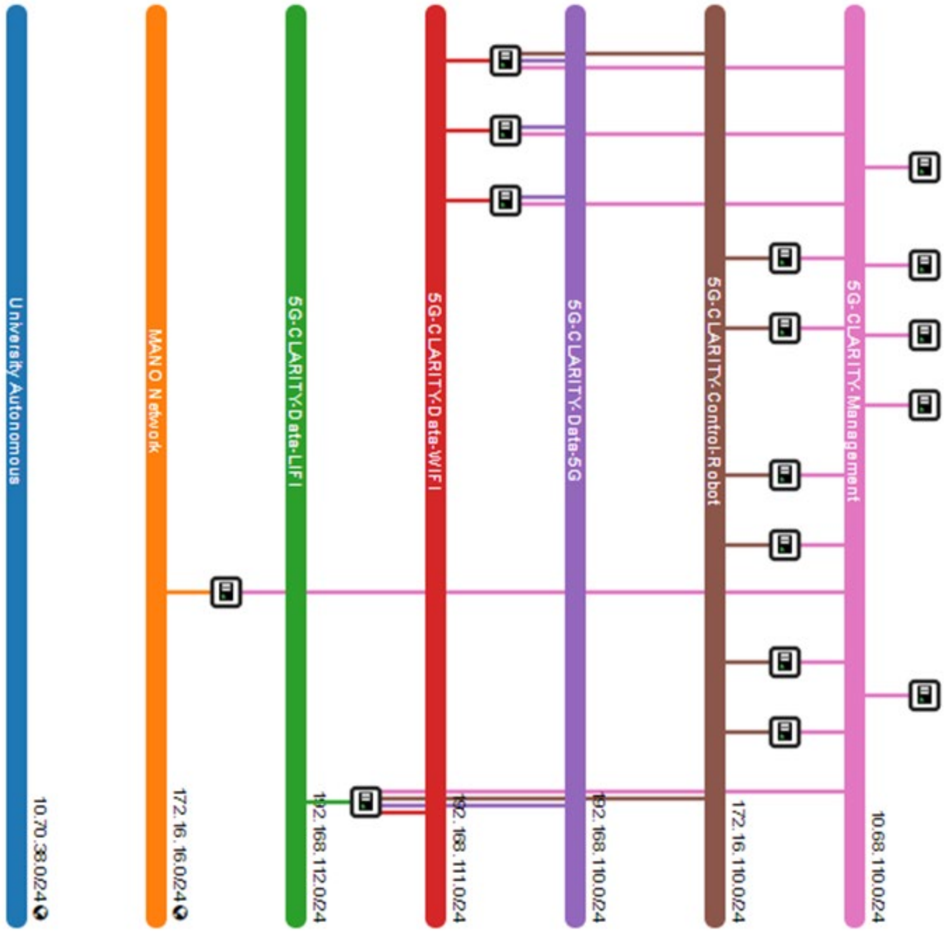


Figure 2-21 An illustration of the network topology describing the VM inter-connection and technology solution integrated for UC1 pilot site

2.1.4.2 Aranjuez edge cluster

The main requirement for the edge cluster deployment at Aranjuez is to have a portable solution that is easy to deploy in the factory. For this purpose, a flight rack depicted in Figure 2-22 will be used, which will be pre-provisioned at i2CAT to then be installed at the factory. It is worth noting that for security reasons the devices deployed in the rack cannot be directly connected to the internal network at the factory. Therefore, a CPE will be used to provision Internet connectivity to the devices in the rack.

Figure 2-22. Flight rack used in Aranjuez factory

The edge cluster server deployed in Aranjuez needs to sustain the following software functions:

- Virtual Infrastructure Manager: Based on OpenStack Victoria [14].
- Network and Application Function Stratum: Including the 5GC and AT3S functions described in Section 2.2.
- Management and Orchestration Stratum: Including the Service and Slice provisioning subsystem described in Section 2.3.
- Intelligence stratum: Including the Intent and AI engines described in section 2.4.

Table 2-1 depicts the technical specifications of the edge cluster deployed at Aranjuez.

Table 2-1. Specs of edge cluster deployed at Aranjuez factory

Computing	GPU	Memory	Disk	Networking	HW security	Management
Intel Xeon 4210 10C/20T (2.4 GHz) x 2	No	128 GB RAM	1 TB SSD	(2x) 1 Gbps Ethernet + support for (2x) 10 Gbps (optic SFP+)	Trusted Platform Module 2.0	iDRAC9 Enterprise

2.2 Network and Application Function Stratum

We describe here the implementation of the Network and Application Function Stratum, which include the following elements in the RAN and Edge Clusters:

- RAN Cluster: Near Real Time RIC, Centralized Unit and Distributed Unit.
- Edge Cluster: 5G Core, AT34S User Plane Function, and Application Functions.

The Network and Application Function stratum integrates several developments that were carried out and validated in WP3. Unless explicitly stated all the functions of the Network and Application Function Stratum are deployed both in the Bristol and Aranjuez use cases.

2.2.1 RAN cluster: near-RT RIC and xApps

Accelleran dRAX™ is a cloud-native architecture based on containerised microservices communicating with each other via an asynchronous messaging framework based on a 5G Standalone architecture. Each of the major components of the RAN (CU-CP, CU-UP, near-RT RIC) are themselves disaggregated into a fine-grained set of service entities. dRAX™ is delivered as a containerised software-only component to be deployed on Kubernetes via Helm charts and installed on a bare metal or VM running on a COTS Server.

The following are the summary HW server requirements for the installation of Accelleran dRAX CU CP, nRT-RIC and xApp SDK including Kubernetes platform:

- Persistent Storage → 256 GB
- RAM → 32 GB
- CPU → 4

In addition to the needed development, integration and optimisation of the control and user plane 5G SA components including third-party DU and RU for 5G-CLARITY, the dRAX platform (NATS, REDIS, Kafka, xApp lifecycle, DU/RU abstraction…) had to be enhanced and extended in order to support multi-WAT technologies in a consistent manner to enable Wi-Fi/LiFi telemetry exposure by the 5G-CLARITY xApps, mainly the MPTCP and multi-WAT Telemetry xApps, and the means to integrate DU/RUs seamlessly with different levels of proprietary management interfaces not fully aligned to O-RAN O1 and E2.

With regards to the xApps running in the RIC, the 5G-CLARITY platform features the Multi-WAT telemetry xApp developed in WP4 and reported in D4.3 [5]. This xApp allows the telemetry subsystem to gather wireless metrics from the 5GNR, Wi-Fi and LiFi technologies and will be used to assess the performance of the multi-connectivity framework in the Aranjuez and Bristol venues.

2.2.2 RAN cluster: centralized unit

Accelleran dRAX™ CU software components support 5G Standalone architecture. The CU-CP and CU-UP communicate northbound with 5GC using 3GPP NG-C (N2) and NG-U (N3) interfaces respectively. CU CP and CU-UP support CUPS using 3GPP E1 interface which is used to allow one particular CU-CP instance to control several CU-UP instances depending on the slicing and MOCN enabled topology. The CU-CP and CU-UP communicate southbound with the DU software components via standard 3GPP F1-C and F1-U interfaces over any IP transport. The CU components are also based on Kubernetes deployed using Helm charts.

One of the important aspects of the CU development for 5G-CLARITY was to support the Network Node Selection Function (NNSF) so that the CU components would be able to support MOCN and Neutral Host topologies needed for the project with a focus on the associated PLMNID-based slicing aspects. Dynamic slicing at CU level was implemented so that this functionality could be leveraged by the management and orchestration stratum.

The following are the summary HW server requirements for the installation of the CU UP for every 1 Gbps of user plane traffic:

- Persistent Storage → 1 GB
- RAM → 1 GB
- CPU → 3

2.2.3 RAN Cluster: Distributed Unit

The Effnet/Phluido DU is also fully SW based, delivered as docker containers running on a bare metal COTS Server with Ubuntu distribution enhanced with the real-time package installation.

The DU software communicates northbound with the Accelleran dRAX CU via 3GPP F1 interface and southbound with the RU using O-RAN fronthaul 7.2 split interface over direct optical fibre. Internally the Effnet L2 part of the DU uses a FAPI-like interface with Phluido UL1 component which is responsible also for the fronthaul 7.2 communication.

The following are the summary HW server requirements for the installation of the Effnet/Phluido DU:

- Any x86 CPU (AMD or Intel) with AVX2 instruction set support (mandatory) or AVX512 instruction set support (recommended) and >3 GHz clock speed.
- Ubuntu 18.04 which has low-latency kernel (part of the Ubuntu package repository, with package name linux-image-lowlatency).
- For commercial RU connectivity that uses fibre, the Intel X520 NIC card with compatible (Intel-approved) SFP+ transceiver is required and using a direct connection to the DU server using 10G fibre (no switches in between). Other NIC cards may also be available once validated.
- For each 1 Gbps user plane traffic:
    - Persistent Storage → 8 GB
    - RAM → 1 GB
    - CPU → 8 (L2 + Upper PHY)

2.2.4 Edge Cluster: 5G Core

The 5G Core implementation being used in 5G-CLARITY is based on open5gs (v2.4.8). Open5gs is an open source dual 4G/5G core that can operate both in NSA and SA modes. In 5G-CLARITY open5gs is used in SA mode. These are the main features of open5gs relevant to 5G-CLARITY:

- Supported 5G Core network functions: AMF, UPF, UDM, AUSF, UDR, PCF, SMF (PGW-c), NRF, NSSF.
- Subscriber management: Subscriber management: Per each subscriber, it supports the configuration of Aggregate Maximum Bit Rate (AMBR) and QCI both in downlink and uplink directions, the configuration of different slices, the configuration of different sessions in each slice (DNN, default bearer, ARP priority level, capability/vulnerability options, Session-AMBR and fixed IP) and the configuration of different PCC rules in each session (uplink/downlink rule, bearer, ARP priority level, capability/vulnerability options, MBR and GBR). Using PLMNID-based slicing 5G-CLARITY can use subscriber management features to provide different QoS (AMBR, QCI) across different slices.

To implement the PLMNID-based slicing feature described in D4.2 [9] and D4.3 [5] we use multiple instances of open5gs, one per slice, and leverage the MOCN functionality available in the Accelleran radios.

In 5G-CLARITY open5gs is packaged as a VM with the following characteristics:

- 4 GB RAM
- 2 vCPUs
- 20 GB disk

It is deployed by Slice Manager and configured via *cloud init*:

- Configuration of AMF (N2 interface for NGAP, PLMNID, TAC, SNSSAI).
- Configuration of SMF (Available Slices, UEs subnet per DNN).

- Configuration of NSSF (Available Slices).
- Configuration of UPF (N3 interface for GTP).
- Configuration of the shared database for Subscriber management (allowed IMISs and their configuration).

2.2.5 Edge Cluster: AT3S User Plane Function

The AT3S user plane function implementation which supports the network part of the multi-connectivity framework is based on the MPTCP VM implementation presented in D3.3 [4]. The CPE's for UC1, UC2.1 and UC2.2 implements the MPTCP kernel 5.5.0 with the corresponding API to allow the dynamic configuration of the schedulers, and to expose the transport telemetry. The MPTCP enabled kernel has been compiled into x86 and ARM architectures, to support the SBCs selected for the CPEs.

2.2.6 Edge Cluster: Application Functions

Virtualised Application Functions (VAFs) are specific to each use case and will be described in their corresponding sections.

2.3 Management and Orchestration Stratum

This section describes our implementation of the Management and Orchestration Stratum, which integrates developments carried out in WP4.

The Management and Orchestration Stratum is a complex stratum composed of multiple subsystems (c.g. D2.2 [1]). To develop the integrated 5G-CLARITY platform we have focused on the Service and Slice provisioning subsystem, which is the key subsystem required to manage 5G-CLARITY infrastructure slices and to implement some of the private network service delivery models that will be demonstrated in the different use cases. The Management Functions (MF) of the Service and Slice provisioning subsystem included in the integrated 5G-CLARITY platform are: i) the NFV orchestrator, ii) the Multi-WAT Non-Real-Time RIC, and iii) the Slice Manager.

In addition, we have integrated a simplified implementation of the Telemetry subsystem to be able to collect and compare network KPIs on the two pilot sites.

All the Management and Orchestration Stratum elements are common in the Bristol and Aranjuez sites.

2.3.1 NFV Orchestrator

5G-CLARITY NFV Orchestrator (NFVO) is an essential component of the 5G-CLARITY Management and Orchestration (M&O) stratum to instantiate the Virtual Network Functions and Network Services. The NFVO is used in conjunction with the 5G-CLARITY Intent Engine and Slice Manager to enable, seamless intent-based NFVIaaS and SLaaS (D4.3) to support Smart Tourism, third-party events, and public safety services as introduced (to be described in the following sections). Figure 2-23 presents a services instantiation test in 5G-CLARITY UC1 as reported in D4.3 [5].

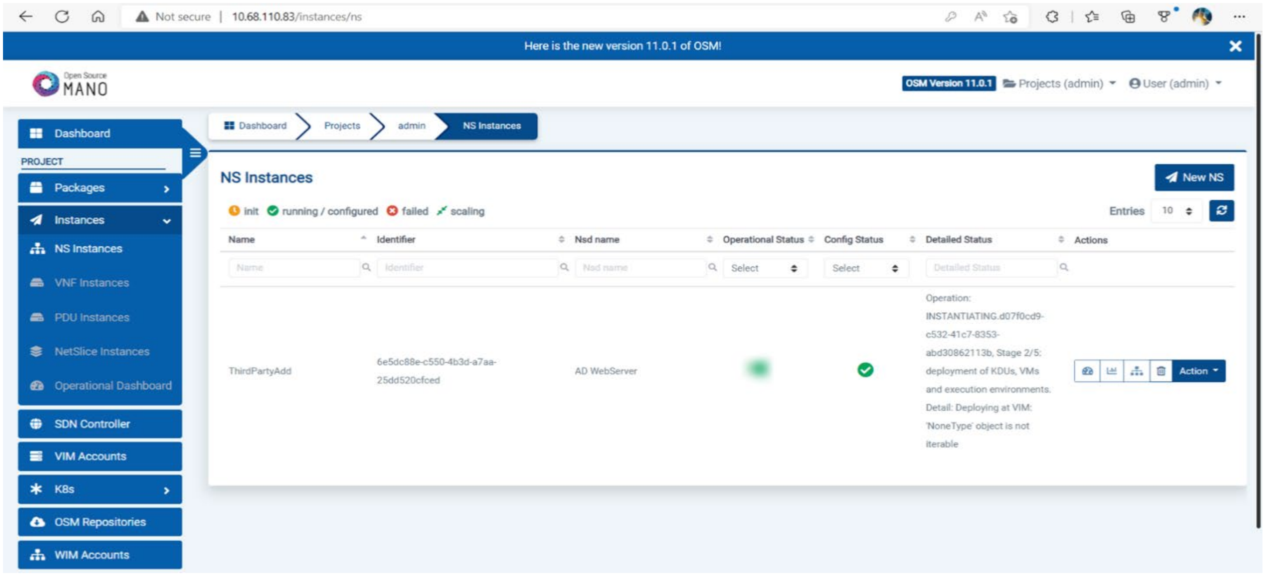


Figure 2-23 Example of a running / configured NS Instance.

2.3.2 Multi-WAT Non-Real Time RIC

The Multi-WAT Non-Real Time RIC is a multi-technology element manager that allows to configure 5GNR, Wi-Fi and LiFi physical network functions, as required to support a given 5G-CLARITY slice configuration. This function has been developed in WP4, where it has been integrated with the three wireless access technologies available in the infrastructure stratum, namely the Accelleran 5GNR, the i2CAT WiFi6 node and the PLF LiFi AP. The interested reader is referred to D4.2 [9] and D4.3 [5] for an accurate description of how these integrations have been performed.

Figure 2-24 provides an example of the JSON body included in a north-bound call to the Multi-WAT Non-Real Time RIC to deploy a multi-WAT service, i.e. to configure the wireless service part of a 5G-CLARITY slice. We highlight the following parts:

- "selectedPhys", containing a list of the identifiers of the cells or APs that will be part of the slice.
- "vlanId", containing the identifier of the transport service that is part of this slice.
- "wirelessConfig", containing the service configuration for the Wi-Fi and LiFi APs included in the slice (i.e. the SSID and security credentials).
- "cellularConfig", containing the service configuration for the 5GNR cells included in the slice. In this case the location of the 5GCore serving the slice is shown.

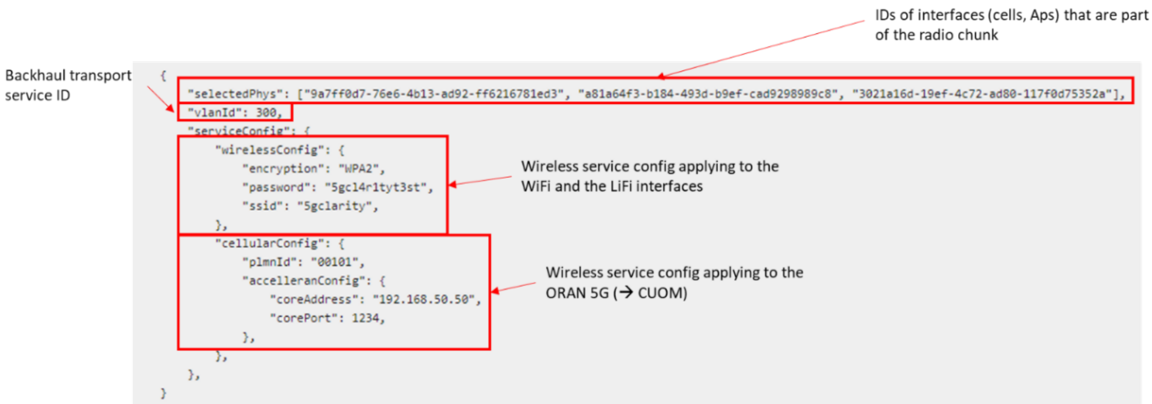


Figure 2-24. Example call to service provisioning endpoint of Multi-WAT non Real Time RIC.

2.3.3 Slice Manager

The 5G-CLARITY Slice Manager function has also been developed in WP4, starting with an initial development carried out in the H2020 5G-City project [15], where it only supported management of LTE and WiFi wireless nodes. The Slice Manager has also been used in WP4 to validate the KPIs related with provisioning time of 5G-CLARITY slices that were described in the 5G-CLARITY DoW.

The main features of the 5G-CLARITY Slice Management Function that will be tested in the WP5 use cases are:

- Slice provisioning: Capability of configuring a slice in the private venue comprising:
  - Compute chunks: Reservation of memory, CPU and storage resources of the edge cluster.
  - Configuration of wireless services, through an integration with the Multi-WAT Non-Real Time function.
  - Deployment of ETSI NFV network services, including 5GCore, AT3S user plane function and application functions.
- Intelligence stratum integration, to enable provisioning of slices using intents.

It is also important to highlight the simplifications we have adopted to maintain the implementation complexity of Slice manager limited:

- The Slice Manager has not been integrated with a Transport SDN controller. Instead, we assume that the transport services (VLANs) are already pre-configured in the Ethernet switches, and the Slice Manager only configures the selected VLAN in the involved wireless access nodes and the edge cluster.
- The Slice Manager is only integrated with the edge cluster, not with the RAN cluster. The reason is that a cloud native RAN cluster based on Kubernetes has been used. However, our Slice Manager does not support Kubernetes VIMs, although it could be extended to do so. This functionality has been left out as it was not required by any of the use cases.

2.3.4 Telemetry Subsystem and KPI collection

In our integrated 5G-CLARITY platform we have developed a simplified Telemetry subsystem. The main goal of the telemetry subsystem is to enable KPI collection in a harmonized way, so that the Bristol and Aranjuez deployments can be effectively compared. Another requirement of the simplified telemetry subsystem is to be able to operate without Internet access, as this may be limited in the Aranjuez site.

Thus, instead of using the full-blown AWS Telemetry subsystem presented in WP4, we have relied on a simplified implementation based on a Prometheus and Grafana stack. Prometheus [16] is an open-source monitoring system and time series database and Grafana [17] is an open-source observability platform. A visualization stack for 5G-CLARITY based on Prometheus and Grafana was already demonstrated at EuCNC 2022 (c.f. D6.7 [18]). This stack has been also integrated with the Near-Real Time RIC to display wireless access metrics through the Telemetry xApp described in D4.3 [5].

The following figures are exported from Grafana dashboard and represent the KPIs related to the throughput and latency for different radio access technologies for both individual link performance and cumulative performance, for a measuring run of two minutes.

Figure 2-25 presents the cumulative traffic while MPTCP is in place, and each line corresponds to a link for both received (top graph) and sent (bottom graph) traffic. In this figure, blue line is the aggregated throughput of all links (5GNR, Wi-Fi and LiFi) while the green is Wi-Fi and the yellow is Wi-Fi plus LiFi.

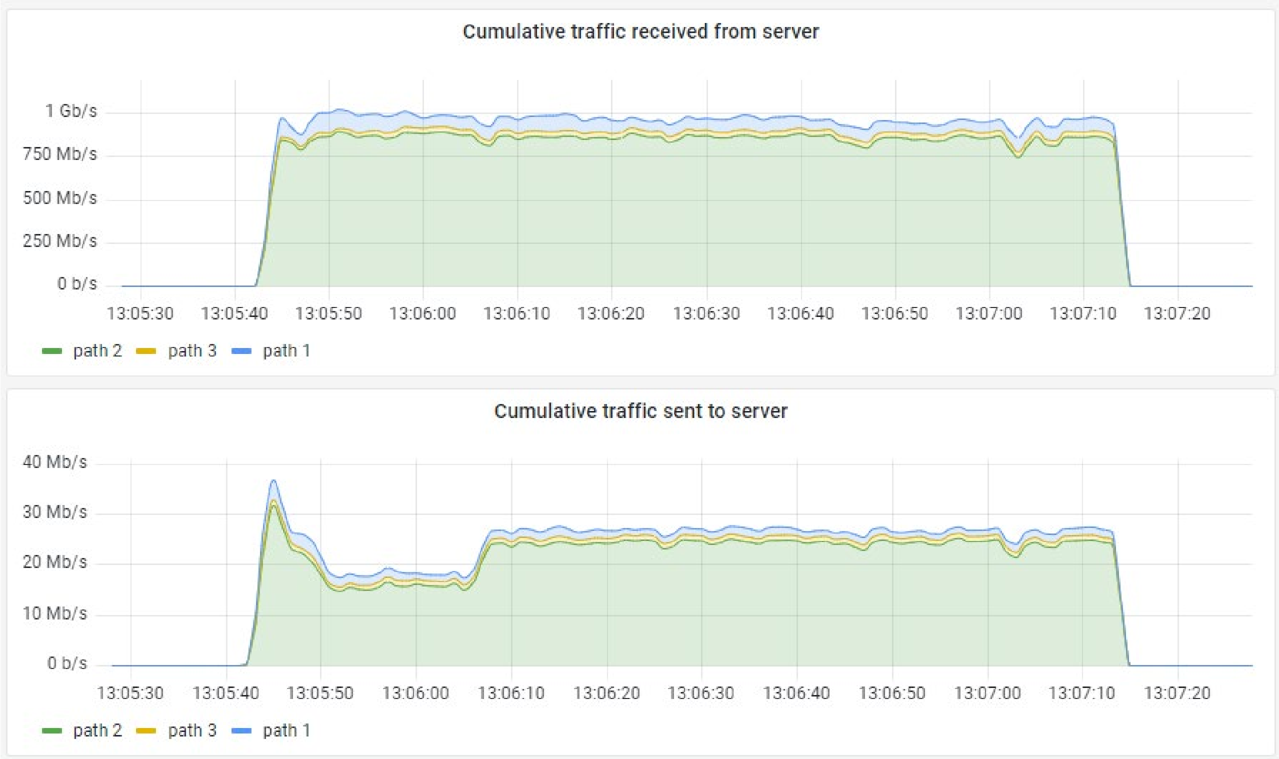


Figure 2-25. Cumulative traffic received and sent over different RATs on CPE

Figure 2-26 presents the individual link performance while MPTCP is in place. Same as previous figure, green line presents the Wi-Fi throughput while the blue and green representing the 5GNR and LiFi throughput

Figure 2-26. Individual traffic received and sent over each RAT interface in CPE.

Round trip time or latency between the CPE and MPTCP proxy is presented in Figure 2-27, each line corresponds to a link. Orange is the 5GNR latency while light blue and dark blue representing the Wi-Fi and

LiFi latency.

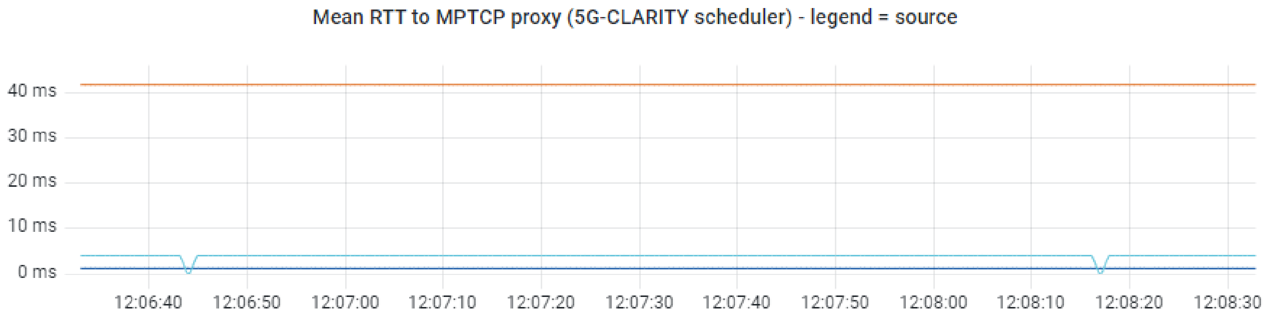


Figure 2-27. Mean RTT between CPE and MPTCP Proxy for different RAT.

The above preliminary results are presenting the performance of the available RATs in Bristol testbed using the 5G-CLARITY telemetry subsystem with the recently integrated Accelleran 5GNR solution. The performance enhancement especially for the 5GNR link is ongoing. This means the high latency and the low throughput of 5GNR link are due to this.

2.4 Intelligence Stratum

The integrated 5G-CLARITY platform includes a complete intelligence stratum composed of the AI Engine and the Intent Engine. Both elements have been developed and validated in WP4 (c.f. 5G-CLARITY D4.2 [9] and 5G-CLARITY D4.3 [5]).

We note that the implementations of the AI Engine and the Intent Engine deployed in Bristol and Aranjuez are the same. However, the actual ML models in the AI Engine or the specific provider integrations in the Intent Engine are particular to each use case and will therefore be described in each use case section.

2.4.1 AI Engine

The AI Engine is built on the Open-source Function-as-a-Service (OpenFaaS) platform. The concepts and technologies of this platform are detailed in 5G-CLARITY D4.2 [9] along with detailed explanations of functionality and the lifecycle management of ML models. In 5G-CLARITY D4.3 [5] this information is utilised by project partners to create, deploy, and invoke their own ML models through the AI Engine.

To start, models are created using the command line interface tool referred to as faas-cli. The AI Engine language template provides a common python language for ML models and additional monitoring capabilities to expose internal model metrics to the Prometheus monitoring system. The model owner is then free to add compiled algorithms to the model and execute them through the *handler.py* file. This process is detailed in 5G-CLARITY D4.3 [5] Section 5. By importing the requests python library and listing it in the requirements file the ML models may query the Data Lake for information related to their execution. This reduces the execution time of the model while accessing up to date monitoring information.

Once the ML model is complete, it may be pushed to the AI Engine where it can be invoked through the client or through the OpenFaaS API. To integrate the model with the Intent Engine, a Functionality Template must be provided through the registration process. This process informs the Intent Engine of the location and functionality of the ML model, enabling the execution of the ML model through the Intent Engine. This process will be expanded on in the next section.

2.4.2 Intent Engine

The Intent Engine is built on the Adaptive Policy EXecution (APEX) engine. The APEX engine contains policy models which are comprised of states. Depending on the outcomes of cross-state decisions and underlying context information, the policy outcome adapts to reflect these changes in real time. How these states can be used in an intent-based scenario and coordinate with the AI Engine is briefly described in 5G-CLARITY D4.2 [9]. A simplified interpretation of this process is represented in 3 stages:

- Translation of a received Intent.
- Identification of an appropriate ML model.
- Communication of ML model results to appropriate actioning body.

To address each of these stages the intent matching mechanism and Functionality Templates were implemented, these are also described in 5G-CLARITY D4.2 [9]. The Functionality Template is a bottom-up approach to function discovery. The Functionality Template would require details on how to trigger a function, the required parameters of that function and the expected result from a successful and unsuccessful execution. This information is often present in API documentation and as a result, Swagger [19] was identified as a suitable specification to build the Functionality Template around. The Functionality Template contained the required information provided by Swagger and additional information such as the location of the described function. This approach allowed models within the AI Engine to become triggerable through the same mechanism. Users could now register their components/models with the Intent Engine by providing a Functionality Template. The intent matching mechanism is used to link the request expressed in the intent message with an available action or set of actions in the system. Intent matching mechanism utilises an NLP based text distancing algorithm to compare the body of an intent request against the descriptions of functions detailed in the Functionality Template. An example of this process is described in 5G-CLARITY D4.2 [9]. The execution of the Intelligence Stratum is presented in 3 demonstrations in 5G-CLARITY D4.3 [5]. For each of these demonstrations' partners integrated their provisioning subsystems and ML models with the Intent Engine through the registration of their Functionality Templates.

3 UC1: Enabling Enhanced Human-Robot Interaction (Smart Tourism)

The 5G-CLARITY Use Case (UC1): Enabling Enhanced Human-Robot Interaction (Smart Tourism) is planned for demonstration at the M-Shed Museum in Bristol. It will show the benefits of 5G-CLARITY framework to enable private and public 5G networks, and multiple wireless access technologies to support guide robot services including other industrial verticals associated to smart tourism. In deliverable D5.1 we introduced UC1 scope, objectives, main components and testbed architecture, potential benefits beyond 5G-CLARITY project, demonstration scenarios, and enablers, and preliminary plan for implementation and validation. This section reports:

a. The extension of the definitions of 5G-CLARITY UC1 introduced in D5.1 [2].

b. The implementation status and preliminary KPI lab validation of early-release components of 5G-CLARITY framework.

c. Progress in the UC1 development, final demonstration plan, and initial KPI validation.

The section is structured as follows: revision of UC1 scope and objectives, narratives, and testbed architecture in lab and in demo location, status of development, component integration and KPI validation, and progress towards final demonstration.

3.1 Scope and Objectives

As in D5.1 [2], we present the main goal of 5G-CLARITY UC1. This is to demonstrate the benefits of the 5G-CLARITY multi-WAT and NPN enabled framework in a museum environment, which enhances the interactions between a guide robot and visitors. This translates into the following objectives:

- To develop, integrate, validate, and demonstrate a smart tourism application within the 5G-CLARITY platform that supports intelligent, flexible, and robust interactions between visitors and a robot as tour guide. This reflects a Standalone NPN (SNPN) scenario described in 5G-CLARITY D2.2 [1].
- To validate the Service delivery models defined in D4.3 [5], which includes Public Network Integrated-NPN (PNI-NPN) scenario described in 5G-CLARITY D2.2 [1]. The 5G-CLARITY UC1 approach underscores the reality of a public-private network integration.
- To provide validation for the 5G-CLARITY transversal KPIs in a real environment. These KPIs relates to the Throughput and Latency validations described in D3.3 [4].
- To showcase the portability in deploying our solution in a typical "plug & play" situation, enabled by the 5G-CLARITY intelligence stratum. Across different scenarios, implementing our solution reflects the ease in deploying services for a third party on top of the private network infrastructure, using the intent engine and the different service delivery models.

