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SEamless integratioN of efficient 6G WirelesS tEchnologies for Communication and Sensing

D5.2 Report on the integration of 6G-SENSES technologies

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Editor(s):	Germán Castellanos (**ACC**)
Authors:	Germán Castellanos (**ACC**), Federico Trombetti, Salvatore Pontarelli, Novella Bartolini (**UNIROMA1**), Khai Nguyen, Mikel Irazabal, Navid Nikaein (**BR**), Vladica Sark, Batuhan Sütbas, Jesús Gutiérrez (**IHP**), Muhammad Umar, Sajjad Ahmad, Padmanava Sen (**BI**), Luis Díez, Neco Villegas, Ramón Agüero, Ignacio Santamaría, Jesús Ibáñez (**UC**), Xi Ding, Nils Hildebrand, Eduard Jorswieck (**TUBS**), Ioanna Mesogiti (**OTE**), Pavlos Doanis, Markos Anastasopoulos, Anna Tzanakaki (**IASA**), Yazhou Zhu, Jessica Sanson, Valerio Frascolla (**INT**), Muhammad Saadi, Shahid Mumtaz (**NTU**).
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Executive Summary

This deliverable presents the current status of the integration of the 6G-SENSES technologies, marking the transition from the architectural design and specification phase to the implementation of interoperable experimental platforms. The work performed within WP5 demonstrates substantial progress towards the realisation of the 6G-SENSES vision, while also highlighting the challenges inherent in integrating heterogeneous technologies into cohesive end-to-end (e2e) systems.

A structured and iterative integration methodology has been adopted, enabling the progressive consolidation of components across the Radio Access Network (RAN), Core Network (CN), and Intelligent Plane. The use of O-RAN principles has provided a modular and programmable framework that facilitates component integration and flexibility. However, achieving full interoperability among solutions developed by different partners remains a significant challenge, particularly regarding interface harmonisation, data model consistency, synchronisation, and coordination across system components.

The three project Proofs of Concept (PoCs) have reached different levels of maturity and provide complementary validation of key 6G-SENSES concepts. PoC#1 "Multi-Technology ISAC Platform" has achieved an advanced integration stage, demonstrating the feasibility of combining multiple wireless access technologies with sensing capabilities and validating the potential of Integrated Sensing and Communications (ISAC) for enhanced network awareness and optimisation. PoC#2 "Cell-Free MIMO Prototype" has successfully demonstrated distributed radio functionalities, including synchronisation, beamforming, and RIS-assisted transmission, while highlighting the need for tighter integration between physical-layer innovations and higher-layer control mechanisms. PoC#3 "Network Digital Twin via RAN Sensing" represents the most ambitious integration effort and remains under active development, with initial achievements in telemetry collection and model generation. Further work is required to ensure model accuracy, maintain consistency between physical and virtual environments, and enable reliable closed-loop operation.

The integration activities have identified several cross-cutting system-level challenges, including interoperability limitations, data consistency and quality issues, scalability constraints associated with distributed processing and AI/ML-driven optimisation, and stringent timing and synchronisation requirements for real-time and near-real-time control loops. Although mitigation measures have been defined and partially implemented, these challenges reinforce the need for continued integration and validation efforts.

Despite these challenges, the project has established a solid foundation for the next phase of testing and evaluation. A common testing framework and methodology has been defined and is being progressively applied across all PoCs, enabling a consistent assessment of performance and functionality. Initial testing activities have already started, while comprehensive validation campaigns will follow the completion of ongoing integration work.

Overall, the integration results provide encouraging evidence that the 6G-SENSES vision—combining sensing, communications, and AI-driven intelligence within a unified architecture—is technically feasible. At the same time, they underline the gap that remains between conceptual designs and fully operational, scalable, and robust systems.

The next phase of the project will focus on completing integration activities, extending testing to realistic and dynamic scenarios, improving system robustness and scalability, enhancing AI/ML-based optimisation mechanisms, and validating end-to-end performance against the defined KPIs. These activities will be essential for demonstrating the practical viability, performance, and impact of the 6G-SENSES technologies and for advancing the development of intelligent, adaptive, and energy-efficient 6G networks.

1 Introduction

The 6G-SENSES project aims to advance beyond current 5G capabilities by introducing a unified and intelligent architecture that seamlessly integrates communication and sensing functionalities. Building upon the architectural foundations defined in Work Package 2 (**WP2**) and the technological developments of **WP3** and **WP4**, **WP5** focuses on the integration, validation, and demonstration of these innovations through a set of Proofs of Concept (PoCs).

Deliverable **D5.1** [1] established the design, specification, and planning of the PoCs, including their functional architecture, key components, and evaluation methodologies. In contrast, this deliverable (**D5.2**) focuses on the integration phase, reporting on how the different technological components are being interconnected, deployed, and prepared for experimental validation across the project testbeds. The integration activities in **WP5** are centred around three complementary PoCs, each addressing a distinct aspect of the 6G-SENSES vision. These PoCs collectively demonstrate the feasibility of combining advanced Radio Access Network (RAN) technologies, sensing capabilities, and AI-driven intelligence within a unified framework.

The primary objective of the integration activities is to ensure that the individual components developed across the project are combined into cohesive and interoperable end-to-end (e2e) systems. This involves not only the physical and logical interconnection of hardware and software elements, but also the alignment of interfaces, data models, and control mechanisms across multiple architectural layers, including the RAN, CN, and Intelligent Plane. A key aspect of this integration is the adoption of Open RAN (O-RAN)-based principles, enabling modularity, openness, and programmability using xApps/rApps and standardised interfaces. Additionally, the integration process incorporates AI/ML-driven functionalities, particularly within the Intelligent Plane, to support data-driven optimisation and decision-making. The integration is being carried out in an iterative and incremental manner, following the methodology defined in deliverable **D5.1** [1]. Initial efforts have focused on component-level validation and interface definition, followed by progressive system-level integration across different testbeds. This approach ensures that interoperability issues are identified at early stages, and are resolved efficiently, while enabling continuous refinement of the system.

Across the three PoCs described in the follow subsections, the project is transitioning from component-level development to system-level integration and validation. While PoC#1 and PoC#2 have reached a higher level of integration maturity, PoC#3 represents a more dynamic and evolving system, driven by data-centric and AI-based processes.

1.1 PoC#1 – Multi-Technology ISAC Platform

PoC#1 focuses on the integration of multiple Wireless Access Technologies (WATs) to enable Integrated Sensing and Communication (ISAC) capabilities. It combines Sub-6 GHz, mmWave, and Wi-Fi technologies, along with radar-based sensing, within an O-RAN-compliant architecture.

The integration of PoC#1 is currently at an advanced stage, with key components such as sensing-enabled RAN elements, xApps for data processing and control, and multi-technology interfaces already deployed and interconnected. Several subsystems, including sensing data acquisition, MAC-level optimisation, and Wi-Fi-based sensing extensions, have been successfully integrated and validated in controlled environments.

Ongoing activities focus on refining interoperability between heterogeneous technologies, improving the fusion of sensing and communication data, and finalising e2e integration across the testbeds. Initial testing and small-scale demonstrations have been conducted, with further validation activities planned to assess performance under more complex scenarios.

1.2 PoC#2 – CF-MIMO Prototype

PoC#2 addresses the implementation of a Cell-Free Multiple-Input Multiple-Output (MIMO) (CF-MIMO) system enhanced with real-time control and optimisation capabilities. It integrates distributed radio units (RUs), Software Defined Radio (SDR) platforms and advanced signal processing techniques, including beamforming and over-the-air reciprocity calibration algorithms.

The integration of PoC#2 is well progressed, with the core hardware and software infrastructure deployed and operational. Key functionalities, such as distributed beamforming, synchronisation mechanisms, and RIS-assisted transmission, have been successfully implemented and are being integrated with higher-layer control components, including the Near-RT RAN Intelligent Controller (RIC).

Current efforts are focused on tight integration between PHY-layer innovations and control-plane functionalities, ensuring seamless interaction between SDR-based implementations and O-RAN interfaces. Validation activities are being progressively expanded to evaluate system performance across different configurations and scenarios.

1.3 PoC#3 – Network Digital Twin (NDT) via RAN Sensing

PoC#3 introduces a Network Digital Twin (NDT) framework that leverages RAN sensing data to model, simulate, and optimise network behaviour. The PoC integrates telemetry collection, simulation environments, and AI/ML-based modelling within an O-RAN architecture.

PoC#3 is currently in an active development and integration phase, with key components such as the Modelling xApp, telemetry ingestion mechanisms, and simulation frameworks being interconnected. Initial datasets have been collected, and early versions of the NDT models are being generated and stored for further refinement. Special attention is paid to the integration of the Intelligent Plane, which supports data processing, model training, and continuous model updating. The system is evolving towards a closed-loop operation, where models are created, validated, and applied to optimise real network configurations.

At this stage, integration efforts are focused on ensuring data consistency, model accuracy, and interoperability between real network measurements and simulation outputs. Initial validation activities are underway, with full closed-loop optimisation to be demonstrated in the final phase.

The integration activities reported in this deliverable provide a consolidated view of how the 6G-SENSES architecture is being realised in practice, highlighting both the achieved progress and the remaining challenges. This work lays the foundation for the final testing, evaluation, and demonstration activities, which will be further detailed in deliverable **D5.3**.