3.2 UC1 Demonstration Narratives

The UC1 demonstration planned for the M-Shed museum in Bristol will follow two key narratives. This section summaries revise or extend narratives of UC1 from D5.1 [2] and relates their outcomes to the 5G-CLARITY objectives.

In 5G-CLARITY D5.1 we introduced three narratives representing services benefited by 5G-CLARITY framework. In this deliverable, we have combined contents of narrative 3 into narrative 1 and 2, in order to focus on the main enablers during the demonstration, capturing the main features identified in D5.1. In this sub-section we extend and enrich the demonstration of each narrative by highlighting additional 5G-CLARITY enablers developed in WP3 and WP4.

- ***Narrative 1:*** *5G-CLARITY SNPN, Multi-WAT and Network-Function-Virtualization as-a-Service (NFVaaS) solutions enhancing seamless connectivity, content delivery, and control in guide robots serving visitors in crowded venues.*
- ***Narrative 2:*** *On-demand surveillance of suspicious activities in the museum 5G-CLARITY Intelligent PNI-NPN, Multi-WAT, and Slice-as-a-Service Solutions for Seamless Surveillance in a crowded venue.*

3.3 5G-CLARITY Architecture and Enablers for UC1 Demonstration

The UC1 demonstration instantiated the 5G-CLARITY platform presented in Section 2, which in turn is derived from the primary 5G-CLARITY system architecture described in D2.3 [20]. In Figure 3-1 we highlight the sections related to UC1 with a red tick on the segments of the architecture stratum.

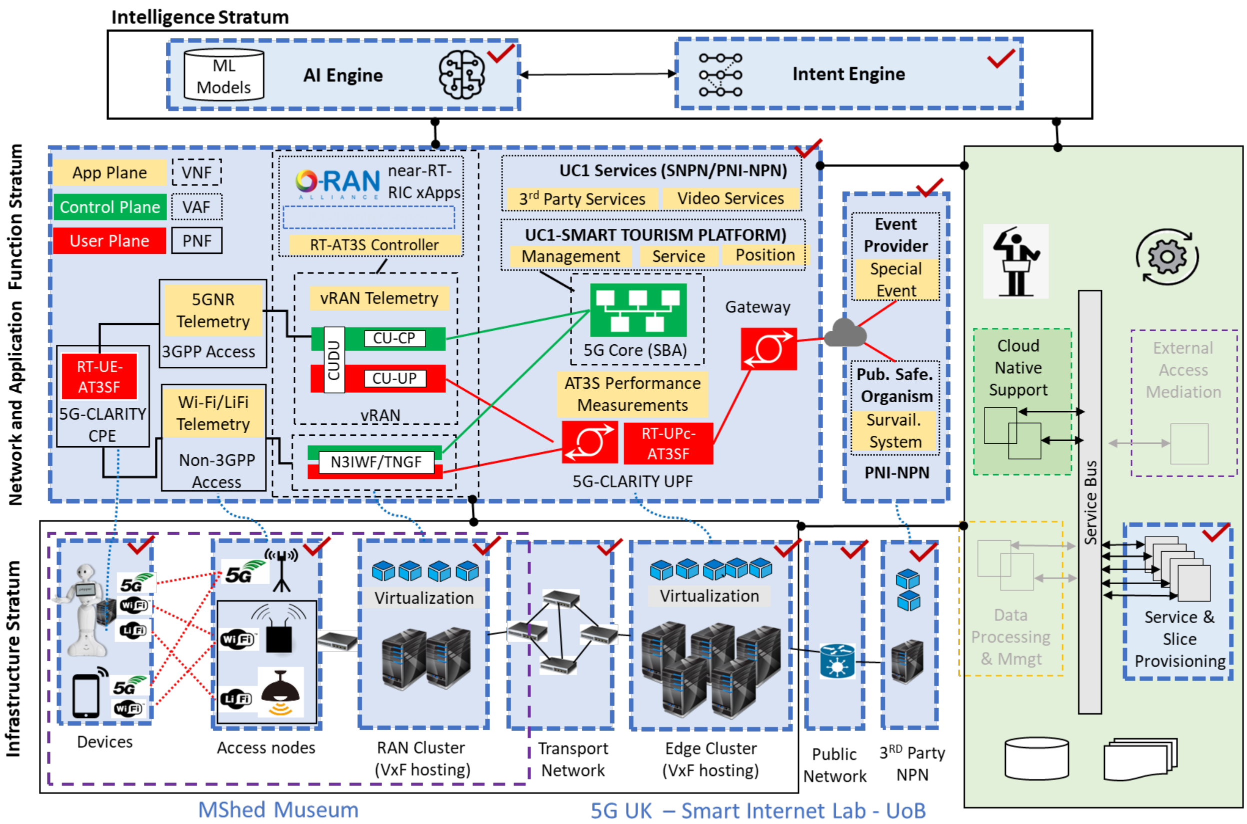


Figure 3-1. 5G-CLARITY system architecture to be used on UC1.

The UC-1 Pilot will deploy components enablers and components in the four strata. Figure 3-1 presents the 5G-CLARITY enablers to be used in the UC1 pilots developed and integrated in WP3 and WP4.

Next, we discuss in detail the WP4 and WP3 components that support UC1.

3.3.1 5G-CLARITY Components Integration Developed in WP4

The WP4 [5] were focused on the 5G-CLARITY Intelligence Stratum and Management and Orchestration Stratum components. To demonstrate UC1 the following components from WP4 were integrated with the ones from WP3 for preliminary validation in laboratory environment:

- 5G-CLARITY Intelligence stratum enablers will be mainly demonstrated in the UC-1 Pilot through the UC-1 Narrative 2, focusing mainly on the interaction between the Intent Engine and AI engine to deploy a ML model based on OpenCV to enable intelligent image recognition services in support of public safety officers and organizations.

- 5G-CLARITY Management & Orchestration stratum enablers to be deployed and demonstrated through the two UC-1 narratives are: Network Function Virtualization Orchestrator (NFVO) based on OSM R11, Virtual Infrastructure Management (VIM) controller and Software Defined Network (SDN) Controller, and the 5G-CLARITY Slice Manager.

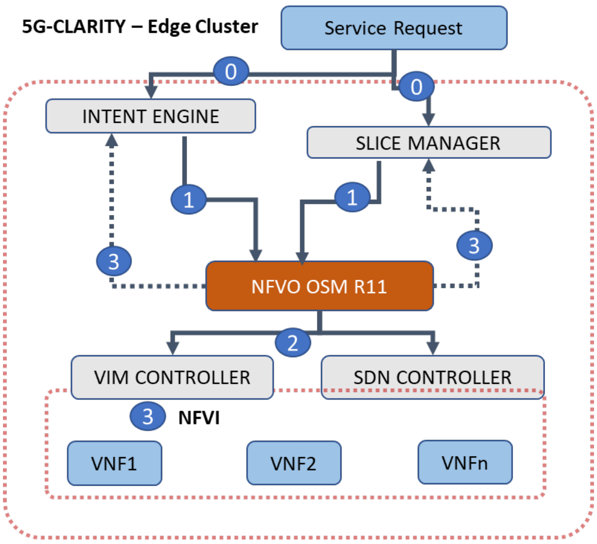


Figure 3-2. Management and Orchestration Stratum Flows.

5G-CLARITY UC-1 Pilot will combine Intelligence, Management & Orchestration strata to demonstrate two service delivery models for either Standalone Non-Public Networks (SNPN) and Public Network Integrated Non-Public Networks (PNI-NPN) enabling 5G-CLARITY framework, namely the NFVIaaS and SlaaS service delivery models. In Figure 3-2, we describe the two service delivery models to be demonstrated in the UC-1 Pilot:

- **Network Function Virtualization Infrastructure-as-a-Service (NFVIaaS)** mainly to be demonstrated in the UC1 Narrative 1 to support the addition of third-party contents in a SNPN deployment for a Smart Tourism solution. The NFVIaaS delivery model will work as follow:
    - **Step 0**: intent is submitted to the Intent Engine.
    - **Step 1**: Intent Engine generated a request to the NFVO OSM R11 to instantiate the Network Services representing one or more virtual network function (VNF).
    - **Step 2**: NFVO OSM R11 receives sends VNFs instantiation requests to the VIM Controller and SDN Controllers.
    - **Step 3**: NFVO confirms the instantiation of the VNFs replying to the Intent Engine, after the VNF1 … VNFn are instantiated.
- **Slice as-a-service (SLaaS)**, to provide Infrastructure slices the Slice Manager is included in the Step 1 to work in combination with the NFVO OSM 11 in order to enable VNFs as part of Slices as well as the slicing of Multi-WAT resources as introduced in D4.3 (Section 6.2.2).

3.3.2 5G-CLARITY Components Integration Developed in WP3

WP3 [4] focused on the 5G-CLARITY Multi-WAT and Multi-Connectivity solutions and Network and Application function stratum. To demonstrate UC1 the following components from WP3 were integrated and validated in laboratory environment to prepare the final demonstration. Several components were already validated in D3.3. Enablers of the 5G-CLARITY Network and Application Function stratum are shown in the UC-

1 pilot detailed in Figure 3-1. It includes the virtualized network and application functions required to host enablers from 5G-CLARITY Intelligence, Management, and Orchestration strata. The main enablers developed and integrated in WP3 are:

5G-CLARITY CPE integrated with MPTCP implementation for multi-connectivity: This device has been designed, built, and deployed at the experimental lab setup in Bristol. Several tests have been performed on the Testbed using the 5G-CLARITY CPE for the initial validation of 5G-CLARITY KPIs. The 5G-CLARITY CPE is built using a Single Board Computer (SBC) running on Linux Ubuntu 20.04. It has provision for wireless access technologies – two SIM slots for 5GNR, a WiFi-6 modem, and multiple USB ports for LiFi dongles. Details of the CPE has been reported in D3.3 [4]. To better understand how different versions of the 5G-CLARITY CPE would perform in a similar scenario, we have recently designed, built, and tested low power version of the CPE using Raspberry Pi. Analysis from results of the testing would be discussed in subsequent deliverable. Figure 3-3 shows the two versions of the 5G-CLARITY UC1 CPE to be used in the setup one for the guide robot and another for the infrastructure cameras.

5G-CLARITY Multi-WAT Access Nodes: The main access technologies of the 5G-CLARITY UC1 testbed, deployed and tested in the Smart Internet Lab for the final UC1 demonstration at M-Shed are:

5G-CLARITY 5G RAN solution

- **(Accelleran Radio)** Band 77, 100 MHz BW, MIMO 4(Rx) x 2(Rx)
- Subcarrier spacing: 30 KHz

5G-CLARITY WiFi-6 solution

- 2x RUCKUS R850 APs
- Wi-Fi Interface Standard: IEEE 802.11a/b/g/n/ac/ax
- Channel width: 80 MHz

5G-CLARITY LiFi PLF Solution:

- 2x Pure LiFi APs
- 1x USB Dongle

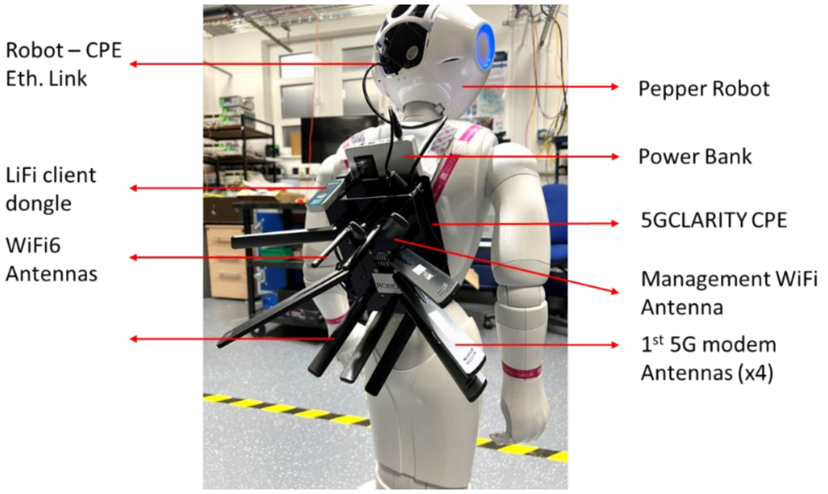


Figure 3-3. Guide Robot with 5G-CLARITY CPE.

Enablers of the infrastructure stratum to be demonstrated in the UC-1 Pilot includes all the on-premises hardware and software resources building up the 5G-CLARITY strata, including user equipment and a wide variety of compute, storage, and networking fabric. Key enablers from the infrastructure stratum deployed for the UC1 demonstration are:

5G-CLARITY RAN Cluster: The segment supports the hosting of virtualized functions and applications from the different 5G-CLARITY system strata and providing an NFV infrastructure environment for their execution. The RAN cluster hosts 5G access nodes such as gNB-CU, DU, and RIC With respect to UC1, the RAN cluster is to host virtualised RAN functions to be deployed at the M-Shed museum Bristol, which is the venue for the final demonstration of UC-1.

5G-CLARITY Edge Cluster: This is the other main location for supporting UC1 demonstration. The location holds some core functions of the 5G-CLARITY strata such as 5GC, NFVO, the network's edge resources, BBU and 10G switch. A fibre link measuring hundreds of meters connects this location to the Activity Zone at M-Shed. Previous deliverable documents D3.1 [8] and D5.1 [2] have reported in detail the functionality which the Edge cluster supports.

Private Gateway (or Gateway): hosted in the Edge cluster to enable connectivity with external resources such as PLMN resources or hyperscale's resources or data and control plane traffic. This is an essential component of 5G-CLARITY solution to connect E2E infrastructure slice of the NPN to external services or NPNs and realize PNI NPN demonstration of the UC-1 Narrative 2.

3.4 5G-CLARITY UC-1- Smart Tourism Framework and Additional Services

In D5.1 [2] we introduced the Smart Tourisms Framework and additional services or content to be used to demonstrate the 5G-CLARITY solution. The framework is developed to connect and control the guide robot, key component in the realization of the two UC-1 Narratives and for enabling the Human and Robot Interaction focus of UC-1. Figure 3-4 summarizes the 5G-CLARITY UC-1 Smart Tourism Framework and services and components associated. In this figure we introduce pictures collected from real lab testing of the first release of the framework.

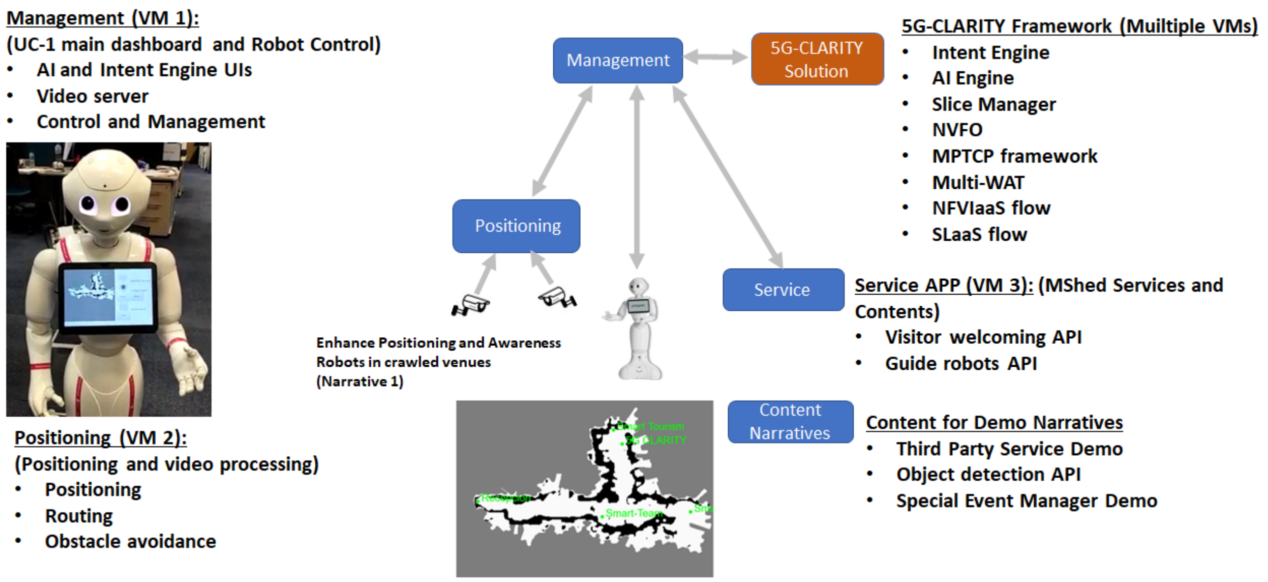


Figure 3-4. UC1-Smart Tourism Framework Components.

In Figure 3-4 we introduce the main application of the UC-1 Smart Tourism Framework composed by three VMs or VNFs hosted in the 5G-CLARITY Edge cluster (Smart Internet Lab).

- **VM1 Management**: Is the most important component of the 5G-CLARITY UC-1 Smart tourism framework and demonstration. It hosts the UC-1 Dashboard running the "UC-1 Panel" API (Figure 3-5 (2)) for managing, controlling, and operating the guide robot (positioning and services) and 5G-CLARITY Framework including the Intent Engine and AI Engine functions.
- **VM2 Positioning**: The second most important element of the framework, which controls the positioning, routing and obstacle detection and avoidance of the guide robot in the crowded event ("Robot_Guide" API - Figure 3-5 (3)). The positioning APIs will exploit the benefits of 5G-CLARITY Multi-Connectivity solution to maintain seamless connectivity to the Guide Robot and Cameras to support management, control, and robot and human interaction in a crowded environment.

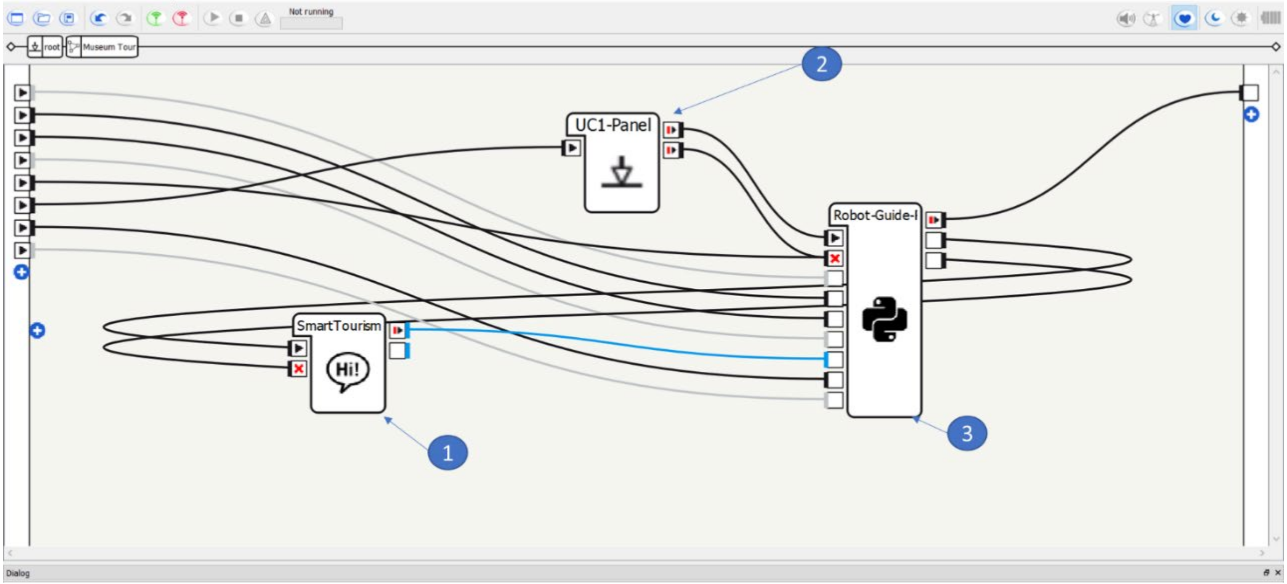


Figure 3-5. First Release of UC1-Smart Tourism Framework APIs written in Python 2.6 and C++ and deployed on IDE-Choreographe 2.5.

Table 3-1. Robot Guide API functions.

Function	Description	Input	Source	Process at the Edge	Output	KPIs
Visitor ()	Detect human approaching the reception and / or requesting support.	(1) Voice (2) Image	(1) Robot Microphone. (2) Cameras (Robot/Inf.)	(1) Speech (NLP) (2) Image (OpenCV)	Visitor = True Run" Welcome Visitor = False Run "general content"	
Welcome ()	Welcome and introduce M-Shed and main guidance	Voice	Robot Mic	Speech (NLP)	Robot speech: "Introduction to M-Shed and Guidance" Run: "Request()"	
Request ()	Process visitor requests	Request Service	Welcome API	Matching Service	Run: "Positioning()" Service: "Guide" Target name (Tn): "Exposition X"	

- **VM3 Services:** It hosts the Smart Tourism API (Figure 3-5 (1)) which enable the robot and human interaction by detecting, welcoming, and processing the request of visitors arriving to M-Shed. The services provided are supported by pre-trained AI functions (e.g., NLP and voice recognition) running at the edge. Table 3-2 list the functionalities enabled by the Smart Tourism API.

Table 3-2. Smart Tourism API functions.

Function	Description	Input	Source	Process at the Edge	Output	KPIs

positioning ()	Update the position of the Guide Robot in the Map.	*Image* *Landmark*	*Robot Cameras* *External Cameras*	Guide Robot Position in the map.	Guide Robot position, P (X ,W, Z) in the map of the venue	Control Latency (Sec)
routing ()	Calculate and Recalculate Route of the Guide Robot from position P to target Tn in the Map	*Guide Robot position P coordinates (X, Y, Z).* *Target name, Tn (String).* *Venue Map*	*positioning()* *request()* *obstacle()*	Target position T *(X_d, Y_d, Z_d).* *Update Venue Map* *Shortest walking (W_{pt})* from *P* to *T*.	Walking path (W_{pt}) for Guide Robot Run: *obstacle()*	Target detection time (Sec) Control Latency (Sec)
obstacle()	Detect obstacle and correct Walking Path (*W_{pt})*	*Image* *Guide Robot Position* *Active Walking Path (W_{pt})*	*External Cameras* *Robot Cameras* *routing() outputs* *positioning() outputs*	Detect obstacle or congestion in Active Robot Walkings (W_{pt}) paths If obstacle = "True" => Update Venue Map	*If obstacle = "True"* => Run: *"positioning()" to update robot position and* "routing()" to avoid obstacles.	Re-routing time (Sec)

The following additional components complement the Smart Tourism framework to provide the functionality required in UC-1:

- **Content Narratives (Application Functions):** To enable demonstration of UC-1 narrative 2 deployment of special functions to be deployed in a single VM and/or one or multiples VNFs.
- **User equipment (UE):** Multi-connectivity enabled mobile phone with 5G and Wi-Fi (and Li-fi if is available).
- **Infrastructure Cameras:** as described on D5.1 [2] multiple infrastructure cameras will be connected to the VM2 Positioning to provide seamless positioning, routing and obstacle avoidance to a remote controlled Guide Robot in a crowded event.

Figure 3-6 introduces the proposed connectivity setup required by the UC-1 Smart Tourisms Framework to demonstrate the benefits of 5G-CLARITY solution. We note that the Edge cluster hosting the Smart Tourism and the Content Narrative VMs will be hosted in the University of Bristol laboratory, whereas the RAN cluster, UEs and cameras will be placed in the M-Shed museum.

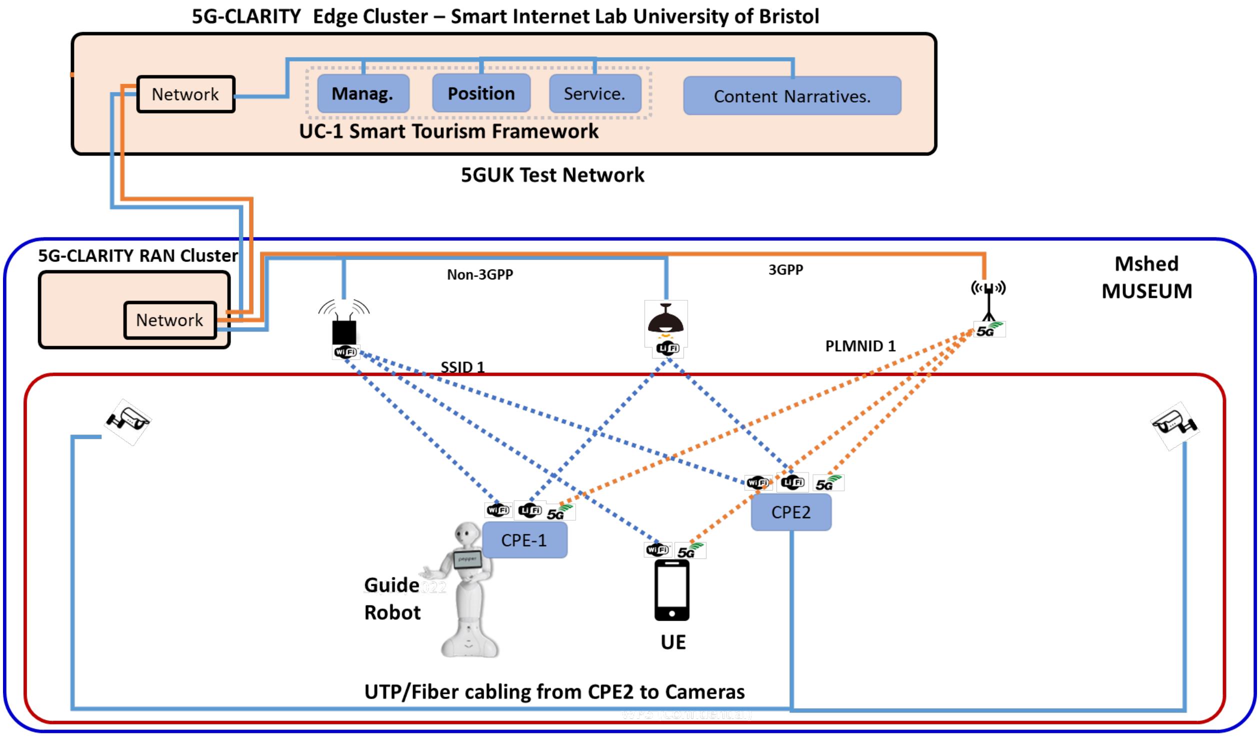


Figure 3-6. Proposed 5G-CLARITY UC1-Pilot Network Setup M-Shed.

3.5 5G-CLARITY UC1 Pilot Setup

In this section, we report based on the 5G-CLARITY architecture, the components that have been deployed on for the 5G-CLARITY Pilot hosted at Smart Internet Lab.

To support the different narratives, two different 5G-CLARITY infrastructure slices (defined in WP4) will be provisioned. In the following sections we described each narrative and their corresponding slice.

3.5.1 Narrative 1 - SNPN with Enhanced Communication and NVFIaaS for Support Smart Tourism.

Narrative 1 will demonstrate the benefits of the 5G-CLARITY Solution to enhance the Human and Robot Interaction and enhance NVFIaaS in SNPN setup. The main technological enablers of 5G-CLARITY solution to be demonstrated and validated are the multi-WAT seamless connectivity: 3GPP and non-3GPP data traffic support for Fronthaul and Backhaul traffic to enhance the control, positioning, and movement of Guide Robot in crowded venues. As well as use the 5G-CLARITY Management and Orchestration framework to allow easy-to-use NFVIaaS support in a SNPN to allow Smart Tourism contents (e.g., exposition). In Figure 3-7 we present the infrastructure slices to support Smart-Tourism framework and contents using NFVIaaS in a SNPN.

3.5.1.1 Infrastructure Slice 1

The 5G-CLARITY Infrastructure Slice 1 for Narrative 1 described in Figure 3-7 enables isolation of user, control, and application plane functions for the standalone Non-Public Network (SNPN), including:

- *Compute Chunk 1.1* enable multi-WAT control and user plane functions, e.g., AMF, UGR, SNF, and N3WF. The *Compute Chunk 1.1* exchanges traffic of the control and user planes, with 3GPP RAN fronthaul through the VLAN 12 providing a virtual link to interconnect with 5G-CLARITY RAN cluster, and with Non3GPP RAN fronthaul through the VLAN 20 connecting virtual link to the LiFi access nodes and through the VLAN 30 connecting a virtual link to the Wi-Fi access nodes.

- *Compute Chunk 1.2* dedicated to the *Smart Tourism Framework* e.g., *Management (MAN)*, *Services (MUS) and Positioning (P&R)* and NFVIaaS. The *Compute Chunk 1.2* exchanges traffic of Smart Tourism Framework with the Guide Robot and infrastructure cameras using the VLAN11 connecting the UPF with the 5G-CLARITY RAN cluster for 3GPP user plane and control traffic and the VLAN 21 for non-3GPP user plane traffic to the Computer Chunk 1.1. At the same time UPF will connect the VLAN 22 available for the VNFs or Service Function Chains of third-party services to be a deployed as part of the NFVIaaS.

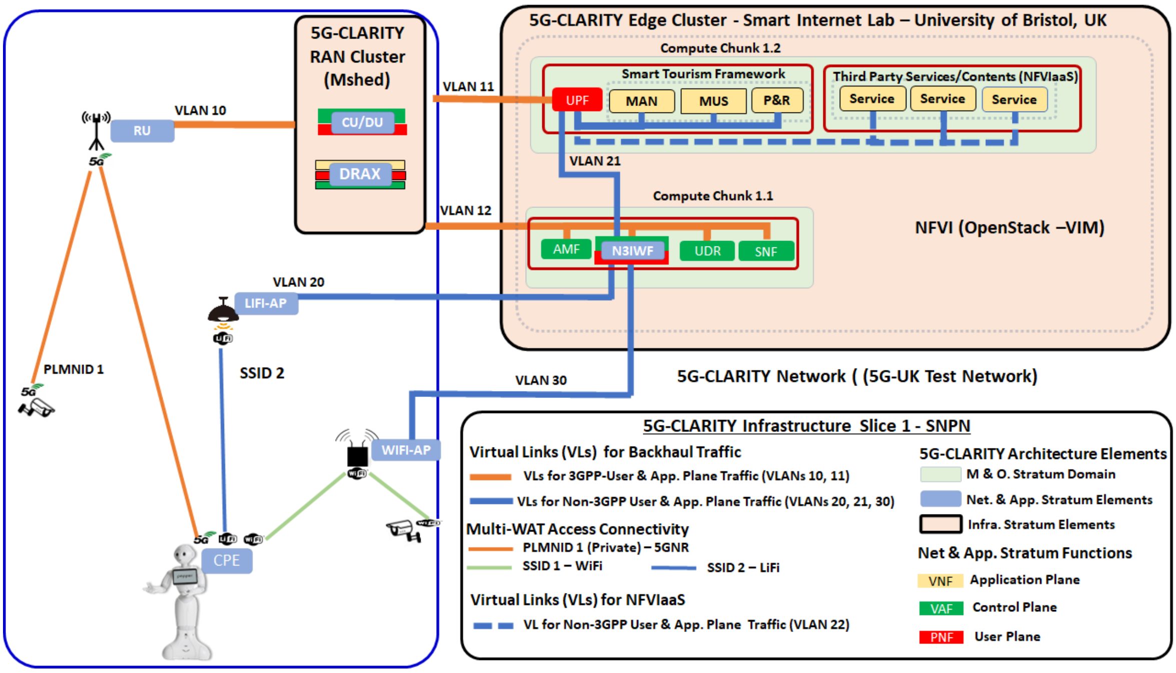


Figure 3-7. **5G-CLARITY SNPN Infrastructure Slice 1 with NFVIaaS for Narrative 1 demonstration.**

3.5.1.2 Demonstration in M-Shed

Figure 3-8 presents the tentative setup and flow of the UC1-Narrative 1 demonstration using the Infrastructure Slice 1.