1.4 Organisation of the Document

This deliverable is structured as follows:

- Chapter 2 presents the mapping of the integration and testing activities to the 6G-SENSES architecture. It describes the adopted methodology, including the testing framework and evaluation cycles, and positions the PoCs within the overall system architecture.
- Chapter 3, Chapter 4, and Chapter 5 provide detailed descriptions of the integration activities for PoC#1, PoC#2, and PoC#3, respectively. Each chapter outlines the implementation approach, integration status, demonstration activities, updated planning, and associated risks and mitigation measures.
- Finally, Chapter 6 summarises the main outcomes of the integration activities and outlines the next steps towards the final validation and demonstration of the 6G-SENSES technologies.

2 Architectural Mapping and Testing activities

This chapter provides a comprehensive mapping between the integration and testing activities carried out in **WP5** and the overall 6G-SENSES architecture defined in previous deliverables. The objective is to position the developed PoCs, experimental setups, and evaluation methodologies within the multi-layered 6G-SENSES framework, ensuring consistency with the architectural principles established in **WP2** and the technological enablers developed in **WP3** and **WP4**. This chapter outlines how the different components, platforms, and functionalities implemented across the PoCs are aligned with the 6G-SENSES architectural layers, including the RAN, CN, Intelligent Plane, and application domains. It further describes how these elements interact through well-defined interfaces and control loops, enabling the integration of sensing, communication, and AI-driven optimisation capabilities.

Additionally, this chapter introduces the adopted testing and evaluation methodology, highlighting the iterative and modular approach followed throughout the project. By linking experimentation activities with architectural components, this section establishes a clear traceability between design, implementation, and validation phases, thereby ensuring that the developed solutions are assessed within a coherent and system-level perspective.

2.1 Mapping to 6G-SENSES Architecture

Figure 2-1 depicts the 6G-SENSES multi-layer, multi-technology architecture, revised in deliverable D2.3 [2]. It is aligned with O-RAN and 3GPP standards to deliver ISAC capabilities and to expose sensing information both within the system and to third-party applications.

The design follows the O-RAN model, which disaggregates traditional RAN functions and incorporates software-defined intelligence and advanced control mechanisms. A disaggregated gNodeB (gNB) comprises the Radio Unit (O-RU), O-DU, and Central Unit (O-CU), interconnected through standardised fronthaul (FH) and F1 interfaces. The figure incorporates the mapping of the different project PoCs to the architecture.

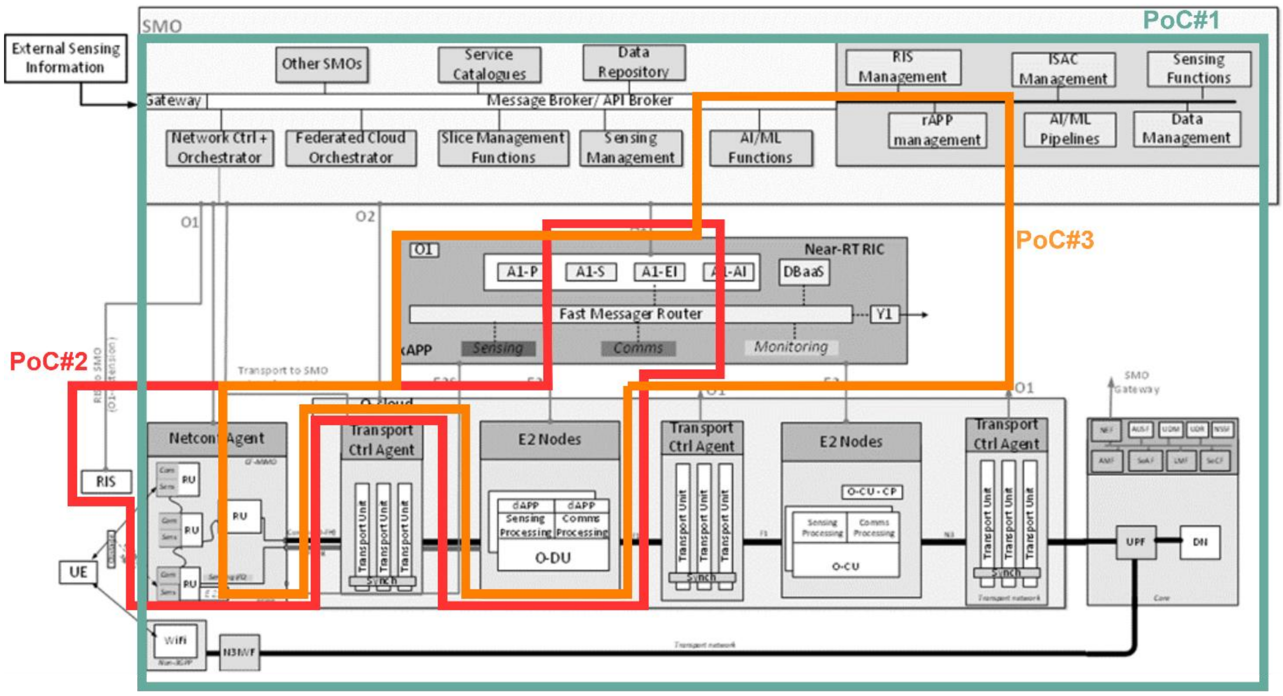


Figure 2-1 Multi-layer 6G-SENSES Architecture and mapping of PoCs

2.2 Testing Activities

2.2.1 Planning, Definition and Testing

The testing methodology adopted in 6G-SENSES follows a structured and iterative approach, based on three main phases: **Design, Implementation, and Testing**, as previously detailed in deliverable **D5.1** [1]. This methodology ensures consistency, reproducibility, and alignment across different testbeds, use cases, and PoCs.

The **Experimentation Design phase**, including the definition of testing frameworks, scenarios, objectives, and required infrastructure, has been completed during the preparation of **D5.1**. It involved the coordination among project partners to define the overall experimentation strategy, identify the System Under Test (SUT) and Device Under Test (DUT), and establish the required tools, datasets, and test conditions.

The **Experimentation Implementation and Integration phase** is currently in its final stages and constitutes the main focus of this deliverable. At this stage, the previously defined experiments are being fully integrated across the different platforms and testbeds. This includes the deployment and interconnection of system components, alignment with the 6G-SENSES architecture, configuration of network elements, and preparation of e2e experimental setups. Particular emphasis is placed on ensuring interoperability between components developed in different WPs, as well as on validating the correct operation of the integrated system.

The **Experimentation Testing phase** is being progressively initiated following the integration activities. This phase will involve the execution of the defined test scenarios, collection of telemetry and performance measurements, and evaluation of results against the predefined KPIs. Initial testing activities are already underway, while full-scale evaluation campaigns will follow once integration is fully completed.

Overall, this deliverable focuses on the transition from design to integration and validation, providing a consolidated view of how the planned experiments are being realised in practice. This approach ensures that the 6G-SENSES technologies are not only conceptually validated (as in **D5.1** [1]), but also effectively integrated and ready for systematic testing and evaluation.

2.2.2 Testing/Evaluation Cycles

The overall testing and evaluation cycles adopted in 6G-SENSES are structured into three main stages (see Figure 2-2): Solution Development, Component Integration & Evaluation, and Vertical Applications & Services Life Cycle Management (LCM). These stages define a comprehensive and iterative methodology for the validation of 6G-SENSES technologies.

The **Solution Development stage**, which includes component design, development, and initial integration, has been largely completed in earlier phases of the project and documented in deliverable **D5.1** [1]. This stage establishes the foundational building blocks and ensures their readiness for system-level integration.

The project has lately focused on the **Component Integration & Evaluation stage**, which represents the core activity of this deliverable. In this phase, the developed components are being integrated into cohesive e2e systems across the different PoCs. This includes validating interoperability, verifying baseline functionalities, and progressively evaluating more complex system behaviours under realistic conditions.

The **Vertical Applications & Services LCM stage** was initiated in parallel with integration activities and focuses on deploying and evaluating the developed solutions within application-driven scenarios, enabling iterative refinement of services based on performance feedback and real-world conditions. The related activities of this stage will be included in deliverable **D5.3**.

Overall, these cycles define a continuous and iterative validation framework, where development, integration, and testing are tightly coupled. This deliverable primarily addresses the transition from solution development to system integration and early evaluation, paving the way for full-scale testing and validation in subsequent project phases.