The UC-1 Narrative 1 flow:

- Provision of Infrastructure Slice 1 between 5G-CLARITY Edge Cluster hosted in Smart Internet Lab and the 5G-CLARITY RAN Cluster and Access Nodes deployed in M-Shed.
- Initializes Smart Tourism Framework initializes the Guide Robot (Figure 3-8 (A)) by setting its position Fig 3-8 (B)).
- Guide Robot is In Reception interacting with visitors (Figure 3-8 (A)).
- Visitor follows the Guide Robot to the Bristol People Exposition (Figure 3-8 (C)).
- 5G-CLARITY CPE Performs Multi-WAT handover and KPI validations (Figure 3-8 (C and D)).
- A third-party organization request by logging and submitting an Intent into the Intent Engine for deploying a VNF as part of the NFVIaaS to run an interactive content in the Tablet of the Guide Robot.
- The Intent Engine requests the NFVO to deploy a VNF to connect the Guide Robot Tablet to an Interactive Web Content.
- The NFVO deploys the VNF and setup connection with the Guide Robot Tablet.
- Guide Robot stops in the requested exposition and deliver the exposition to the Visitor including the content from the VNF deployed in the NFVI (Figure 3-8 (D)).

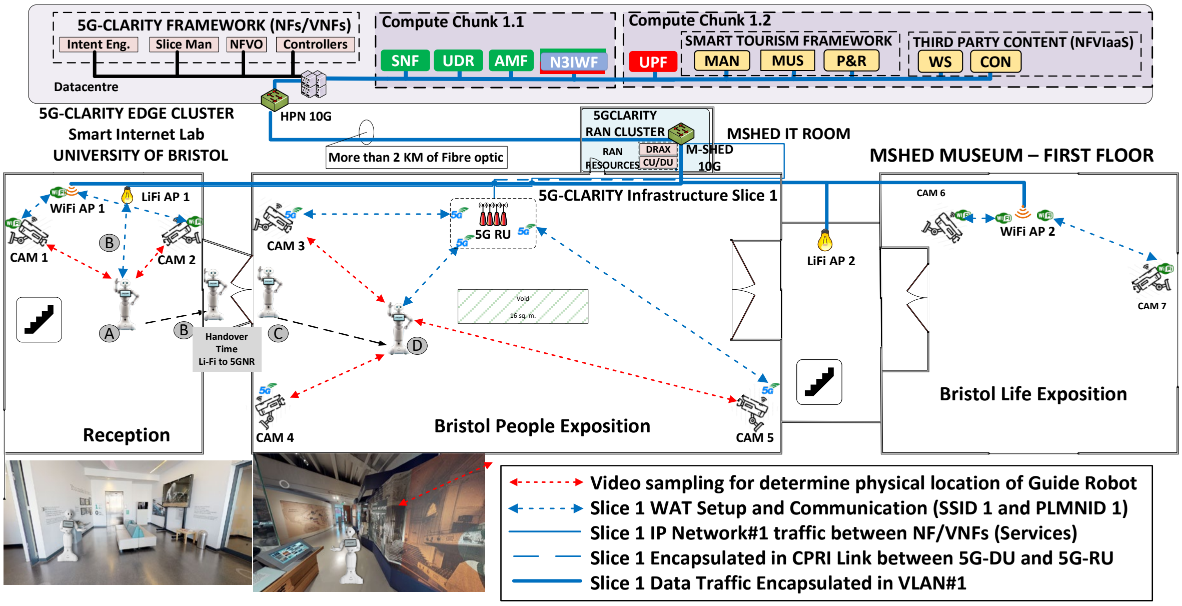


Figure 3-8. 5G-CLARITY UC-1 Narrative 1 setup and flow for M-Shed Museum.

3.5.2 Narrative 2 - PNI-NPN with Intent Based, Enhanced Communication and SLaaS

UC-1-Narrative 2 demonstrates the benefits of 5G-CLARITY solutions for on-demand and dedicated Public Safety Surveillance as extension of the UC-1 Narrative 1 demonstration by adding an Intent-driven Slice-as-a-Service (SLaaS) capability for provisioning the PNI-NPN-enabled Infrastructure Slice 2 to connect the Guide Robot Cameras (top and bottom), the Infrastructure Cameras with a User Equipment (UE) of the Public Safety Officer and a and external Public Safety Organization and a MNO network (as PNI-NPN examples). The Infrastructure Slice 2 will also demonstrate the benefits of the 5G-CLARITY Multi-Connectivity framework to provide Seamless and Interactive multiple Video Surveillance with object detection.

3.5.2.1 Infrastructure Slice2 for PNI-NPN

The planned Infrastructure Slice 2 is introduced on Figure 3-9. The Public Safety Surveillance requires dedicate virtual links and RAN functions to isolate control, user, and application plane traffic (e.g., Video Streaming). Hence, the Infrastructure Slice 2 uses the *Compute Chunk 2.1* as NSO2 to instantiate isolated or dedicate control and user plane functions for 3GPP and non-3GPP RAN to enable the PLMNID 2 and SSID 2 (MNO) only available in the UE for Public Safety Officers member of the Public Safety Agency and MNO. Then it uses the *Compute Chunk 2.2* to instantiate the application plane *VNF "CamSur"* to run a centralized *Video Server* with AI-based image processing capabilities, and user plane functions including the *Private Gateway (GW)* adding PNI-NPN capabilities into the Infrastructure Slice 2. The GW setups a VPN connection to another GW of the NPN or a Cloud Server managed by the Public Safety Entity and connect to an MNO control plane. The Infrastructure Slice 2 isolates surveillance traffic by using dedicated VLANs for connecting Compute Chunks, multiple WAT access nodes and external organizations.

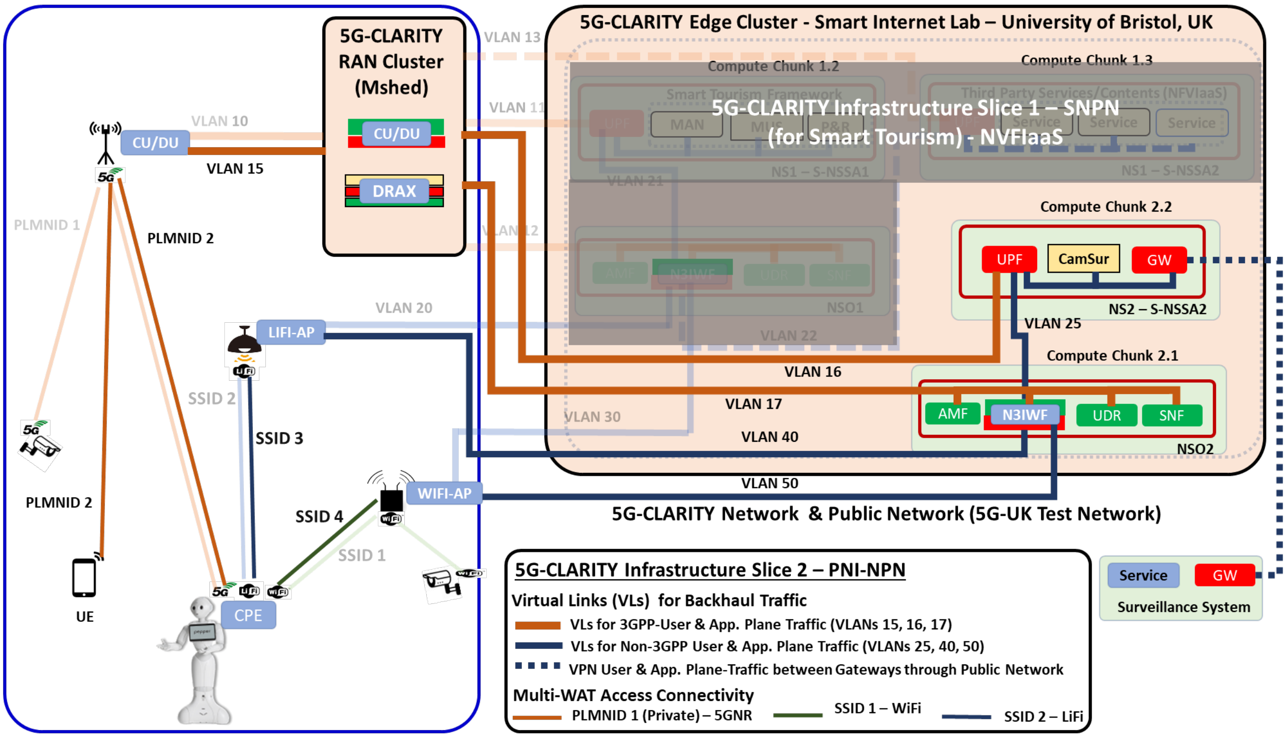


Figure 3-9. 5G-CLARITY PNI-NPN Infrastructure Slice 2 with SlaaS for Narrative 2 demonstration.

The *Compute Chunk 2.1* exchanges traffic of the control and user planes, with 3GPP RAN fronthaul through the VLAN 17 providing a virtual link connected to the 5G-CLARITY RAN cluster to enable access for UEs with SIM card configured with the PLMNID 2, and with Non3GPP RAN fronthaul through the VLAN 40 connecting a virtual link to the LiFi access nodes (only for the SSID 3) and through the VLAN 50 connecting a virtual link to the Wi-Fi access nodes (only for the SSID 4). The *Compute Chunk 2.1* interchanges Video Streaming for production or/and broadcasting with *Compute Chunk 2.2* using VLAN 25.

The *Compute Chunk 2.2* exchanges traffic of Video Streaming, produced from multiple sources including the Guide Robot and Infrastructure Cameras and Broadcasted to the UE of the Public Safety Officer. When the Guide Robot and Infrastructure Cameras are connected to the 3GPP RAN fronthaul, they use VLAN 15 to connect the 5G-CLARITY RAN cluster with the Backhaul Because the Video Streaming came from multiple sources it uses Non-3GPP RAN application plane traffic through VLAN 40 when the Video Streaming is produced and/or broadcasted while Guide Robot and/or UE of the Public Safety Officer and/or an Infrastructure Camera requires a connection to the LiFi fronthaul. Similarly, when the Video Streaming is produced and/or broadcasted in the domain of the Wi-Fi access nodes (using or not-using multi-WAT aggregation). The *Compute Chunk 2.2* interchanges Video Streaming produced and processed in the Video Server hosted in CamSur by connecting the private GW with the Public Safety Entity GW through public network.

3.5.2.2 Demonstration in M-Shed

Figure 3-10 presents the tentative setup and flow of the UC1-Narrative 2 demonstration using the Infrastructure Slice 2 described in the Figure 3-9.

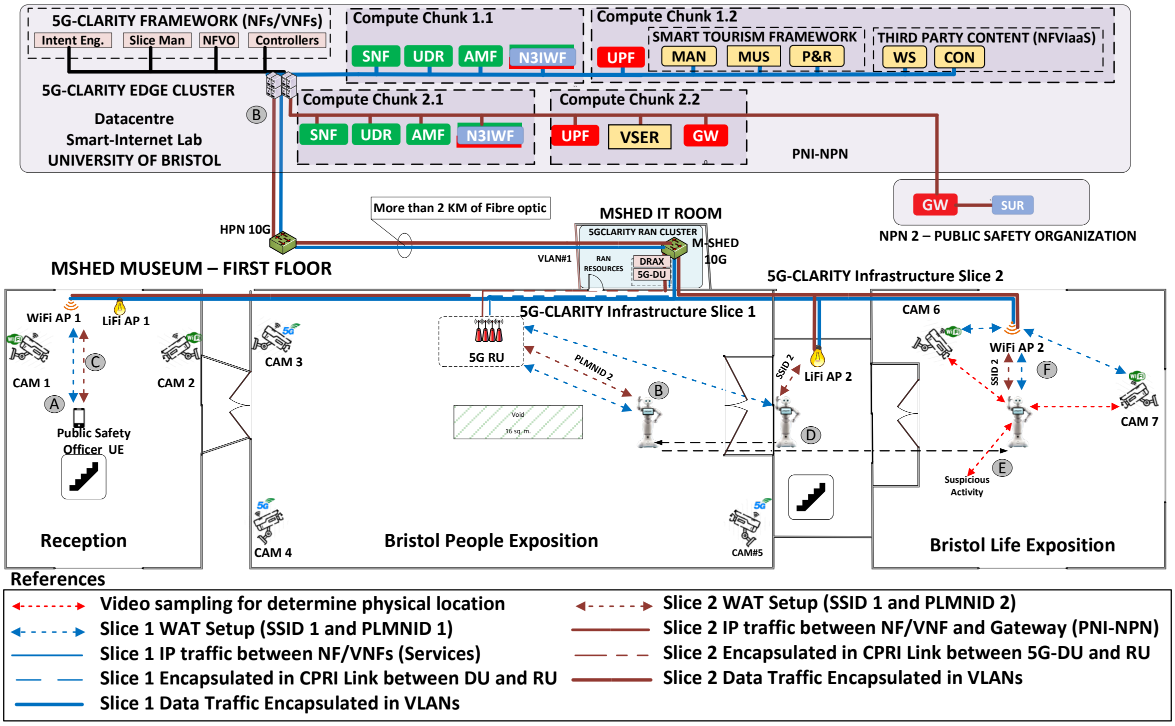


Figure 3-10. 5G-CLARITY UC-1 Narrative 2 setup and flow for M-Shed Museum.

Tentative UC-1 Narrative 2 Demonstration flow:

- *Public Safety Officer* arrives to the *M-Shed Reception Hall* and Connects her/his UE to the Wi-Fi AP1 as guest user using the Infrastructure Slice 1.
- *After logging* submit an Intent to the Intent Engine requesting dedicated Surveillance for Suspicious Activities (Figure 3-10 (A)).
- *Intent Engine* requests and the provisioning of the 5G-CLARITY Infrastructure Slice 2 as SLaaS, to setup PNI-NPN connection to the Public Safety Organization.
- While the *Guide Robot* is walking with visitors in *Bristol People Exposition Hall* the *Slice Manager* setups the Infrastructure Slice 2 (Figure 3-10 (B)) described on Figure 3-9 by provisioning the Computer Chunks 2.1 and 2.2 with all the control, user, and application plane functions (e.g., CamServ and requests the infrastructure controllers (e.g., Not-RT-RIC) the VLANs and RAN parameters.
- The created Infrastructure Slice 2 between 5G-CLARITY Edge Cluster hosted in Smart Internet Lab and the 5G-CLARITY RAN Cluster and Access Nodes deployed in M-Shed will connect the Public Safe Officer UE with the Guide Robot without interrupt its walking with visitors (Figure 3-10 (C)).
- 5G-CLARITY CPE Performs Multi-WAT handover and KPI validations (Figure 3-10 (D and E)).
- Suspicious activity is detected through the Guide Robot cameras as a result the Public Safety Officer Requests to the Smart Tourism framework the Guide Robot Position and more images (Figure 3-10 (E and F)).
- KPIs are measured during the process.

3.6 UC1 Lab Setup and Validation

In this section we describe the integration and preliminary validation of components developed in different work package part of the 5G-CLARITY UC1 Pilot.

3.6.1 UC1 Lab Environment

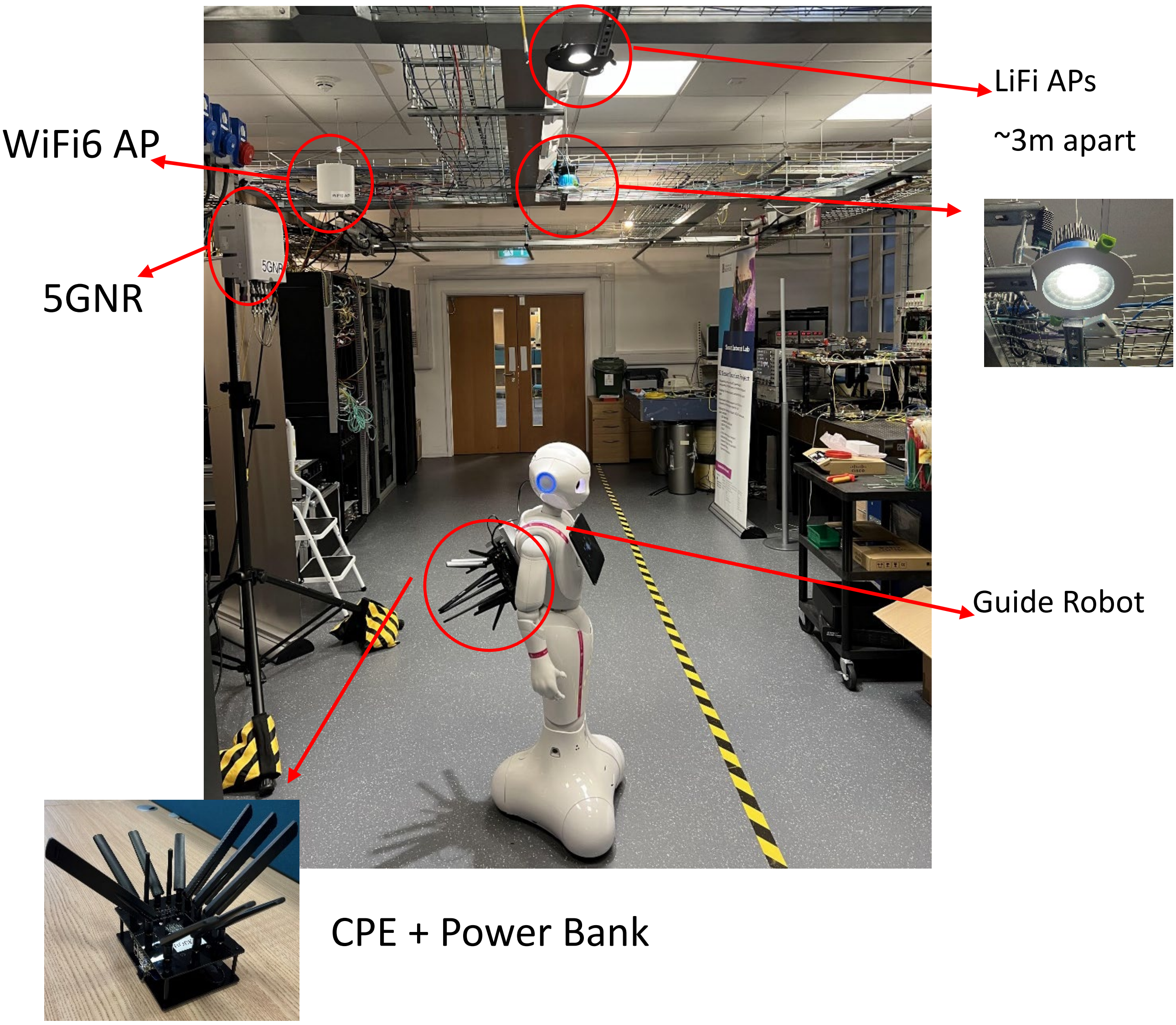
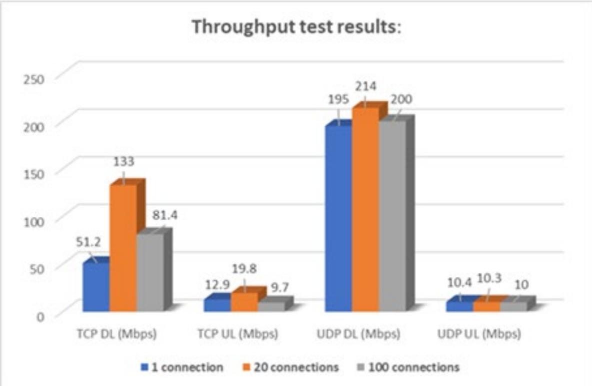


Figure 3-11. 5G-CLARITY UC-1 Lab Setup Smart Internet Lab.

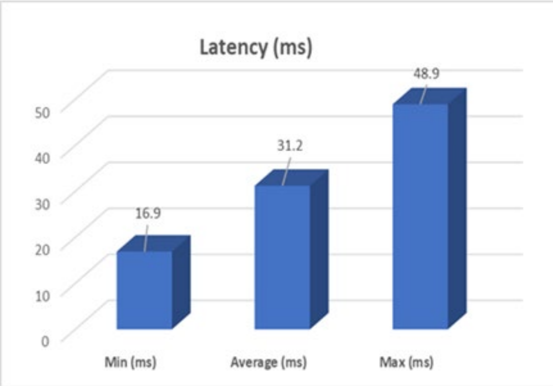
3.6.2 UC1 Lab Validation of transversal KPIs

We present ongoing testing results for latency and throughput using the integrated Accelleran 5GNR solution. The Accelleran 5G RAN is based on O-RAN solution, with conventional CU + DU configuration and currently deployed with 40 MHz bandwidth capacity at the Smart Internet Lab in Bristol. This is a proprietary solution that comes with a technology that is still maturing. The latency and throughput results reported here reflects the current state of the 5GNR solution and are only initial results of an ongoing testing. These results show the integration of the Accelleran solution to the 5G-CLARITY testbed in Bristol.

Figure 3-12 shows the throughput and Latency results from an ongoing test of 5GNR performance using the Accelleran 5GNR solution in the Lab environment. This is an individual test result for 5GNR. The curve displays the average measures after performing the experiment ten times with a round length of 60 seconds. The results show improvements in throughput and latency performance after Accelleran optimised the system. The test on the 5GNR link was performed using various parallel connections - 1, 20 and 100. The result indicates an optimum link performance at 20 parallel connections. Using 20 parallel connections, we achieved 214 Mbps UDP downlink. In the three parallel connections - 1, 20 and 100, UDP performed better than TCP in the DL. While this is expected, we believe the significant throughput performance difference of 82% on average between TCP and UDP is due to implementation issues within the radio stack, which would require support from the DU and RU vendors[1] to be debugged. After our initial throughput and latency testing, TCP measurements have shown reasonable improvements. In the UL, there is a mix performance between both protocols. Here, the average difference between TCP and UDP is much smaller across the parallel connections at 29%, which can be explained due to fluctuations in the wireless channel.



(a)



(b)

Figure 3-12. 5GNR test results for (a) Throughput and (b) Latency performance of the ORAN 5GNR system.

Regarding latency performance, we report only the performance with the ORAN gNB, as Wi-Fi and LiFi performance was already provided in D3.3. For the ORAN gNB we recorded an average latency of 31.2 ms running a ping with the network idle. These performance results were obtained using the 40 MHz bandwidth capacity of the 5GNR RAN solution. In Figure 3-13 we provide the DU specifications showing the TDD pattern, subcarrier spacing with the downlink and uplink slots and symbols. It specifies the new radio frequency band, bandwidth capacity and number of resource blocks.

```
"frequency_band_list": [
        {
          "nr_frequency_band": 77
        }
      ]
    },
    "transmission_bandwidth": {
      "bandwidth_mhz": 40,
      "scs_khz": 30,
      "nrb": 106
    },
    "pattern": {
      "periodicity_in_slots": 10,
      "downlink": {
        "slots": 7,
        "symbols": 6
      },
      "uplink": {
        "slots": 2,
        "symbols": 4
      }
    }
```

Figure 3-13. DU configurations showing TDD pattern.

[1] RU and DU vendors are not part of the 5G-CLARITY consortium

Table 3-3. Parameters in E2E test between CPE and MPTCP Proxy.

Parameter	Value
kernel.osrelease	5.5.0-mptcp
net.mptcp.mptcp_checksum	1
net.mptcp.mptcp_debug	0
net.mptcp.mptcp_enabled	0
net.mptcp.mptcp_path_manager	fullmesh
net.mptcp.mptcp_scheduler	round-robin
net.mptcp.mptcp_syn_retries	3

Combining the technologies mentioned above for the different access networks, using we achieved 931.69 Mbps aggregated throughput performance, which is close to the 5G-CLARITY KPI of 1 Gbps. Figure 3-14 presents the aggregated Download throughput result over 5GNR, WiFi-6 and LiFi with MPTCP in place, during a 4 minute experiment run. Table 3-3 depicts the MPTCP settings used in the experiment.

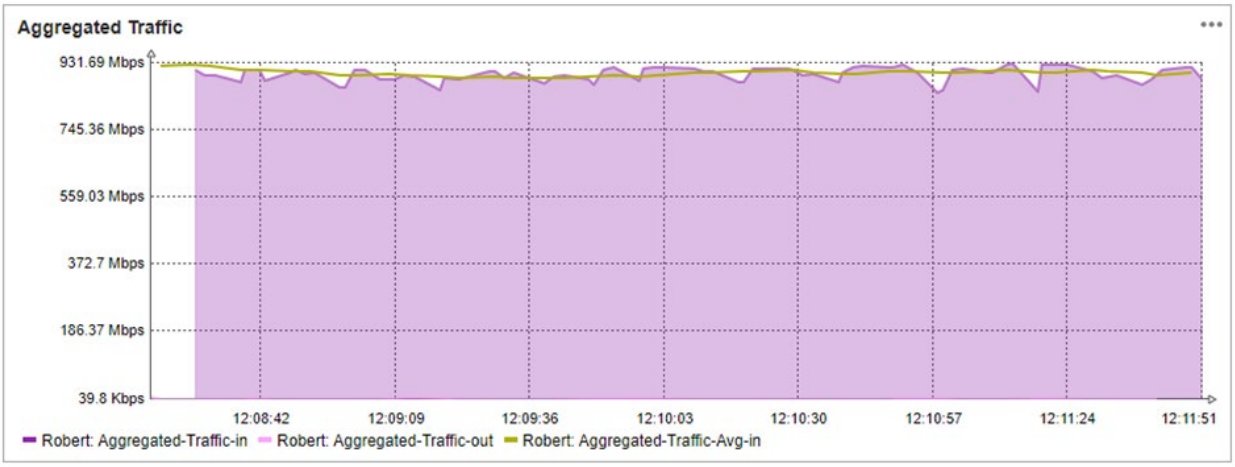


Figure 3-14. Aggregated Download Throughput over 5GNR, WiFi-6 and LiFi with MPTCP running.

Results from the different access networks reveals a weak 5GNR performance. During the aggregation test, the result of download throughput for 5GNR when MPTCP is in place reveals a peak performance of 73.08 Mbps as Figure 3-15 shows.

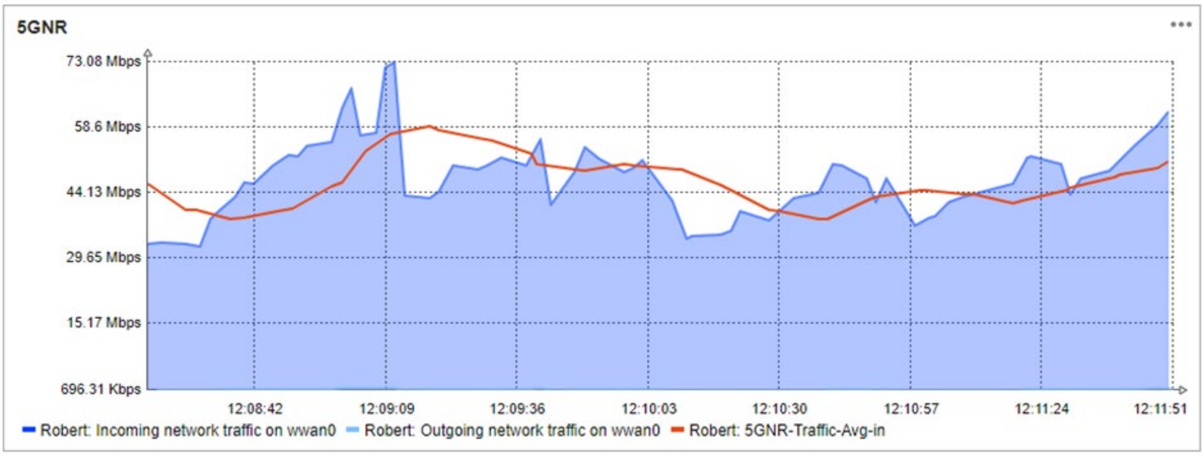


Figure 3-15. 5GNR download throughput with MPTCP running.

An overview of the entire results is presented in Figure 3-16. It illustrates the performance of all the access networks - Accelleran 5GNR, Ruckus WiFi-6 and PureLiFi access networks, throughout a 4 minute run. We have focused more on Accelleran 5GNR here as test results from Ruckus WiFi-6 and PureLiFi had been reported in previous deliverable report D3.3 [4].

Figure 3-16. An overview of Throughput results for all the access networks with MPTCP in place.

The use of 40 MHz bandwidth imposes limitation on the expected link performance as the results have re-vealed. With higher bandwidth capacity, we expect to achieve better link performance. We have expressed the risk associated with this situation and offered a mitigation plan in UC1 risk description in Sect. 3.8 of this document.

3.6.3 Validation of application level KPIs

The application KPI validation introduced in the D2.2 presents the baseline performance of the UC-1 framework without the 5G-CLARITY framework. This first set of results we obtained by implementing and testing *UC-1 - Narrative 1 - The guide robot serves visitors in the museum.*

Table 3-4. KPIs measurements for narrative 1 of UC1.

References	Name	KPI	Laboratory Measurement Strategy	Laboratory Results
FUNC-REQ-35 FUNC-UC1-04	Target recognition and path planning for specific task (robot)	Target recognition time < 1s	• *Measure the time seconds (s) between a target request is received and beginning of the routing.* • *Repeat the process multiple times to record the average, consistency, and robustness.*	Average 0.3 sec.
		Routing planning time < 1s	• *Measure the time in (s) between the beginning of process to plan the route and the start of the waking.* • *Repeat the process multiple times to record average, consistency, and robustness.*	Average. 0.5 sec.
FUNC-UC1-05:	Environment awareness and surveillance with cameras (robot)	Obstacle detection time < 1s	• *Add fixed obstacles in the route of the Guide Robot* • *Collect the images captured by cameras in Guide robot eyes.*	Average 0.7 sec.

			• *Measure the time between Guid robot is detecting the obstacles and update the route.* • *Repeat for multiple obstacles, moving obstacles and with cameras.* • *Record averages time, consistency, and robustness.*	
FUNC-REQ-34 FUNC-UC1-03	Computer vison-based positioning	Position accuracy < 10cm	• *After training the computer vision model for positioning the robot.* • *Mark each recorded reference with circles of 20 cm diameter.* • *Request a routing to each reference in multiple combinations.* • *Measure the matches and misses of the circle.* • *Calibrate if needed the computer vision accuracy and retest*	Average 9.5 cm
FUNC-REQ-30 FUNC-UC1-01	Multi-WAT connectivity: CPE/UE/Robot	TP > 100Mbps	• E2E data-rate bps (e.g., iperf).	Maximum 1.4 Gbps
		Switching Time < 1 second	• *Force Multi-WAT handover by reducing the signal of one WAT radio/AP* • *Measure the time required to switch from one WAT port to another using (e.g., ping, iperf, telemetry) in the CPE.* • *Repeat multiple time to record average, consistency, and robustness.*	No Collected
FUNC-REQ-38 FUNC-UC1-06	Edge-computing based video processing and analysis	Total processing time < 200ms (5fps)	• *Measure the time required to process one video contribution in 5fps (e.g., infrastructure cameras and or robot camera)* • *Record average and consistency.*	No Collected
FUNC-REQ-37 FUNC-UC1-07 TECH-UC1-04	Handover between private and public 5G networks	Handover time < 500ms	• *Create two slices Slice 1 - Local service working with Wi-FI and Slice 2 Third-party service with 5GNR.* • *Measure the time required to switch from Slice 1 to Slice 2.*	Average 350 ms *

3.7 UC1 – Overall Progress

The Accelleran 5G RAN solution has been integrated to the 5G-CLARITY testbed for UC1. This solution is expected to provide 5G access for the final 5G-CLARITY UC1 demonstration at the M-Shed museum in Bristol. Some pending tasks would be the UC1 venue demonstration setup, which is considered the next milestone. Some of the infrastructure to support the demonstration are already in place at the Smart Internet Lab University of Bristol as presented below.