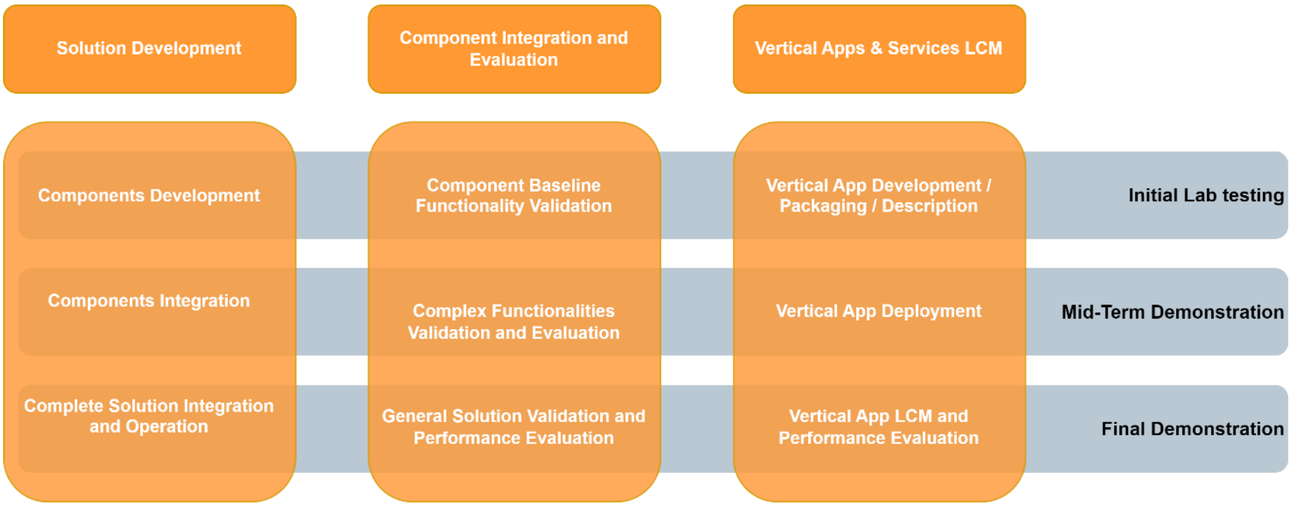


Figure 2-2 6G-SENSES Testing and evaluation cycles

3 PoC#1 – Multi-Technology ISAC Platform

PoC#1 builds an e2e demonstration showing the potential of a multi-WAT ISAC platform, with the possibility to leverage sensing data stemming from different WATs acting as "sensors" (non-3GPP non-Wi-Fi and Wi-Fi) complementing O-RAN Radio Units (O-RUs), Distributed Unit (DU), and Central Unit (CU)/User Plane Function (UPF) pools with a real-time control fabric providing sub-millisecond control loop over each 3GPP network component. The architecture of the 6G-SENSES RAN relies on a multi-layer structure, inspired by the 3GPP and O-RAN standards, which has been recently revised in deliverable D2.3 [2]. Extensions are required to support ISAC services both at the CN and RAN – Near-Real-Time (Near-RT) and Non-Real-Time (Non-RT) RAN Intelligent Controllers (RICs) – to dynamically adjust network behaviour.

3.1 PoC#1 integration and demonstration activities

PoC#1 activities are organised in two sites, UC and IASA facilities. The former implements a multi-WAT ISAC solution that consists of Non-3GPP and 3GPP technologies able to either provide sensing information to the O-RAN RIC or, alternatively, to perform communication and sensing simultaneously using the same hardware and 5G communication signals (which is known as ISAC). The testbed from IASA focuses on how optical/optoelectronic transport networks can facilitate sensing services. The following sections present a description of both implementations.

3.1.1 Implementation at UC

PoC#1 implementation at UC considers the presence of User Equipment (UEs) in an indoor -lab-environment that are expected to pass through, where the different radar-based sensing –sensing-Radio Unit (sRU) – and active sensing technologies are deployed (as depicted in Figure 3-1).

While communicating with the UEs, the radar-based sensing technologies can sense the environment and provide sensing data with different granularities to the RIC, depending on the frequency band, antenna array and output power of the WAT. The comm+sensing technologies maintain the communication with the UEs while inferring their position. Having these two sources of sensing information, the xApps behind the O-RAN RIC can exploit *comm+sensing* merged data to anticipate communication impairments, and react accordingly, optimizing the usage of radio resources by reconfiguring the MAC scheduler.

Figure 3-1 shows different WATs, such as Commercial-Off-The-Shelf (COTS) 5G/O-RAN technologies, i.e. LiteOn and Benetel O-RUs, INT Wi-Fi laptop and other prototypes such as the mmWave solution from IHP and the extended IHP/UC Sub-6 solution (sec. 3.2.2 in deliverable D3.1 [5] and sec. 2.1.2 in deliverable D3.2 [6]). The figure also depicts the O-RAN testbed from BubbleRAN (BR) (sec. 3.2.4.1 in deliverable D3.1 [5]).

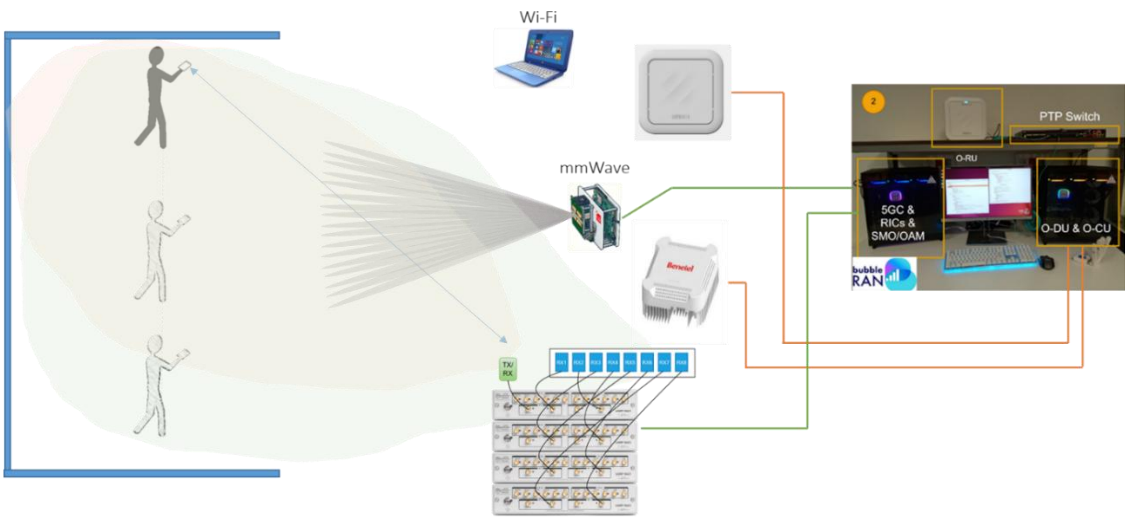


Figure 3-1 Sketch of the UC indoor lab hosting multiple sensing-capable technologies

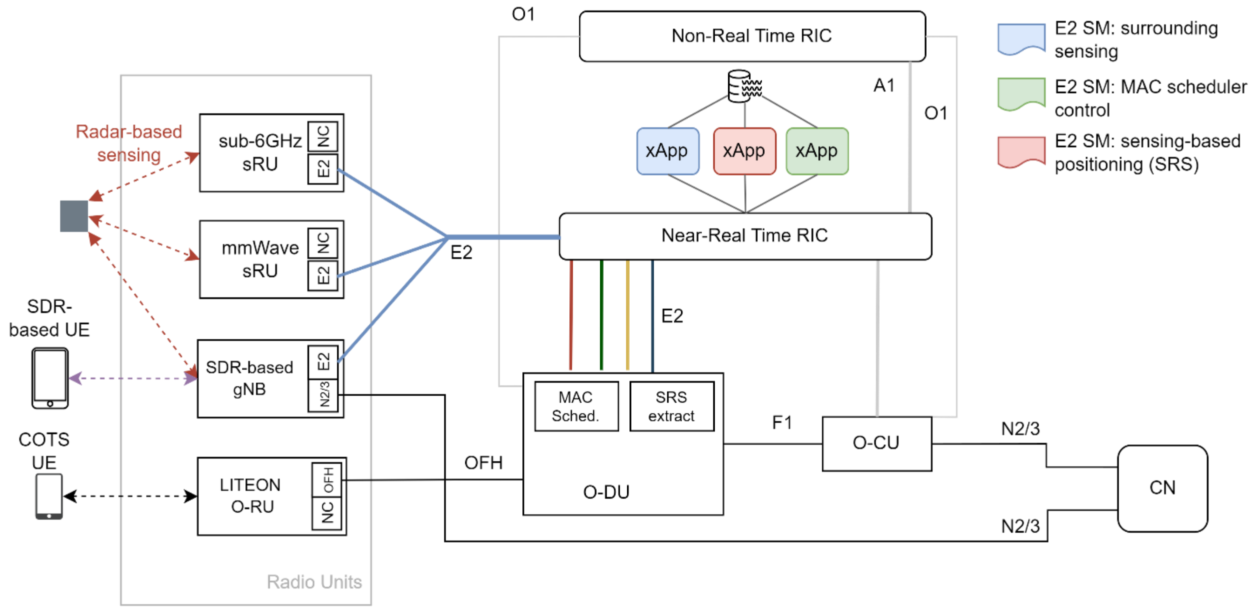


Figure 3-2 Implementation of the 6G-SENSES architecture for PoC#1 at UC

Figure 3-2 depicts the current implementation at the UC testbed, indicating both the hardware and software components that have been integrated as part of the testbed.

3.1.1.1 Service Model for sensing

The Service Model (SM) has been designed to support sensing-oriented data exchange between the E2 Node (E2 agent) and the Near-RT RIC xApp through the O-RAN E2 interface, following the standard E2SM structure for RIC Subscription, RIC Indication, and RIC Control procedures. More general information has been provided in deliverable D2.3 section 2.3 [2].

The main objective of this SM is to enable the remote monitoring and dynamic configuration of an sRU. The model supports both uplink reporting of sensing information (to the RIC) and downlink control of sensing configuration parameters at the sRU. Among the key messages, we can distinguish the RIC Indication message and the RIC Control message. The description provided in the following sections will focus on the functionalities and software implementation of the SM. Then, we discuss the systems where the SM has been integrated and validated.

RIC Indication Message: The RIC Indication Message is used to transmit sensing data from the E2 Node to the Near-RT RIC. This mechanism allows the xApp to receive periodic or event-triggered information regarding the sensing environment, such as range-angle measurements, radar maps, or object detections. The fields of the overall structure are defined in Table 3-1.