In preparation for the final UC1 demonstration at the M-Shed museum in Bristol, the following key components have been configured and deployed:

- Network connectivity including fibre optic cables and switches at main locations are in place.
- Edge compute resources, VIMs and orchestrator are configured.
- 5G-CLARITY CPE designed, built, and deployed with MPTCP.
- 5G-CLARITY Test Lab for experimental setup – completed.
- Initial KPI validation performed and continues.
- Guide robot in place and application development in progress.
- Multiple cameras to connect robot in lab testbed – in place.
- Basic infrastructure support for final UC1 demonstration venue – in place.

The overall progress towards UC1 final demonstration is in line within the milestones set out in the 5G-CLARITY time plan. Associated risks and mitigation plan have been outlined in D5.1 [2].

3.8 UC1 demonstration Risk and Mitigation

The UC1 implementation risks and mitigation plan has been reported in detail in D5.1 document [2]. The software integration of the Accelleran 5GNR solution and results from ongoing testing presents a new risk which was not captured in the D5.1 report. As reported earlier in this section, the Accelleran 5GNR solution has an installed bandwidth capacity of 40 MHz. Results from the current state of the solution would not meet the 5G-CLARITY > 1 Gbps Throughput KPI requirement for the final demonstration. The 1.45 Gbps aggregated throughput validated during the Lab testing was achieved using a more matured technology with 100 MHz bandwidth capacity. Presented in Table 3-5 is a description of the risk and mitigation plan that was not captured in D5.1 as the situation had not presented itself at the time.

Table 3-5. Mitigation plan.

Risk ID	Description	Impact	Mitigation Plan
UC1-R1	Inability to achieve > 1 Gbps Throughput using the current 40 MHz Bandwidth capacity of the Accelleran 5GNR solution.	Low	• Narratives can be implemented with throughput performance not reaching 1 Gbps KPI expectation. • Seek Accelleran support to optimize the 5G Radio solution towards improving throughput performance. • Revert to the Nokia 5GNR solution with 100 MHz bandwidth capacity used during the initial Lab validation.

Risk ID	Description	Impact	Mitigation Plan
UC1-R2	Temporary wiring and fixing of cameras and prototype access points on walls and ceilings of the Museum's Exhibition Halls may be a challenge in seeking building manager's approval for the scale of this demonstration.	Low	• The implementation of the equipment for the use case in the Museum will be scaled to the level that can be approved by the museum's building manager demonstrating the technology. • The Access points and cameras will be installed on temporary tripods with temporary extension wiring back to the IT room within the Museum as the option to seek the building manager's approval for safe operation of this demonstration. Such wiring will be setup at start of the day and removed at the end of the trial.

4 UC2.1: Infrastructure slicing to support Industry 4.0 services

4.1 UC2.1 scope and project objectives addressed

In this section we describe the progress towards UC2.1 "5G-CLARITY *infrastructure slicing supporting Industry 4.0 services*", which will be demonstrated at the BOSCH factory at Aranjuez.

The first point to notice is that the scope of UC2.1 has been updated since D5.1 [2], where UC2.1 was referred to as "*Alternative Network to Exchange Production Data*". The rationale for changing the name of UC2.1 is that we have expanded the scope of UC2.1. Originally UC2.1 was restricted to validating the replacement of Ethernet based connectivity of production lines by a 5G-CLARITY wireless network using both a Standalone Non-Public Network (SNPN) slice and a Public-Network Integrated (PNI) NPN slice, thus the UC was referred to as "*Alternative Network to Exchange Production Data*". In this updated version of UC2.1 we have decided to dedicate the PNI-NPN slice to serve a different Industry 4.0 application to be demonstrated in Aranjuez, which will consist in a computer vision function used to detect obstacles encountered by an Automated Guided Vehicle (AGV) in the factory. To highlight the fact that this demonstrator consists now in two different services supported by different slices we have updated the UC2.1 title to "*5G-CLARITY infrastructure slicing supporting Industry 4.0 services*".

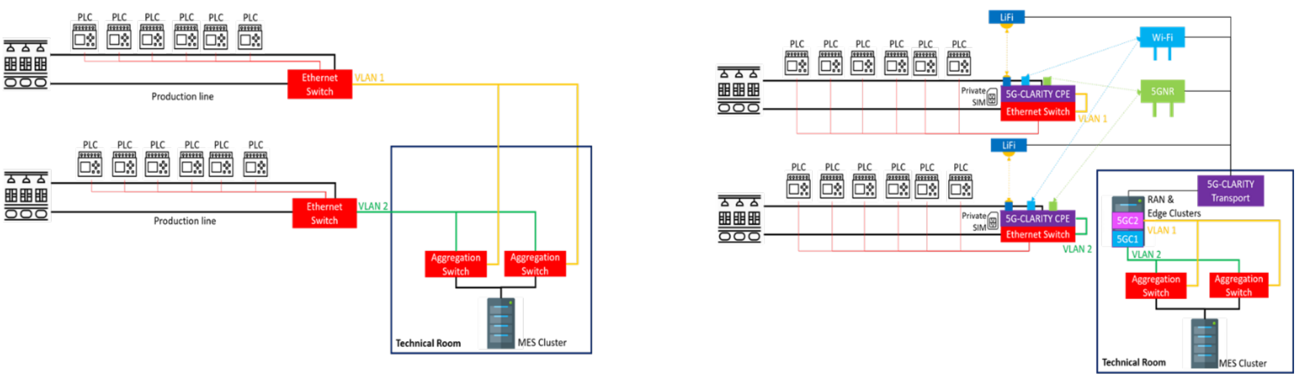
As mentioned above, each service will be supported by a dedicated 5G-CLARITY infrastructure slice. Thus, we hereafter use the following terminology:

- SNPN slice: Slice configured in the 5G-CLARITY private network deployed at Aranjuez used to support the Ethernet replacement service. This slice supports the service that in D5.1 was referred to as "*Alternative Network to Exchange Production Data*".
- PNI-NPN slice: Slice configured in the 5G-CLARITY private network to connect to a Mobile Network Operator (MNO), which in our case is Telefonica, to support the obstacle detection service that has been introduced in this deliverable.

In the next two sections we describe in detail the intended setup for these slices.

4.1.1 Standalone NPN (SNPN) slice

As described in D5.1 [2] the goal of the SNPN slice experiment is to evaluate whether the 5G-CLARITY network can be used to replace the current 100Mbps Ethernet based setup used to connect production lines to the MES server in the BOSCH factory in Aranjuez. Figure 4-1, extracted from D5.1, represents the current network topology (left) and the topology that 5G-CLARITY aims to validate (right).



Current setup

5G-CLARITY vision

Figure 4-1. SNPN slice vision.

The production line that will be used to support this service is depicted in the upper part of Figure 4-2. This production line is used to manufacture urea filters that are used to reduce polluting gases in diesel engines. As depicted in Figure 4-2, the production line is composed of six different working stations, St30 to St80, where each working station contributes to the production of the filter. A picture of the processed output (finalised urea filter) is included in the right part of Figure 4-2. Each working station in the production line is managed by a Programmable Logic Controller (PLC), which is coordinated by a centralized Manufacturing Execution Server (MES). The MES server, depicted in the lower part of Figure 4-2, acts as a controller of the production line, collecting the results of the outputs of each working station. For example, for station 40, the MES server records the temperature and power of the IR light used in the welding. This information is then correlated to the number of defect pieces observed in subsequent stages of the production line and is used to optimise the overall production efficiency. Hence, the connection between the production line and the MES server is critical and is currently implemented using Ethernet connecting each PLC to a head of line switch, which is then connected to the technical room, as depicted in Figure 4-1 (left).

A critical aspect to consider when executing this demonstrator is not to interfere with the production line, which in operational conditions is connected to the production MES server deployed in the Aranjuez plant. To this end, BOSCH has deployed a mock-up MES server to support the demonstration. However, the mock-up MES server has the limitation that it can only receive data sent by the PLCs but it cannot send commands down to the PLC. This is because the mock-up MES server is not authorized to interfere with a PLC used in production.

Considering these limitations, the SNPN slice experimentation has been designed in the following way. Given that the mock-up MES server supports only uplink traffic, we have decided to focus our evaluation on the uplink segment. Thus, the objective of the SNPN slice experiment is: "*to compare the uplink performance of the communication between the selected PLC and the mock-up MES server when using the standard Ethernet network deployed in the BOSCH factory and when using the 5G-CLARITY network*". The following methodology has been designed to achieve this goal:

- A dedicate toolkit to measure uplink performance of a network has been designed to support this use case. This toolkit is described in Subsection 4.3.3.
- The toolkit will first be used to measure uplink performance between PLC and MES server when using the production Ethernet network. This measurement campaign will last for 2 days.
- Then, the PLC will be disconnected from the Ethernet switch and connected to the 5G-CLARITY network, where the mock-up server is also connected (c.f. Figure 4-9). The uplink measurement toolkit will be used in this network again for 2 days to evaluate uplink performance over the 5G-CLARITY network.
- Performance over the two networks will be compared by post-processing the two obtained datasets.

In this deliverable we report the development and evaluation of the uplink measurement toolkit in a laboratory environment. Results in the production line will be reported in deliverable D5.3 [6].

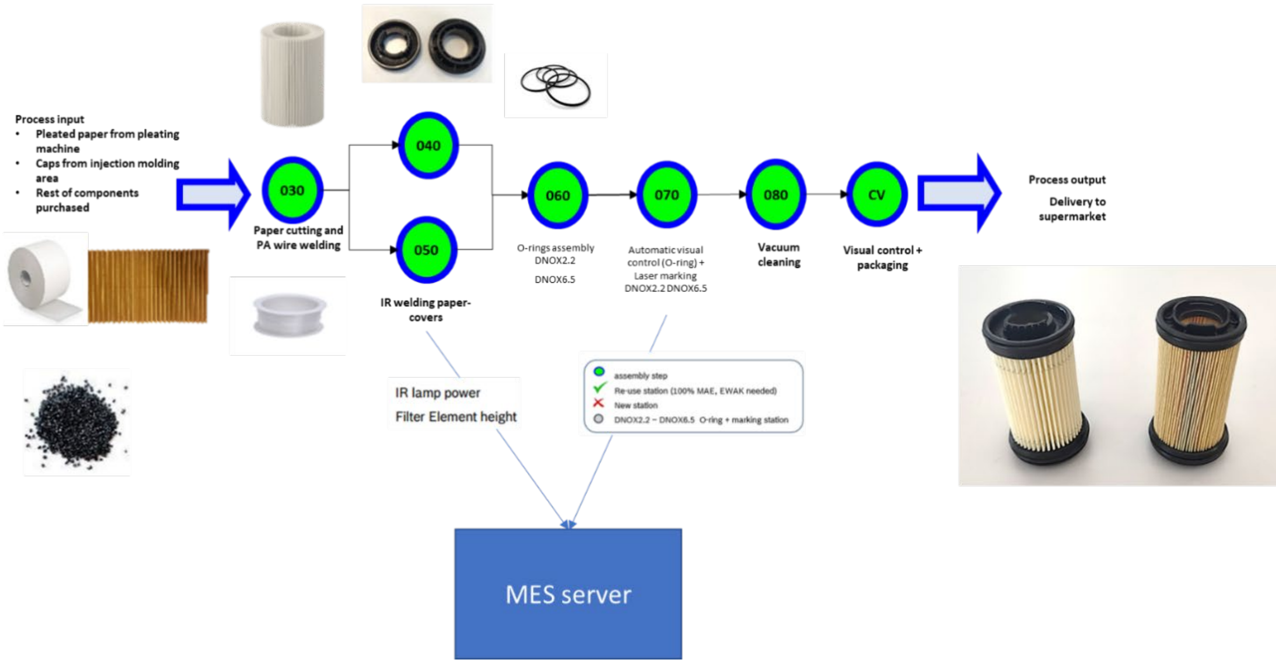


Figure 4-2. Target production line for UC2.1 and corresponding manufacturing process.

4.1.2 PNI-NPN slice

The PNI-NPN slice added to UC2.1 is used to enhance the functionality already provided by UC2.2. In a nutshell, UC2.2, described in detail in Sect. 5, provides a tracking system to accurately track the movement of AGVs inside the factory[2]. An outcome of this accurate tracking is to understand if the AGVs experience sudden stops during their journeys. However, the tracking system developed in UC2.2 can only identify that there has been a stop, but it cannot determine the reason for such stop, e.g., *did the AGV stop because a worker crossed the path of the AGV?* Or *some obstacles on the ground floor are blocking the path of the AGV?* Understanding the reason behind the unplanned stops of the AGV provides business intelligence to BOSCH that can be used to optimise the internal processes in the factory. Hence, the goal of the PNI-NPN slice is to deliver a service that allows BOSCH to understand what type of obstacle is blocking the path of the AGV when there is a stop. Figure 4-3 provides some examples of the type of obstacles that can be encountered by an AGV on the factory floor.

[2] Notice that in the current production system AGVs have autonomous navigation capabilities to go from point A to point B, but the actual trajectories taken by the AGV are not known to the BOSCH factory engineers.

Figure 4-3. Example obstacles that may be encountered by AGVs along their routes in the factory floor.

Another business aspect that is explored in the PNI-NPN slice is the collaboration between MNOs and Industry 4.0 agents to provide value added services for Industry 4.0. For example, services based on Machine Learning (ML) functionality, which may require significant computational requirements, could be offloaded from factories to Telco edge resources offered by MNOs.

Following the previous business aspects, Figure 4-4 provides a high-level design of the PNI-NPN slice, featuring the following elements:

i. A 5G-CLARITY CPE with a connected camera is mounted on the AGV. The camera will be used to take pictures of an obstacle, once the AGV is detected to have stopped. Notice that due to strict privacy regulations in the factory it is not possible to have a camera doing a continuous recording inside the factory. The tracking system developed in UC2.2 will be used to understand that the AGV has stopped and trigger a capture from the camera. The obtained image will then be transmitted to the obstacle detection function hosted at the Telco Edge domain to resolve the type of obstacle.

ii. The 5G-CLARITY edge cluster deployed at BOSCH will contain network functions to support the PNI-NPN slice, including a standalone 5GCore and an AT3S user plane function. Logical connectivity to the remote telco edge will be provided using a virtualized VPN network service added as part of the PNI-NPN slice. Physical connectivity to the Telco edge will be implemented using a cellular CPE, which will connect to the Internet through the public mobile network available outside the factory. This is again due to security restrictions inside the BOSCH factory in Aranjuez, which do not allow to provide Internet connectivity to the 5G-CLARITY infrastructure.

iii. The telco edge will be provided by TID through their 5TONIC infrastructure [21]. 5TONIC provides an ETSI NFV compliant NFVI, including an orchestrator based on OSM [22] and an OpenStack based VIM. This infrastructure will be used to deploy the obstacle detection function.

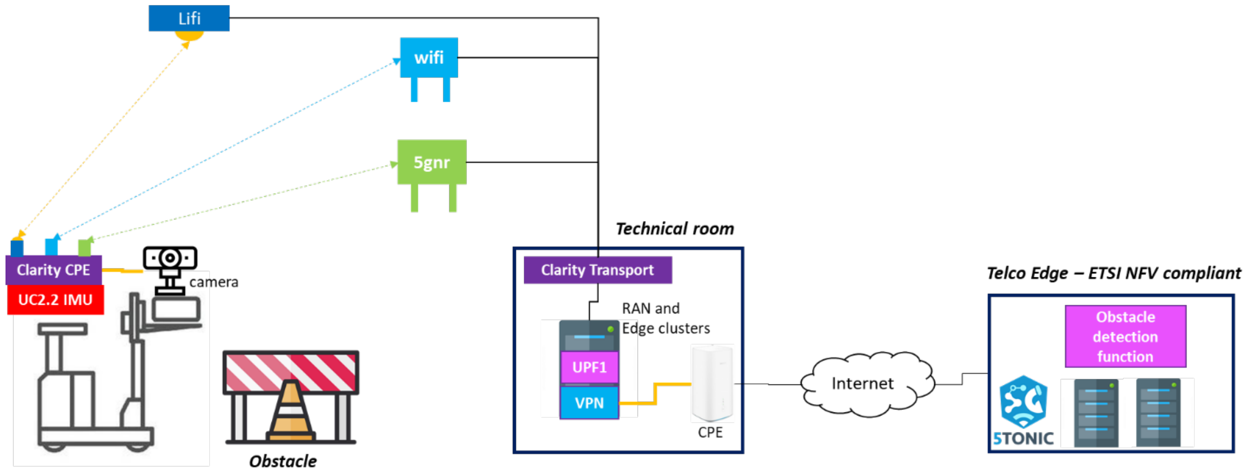


Figure 4-4 High-level design of PNI-NPN slice.

4.1.3 Update on UC2.1 related requirements

We provide in this section an update on the UC2.1 specific requirements that were originally identified in deliverable D2.1 [3]. We also identify new UC2.1 specific requirements that have appeared since our original definition of UC2.1 in D2.1. Table 4-1 captures these requirements, highlighting in the first and second column if the requirement was captured originally in D2.1, or if they have been added in D5.2. We also identify for each requirement if it refers to the SNPN or the PNI-NPN slice in the column "Slice".

We also would like to emphasize that the requirements listed in Table 4-1 are additional requirements imposed by UC2.1. These are therefore complementary to the general 5G-CLARITY requirements identified in [3], which need to be fulfilled by the 5G-CLARITY system. As described in Section 1.4 both transversal and UC-specific requirements will be validated in the BOSCH pilot.

Table 4-1. UC2.1 requirements

Original REQ ID[3]	Req. Source	Slice	Req Description	Status in D5.2
FUNC-UC2.1-01	D2.1	SNPN	Wireless production-line connectivity	In Section 4.4.1 of D5.2 we validate in the lab the connectivity between two external endpoints connected to the 5G-CLARITY network. These endpoints represent the MES server and the PLC that will be used in the BOSCH factory. In D5.3 [6] we will demonstrate connectivity with the real production line.
FUNC-UC2.1-02	D2.1	SNPN	Enhanced wireless connectivity for factory engineers (Wi-Fi)	This requirement is addressed by the laboratory testbed described in 4.2, which is based on the 5G-CLARITY multi-connectivity framework and allows unmodified Wi-Fi-only clients to access the 5G-CLARITY network as a regular Wi-Fi station. The testbed described in 4.2 is the same one that will be deployed in the BOSCH factory in D5.3.
FUNC-UC2.1-04	D2.1	PNI-NPN	Real-time connectivity (bidirectional) from the factory to outside world (Internet) - [private-public networks connectivity]	This requirement is addressed with the laboratory testbed KPIs described in 0 where the connectivity to the 5TONIC testbed is evaluated. 5TONIC is used as the testbed supporting the obstacle detection function in the PNI-NPN slice. In D5.3 this requirement will be evaluated from the BOSCH

[3] This is the requirement ID used in section 5 of D2.1.

				factory in Aranjuez.
FUNC-UC2.1-05	D2.1	PNI-NPN	Secure inter-factory (BOSCH factories in different locations) connectivity using slicing concept	Inter-factory connectivity is possible extending the PNI-NPN slice to multiple factories. A functional demonstration however has not been included in UC2.1, as BOSCH could only provide a single location to support this use case.
	D5.2	PNI-NPN	Accuracy of detection dataset	This requirement has been evaluated in Section 5.4.3 where the accuracy of the obstacle detection function is evaluated offline with different obstacles available in a dataset provided by BOSCH to train the obstacle detection function. In D5.3 accuracy will be evaluated using the real AGV when operating in production.
	D5.2	PNI-NPN	Time to detect obstacles below 1 minute	An initial evaluation of this KPI is available in Section 4.4.3. A complete evaluation will be carried out in the BOSCH factory and reported in D5.3 [6].
	D5.2	SNPN	UL one way delay between PLC and MES server equivalent or better than Ethernet	In Section 4.4.2 we demonstrate how the measurement toolkit that we have developed to measure UL one-way delay performs on our laboratory testbed. In D5.3 this obtained one-way delay through the 5G-CLARITY network will be compared to the delay obtained through Ethernet.

4.2 UC2.1 laboratory testbed

Figure 4-5 describes the 5G-CLARITY laboratory testbed that has been setup at i2CAT to support UC2.1. This testbed is self-contained and contains all the elements that will be deployed at the BOSCH factory in Aranjuez during the demo event. The testbed includes the following elements:

- 5G-CLARITY CPE: As described in Section 2.1.1.
- Multi-WAT 5G-CLARITY network, including:
    - ACC 5G gNB, consisting of a Dell PowerEdge R630 vRAN server featuring the near-RT RIC and CU components from ACC, and the Phluido DU. The vRAN server is connected to a Radio Unit (RU), which like in D4.3 [5], is based on an Ettus USRP B210. We notice that our original plan for this deliverable was to be able to report on the integration of the ACC 5G gNB with the Benetel B550 radio that will be the one demonstrated in the BOSCH factory. This has unfortunately not been possible due to problems in providing a reliable synchronization signal to the Benetel radio in an indoor environment[4]. This issue is captured as a critical risk in Section 4.4, and will be given the maximum priority after completing D5.2. The detailed configuration of the 5G radio is reported in Table 4-2.
    - I2CAT WiFi 6 AP, consisting of a Gateworks Venice single board computer and one Intel AX200 Wi-Fi 6 module. The detailed configuration of the WiFi6 AP radio is reported in Table 4-2.
    - The PLF LiFi-XC AP, with standard configuration.
- The 5G-CLARITY edge cluster consisting of a DELL server described in Section 2.1.4.2. An OpenStack Victoria is used as VIM in the cluster, which supports the network functions required for the SNPN

[4] The Benetel B550 needs a 10MHz 1 PPS input signal with a 50% duty cycle to boot. This signal is typically derived from a GPS signal, which is however not available indoors. An indoor synchronization solution is currently under investigation, which will require a 1588 PtP grandmaster with sufficient clock accuracy, or a standalone 1 PPS generator with sufficient accuracy.

and PNI-NPN slices of UC2.1, namely:

- SNPN slice (blue): Consisting of an open5gs VNF with PLMNID 00102 and an MPTCP proxy VNF representing the AT3S user plane function.
- PNI-NPN slice (orange): Consisting of an ioen5gs VNF with PLMNID 00103, an MPTCP proxy VNF and a L2VPN VNF used to connect to the 5TONIC infrastructure that sustains the obstacle detection function of the PNI-NPN slice.

- A Huawei 5G CPE, used to provide remote connectivity to the 5TONIC infrastructure for the PNI-NPN slice. The rationale of using a commercial CPE to connect to the 5TONIC infrastructure is the fact that due to strict security policies we are not allowed to connect any 5G-CLARITY infrastructure directly to the BOSCH network in Aranjuez.
- End devices required to validate the SNPN and PNI-NPN slices. These devices will be described in Section 4.4.
- An Edgecore 4610-54T-O-AC-F Ethernet switch connecting the elements of the private network.

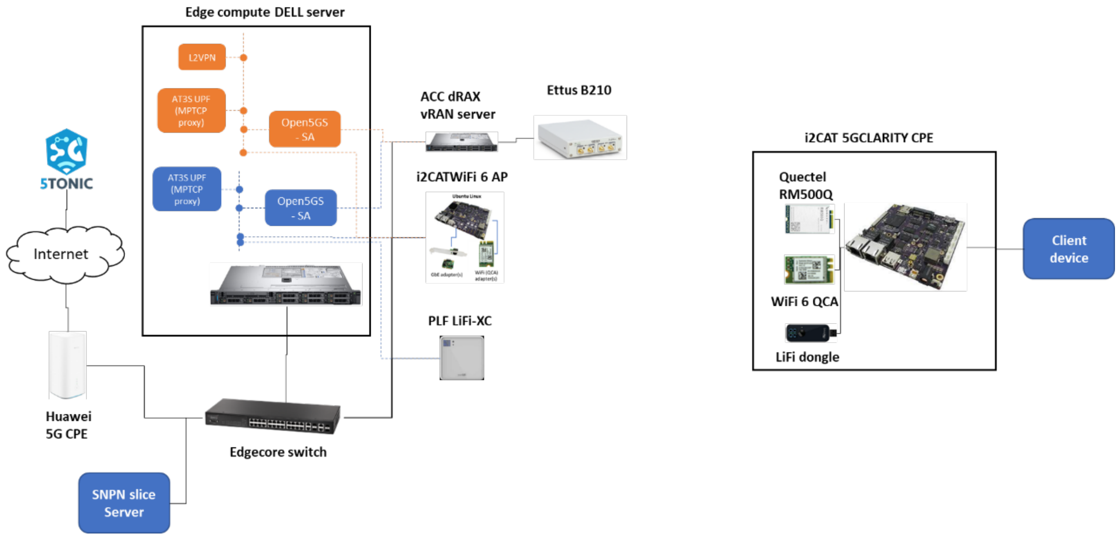


Figure 4-5. UC2.1 laboratory testbed at i2CAT.

Table 4-2 provides summarizes the main configuration parameters used in the i2CAT laboratory testbed.

Table 4-2. I2CAT lab configuration parameters

Parameter	ACC- 5GNR	WiFi 6	LiFi
Channel/Band	n78 (3.3 GHz)	149 (5745 MHz)	DL: 450 nm, UL: 850nm
Carrier Bandwidth	20MHz	40MHz	16,6MHz
MIMO configuration	DL: 1x1, UL: 1x1	DL: 2x2, UL: 2x2	DL: 1x1, UL: 1x1
Subcarrier spacing	30 KHz	312.5 KHz	319 KHz
TDD pattern	period: 2.5ms, dl_slots:3, ul_slots: 1	N/A	-

4.3 UC2.1 component integrations

We describe in this section the 5G-CLARITY developments that will be contributing to UC2.1. First, we describe in Section 4.3.1 the involved 5G-CLARITY technologies that have been developed in WP3 and WP4, and which have been introduced in Section 2. In Section 4.4.2 we describe the detailed networking design of the SNPN and PNI-NPN slices. In Section 4.3.3 we describe a measurement toolkit we have development to assess KPI measurements in the SNPN slice. In Section 4.3.4 we describe the required adaptations performed to the obstacle detection function used to support the PNI-NPN slice.

4.3.1 Mapping of 5G-CLARITY architecture and WP3 and WP4 involved components

Figure 4-6 depicts the 5G-CLARITY architecture designed in WP2, and highlights in blue the elements that will be integrated in UC2.1. As we can the four 5G-CLARITY stratums are involved in the demonstration. We describe now in more detail each stratum, highlighting the use case specific aspects.

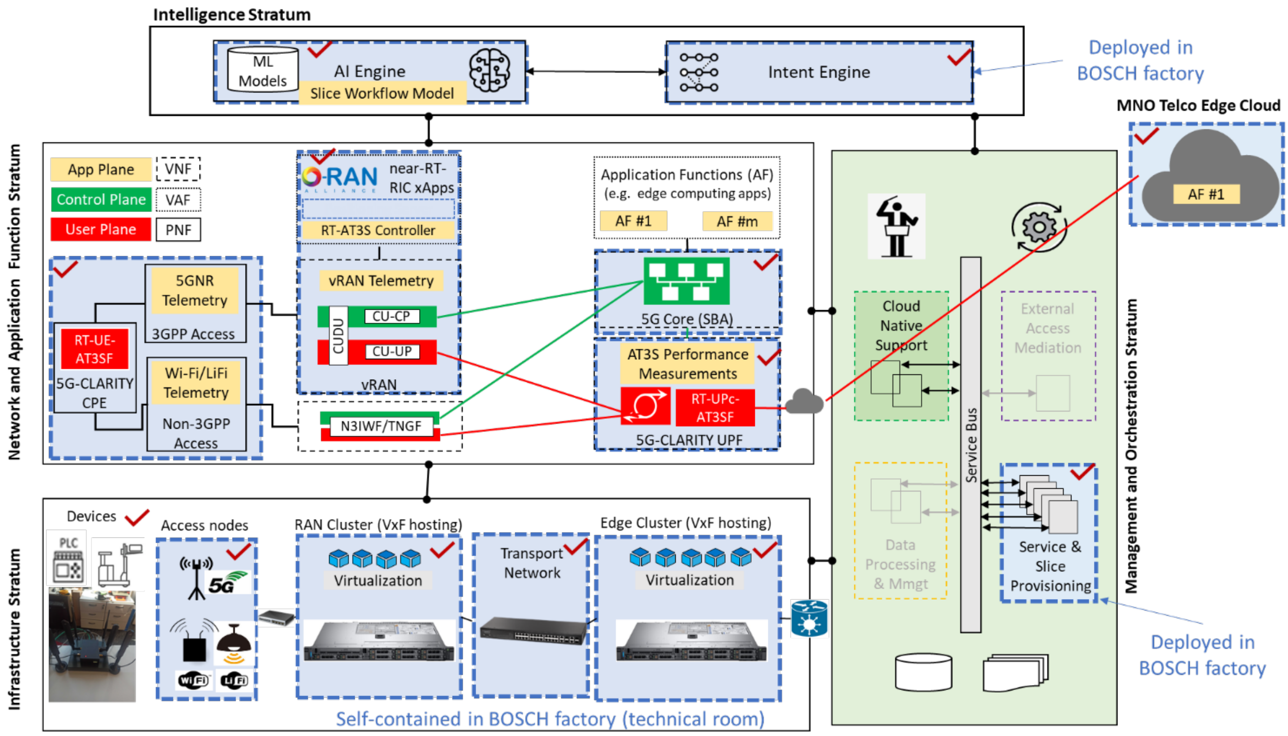


Figure 4-6. Mapping of 5G-CLARITY architecture to UC2.1

Starting from the infrastructure stratum we notice the following relevant aspects:

- The BOSCH CPE introduced in Section 2.1.1.3 is the key device that allows a PLC (for the SNPN slice) and an AGV (for the PNI-NPN slice) to access the 5G-CLARITY network.
- The infrastructure stratum is composed of the access nodes: 1 Benetel RU, 1 WiFi6 AP and 2 LiFi APs, and a portable rack featuring two servers for the RAN and the edge clusters and an Ethernet switch. It is worth noting that the 5G-CLARITY system deployed in the factory needs to be fully isolated from the BOSCH operational network. Therefore we decide to deploy all the functions of the different elements of the 5G-CLARITY system in a portable rack that will be deployed in a technical room at BOSCH.