Table 3-1 Structure of the indication message

Field	Type	Description
`data`	sensing_data_t*	Pointer to the sensing payload containing the actual sensing information transmitted from the E2 Node to the Near-RT RIC.
`len`	uint16_t	Total length of the payload, indicating the size of the sensing data message.
`tstamp`	int64_t	Timestamp associated with the sensing acquisition, used for latency measurement, and real-time monitoring.

Table 3-2 Structure of the sensing data

Field	Type	Description
`theta_init`	float	Initial angular value of the sensing sector.
`theta_step`	float	Angular step between consecutive sensing measurements.
`theta_end`	float	Final angular value of the sensing sector.
`r_init`	float	Initial radial value of the sensing range.
`r_step`	float	Radial step between consecutive sensing measurements.
`r_end`	float	Final radial value of the sensing range.
`precision`	ElementType	Numerical precision used to represent the sensing information.
`sensinginfo`	Char[]	Array containing the actual sensing payload, such as radar measurements, heatmaps, or processed sensing data.

Table 3-3 Structure of the pixel

Field	Type	Description
`r`	float	Radial distance of the detected point or pixel within the sensing map.
`theta`	float	Angular position of the detected point or pixel within the sensing sector.
`strength`	float	Timestamp associated with the sensing acquisition, used for synchronisation, latency measurement, and real-time monitoring.

Table 3-4 Structure of the RIC control message

Field	Type	Description
`num_tlvs`	uint32_t	Number of TLV elements included in the control message payload.
`msg_lend`	uint32_t	Total length of the control message payload.
`payload`	ctrl_tlv_t*	Pointer to the array of TLV elements containing the control commands and configuration parameters sent from the Near-RT RIC to the E2 Node.

As can be seen, this message contains three main fields: (i) the `data` field is a pointer to the sensing payload, (ii) `len` indicates the total payload length, and finally (iii) the `tstamp` field is a timestamp associated with the instant of the sensing acquisition. The actual sensing information is stored in the `sensing_data_t` structure, detailed in Table 3-2.

This configuration allows angular as well as radial configuration and data precision. The latter field defines how the binary payload inside `sensinginfo[]` must be interpreted. Supported formats include: `integer`, `float and double`. This gives additional flexibility, depending on the sensing algorithm and required precision. The sensing payload is carried by a flexible array that contains the actual serialised sensing information. Therefore, this allows variable-size payloads without restricting the sensing application to a fixed data format. Additionally, the structure `pixel_t` can be used to represent pixel by pixel information with the structure detailed in Table 3-3, thus enabling target-level reporting instead of full matrix transmission.

RIC Control Message: The RIC Control Message enables the Near-RT RIC xApp to remotely configure the sensing behaviour of the E2 Node. This allows dynamic adaptation of sensing parameters according to network conditions, service requirements, or application-specific policies. Its structure is defined in Table 3-4.

Table 3-5 Structure of the TLV-based sub-message

Field	Type	Meaning
`Type`	uint8_t	Identifies the type of control command or parameter being transmitted (e.g., reporting periodicity, resolution, angular range, etc.).
`Len`	uint8_t	Indicates the size of the `value` field, that is, how many bytes the transmitted value occupies.
`value`	char[]	Contains the actual control value or configuration parameter. It is implemented as a variable length array.

Table 3-6 Control message types

Control Type	Value
`SENSE_CTRL_SELECT_ANGLE`	Updates the angular sensing sector, defining the angular region where sensing is performed.
`SENSE_CTRL_SELECT_RADIO`	Updates the radial sensing sector, defining the sensing range or distance interval to be monitored.
`SENSE_CTRL_SELECT_PERIODICITY`	Configures the reporting periodicity, that is, how frequently the sensing data is generated and transmitted.
`SENSE_CTRL_SELECT_RESOLUTION`	Adjusts the numerical precision or resolution used to represent the sensing information.

This implementation follows a Type-Length-Value (TLV) approach, allowing multiple control commands to be included within a single control transaction. The format of each control sub-message is detailed in Table 3-5.

The field `type` identifies the control category, while `len` corresponds to the payload size, and `value` contains the actual control parameters. Hence, this approach improves extensibility and supports multiple simultaneous configuration updates. The supported control operations are defined Table 3-6.

These correspond to four different sensing control operations, as well as four different embeddings of the data: (i) angular selection, which enables updating the angular sensing sector; (ii) radial selection, which allows updating the sensing range sector; (iii) reporting periodicity, which defines the sensing rate, that is, how frequently the sRU processes the data to make it available and, finally, (iv) resolution selection, which determines the numerical precision of the sensing information.

3.1.1.2 Non-3GPP Integration

The previously described SM has been adopted to transport the sensing information gathered by the sRU using both Sub-6 and mmWave radar technologies. In this context, two configuration setups have been considered.

3.1.1.2.1 Sub-6

In this particular setup, four USRP N321 SDRs have been deployed to perform sensing in a radar-based localisation scenario. As depicted in Figure 3-3, a PC connected to the USRPs is responsible for transmission, reception, and data processing.