Looking at the Network and Application Function Stratum we can see:

- All the necessary components for the 5G-CLARITY multi-connectivity framework, introduced in D3.2 [7] and evaluated in D3.3 [4], are considered. The 5G-CLARITY multi-connectivity framework allows to connect devices to the 5G-CLARITY network, multiplexing their transmitted data over the multiple access networks supported in 5G-CLARITY, i.e., 5GNR, Wi-Fi and LiFi. For UC2.1 the MPTCP proxy component of the 5G-CLARITY multi-connectivity framework is deployed as a network function in both the SNPN and PNI-NPN slices. The CPE also incorporates MPTCP. In addition, the end-to-end

TCP proxy function reported in D3.3-Section 3.2.4 [4] is also included in the CPE and MPTCP proxies used in UC2.1 to support end-to-end connectivity for both the SNPN and the PNI-NPN slices.

- No application functions are instantiated in the edge cluster. Instead, the PNI-NPN application is instantiated remotely in a public network (Telco edge cloud in Figure 4-6), and for the SNPN slice the Application Function (AF) is a physical appliance, i.e. the MES server, that will be connected to the portable rack. This AF is the Obstacle detection function, described and evaluated in deliverable D4.2 [9]. This obstacle detection function has been trained with a dataset generated by BOSCH to support the obstacle detection service of the PNI-NPN slice. In addition, an ETSI NFV network service descriptor has been developed to onboard this function into the orchestrator used in 5TONIC to support the PNI-NPN service.

Regarding the management and orchestration stratum, the Management stratum service and slice provisioning subsystem is considered, which was introduced in D4.2 [9] and evaluated in D4.3 [5]. It is used in UC2.1 to configure the 5G-CLARITY private network infrastructure that will be deployed at BOSCH with two slice, namely the SNPN and PNI-NPN slices. The "PLMNID-based" slicing mechanism described in D4.2 [9] is the approach used to implement these slices. In the next section we describe in detail the networking design for each slice. In addition, we use the end-to-end slice connectivity capability described in D4.3 [5] to evaluate the end-to-end (e2e) slice provisioning between a 5G-CLARITY private network domain and the public network domain represented by 5TONIC. Concretely the e2e slice provisioning work performed in D4.3 required the development of a custom network service providing layer two connectivity between the 5G-CLARITY private network and the 5TONIC infrastructure. This network service is reused in UC2.1 to implement the connectivity required for the PNI-NPN slice.

Finally, the intelligence stratum is considered in UC2.1 to enable the easy provisioning of the end-to-end network slice. This capability is based on the Slice Workflow Model and intent-based slice provisioning capability evaluated in D4.3 [5].

4.3.2 SNPN and PNI-NPN slice design

In this section we provide a detailed description of the networking configuration used to deploy the SNPN and PNI-NPN slices.

Figure 4-8 and Figure 4-8 depict respectively the network design of the SNPN and PNI-NPN slices validated in the laboratory testbed. We highlight the following aspects of the design:

- Following the PLMNID-based slicing design introduced in D4.2 [9], each slice features a dedicated virtualized 5GCore based on open5gs [23]. A different PLMNID is therefore used in each slice and dedicated SIM cards are required to connect to each slice.
- Each slice also features a dedicated virtualised AT3S user plane function (MPTCP proxy). This provides the capability of configuring the MPTCP scheduler that best adapts to the service provided by each slice. For example, the redundant MPTCP scheduler could be configured in the SNPN slice to reduce latency and increase reliability, and the round-robin scheduler could be configured in the PNI-NPN slice to increase data rate. Table 4-3 provides the detailed configuration of the MPTCP proxy. The MPTCP scheduler to be used in each slice will be decided during the site survey in the BOSCH factory.
- A dedicated VLAN (green) is provisioned for the 5G backhaul (vRAN to core connectivity), which is shared across the two slices. The reason for sharing this transport service was a limitation in the ACC vRAN server to automatically provision VLANs.
- A per-slice VLAN (blue and orange) is provisioned in the Wi-Fi and LiFi APs that connects user traffic

to a dedicated virtual network inside the edge cluster. This is the blue or orange network where the 5GC and the AT3S user plane function are connected to.

- A dedicated L2VPN network function is added to the PNI-NPN slice to connect to the 5TONIC infrastructure representing the MNO, where the obstacle detection function is deployed. This L2VPN is based on VXLAN and it has been described in detail in D4.3 [5].

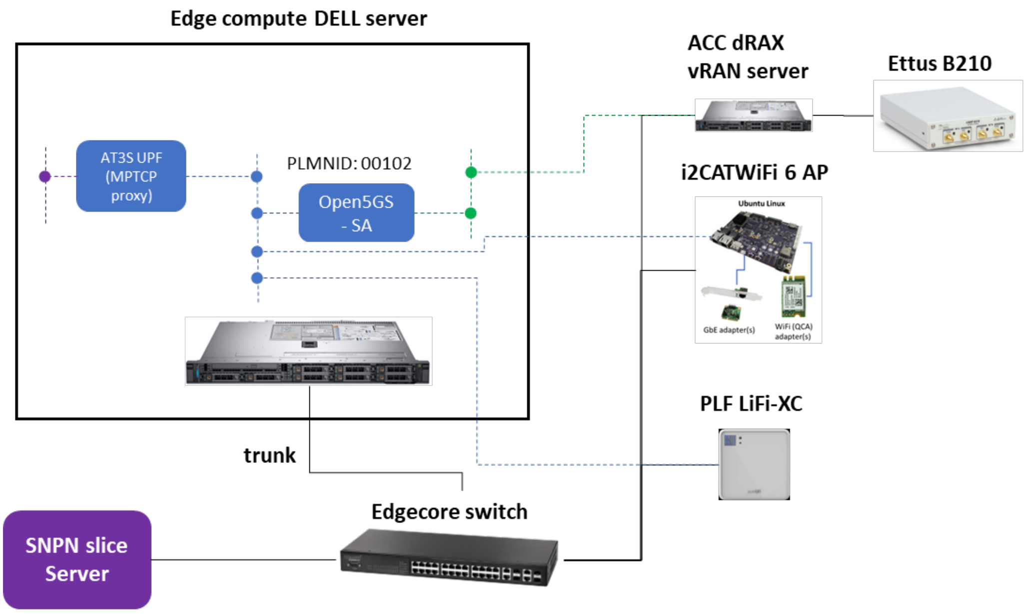


Figure 4-7. SNPN slice design.

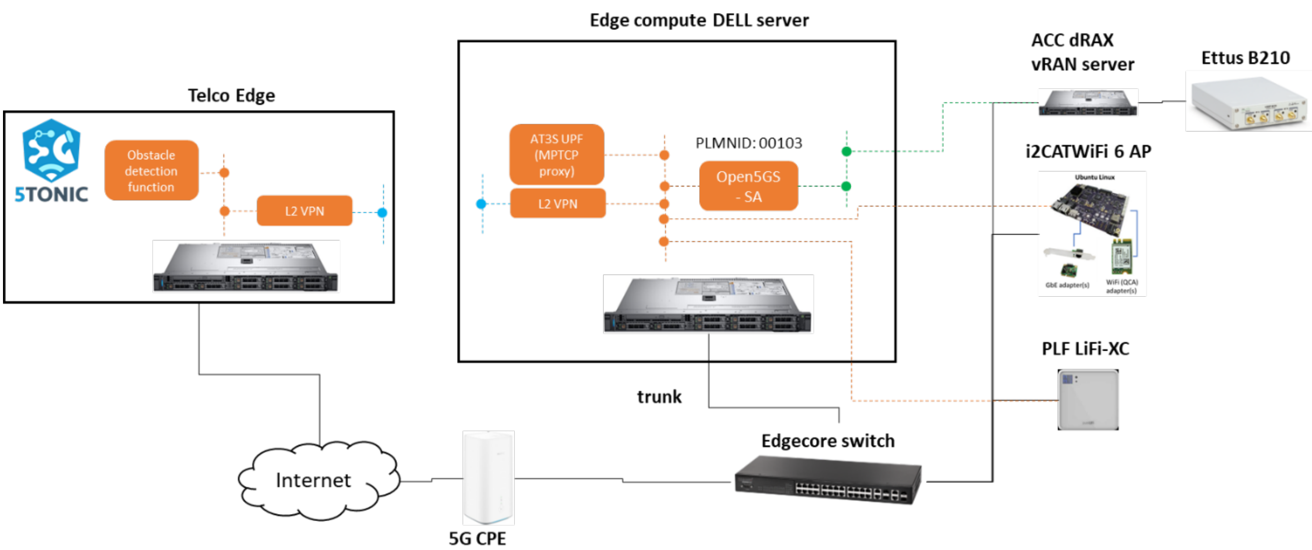


Figure 4-8. PNI-NPN slice design.

Table 4-3. MPTCP proxy configuration

Parameter	Value
kernel.osrelease	5.5.0-mptcp
net.mptcp.mptcp_checksum	1
net.mptcp.mptcp_debug	0

net.mptcp.mptcp_enabled	0
net.mptcp.mptcp_path_manager	Fullmesh
net.mptcp.mptcp_scheduler	redundant (SNPN), round-robin (PNI-NPN)
net.mptcp.mptcp_syn_retries	3
net.mptcp.mptcp_version	0

4.3.3 Standalone NPN KPI measurement toolkit

As described in Section 4.1, the goal of the SNPN slice is to validate how effective the 5G-CLARITY network can be in replacing the Ethernet based setup currently used in Aranjuez to connect production lines. To that end the PLC of a real production line is connected to an emulated MES server that has been setup for the purpose of this demonstration. A limitation of this setup though is that the emulated MES server can only receive traffic from the PLCs (5G uplink traffic) but cannot send commands towards the PLCs (5G downlink traffic), as this violates security policies from the factory.

Thus, to compare the performance of the 5G-CLARITY network versus the Ethernet based setup we need to be able to measure performance of uplink-only communications. More concretely the goal is to compare the 5G-CLARITY and the Ethernet network in terms of latency and reliability. Standard network measurement tools, such as ping or iperf, are not suited for our goal because they always require bidirectional communications to perform a round trip measurement. To solve this problem, we have developed a custom toolkit to measure uplink latency in a network. The design of this toolkit is illustrated in Figure 4-9, and consists of:

- Two probes (Probe 1 and Probe 2), each connected via Ethernet to the end devices that transmit and receive traffic. In our case the end devices will be the PLC on one side, and the MES mock-up server on the other side.
- A third device acting as KPI measurement server, which is Ethernet connected to the two Probes.

The Probes feature a software bridge based on Open vSwitch [24] that duplicates each received packet transmitting it both towards the network and towards the KPI measurement server. Thus, the KPI measurement server receives through one of its interfaces (eth0 in Figure 4-9) packets before they enter the network under test, and through the other interface (eth1 in Figure 4-9) the same packets once they leave the network under test. Since packets received on each interface of the KPI measurement server are timestamped, the KPI measurement server run a process that identifies the same packet when captured on each interface and subtracts the two timestamps for each packet to compute the time the packet has been in transit within the network under test. The KPI measurement server generates reports of the computed delays and displays them on a web interface.

In Section 4.4.2 we evaluate the performance of our uplink delay measurement toolkit on the 5G-CLARITY laboratory testbed.

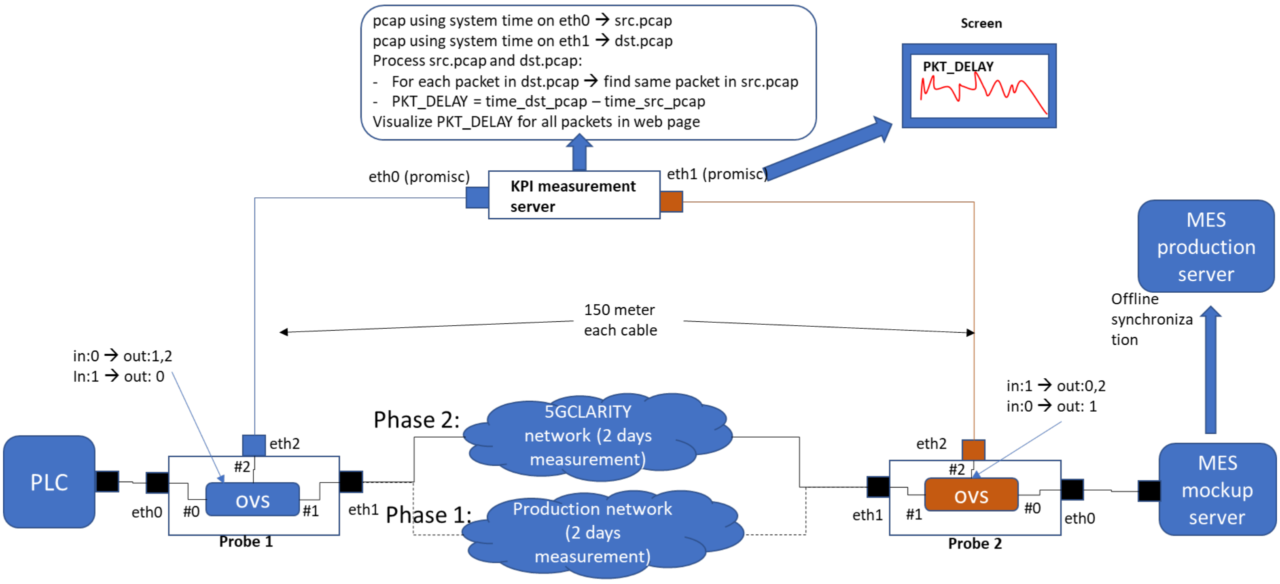


Figure 4-9. Design of one-way UL delay measurement toolkit.

In addition to developing the UL measurement toolkit, to prepare for the integration in the factory, we have characterised the traffic generated by the production line when communicating with the MES server. To this end, BOSCH carried out a packet capture during 15 minutes in the production line using Wireshark [25]. Figure 4-10 reports the results of this traffic analysis, where we can extract the following conclusions:

- All packets between the PLC and the MES server are transmitted over TCP, which is aligned to the design of the 5G-CLARITY multi-connectivity framework.
- PLCs generate a limited amount of traffic, with a maximum of six consecutive packets per second. Half of the packets are of size 40-79 Bytes (55%), and the maximum observed size is below 1280 Bytes.

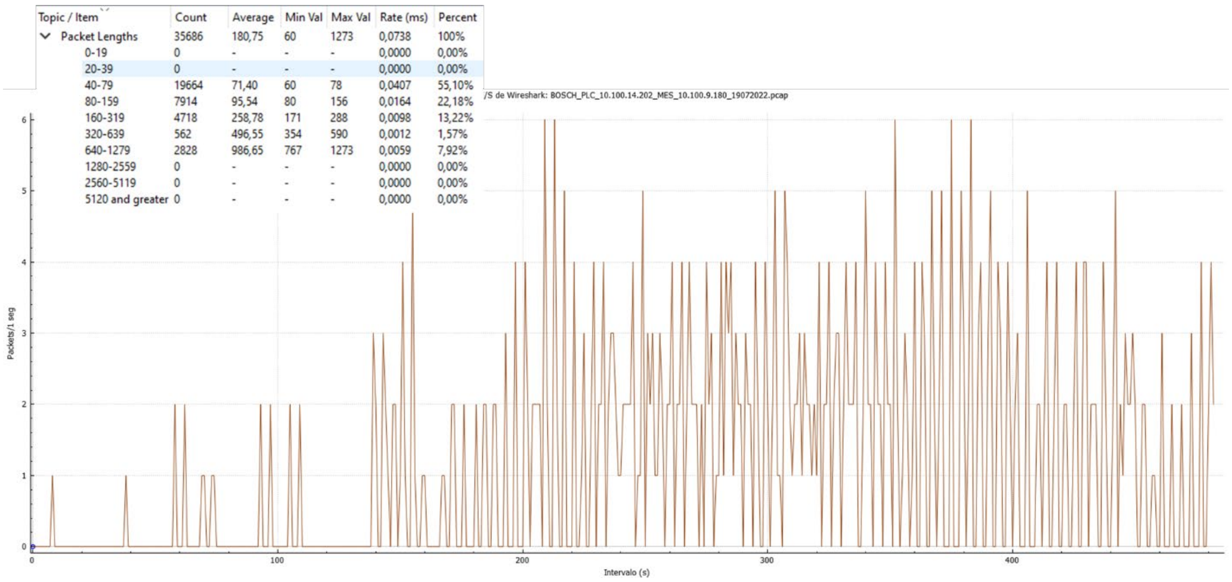

Topic / Item	Count	Average	Min Val	Max Val	Rate (ms)	Percent
Packet Lengths	35686	180,75	60	1273	0,0738	100%
0-19	0	-	-	-	0,0000	0,00%
20-39	0	-	-	-	0,0000	0,00%
40-79	19664	71,40	60	78	0,0407	55,10%
80-159	7914	95,54	80	156	0,0164	22,18%
160-319	4718	258,78	171	288	0,0098	13,22%
320-639	562	496,55	354	590	0,0012	1,57%
640-1279	2828	986,65	767	1273	0,0059	7,92%
1280-2559	0	-	-	-	0,0000	0,00%
2560-5119	0	-	-	-	0,0000	0,00%
5120 and greater	0	-	-	-	0,0000	0,00%

Figure 4-10. PLC - MES communication analysis.

Based on this preliminary analysis we conclude that in terms of required data rates the 5G-CLARITY network will easily be able to address the demand coming from the production line. The KPI evaluation will therefore focus on latency and reliability, to see if 5G-CLARITY can provide an equivalent service to Ethernet.

To compare the 5G-CLARITY and Ethernet networks in terms of latency and reliability it is necessary to deploy our system in the BOSCH factory. Therefore, these results will be reported in D5.3 [6].

4.3.4 PNI-NPN obstacle detection application function

The application function developed for PNI-NPN obstacle detection is an updated version of AI-based defect-detection algorithm reported in D4.2 [9]. The purpose of such an application function is to enable business intelligence and root cause of unexpected stops of an AGV within BOSCH factory shop floor as explained in Section 4.1.2. In the obstacle detection algorithm, the YOLO “you look only once” algorithm version 3 (YOLOv3) [26] that is built on Darknet is used to process the images. Previously, the algorithm is trained to detect defective items where items were marked to make them defective. In the PNI-NPN obstacle detection application function, a new image set that is provided by BOSCH and has 212 images is used to re-train the Darknet-53 trained model that is trained with Imagenet classification data set. In the new image set, five different items are indicated as possible obstacles that may break AGV’s planned route and let AGV to stop/break unexpectedly. These items are pallets, forklifts, boxes, trolleys and pallet-trucks as some of them are shown in Figure 4-3. Accordingly, the trained model for obstacle detection has five object classes and should accurately detect any of these object classes in each image provided by AGV’s camera. During the new training phase, 85% of the images (181 images) is used for training and the remaining 15% of the images (31 images) is used to test and validate the detection accuracy.

The PNI-NPN obstacle detection application function is then deployed on telco edge that is 5TONIC premises as depicted in Figure 4-4. The application is deployed as a network service image along with required libraries including Darknet, Python, object detection configuration and trained model weights.

Once the application is deployed at 5TONIC premises, the application should run when there is an image sent from the AGV’s camera. To enable such a triggering mechanism, an API is developed to push image(s) and run the obstacle detection application at the same time. The purpose of the API development is to mitigate periodic checks or calls for application function to look and understand whether there is a new image being pushed or not. The API enables POST, GET and DELETE functions where POST is used to upload/push a new file and trigger the application function to be run, GET is used to obtain the list of images both the uploaded (unprocessed) and detected (processed) images, and DELETE is used to deletion of an uploaded or detected image file. In addition to the detected image file, the application creates a log file to capture the image details (file name), what item is detected as an obstacle, how long it took for application to process the image, detection accuracy level and a timestamp that indicates when the application is run to perform detection.

A functional validation of the developed obstacle detection function is reported in Section 4.4.3.

4.4 UC2.1 validation results

In this section we describe the lab-based validations obtained for the SNPN and PNI-NPN slices in laboratory conditions.

We note that in D5.2 we have focused on performing in the lab functional validations that will be required for the demonstration in the BOSCH factory. We have not focused in D5.2 in KPI extraction because we have not yet been able to integrate the Benetel radio (c.f. Section 4.2). KPI extraction will be then performed in the BOSCH factory and reported in D5.3 [6].

We provide in Table 4-4 an update to the UC2.1 validation methodology that was originally described in D5.1 [2].

Table 4-4. Update on lab testing methodology suggested in D5.1

Test ID in D5.1	Description	Status in D5.2
UC2.1-Lab-T1	Initial lab benchmark with the portable testbed	KPI extraction (throughput, delay, etc) has been delayed until the Benetel radio can be successfully integrated. Then KPIs will be extracted in the lab and then in the BOSCH factory.
UC2.1-Lab-T2	Benchmark with synthetic traffic traces	We have been able to sniff the PLC traffic, as reported in Section 4.3.3. This traffic has been used to validate the UL measurement toolkit in Section 4.4.2.
UC2.1-Lab-T3	Slice isolation in front of interferer	Logic Isolation between the SNPN and PNI-NPN slices is validated in Section 4.4.1, showing that we can have two UEs simultaneously connecting to the two slices. Study of performance isolation requires to stress the network and is therefore postponed until the Benetel radio can be integrated. It will be reported in D5.3 [6].
UC2.1-Lab-T4	AI-based object detection algorithm	These tests are performed in D5.2 and reported in Section 4.4.30.
UC2.1-Lab-T5	Data lake solution	These tests are not reported in D5.2 since they have already been reported in D4.3 [5].

We now describe the lab-based functional validations for UC2.1, which have focused on the following three aspects:

i. Functional validation of multi-slice support in the 5G-CLARITY infrastructure. We do not consider in our evaluation the intent engine integration since this was already validated in D4.3 [5].

ii. Functional validation of the SNPN UL measurement toolkit.

iii. Functional validation of the end-to-end connectivity required for the PNI-NPN slice.

4.4.1 Functional validation of multi-slice support in the 5G-CLARITY infrastructure

In D4.3 [5] we reported on the integration of the ACC ORAN gNB with the 5G-CLARITY service and slice provisioning subsystem. We also described how the service and slice provisioning subsystem can be used to provision a 5G-CLARITY infrastructure slice by configuring MOCN[5] lists in the ORAN gNB and deploying a corresponding 5GCore through the Slice Manager. In D4.3 [5] though, we were only able to validate and benchmark the deployment of one 5G-CLARITY infrastructure slice. This is not enough for UC2.1, where 2 slices need to be deployed and be simultaneously active over the 5G-CLARITY infrastructure. Thus, we present in this section a functional validation showcasing how two end devices can connect simultaneously to two 5G-CLARITY infrastructure slices.

To validate that we can support a deployment with two concurrent 5G-CLARITY slices over the Accelleran ORAN gNB, we deploy a testbed with the following setup:

- Service and Slice provisioning subsystem: Multi-WAT Near Real Time RIC.
- Network infrastructure: RAN cluster connected to Ettus B210.

[5] Multi-Operator Core Network

- ORAN network functions in RAN cluster: One CU-CP deployed via dRAX dashboard, two CU-UPs, one per slice, deployed via dRAX dashboard.
- Core network functions in Edge cluster: PLMNID-based slicing is used with two cores representing each 5G-CLARITY slice. PLMNIDs 00102 and 0013 are used for each slice respectively.
- UEs: 2 Quectel Modems RM500Q-GL (laptop and 5G-CLARITY BOSCH CPE), each one using an IMSI with a different PLMNID (00102 and 00103). Distance between modems and Ettus: Laptop ~ 1m, CPE ~ 2m.

Figure 4-11 and Figure 4-12 depict the resulting configurations in each ORAN function, namely DU, CU-CP and CU-UP, after the 5G-CLARITY Multi-WAT Near real time RIC completes the slice provisioning process:

- We can see that three PLMNIDs are configured in the DU (Figure 4-11-left), one for each slice 00102 and 00103. An additional PLMNID 00000 labelled as "fake" is also observed in the DU configuration. The reason for the additional fake PLMNID is to bypass a shortcoming of the current implementation where the DU needs to have a pre-configured core upon boot, even if no slices have been configured yet. This is a misbehaviour that will be addressed soon and does not block the provisioning of 5G-CLARITY slices.
- In the CU-CP configuration (Figure 4-11-right), we can see how two operators are configured. Each contains the IP address in the edge cluster where the core network serving the corresponding slice (00102 and 00103) can be reached. The CU-CP proactively opens connections with those cores and discovers the PLMNIDs served by each core.
- Figure 4-12 depicts the resulting configuration in the two CU-UP functions, where we have one CU-UP function dedicated to each slice, as described in D4.3 [5].

To validate the connectivity of the 2 UEs to their corresponding core, we depict the dRAX dashboard in Figure 4-13 showing the 2 connected UEs and configured PLMNIDs. In addition, Figure 4-14 provides evidence of the connectivity between each UE and the core serving their slice.

Figure 4-11. DU and CU-CP resulting configurations.

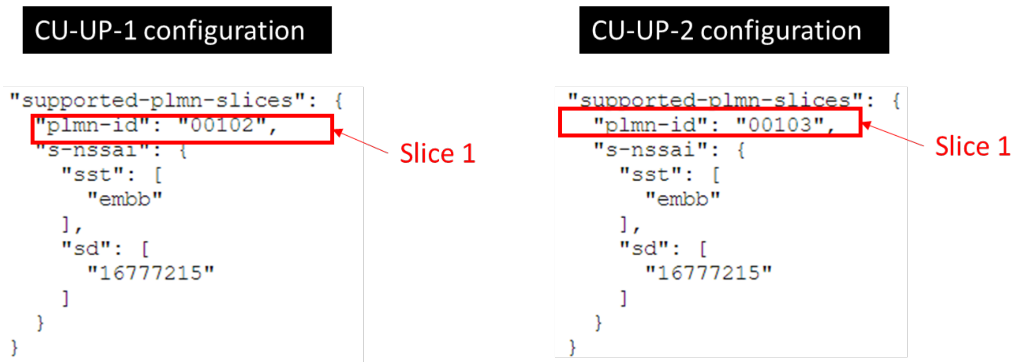


Figure 4-12. Slice 1 CU-UP and Slice 2 CU-UP configurations.

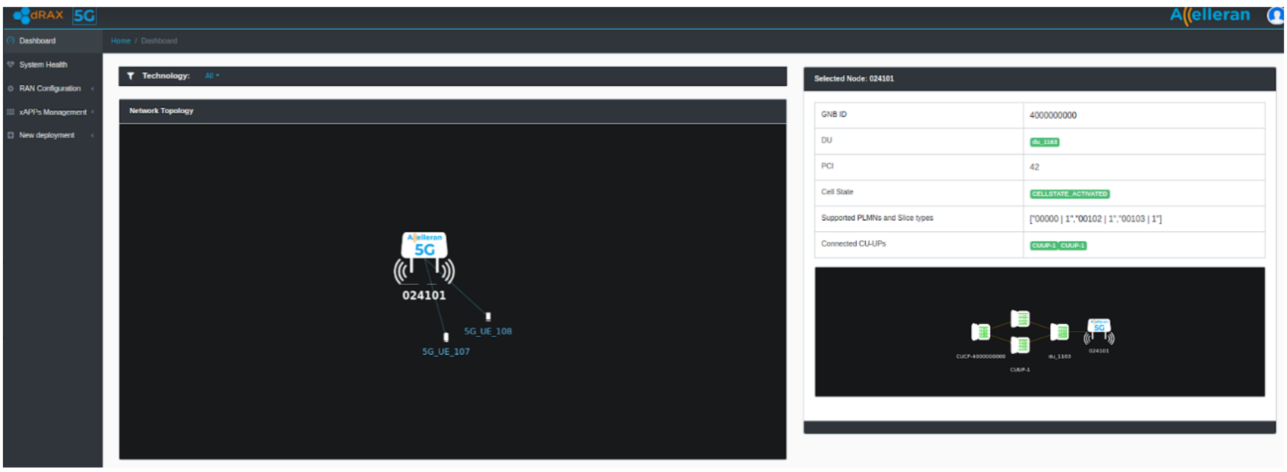


Figure 4-13. dRAX dashboard with 2 connected UEs, one UE belonging to each 5G-CLARITY slice.

Slice 1 connectivity   Slice 2 connectivity

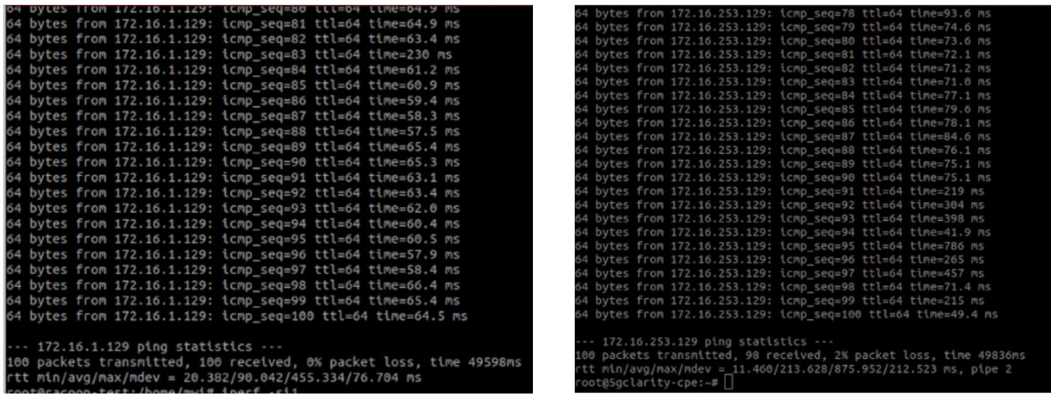


Figure 4-14. Connectivity from each UE to the core corresponding to their slice.

After having functionally verified the ability to provision two slices over the 5G ORAN gNB and to simultaneously connect UEs to each slice, we will continue working to validate the performance achieved by each slice once we manage to connect the Benetel radio. Performance results will be reported in D5.3.

4.4.2 Standalone NPN application KPIs

We report in this section the functional validation of the UL measurement toolkit described in Section 4.3.4. The validation was carried out using our laboratory network, with the following additions:

- Network probes: As depicted in Figure 4-9, two probes are required at the entry and exit points of the network to duplicate traffic towards the measurement server. These probes are implemented using Single Board Computers (SBCs), which are also used to generate the end-to-end traffic.
- Measurement server: Also depicted in Figure 4-9, the measurement server receives the copies of the packets at the entry and exit points of the network and computes the one-way latency. The measurement server is implemented in our lab using a Raspberry Pi device.

In our evaluation we use the testbed described in section 4.2, adding the two network probes depicted in Figure 4-9 that also act as traffic source and sink respectively. Our goal is to validate the UL delay measurement toolkit with a traffic pattern similar to the one measured for the PLC to MES communication reported in section 4.3.3. Hence, we use the network measurement tool lagscope [27] to generate TCP packets with a periodicity of 1 second. Our goals with this functional validation are:

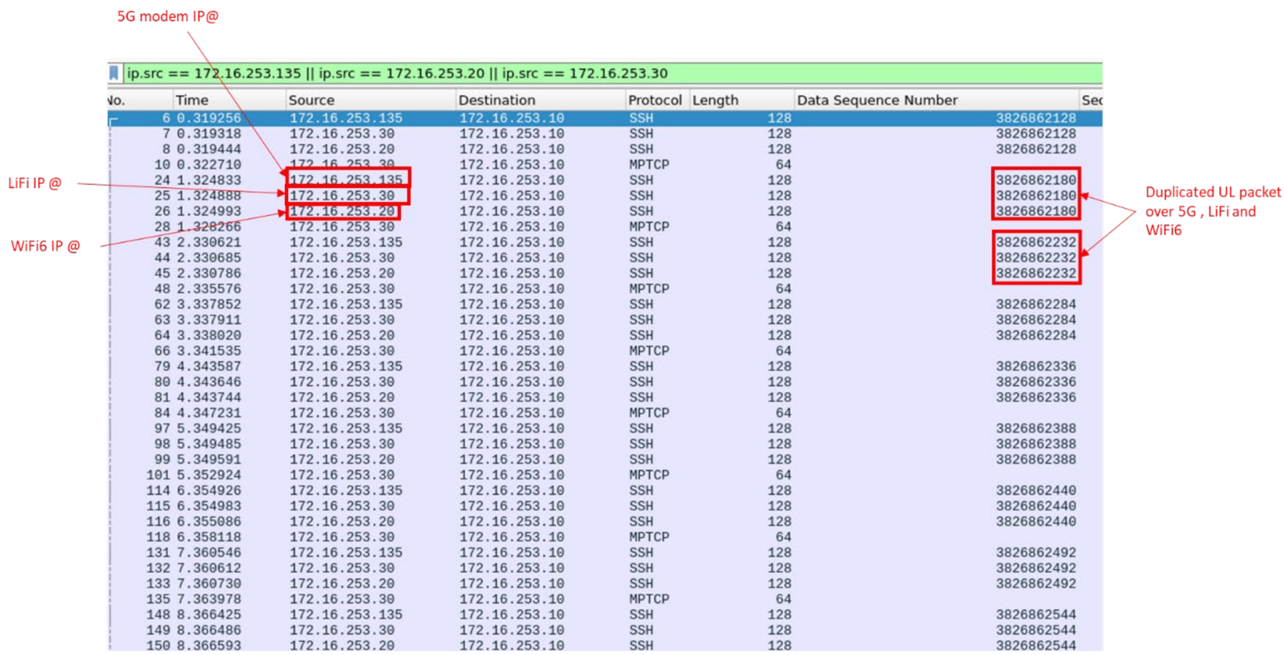
- First, validate that we can establish end-to-end communication between the two network probes generating TCP traffic over the 5G-CLARITY network. Notice that the network probes are not MPTCP capable. Therefore, we need to tunnel the TCP traffic generated by the probes into an MPTCP tunnel using the SSHuttle mechanism described in D3.3 [4]. This will ensure that when deployed over the BOSCH factory, the PLC can communicate with the MES server over the 5G-CLARITY network.
- Second, we want to validate that our KPI measurement toolkit is indeed able to identify the TCP packets entering and leaving the network and compute the resulting UL delay.

Figure 4-15 depicts a Wireshark capture of the packets transmitted by the 5G-CLARITY CPE into the network. The packets are originated by the probe (representing the PLC), so what we see in the figure are the packets already relayed into the MPTCP tunnel. We observe the following:

- The 5G-CLARITY CPE has three IP interfaces on the same network representing the WiFi6 interface

(172.16.253.20), the LiFi interface (172.16.253.30) and the 5G modem (172.16.253.135). Having the three interfaces in the same network corresponds to the network slice design used in this use case.

- Each TCP packet generated by the probe is duplicated in the Wi-Fi, LiFi and 5G networks, as it can be seen by the duplicated Data Sequence Number in the figure. The reason for this is that we are using an MPTCP scheduler in redundant mode, because our goal for the SNPN slice is to minimize latency and increase reliability.



No.	Time	Source	Destination	Protocol	Length	Data Sequence Number
6	0.319256	172.16.253.135	172.16.253.10	SSH	128	3826862128
7	0.319318	172.16.253.30	172.16.253.10	SSH	128	3826862128
8	0.319444	172.16.253.20	172.16.253.10	SSH	128	3826862128
10	0.322710	172.16.253.30	172.16.253.10	MPTCP	64	
24	1.324833	172.16.253.135	172.16.253.10	SSH	128	3826862180
25	1.324888	172.16.253.30	172.16.253.10	SSH	128	3826862180
26	1.324993	172.16.253.20	172.16.253.10	SSH	128	3826862180
28	1.328266	172.16.253.30	172.16.253.10	MPTCP	64	
43	2.330621	172.16.253.135	172.16.253.10	SSH	128	3826862232
44	2.330685	172.16.253.30	172.16.253.10	SSH	128	3826862232
45	2.330786	172.16.253.20	172.16.253.10	SSH	128	3826862232
48	2.335576	172.16.253.30	172.16.253.10	MPTCP	64	
62	3.337852	172.16.253.135	172.16.253.10	SSH	128	3826862284
63	3.337911	172.16.253.30	172.16.253.10	SSH	128	3826862284
64	3.338020	172.16.253.20	172.16.253.10	SSH	128	3826862284
66	3.341535	172.16.253.30	172.16.253.10	MPTCP	64	
79	4.343587	172.16.253.135	172.16.253.10	SSH	128	3826862336
80	4.343646	172.16.253.30	172.16.253.10	SSH	128	3826862336
81	4.343744	172.16.253.20	172.16.253.10	SSH	128	3826862336
84	4.347231	172.16.253.30	172.16.253.10	MPTCP	64	
97	5.349425	172.16.253.135	172.16.253.10	SSH	128	3826862388
98	5.349485	172.16.253.30	172.16.253.10	SSH	128	3826862388
99	5.349591	172.16.253.20	172.16.253.10	SSH	128	3826862388
101	5.352924	172.16.253.30	172.16.253.10	MPTCP	64	
114	6.354926	172.16.253.135	172.16.253.10	SSH	128	3826862440
115	6.354983	172.16.253.30	172.16.253.10	SSH	128	3826862440
116	6.355086	172.16.253.20	172.16.253.10	SSH	128	3826862440
118	6.358118	172.16.253.30	172.16.253.10	MPTCP	64	
131	7.360546	172.16.253.135	172.16.253.10	SSH	128	3826862492
132	7.360612	172.16.253.30	172.16.253.10	SSH	128	3826862492
133	7.360730	172.16.253.20	172.16.253.10	SSH	128	3826862492
135	7.363978	172.16.253.30	172.16.253.10	MPTCP	64	
148	8.366425	172.16.253.135	172.16.253.10	SSH	128	3826862544
149	8.366486	172.16.253.30	172.16.253.10	SSH	128	3826862544
150	8.366593	172.16.253.20	172.16.253.10	SSH	128	3826862544

Figure 4-15. Capture of TCP packets generated by 5G-CLARITY CPE for UL measurement toolkit validation experiment

Figure 4-16 depicts a measurement dashboard that we have developed using Grafana [28] to display in real-time the UL delay of the packets traversing the network, as well as the maximum jitter, the latency histogram and the cumulative distribution function. The historic data is persisted, and the visualization window can be adjusted. The results validate our implementation of the UL measurement toolkit in a laboratory environment, delivering UL latencies below 5 ms.

In the upcoming deliverable D5.3 we will compare the UL delay performance achieved by the 5G-CLARITY network, with the performance currently available in the BOSCH factory using Ethernet. In addition, we will consider different patterns of interference to provide a realistic evaluation of the expected 5G-CLARITY performance.

Figure 4-16. Measured UL network latency using our UL measurement toolkit

4.4.3 PNI-NPN application KPIs and lab-based validation

The KPIs for the PNI-NPN obstacle detection application function are the accuracy level of the detected objects and time to detect an object once the image has been sent to the application function via the API.

As noted in Section 4.3.4, 15% of the image set was not used in the training phase instead used to test and validate the trained model performance. Hence, the accuracy performance is evaluated offline with different images that are put apart for trained model test and validation. The figure below shows the processed image output of the application function. In these processed images, the application function adds a coloured box around the detected object and provides the obtained accuracy level of each detected object in case there are multiple objects exist at the same time in the same image.

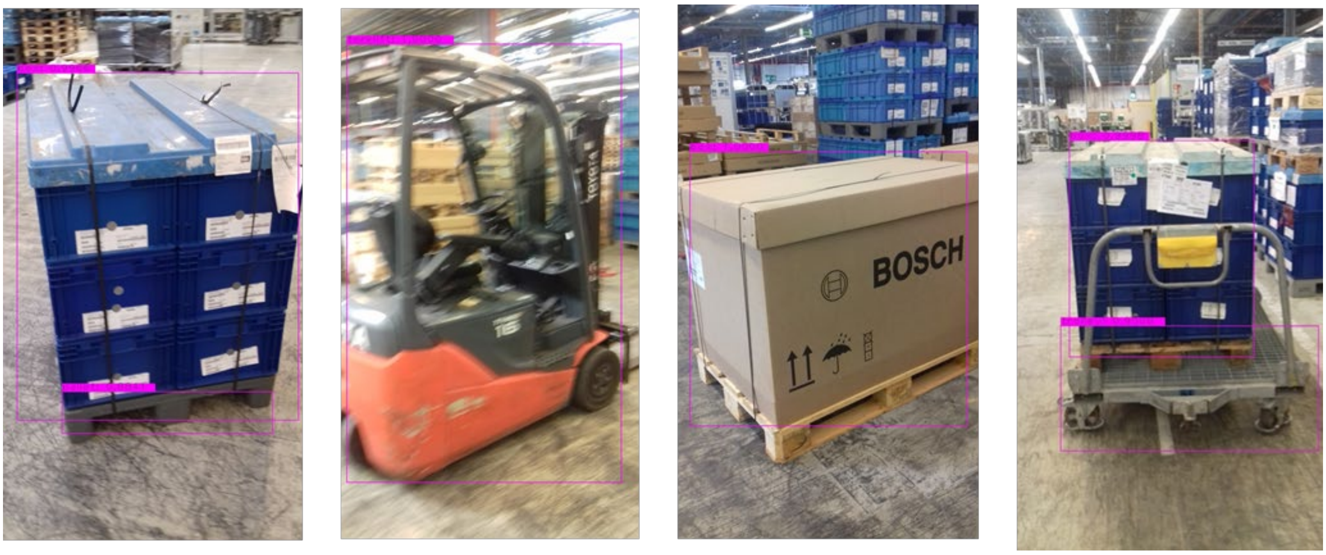


Figure 4-17. Sample images of the dataset

In addition to the processed image output, the accuracy level performance of all images including the ones used during the training phase is provided in Figure 4-18 for each object class. Among different classes, the accuracy level performance drops to 60% for very few samples only for trolley images. For other object classes, the accuracy level mostly close to 100% with some drops to around 80% for few samples.

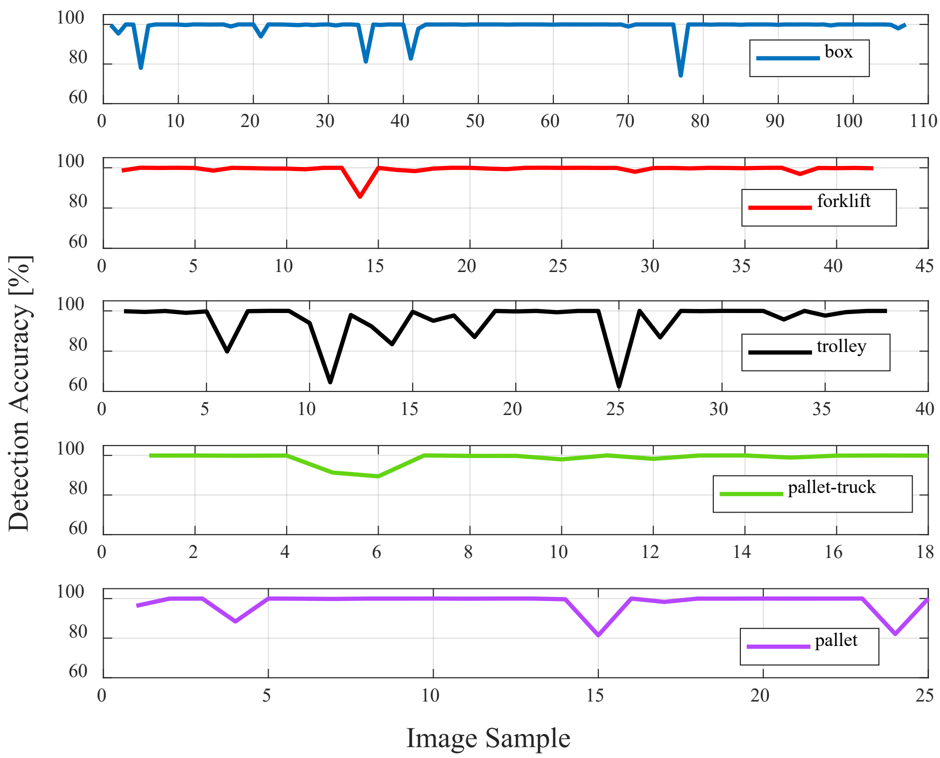


Figure 4-18. Detection accuracy results according to object type

Figure 4-19 shows the cumulative distribution function (CDF) of all images for accuracy level (left) and detection time (right). As it can be observed from the figure, the average detection accuracy performance is around 98% and the average detection time which is the time for application function to detect and object and report the output is 48 ms.

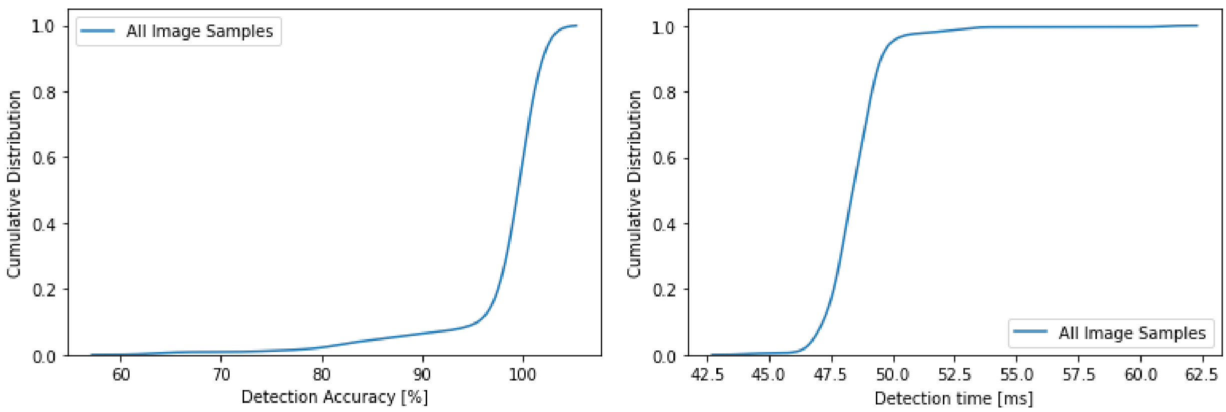
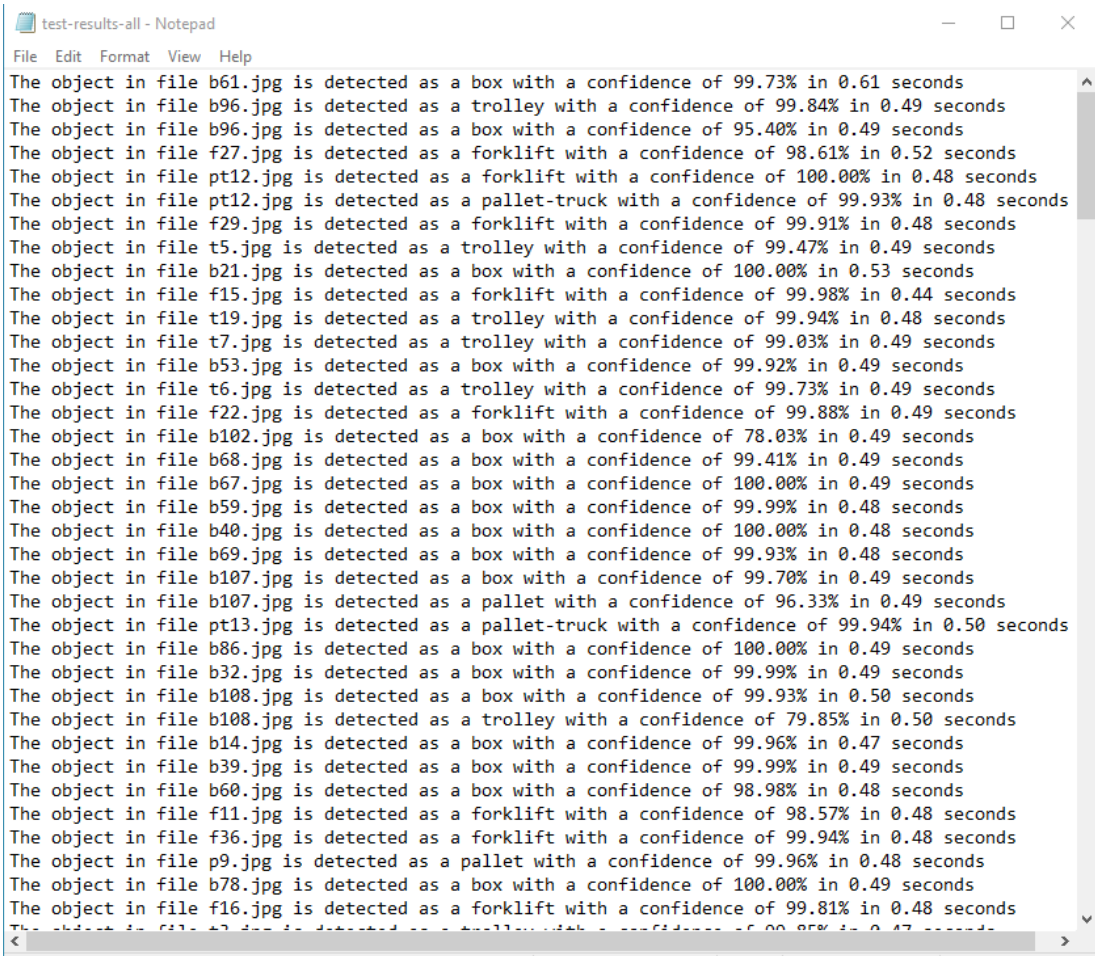


Figure 4-19. Cumulative distribution of combined detection accuracy and detection time

The application function also logs the detection output in a text format where it provides uploaded image name, detected obstacle class, detection accuracy level as a confidence and time to detect the obstacle after running the application function. Figure 4-20 shows a snapshot of the output in text format. In the figure, file name letters “b”, “t”, “f”, “pt” and “p” represent object class box, trolley, forklift, pallet-truck and pallet, respectively.



test-results-all - Notepad

File Edit Format View Help

```
The object in file b61.jpg is detected as a box with a confidence of 99.73% in 0.61 seconds
The object in file b96.jpg is detected as a trolley with a confidence of 99.84% in 0.49 seconds
The object in file b96.jpg is detected as a box with a confidence of 95.40% in 0.49 seconds
The object in file f27.jpg is detected as a forklift with a confidence of 98.61% in 0.52 seconds
The object in file pt12.jpg is detected as a forklift with a confidence of 100.00% in 0.48 seconds
The object in file pt12.jpg is detected as a pallet-truck with a confidence of 99.93% in 0.48 seconds
The object in file f29.jpg is detected as a forklift with a confidence of 99.91% in 0.48 seconds
The object in file t5.jpg is detected as a trolley with a confidence of 99.47% in 0.49 seconds
The object in file b21.jpg is detected as a box with a confidence of 100.00% in 0.53 seconds
The object in file f15.jpg is detected as a forklift with a confidence of 99.98% in 0.44 seconds
The object in file t19.jpg is detected as a trolley with a confidence of 99.94% in 0.48 seconds
The object in file t7.jpg is detected as a trolley with a confidence of 99.03% in 0.49 seconds
The object in file b53.jpg is detected as a box with a confidence of 99.92% in 0.49 seconds
The object in file t6.jpg is detected as a trolley with a confidence of 99.73% in 0.49 seconds
The object in file f22.jpg is detected as a forklift with a confidence of 99.88% in 0.49 seconds
The object in file b102.jpg is detected as a box with a confidence of 78.03% in 0.49 seconds
The object in file b68.jpg is detected as a box with a confidence of 99.41% in 0.49 seconds
The object in file b67.jpg is detected as a box with a confidence of 100.00% in 0.49 seconds
The object in file b59.jpg is detected as a box with a confidence of 99.99% in 0.48 seconds
The object in file b40.jpg is detected as a box with a confidence of 100.00% in 0.48 seconds
The object in file b69.jpg is detected as a box with a confidence of 99.93% in 0.48 seconds
The object in file b107.jpg is detected as a box with a confidence of 99.70% in 0.49 seconds
The object in file b107.jpg is detected as a pallet with a confidence of 96.33% in 0.49 seconds
The object in file pt13.jpg is detected as a pallet-truck with a confidence of 99.94% in 0.50 seconds
The object in file b86.jpg is detected as a box with a confidence of 100.00% in 0.49 seconds
The object in file b32.jpg is detected as a box with a confidence of 99.99% in 0.49 seconds
The object in file b108.jpg is detected as a box with a confidence of 99.93% in 0.50 seconds
The object in file b108.jpg is detected as a trolley with a confidence of 79.85% in 0.50 seconds
The object in file b14.jpg is detected as a box with a confidence of 99.96% in 0.47 seconds
The object in file b39.jpg is detected as a box with a confidence of 99.99% in 0.49 seconds
The object in file b60.jpg is detected as a box with a confidence of 98.98% in 0.48 seconds
The object in file f11.jpg is detected as a forklift with a confidence of 98.57% in 0.48 seconds
The object in file f36.jpg is detected as a forklift with a confidence of 99.94% in 0.48 seconds
The object in file p9.jpg is detected as a pallet with a confidence of 99.96% in 0.48 seconds
The object in file b78.jpg is detected as a box with a confidence of 100.00% in 0.49 seconds
The object in file f16.jpg is detected as a forklift with a confidence of 99.81% in 0.48 seconds
```

Figure 4-20. Functional validation of detection function.

We conclude this section discussing a functional validation of the PNI-NPN end-to-end functionality that we carried out connecting a prototype factory environment at the i2CAT lab, with the obstacle detection function instantiated at 5TONIC. This functional validation was part of the ETSI Zero Touch Service Management (ZSM) PoC demonstration that was done in WP4. A public demonstration of this PoC has been published in the 5G-CLARITY YouTube channel [29].

To emulate the factory environment at i2CAT what we did was to have a monitor displaying pictures of real obstacles taken in the BOSCH factory in Aranjuez. We then had a webcam connected to the 5G-CLARITY CPE periodically taking pictures of the monitor, such that the image displayed in the monitor would appear in the picture frame. This setup is illustrated in Figure 4-21, where the monitor displays the picture of a forklift in the factory floor.

The full PNI-NPN slice described in 4.1.2 was deployed at the i2CAT lab and connected to the 5TONIC infrastructure where the obstacle detection function was instantiated. Thus, the obstacle detection function was receiving the pictures from the webcam, detecting the type of obstacle, and displaying the result in a custom-made user interface. Figure 4-22 displays the outcome of the obstacle detection function when detecting the forklift.

With this experiment we consider the PNI-NPN slice functionally validated. The next challenge towards the final demonstrator will be to demonstrate this setup in an operational environment, with the 5G-CLARITY CPE and webcam deployed on the AGV. To this end, a mechanism to automatically trigger pictures when the AGV stops will need to be developed.

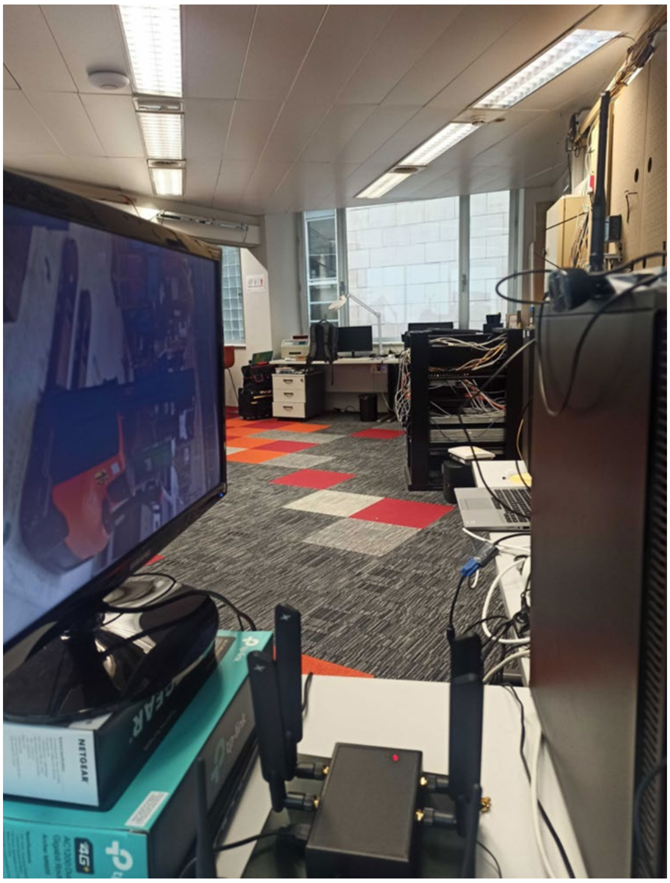


Figure 4-21. Lab setup at i2CAT for PNI-NPN slice functional validation

Figure 4-22. Obstacle detection function in PNI-NPN at 5TONIC detecting obstacles from i2CAT lab monitor

4.4.4 Update on demonstration risks and mitigation plans

We provide in this section and update on the UC2.1 related risks that we identified in D5.1 [2].

Risk ID	Description	Impact	Status in D5.2

UC2.1-R1	Lack of spectrum license for 5G	High	This risk has not materialized as Telefonica has confirmed spectrum availability for the demonstration.
UC2.1-R2	Radio units are not available on time for testing	High	This risk materialized and we had significant delays on the delivery of the n78 units required for UC2.1. Reasons for these delays have been the global supply chain problems. In addition to the delays in delivering the radio units, we are currently experiencing integration problems due to the synchronization signal requirements of the radio. ACC and i2CAT are actively working to resolve this issue.
UC2.1-R3	MES cannot be emulated in the emulation production line setup	Medium	This risk has not materialized, as we found a way to emulate a MES server and connect the PLC used in production
UC2.1-R4	Interconnect with MNO network cannot be delivered due to stringent interconnectivity security requirements in BOSCH factory	High	Security policies at BOSCH indeed forbid direct connection to the MNO network that is required for the PNI-NPN slice. We have been able to mitigate this risk using the cellular public network to interconnect the BOSCH factory and the Telco edge. This option reduces the available data rate of this interconnect, but this is not a critical parameter for the obstacle detection service used in the PNI-NPN slice.
UC2.1-R5	Traffic cannot be sniffed from active production line	Low	This risk has not materialized. PLC traffic was sniffed, and the findings were used to design a proxying solution that worked for TCP traffic and to validate the UL measurement toolkit.
UC2.1-R6	Only one moulding machine available	Medium	This risk has materialized. This is the reason why in D5.2 we have decided to use the second slice for a different service (obstacle detection function), instead of using it to support a second production line as described in D5.1.
UC2.1-R7	Distributed UPF provisioning not possible with the Ericsson core in 5TONIC	Medium	This risk has materialized. The mitigation has been to use the Telco edge domain to host only the application function (obstacle detection), instead of using a distributed core deployment.

5 UC2.2: Enhanced AGV Positioning for Intralogistics (Industry 4.0)

5.1 UC2.2 scope and project objectives addressed

In this section we provide the details of the multi-WAT positioning system that will be subject of demonstration at the BOSCH factory in Aranjuez. As presented in deliverable D5.1 [2], the scope of UC2.2 is to deploy all 5G-CLARITY positioning technologies at the BOSCH production floor in Aranjuez, Spain, and to perform position estimation of an AGV used for delivery of raw materials and collection of the produced goods.

UC2.2 addresses objective **OBJ-TECH-5**, which relates to multi-WAT positioning. The part of **OBJ-TECH-5** concerning wireless synchronization is a theoretical work performed in WP2 and reported in D2.3 [20]. This work is mainly focused on the theoretical aspects of joint synchronization and localization and the achieved Technology Readiness Level (TRL) is not sufficient to be included in UC2.2 demonstration.

With respect of the positioning part of **OBJ-TECH-5**, the performance of the developed positioning technologies will be demonstrated and evaluated as part of UC2.2 demonstration, which is scheduled to take place on late November 2022. As part of UC2.2, the KPIs associated with the developed positioning technologies should be evaluated in a realistic environment, in this case the BOSCH production floor in Aranjuez.

5.2 5G-CLARITY Architecture and Enablers for UC2 Demonstration

UC2.2 demonstration instantiate few of the 5G-CLARITY strata from those presented in Figure 2-1, Section 2. We present in the sequel which strata play a role in this demonstration, which is illustrated in Figure 5-1:

- Infrastructure Stratum: UEs and WATs that take part in the localization demonstration, i.e. Sub-6 GHz, mmWave and LiFi, whose components are integrated together to provide position estimates to the localization server. The infrastructure stratum is composed of the ANs: 2 mmWave units, 6 Sub-6 Ettus N321 and 2 LiFi APs, plus the respective UEs: 1 mmWave, 1 Ettus and the LiFi dongle. Again, for this UC, the 5G-CLARITY system deployed in the factory needs to be fully isolated from the BOSCH operational network.
- Network and Application Function Stratum, where the localization server could be instantiated (it will be running in an x86-based platform for UC2.2.
- Intelligence stratum, where the non-line of sight (NLOS) detection algorithms are deployed (this has been shown in WP4 demos, will not be part of UC2.2).

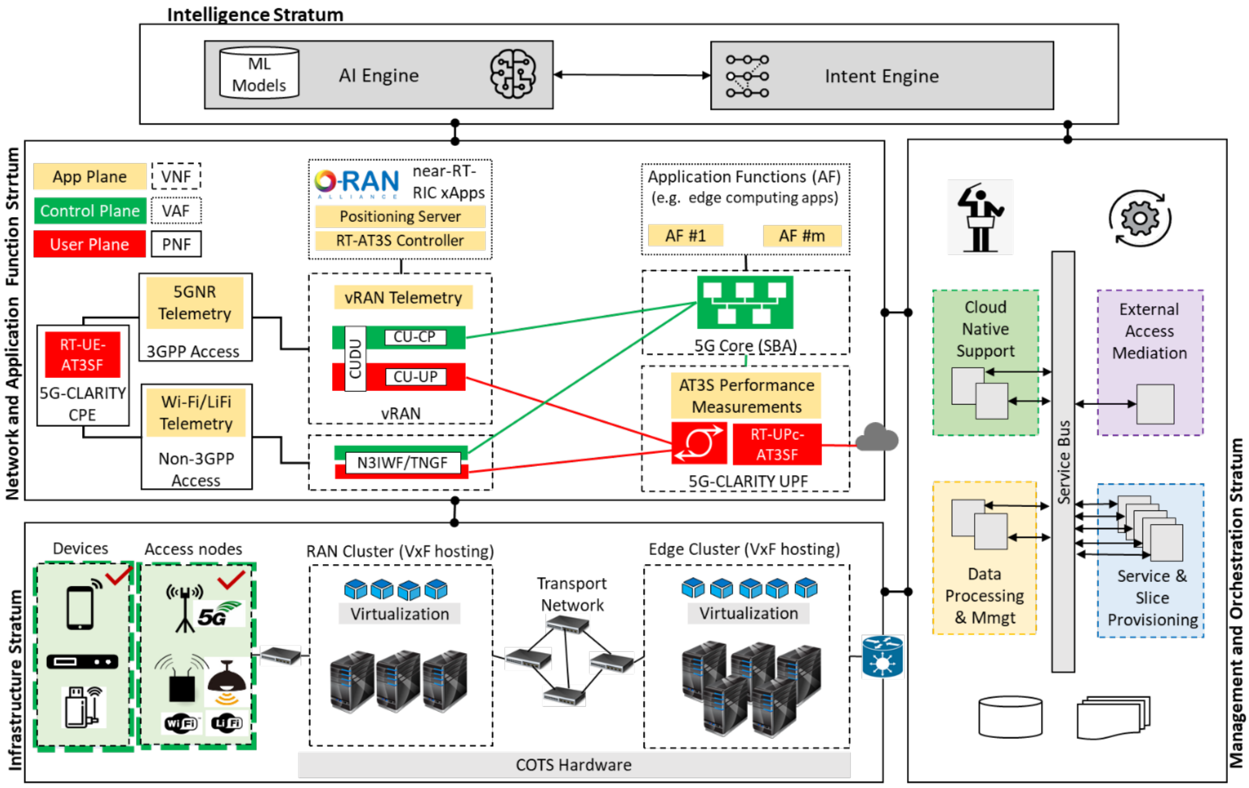


Figure 5-1. 5G-CLARITY system architecture to be used on UC2.2.

5.2.1 Positioning technologies and possibilities for deployment

The positioning technologies that were presented in D3.3, i.e. mmWave, sub-6 GHz and LiFi, would be integrated and shown together in the UC2.2 demo in BOSCH factory in Aranjuez. The deployment options for each technology are given in the sequel.

5.2.1.1 Sub-6 GHz

The sub-6 GHz band is one of the best candidates for positioning, as many current Wi-Fi-like devices are of widespread use and hardware manufactures anticipate integration of positioning algorithms. It is worth mentioning that the implementation of the 5G-CLARITY positioning framework in this band for Wi-Fi standard devices is out of the scope of this project. Therefore, without loss of generality, the developed sub-6 GHz positioning framework will be deployed independently of the existing Wi-Fi networks and will not offer wireless data transmission for the users.

The proposed system, presented in deliverables D3.2 and D3.3, will consist of multiple anchor nodes (AN)[6] or access points (AP) that will be tightly synchronized and will be transmitting frames with precise time stamps. The number of ANs to be deployed is dependent of the area to be covered. For UC2.2 demonstration at BOSCH production floor, only a limited area within the building will be covered due to the limited number of ANs available.

The device acting as the UE is located at the AGV and it will receive the timestamped frames from the different ANs. Based on these, the UE then estimates their time of arrival (ToA) to further estimate its own position. Alternatively, the ToAs can be sent to the localization server and the server will estimate the position of the UE.

[6] The nomenclature followed in this deliverable is that ANs are indeed APs with known position.

For UC2.2 demonstration, a total of 6 ANs and a single UE will be deployed. The coverage area will be not more that 50-100 m^2. Larger areas can be also covered with the same number of ANs but this will reduce the achievable positioning precision, which we would like to keep under 1 meter.

5.2.1.2 mmWave

The mmWave system developed within the 5G-CLARITY project uses a bandwidth of up to 2 GHz in the 60 GHz ISM band (for more details please refer to deliverables D3.2 and D3.3). Such high bandwidth provides the mmWave system with the capability of high precision localization with a positioning error of up to a few centimetres. A typical deployment would consist of a few ANs and UEs. The distance between the ANs and the UEs is measured using two way ranging (TWR) and the position is estimated using trilateration.

With respect to the demonstration, and due to the limited number of mmWave nodes available, the deployment in UC2.2 will comprise 2 ANs and a single UE, being the ANs located at fixed positions while the UE is attached to the AGV. From the distances between the UE and the ANs, the position can be estimated in the UE/ANs or, alternatively, the distances can be transferred to the localization server where the position is estimated. Figure 5-2 sketches the set up at the BOSCH production floor, where two APs will be used for the estimation of the UE at P4. The environment itself adds the constraint of a wall to avoid estimating a wrong position (P3 in the figure).

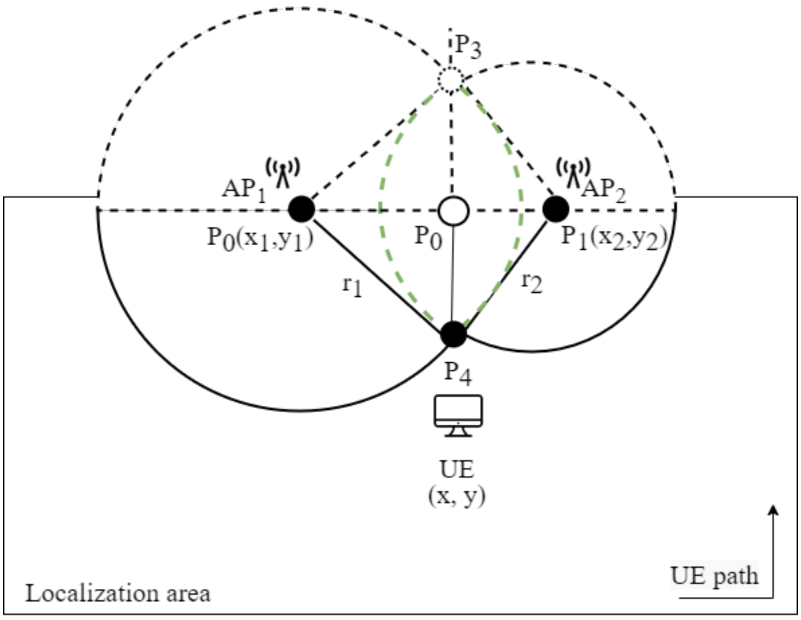


Figure 5-2. mmWave positioning scenario.

5.2.1.3 LiFi

The LiFi system provides primarily a wireless data transmission service to the UEs. In 5G-CLARITY, in addition, this system is also capable of providing a positioning service to the UEs. To do this, the LiFi system uses the RSS to estimate the distances among the UE and the LiFi ANs (see deliverables D3.2 and D3.3 for more details). This approach does not lead to high positioning precision but, instead, it offers a complementary positioning information that can be used to improve the positioning precision in scenarios where the deployment of the other positioning technologies is sparse or not available at all. Additionally, it can be used to cover areas where only lower positioning precision is required.

In the UC2.2 demonstration, a few (2 or 3) ANs will be deployed on the ceiling of the production floor. To better showcase the positioning precision of this technology, it would be suitable to allow for overlapping areas with other technologies, facilitating the demonstration of its performances when working standalone and when working in conjunction with other positioning technologies.

5.2.2 Other relevant developments

5.2.2.1 Localization server

The localization server was assessed in an emulated environment in deliverable D2.3. For the field trial at Bosch production floor, all WATs deployed in this infrastructure will be connected to the localization server. The localization server will be deployed as a virtualized application function in the 5G-CLARITY edge cluster. The server collects all of the localization relevant data from each WAT, in order to perform a position estimate for the given UE (AGV in this case).

5.2.2.2 Visualization tool

Visualization often simplifies the understanding of a complex system. Some visualization tools can also facilitate interactions between an operator and a system, enabling the operator to give inputs to the system and observe the impact instantly. Perhaps one of the most famous and user-friendly visualization tools is Streamlit [30], which is an open-source application framework in Python. It is, in particular, suitable for developing web applications for models involving data analysis, signal processing, and machine learning.

We rely on Streamlit to develop a visualization framework for the Localization server. As shown in Figure 5-3, on the left-hand side, we provide the possibility for the operator to interact with the server. In particular, the user can observe whether the server is active or whether there is a connection between the server and the technologies. Furthermore, for evaluation purposes, one can specify the ground truth trajectory of a user and compare it to the true trajectory, thereby analysing the accuracy of the position estimation. On the right-hand side, the access points, AGV's ground truth trajectory, and AGV's estimated positions are visualized.

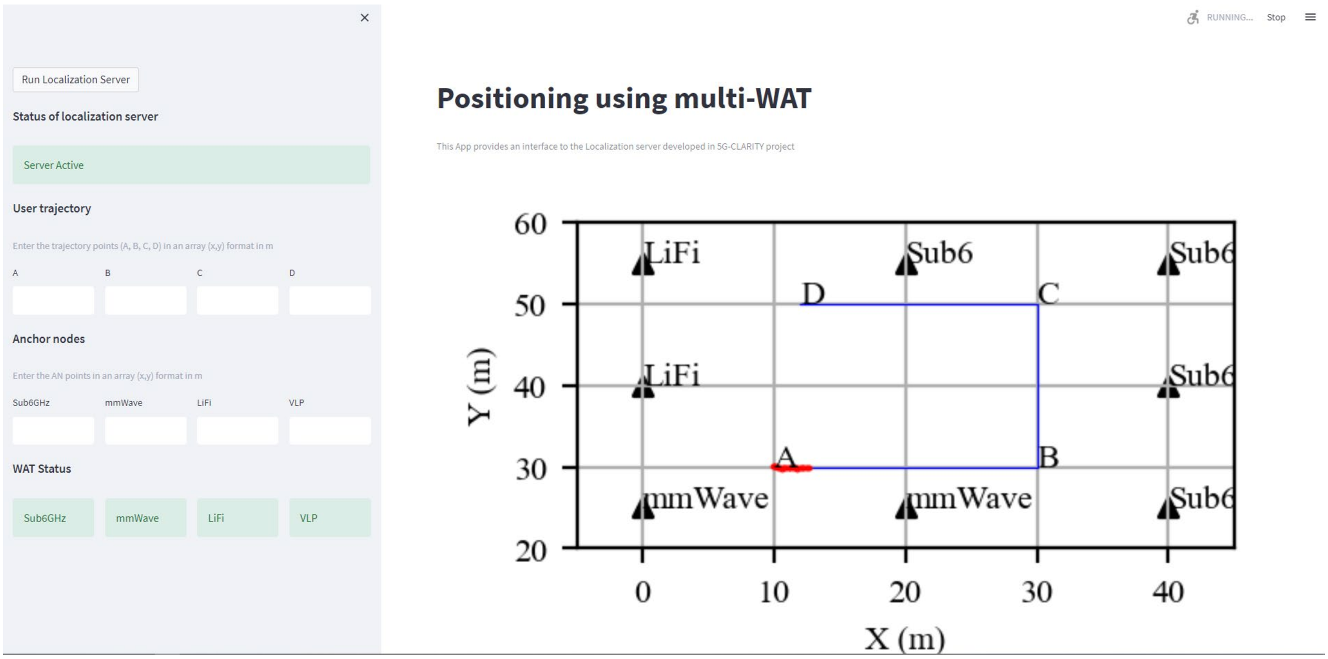


Figure 5-3. A screenshot of the localization server visualization tool.

5.2.3 Validation approach

To validate the feasibility and performance of the multi-WAT positioning approach in laboratory conditions, all the technologies should ideally be deployed at a single physical location and connected to the localization server. The performance of each positioning technology should be evaluated independently and, additionally, it should be also evaluated using the data fusion approach presented in deliverable D2.4 [31].

Due to space limitation in the laboratory at IHP, the LiFi system cannot be validated in lab conditions. This is mainly true for the height available in the lab compared to the one which is available in the Bosch factory. Additionally, the width and length of the available laboratory at IHP do not allow similar deployment as the one at the Bosch factory. Namely, the initial idea is to deploy the technologies with slight overlapping of the coverage areas in order to show how the localization accuracy changes depending on the technologies available. Having the limited size of the available laboratories at IHP, the only possible deployment would be to overlap the coverage areas of all three technologies. Additionally, if the LiFi is not deployed at a similar height as the one available in the Bosch factory, the number of available received signal strength (RSS) levels would be different and the achieved precision would not represent the one that would be available in the factory.

This way, the precision and accuracy of the position estimates extracted from using the Sub-6 and mmWave WATs have been evaluated in a laboratory environment at IHP premises. Results of this evaluation are presented in this deliverable in section 5.4.1.

The LiFi WAT has been tested at PureLiFi premises and it is already installed on the ceiling of the production floor. The assessment of the position estimates will be validated directly at the production floor since the conditions of such environment (height, expected SNRs) cannot be replicated in the lab.

The performance of each of the localization systems will be evaluated at the production floor, and it is as well possible to test the technology along with the localization protocol, i.e. the communication with the localization server. Thereafter, the obtained position estimates could be further incorporated in the models for each of the localization systems developed within D2.4. Subsequently the localization performance of all of the systems working together can be evaluated using the data fusion algorithm.

The testing procedures of the protocol when using the localization server validate that each of these technologies are able to exchange data with the localization server, therefore mitigating any risk stemming from the integration of all systems at BOSCH production floor. The initial on-site integration will take place in early November 2022 at the BOSCH production floor in Aranjuez including all WATs.

5.3 UC2.2 validation scenarios setup

5.3.1 Laboratory Testbed

The localization system shown in Figure 5-4 provides a common framework for enhanced user positioning. The objective of the system is to perform user positioning independently of the underlying WATs. This system is also deployed in laboratory in order to test and evaluate the developed positioning technologies.

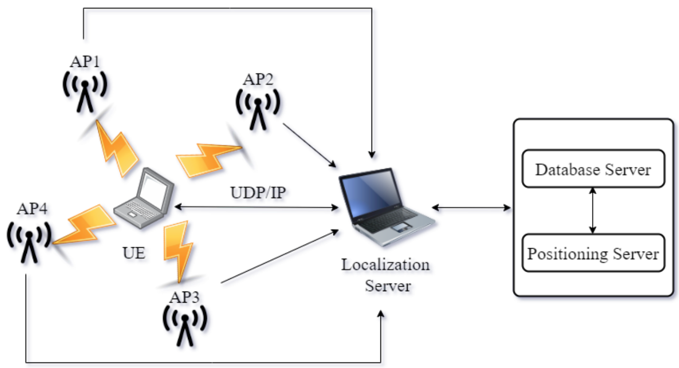


Figure 5-4. Laboratory testbed for testing the developed localization systems

The localization system consists of ANs corresponding to the same or different WATs, a UE, and a localization server. Each WAT delivers the estimated positioning parameters, e.g. obtained via RSS or ToF, to the localization server. Multiple WATs like mmWave, sub-6 GHz and LiFi technologies can be deployed. The localization server controls and processes requests within the localization system framework to calculate the distance between a UE and an AN. In addition, the localization server consists of a database and a positioning server. The former contains information about the AP positions of different technologies and the radio map of the environment, which provides the true UE positions used to calculate the position estimation error. The latter consists of unique positioning algorithms employed by different WATs and the fusion algorithm.

In Figure 5-5 an actual deployment of the sub-6 GHz system is shown. In Figure 5-6, a deployment of the mmWave system, together with a sub-6 GHz node is shown. Both figures show a setup in a single room, where both sub-6 GHz and the mmWave system are deployed.

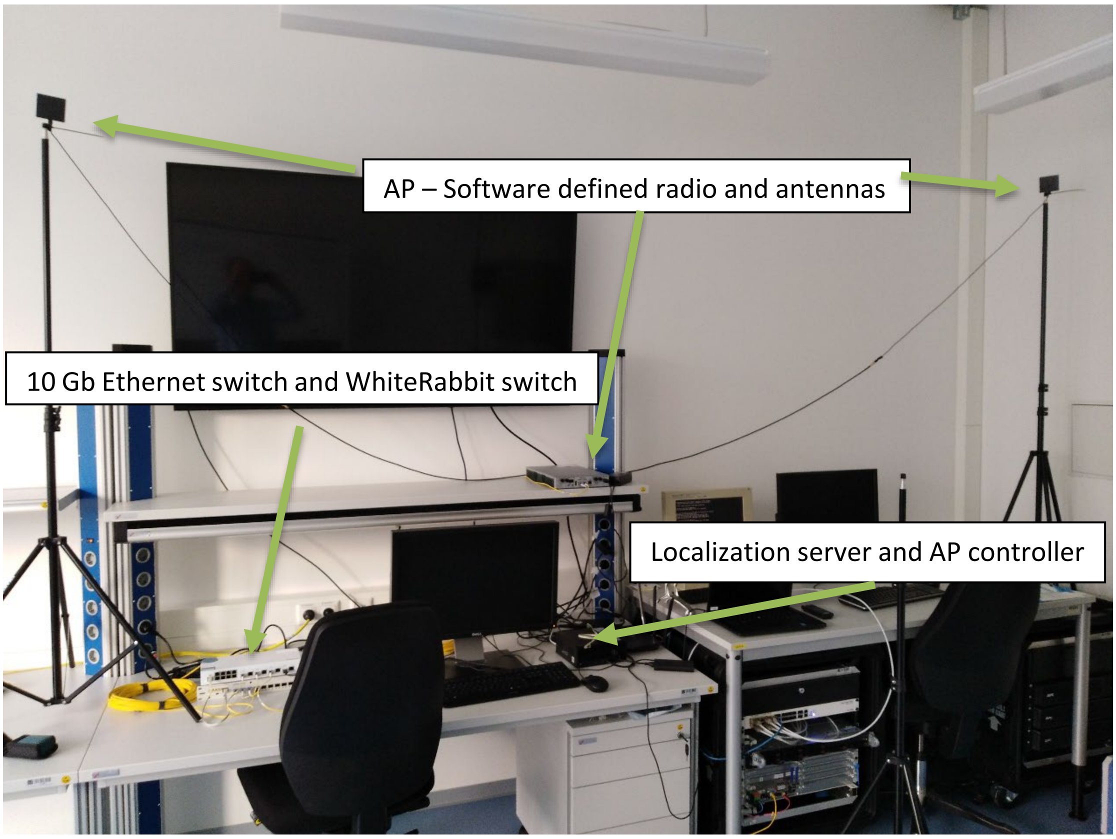


Figure 5-5. Sub-6 GHz localization setup - AN, localization server and AN controller.

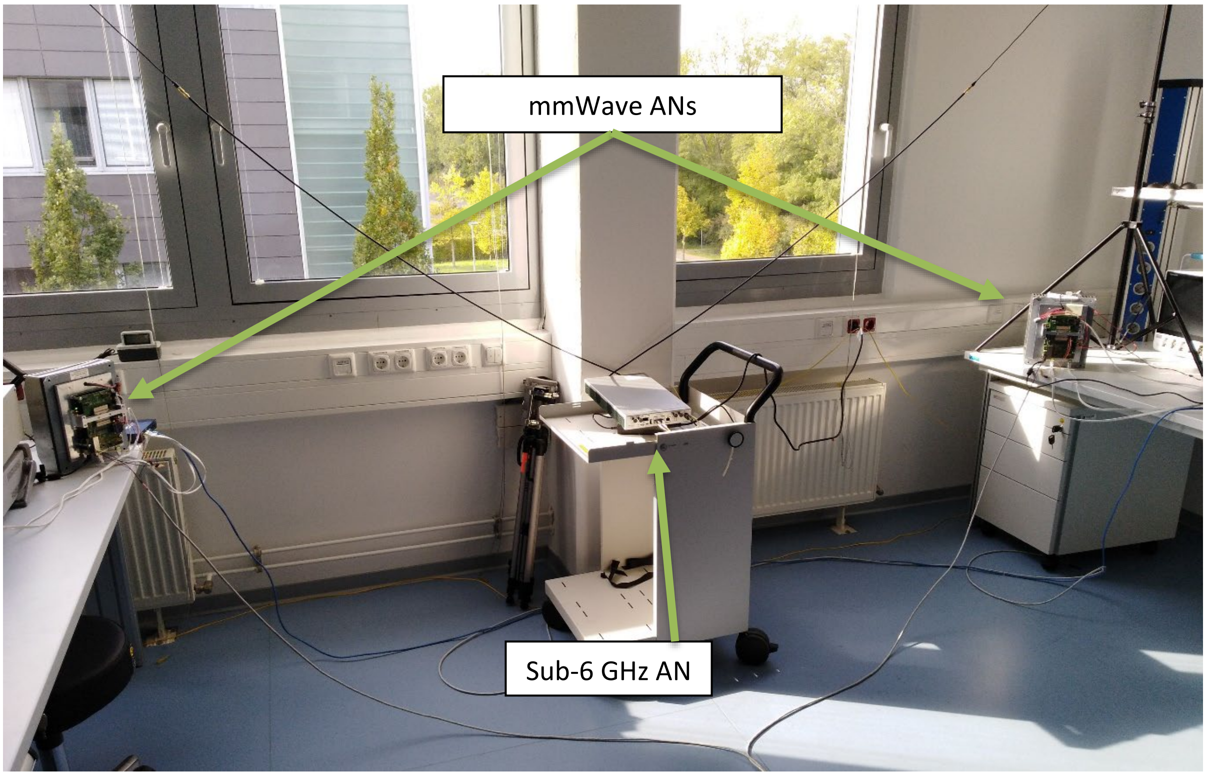


Figure 5-6. mmWave ANs and a sub-6 GHz AN.

To test both systems simultaneously in a common environment, a mobile cart equipped with a sub-6 GHz system and a mmWave system was built, as shown in Figure 5-7. This cart has a sub-6 GHz software defined radio, has a mmWave modem, the necessary power supplies and a large battery needed to power supply the needed equipment. For performing the positioning tests, the cart can be freely moved around in the room.

The configuration of the setup and the positions of the anchor nodes is shown in Figure 5-8. The black triangles are the positions of the sub-6 GHz ANs, a total of 6, and the green triangles are the 2 mmWave ANs. The black straight line represents the boundaries, i.e. the walls of the lab where the experiment is being performed.

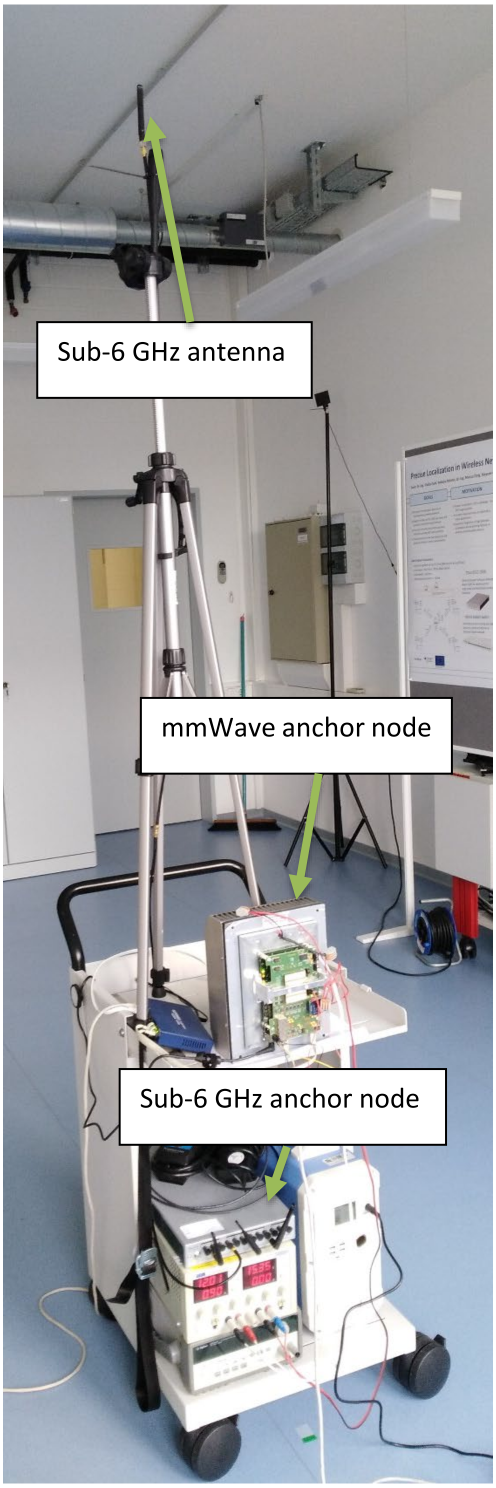


Figure 5-7. Mobile node/UE - mmWave and sub-6 GHz.

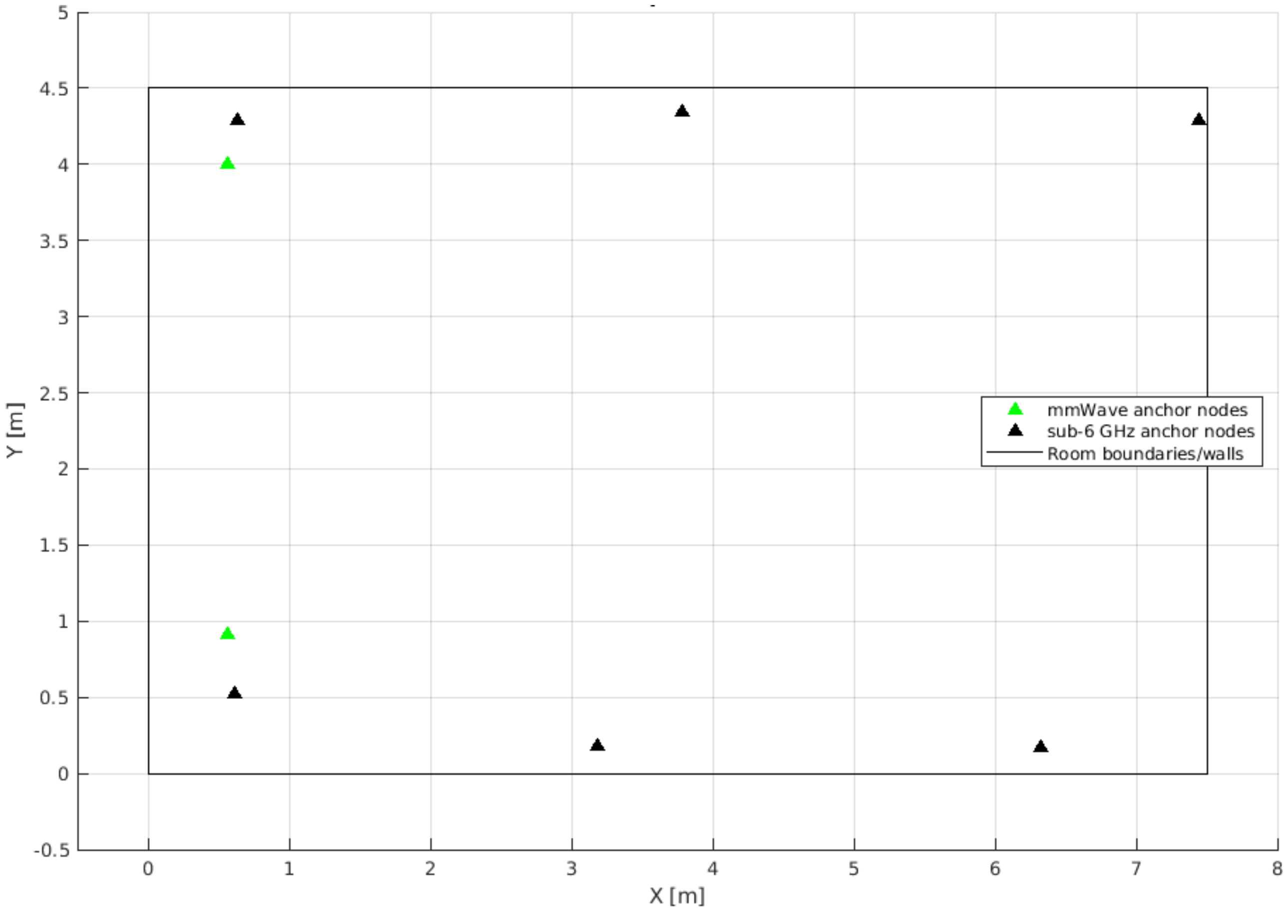


Figure 5-8. Positions of the ANs in the laboratory.

For the localization server, a modified version of the Publish-Subscribe communication protocol is adopted to communicate within the different localization system components. Communication between system components is established by using the User Datagram Protocol (UDP) over the Internet Protocol (IP). Publishers are the message senders, and subscribers are the message receivers. In this architecture, shown in Figure 5-9, the different WATs are the publishers, meaning they publish the distance or position information to the localization server. The subscriber is a component within the system architecture that initiates the UE position request. Unlike the client-server model, the publish-subscribe model does not establish direct contact between publishers and subscribers. The localization server acts as an intermediary entity between subscribers and publishers (cf. Algorithm 1). The server acts as a broker that controls, transmits, receives, and distributes data between the components of the localization system. Subscribers and publishers communicate independently on the basis of the topic-based publish-subscribe architecture. Subscribers send a request to the publishers through the server. The localization server serves as the main component of the architecture of the localization system and provides an interface to subscribers and publishers. The localization server consists of control functions, the user position estimation algorithm independent of the underlying WAT, and a fusion algorithm to obtain higher localization precision. The publishers provide the positioning parameters, i.e., position or distance estimates, using positioning algorithms specific to individual access technologies. Each WAT considers a noise model to obtain a more realistic scenario. The positioning parameters for each of the individual technologies are further fed to the localization server from the publishers, to integrate and estimate a high accuracy user position within the localization server.

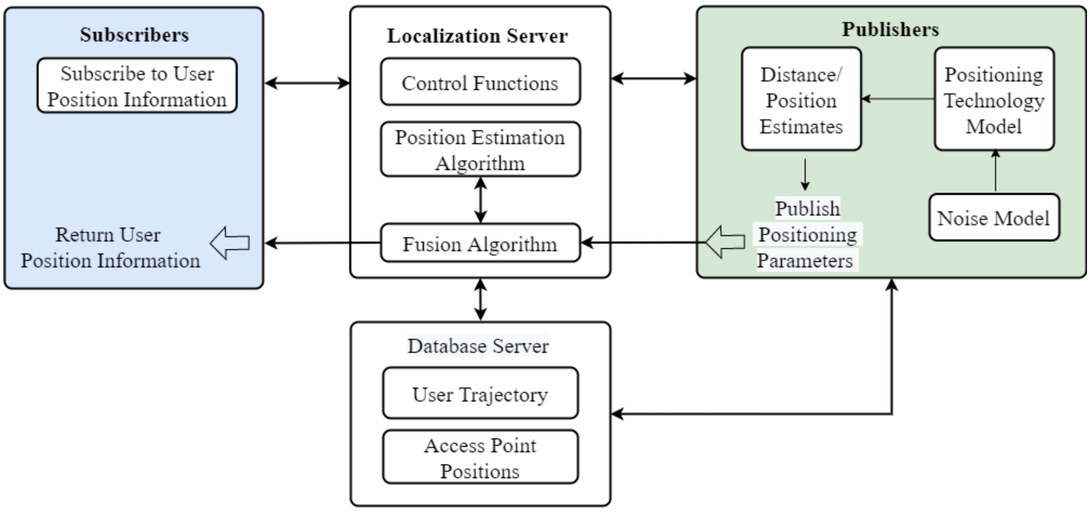


Figure 5-9. Integrated localization system architecture

Algorithm 1 Localization Server Algorithm

```
while Localization Server is listening do
    if Subscriber then
        if Request = Connection Setup then
            Add the Subscriber Information into the server Database
        else if Request = Position Estimation then
            Forward the Subscriber Request to all Publishers
            Wait for response from the Publishers
        end if
    else if Unsubscribe then
        Remove the Subscriber Information from server Database
    end if
    if Publisher then
        if Request = Connection Setup then
            Add the Publisher Information into the server Database
        else if Request = Position Estimation then
            Receive Position Parameters from Publishers
            Fuse the Position Parameters from different Publishers to obtain User Position
            Send the User Position to Subscriber
        end if
    end if
end while
```

5.4 UC2.2 validation results

5.4.1 Sub-6 GHz and mmWave system localization test in laboratory environment

In this section we present the initial tests involving the integrated solution mmWave - sub-6 GHz that have been run at IHP's laboratory. The setup of the test scenario is shown in Figure 5-5, Figure 5-6 and Figure 5-7. The positions of the ANs are shown in Figure 5-8.

During the tests, both positioning systems were running simultaneously and were used for position estimation. Two different tests were performed. The first test is a static test in which the mmWave and the sub-6 GHz UEs are located onto the movable cart, i.e. as in Figure 5-7. The cart was placed at predefined reference points with known coordinates, and both positioning systems performed multiple position estimates. In the second test, the cart with both positioning technologies was moved along a predefined path and the positions were estimated. The second test was performed to evaluate the positioning system in a dynamic environment.

5.4.1.1 Static test

For the first test, a total of 5 different reference positions were defined. The positions are shown in Figure 5-10, depicted with red triangles. Additionally, the coordinates of the positions are given in Table 5-1.

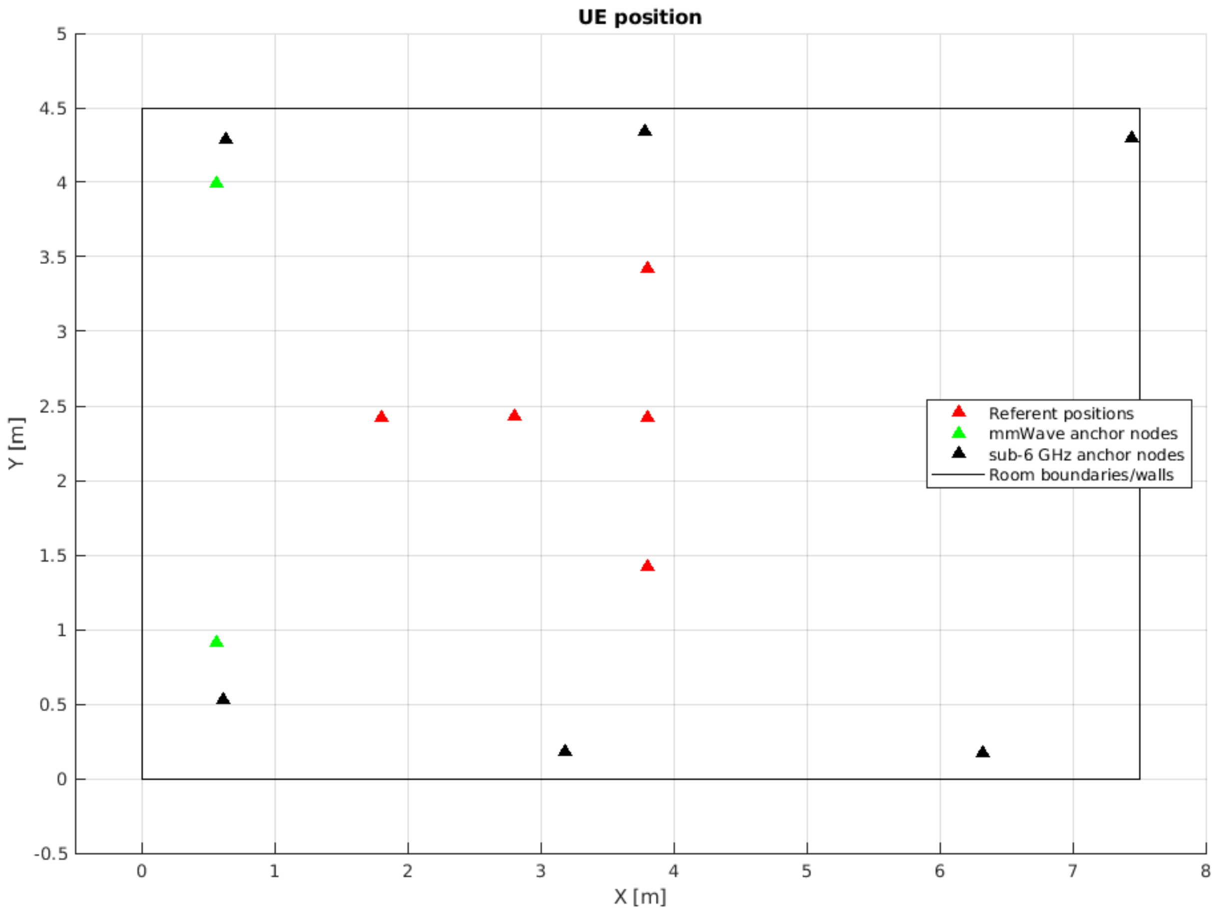


Figure 5-10. Positions of the reference points in the test scenario

Table 5-1. Positions of the reference points

	X [m]	Y [m]
Reference point 1	**2.809**	**2.426**
Reference point 2	**1.809**	**2.426**
Reference point 3	**3.809**	**2.426**
Reference point 4	**3.809**	**3.426**
Reference point 5	**3.809**	**1.426**

For the first test, the cart with the mmWave and the sub-6 GHz system, was moved to each of these points and multiple (approximately 200) position estimates were performed. These position estimates were saved and plotted in a plot similar to that of Figure 5-10. The estimated positions are given in Figure 5-11. As can be noted, the estimated positions match the ground truth accurately. For reference point 1, with coordinates (2.809, 2.426), we created an additional plot, which is shown in Figure 5-12. This is a close up of the position estimates obtained using both technologies. As can be noticed, mmWave position estimates (the green cloud of points) are grouped in a circle with a diameter of less than a centimetre, while the position estimates obtained with the sub-6 GHz system (the blue cloud of points) are distributed within a circle with a diameter of approximately 5 centimetres.

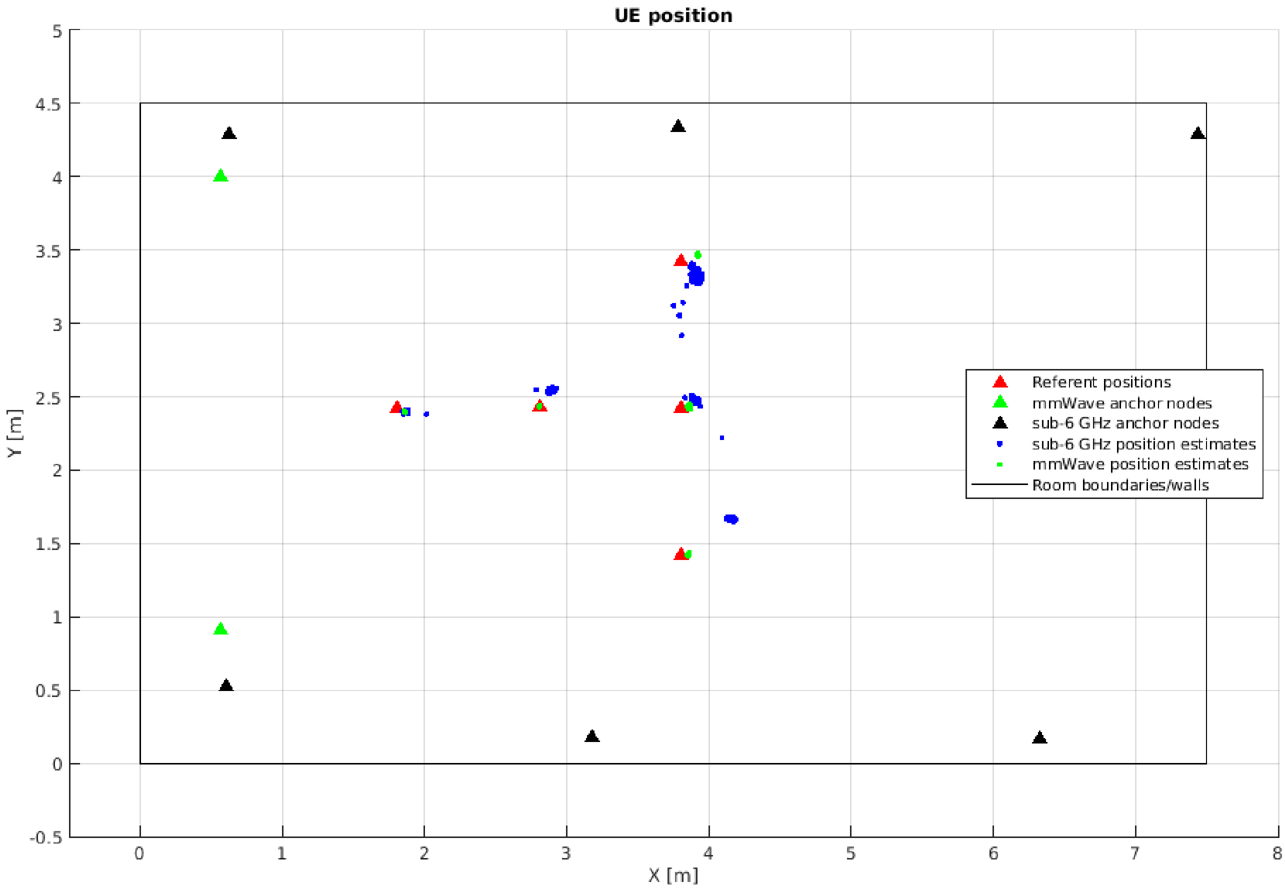


Figure 5-11. Position estimates for the static scenario

It can be noticed from Figure 5-11 that the mmWave position estimates (green points) are well grouped around the reference points (red triangles). This also applies to the sub-6 GHz system, but small deviations are noticeable, especially for the lowest reference point. For this particular case, the deviation is in the order of a few of 10's of centimetres, being generally below half a meter. This is the accuracy of the system and in our test it is better than half a meter. The accuracy for the sub-6 GHz system is strongly affected by the multipath propagation. Namely, this system uses a bandwidth of 160 MHz and cannot resolve multipath components differing in travel path of less than a few meters. This is the reason why its deviations in the position are significant in the sub-6 GHz system. Based on the situation in the BOSCH factory, it is not expected that the performances would be affected significantly. Namely, the space in the production floor is not densely packed, therefore, the path differences between the direct path and the reflections is expected to be significant which would not affect the estimation of the time of arrival of the direct path wave.

The mmWave (60 GHz) system uses much larger bandwidth, i.e. 500-2000 MHz, which allows for resolving the different multipath components that differ in the travelled path of more than a couple of 10's of centimetres. Therefore, in the presence of multipath, the accuracy of the 60 GHz system would be much better.

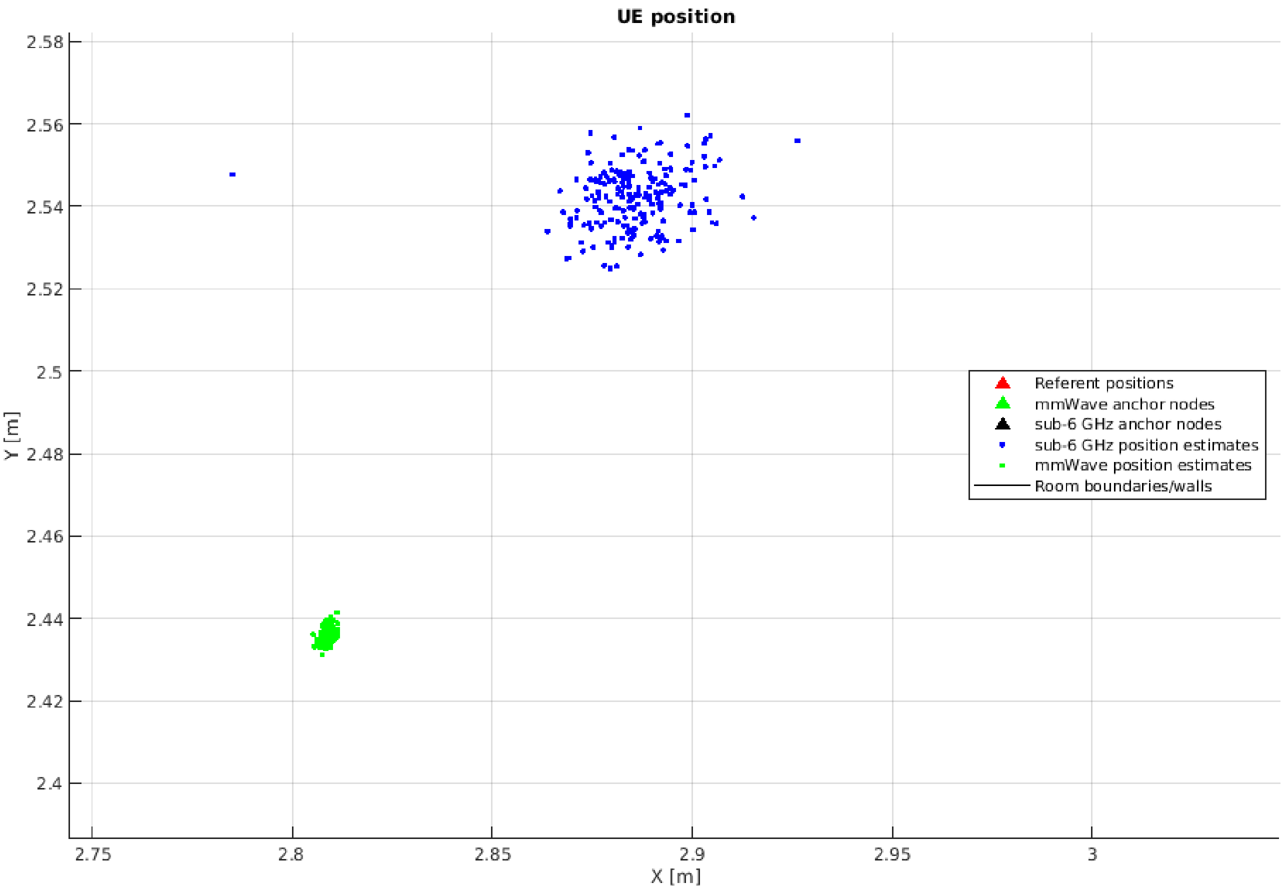


Figure 5-12. Position estimates for the reference point 1

In order to estimate the positioning system precision, the empirical cumulative distribution function (eCDF) for both systems was estimated. The eCDF shows the positioning error distribution around the mean point of all the position estimates for a given reference position. This is a measure for the precision of the system and not for the accuracy.

In Figure 5-13, the eCDF of the position estimation error of the mmWave positioning system is given. Each of the different lines is representing the eCDF of for the positioning error for a single reference point. As can be noticed, 90 percent of the positioning errors are below 1.5 centimetres.

In Figure 5-14, the eCDF functions for the positioning error for positions obtained using the sub-6 GHz system are given. As can be noticed, 90 percent of the errors are smaller than 3.5 centimetres. This is again due to the lower bandwidth used by the sub-6 GHz system compared to that of the mmWave system.

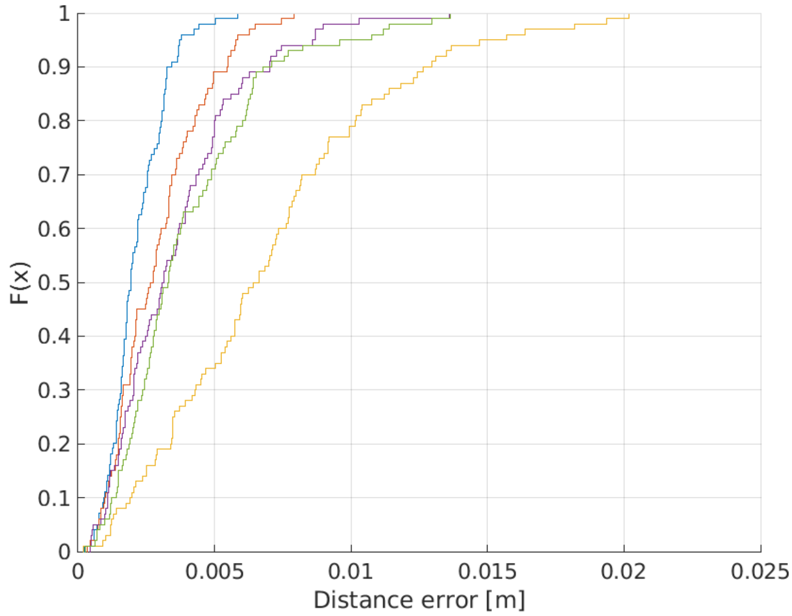


Figure 5-13. Empirical cumulative distribution function (eCDF) of the positioning error of the mmWave system

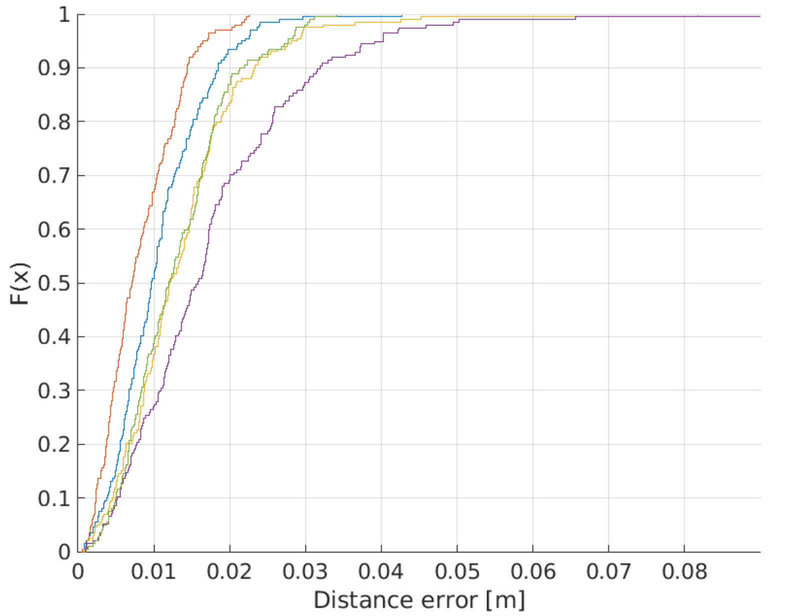


Figure 5-14. Empirical cumulative distribution function (eCDF) of the positioning error of the sub-6 GHz system

5.4.1.2 Dynamic test

Finally, both systems were tested in a common scenario, where both systems – mmWave and sub-6 GHz – are mounted on the mobile cart (see Figure 5-7). The cart was moved along a path describing the letter "L" rotated for 90 degrees, counterclockwise, starting from the topmost reference point and ending to the leftmost reference point. During this movement the position of the cart is continuously estimated by using both mmWave and sub-6 GHz technologies. We provide a single run, in order to compare clearly the estimation errors of both technologies. Previously, multiple runs have been carried out to fine tune the algorithms' tolerance of the algorithms under different signal conditions (e.g. different signal strength – near/far; multipath propagation etc.)

The obtained results are provided in Figure 5-15. The green line describes the path estimated using the mmWave system, while the blue path is the path estimated by the sub-6 GHz system. As can be noticed, both paths overlap and represent the real movement. It should be noted that, since the cart is moved manually, the path at which the cart moves is not ideal, since it is not possible to manually move the cart along a straight line. Nevertheless, it can be noticed that the positioning accuracy in this case is better than a half meter for the sub-6 GHz system and even more accurate when using the mmWave system.

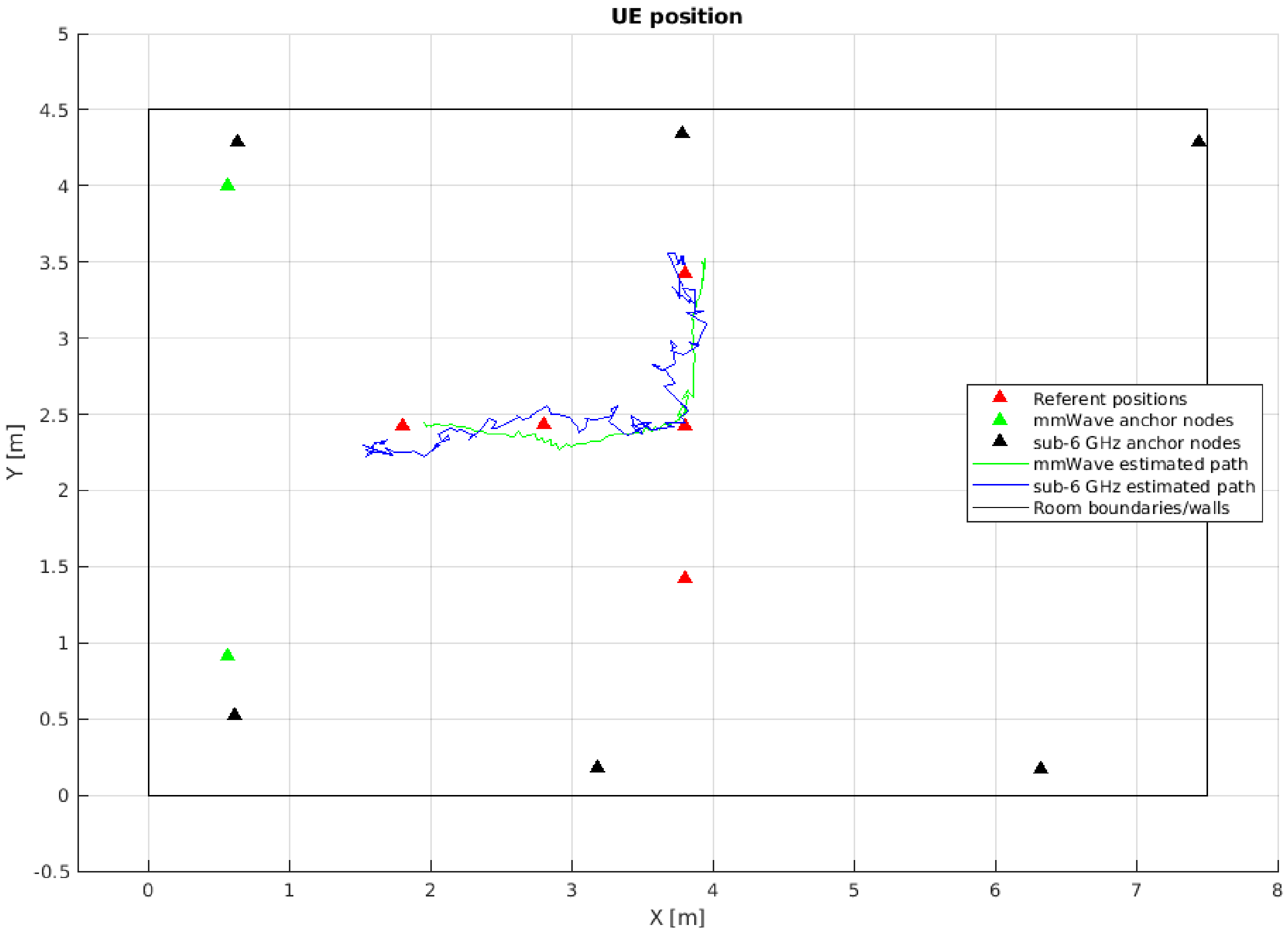


Figure 5-15. Estimation of the path followed by the cart in a mobile scenario

5.4.2 Evaluating the overall localization system architecture

In this section, the positioning system architecture is evaluated, where each of the WATs, i.e. mmWave, and Sub-6 GHz, are emulated based on the measured results, in order to provide the distance estimates. The uncertainty in the measurements is introduced as a function of the distance estimates from individual ANs. The uncertainties of the distance estimates of the individual technologies are available at the localization server. The data about the uncertainty of the distance estimates obtained by the partners responsible for the positioning technologies was used for emulation of the technologies and evaluation of the performance of the overall system.

The localization system has been further evaluated with the publish-subscribe communication protocol, the localization server, the different WATs, and the UE. The cumulative probability density (CDF) of the positioning estimation error is computed using the data available at the localization server. The position estimate using the individual technologies was performed using the non-linear least squares (NLLSQ) method. The distance estimates from individual technologies were merged using Bayesian recursive filter (BRF). The sub-6 GHz and mmWave systems show a mean positioning error of 5 cm and 2 cm respectively. The positioning error of individual technologies is dependent on the uncertainties Introduced in the distance estimates of the ANs. Additionally, we can also observe that the fusion of positioning estimates reduces the average positioning estimation error to around 1.5 cm, improving the overall positioning precision.

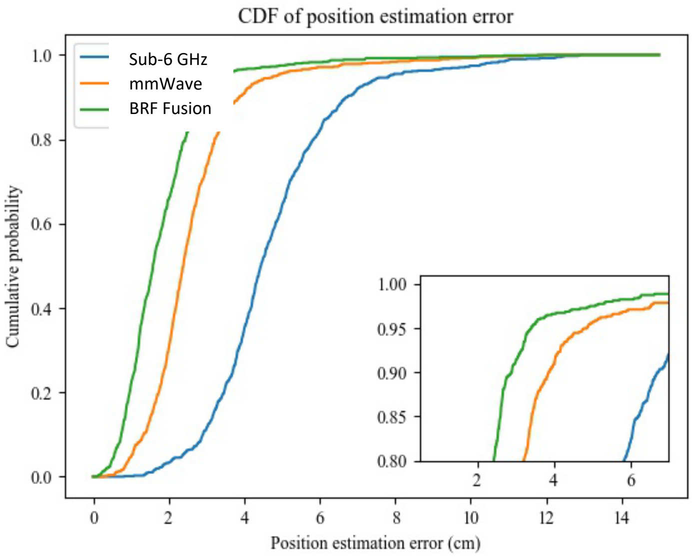


Figure 5-16. Performance of the overall simulated system, using the measured positioning technology parameters.

5.5 Update on demonstration risks and mitigation plans

We provide in this section an update on the UC2.2 related risks that we identified in D5.1 [2].

Risk ID	Description	Impact	Status in D5.2
UC2.2-R1	Delays in the integration of the 5G-CLARITY technologies in use case site	Low	A progressive roll-out of technologies will be considered that can be used to validate the intended KPIs. KPI validation will be performed as soon as the required technology is deployed.
UC2.22-R2	AGV power limitations to supply 5G-CLARITY modems	Low	Use batteries to power 5G-CLARITY WATs and the necessary devices (switches, C&S, etc.).
UC2.2-R3	Problems with the attachment of units to the ceiling/wall of the production building	Low	LiFi WATs are already attached to the ceiling. To facilitate the normal operation of the production floor we have decided to place the remaining WATs (Sub-6 and mmWave) on stands/tripods that can easily be deployed/relocated.
UC2.2-R4	Additional wireless equipment for 5G-CLARITY mounted on AGV will be exposed to outdoors environment conditions and vibration.	Low	The wireless equipment will only be exposed to the indoor environment of the production floor.
UC2.2-	Problems with the	Low	Server already deployed and the amount of ports/cables and

R5	connectivity between server and WATs due to lack of ports, cabling, etc.		switching devices has been already accounted for.
UC2.2-R6	5G-CLARITY network makes interference for the existing wireless network and equipment	Low	Wi-Fi spectrum planning already carried out not to interfere with the spectrum planning of the production floor and that of UC2.1.
UC2.2-R7	Positioning is not as precise as required due to non-optimal placement or insufficient number of APs, i.e. wireless nodes, etc.	Low	Area for the demo already surveyed. The placement of sub-6 and mmWave WATs on tripods allow for a flexible deployment aside the AGV path in the designated area. The number of anchor nodes has already been fixed to provide precise positioning results given the selected area.
UC2.2-R8	If proprietary frames are used, CSMA/CA would be challenging to implement with SDRs	Low	To avoid collisions with existing Wi-Fi and other systems in the factory, the partners involved have already evaluated which channels will be used in the ISM band.
UC2.2-R9	Use of cable-based synchronization for mmWave nodes	High	Due to limited space on the field programmable gate arrays (FPGA), on the mmWave modems, it is challenging to implement additional synchronization procedures. Larger FPGA device is needed, but a larger FPGA with the same footprint is not available from the manufacturer.
UC2.2-R10	Less Sub-6 spectrum available	Medium	The availability of less spectrum (less than 160 MHz that USRP 321 is able to offer) would lead to achieving worse localization precision at Sub-6, which can be improved using mmWave.
UC2.2-R11	Increased multipath present in the production floor than expected	Medium	Increased multipath in such an environment is an expected effect that can be compensated by setting the ANs and UE at higher positions.
UC2.2-R12	Low availability of AGV to perform tests in the factory	Low	The AGV will be available during the mornings to perform tests. A cart will be attached to the AGV, as this cart will host the WATs installed at the AGV. Whenever the AGV is not available we can use the cart alone throughout the AGV path.

5.6 Conclusion

The availability of multiple WATs capable of offering positioning estimates is key for improving the position precision in indoor environments. This section proposes an architecture for a generalized localization system that interfaces different WATs and is able to merge/fuse the position estimates to improve the overall localization performance. The localization server has been proposed to act as an interface to control the localization requests and to combine multiple position estimates into an enhanced user location estimate. We evaluated this architecture in a simulated environment and in a real laboratory environment, resulting in an improved localization accuracy with a fusion of distance estimates from individual WATs. This positioning system will be tested in an operational environment (BOSCH production floor) in November 2022.

6 Summary and Concluding Remarks

Prior to the final demonstrations, Deliverable D5.2 seeks to demonstrate the integration of key 5G-CLARITY enablers in a controlled laboratory setting. These elements were identified in WP2 and designed and assessed in WP3 and WP4 utilising equipment that was available or through simulation.

In contrast to earlier evaluations, which were done for transversal KPIs, we mainly present in this deliverable the evaluation of specific KPIs for the use cases taken into consideration for the project. The evaluation of the majority of the KPIs assessed has been made by using the integration of the equipment that will be deployed at the venues.

This document describes the components of the unified 5G-CLARITY architecture that are required for each use case, showing its versatility, and illustrating how it can be adapted according to the specific requirements of a particular deployment. Moreover, we describe the precise equipment that will be installed at the venues. In this regard, we present several CPE's hardware configurations that are compatible with the 5G-CLARITY architecture.

In addition to D5.1, D5.2 aims to provide the inputs for D5.3 and D5.4, devoted to the final demonstrations and transversal as well as use case specific KPIs. Therefore, for each case we present the layout and installation details at the venues, and we provide additional and updated risks mitigation plan.

In this deliverable we established the connection between two UC1 demonstration narratives and the 5G-CLARITY final system architecture. We also reported the integration of the Accelleran 5GNR solution to the UC1 Lab setup in Bristol and presented our initial validation results from this integration.

In this document we report on the integration in the i2CAT laboratory of the 5G-CLARITY platform components required to support UC2.1. Using this platform we validated in the lab three 5G-CLARITY technical concepts: i) multi-WAT connectivity from the CPE, ii) infrastructure slicing supporting the SNPN and the PNI-NPN slices, and iii) end-to-end slicing connecting the PNI-NPN slice to the 5TONIC infrastructure. We also reported on the development of the applications required to support the demonstrations, namely the UL measurement toolkit for the SNPN slice and the computer vision application for the PNI-NPN slice.

The main priority to continue developing UC2.1 is to deploy the equipment in the BOSCH factory and carry out an extensive site survey. A major risk has been identified in this regard, which is problems in the integration of the Benetel n78 radio required for the demonstration.

Finally, for UC2.2 we have reported the results of the integration at IHP's labs of a localization server based on a publish-subscribe protocol which fuse the position estimates based on different WATs (mmWave and Sub-6 GHz). We have also described the localization server and the visualization tool that will be used in the final demonstration. We have conducted experiments in the laboratory with the equipment to be deployed for the pilot. The experiments comprise the evaluation of the positioning estimation error for static and moving UEs, using the fusing approach defined for 5G-CLARITY. The experimental results show that estimation calculated by fusing the measurements from the different WATs improves the overall localization performance to and mean positioning error of 1.5cm.

Our next steps for UC2.1 and UC2.2 are focused on installing and fine tuning at BOSCH's factory the integrations validated in D5.2. For UC1, we need to finish the full installation at the venue, and fine tune the configurations, to perform the KPIs' measurement. At the time being, the installations and firsts measurements have started.

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