Once the data has been processed, it is sent to the E2 agent, which is in charge of interacting with the RAN. The sensing information is transmitted through the E2 interface using the SM. Subsequently, the near-RT RIC orchestrates the collection of this information in real time through the xApp, which stores the data in a database for further analysis and visualisation.

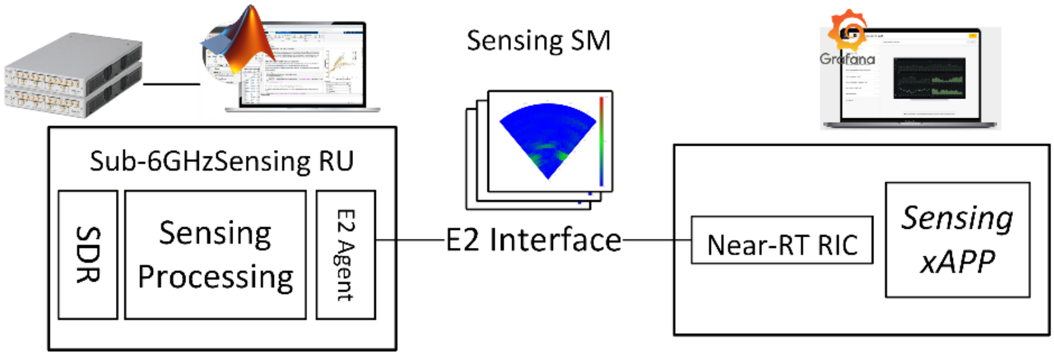


Figure 3-3 Validation setup of the sensing SM over Sub-6GHz WAT

Finally, the gathered sensing data is visually represented with the Grafana[1] framework in the form of a radial heatmap. This workflow enables the sRU to be equipped with an E2 agent for interaction with the O-RAN architecture, supports local processing to generate lightweight sensing data (for instance, heatmaps) that are forwarded through the E2 agent, and incorporates an xApp for data storage and visualisation.

3.1.1.2.2 mmWave

In this setup, depicted in Figure 3-4, a real-time mmWave ISAC system operating in the 60 GHz band is employed to perform sensing and bidirectional data transmission. The system is built on an mmWave SDR platform extended with a real-time Orthogonal Frequency-Division Multiplexing (OFDM) baseband processor and additional components to support integrated sensing and communication functionalities. Key hardware elements include the AMD ZCU111 evaluation board, equipped with high-speed data converters, and dual phased-array antenna modules that enable beam steering within a ±45° angular range. The system operates at a sensing rate of 100 Hz, requiring a data transfer rate of 156.5 Mbps to collect the Channel Heat Estimates (CHEs), which consist of 63 beams covering different angular directions and 1024 subcarriers, of which 828 are used for channel estimation. After local post-processing, a 1024-point inverse Fast Fourier Transform (iFFT) is applied to the CHEs from all beams, generating an environmental heatmap represented as a 63 × 128 (angle × range) matrix. This lightweight sensing information is forwarded to the E2 agent, which interacts with the RAN through the E2 interface using the SM. The Near-RT RIC then manages the real-time collection of sensing information through the xApp, which is responsible for storing the data and enabling its monitoring and visualisation. Furthermore, the xApp is also capable of sending hardcoded control commands to demonstrate control functionality and validate system performance, changing the angular and radial range as well as the sensing rate.

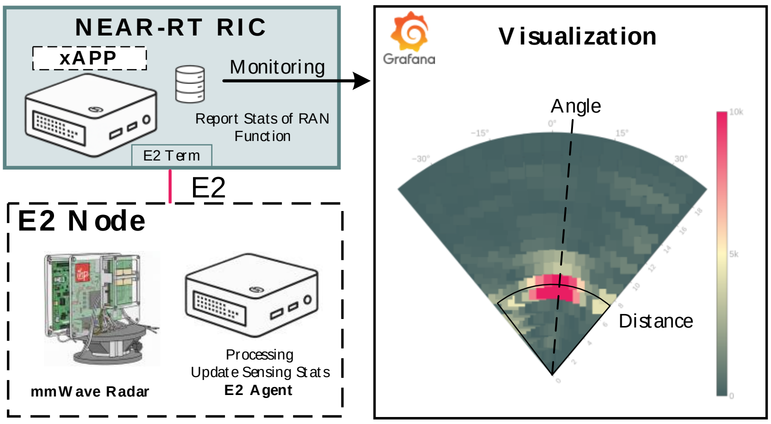


Figure 3-4 Validation setup of the sensing SM over mmWave WAT

[1] https://github.com/grafana/grafana

3.1.1.3 3GPP-based WATs integration

This section discusses the 3GPP-like integration activities carried out to incorporate both COTS 3GPP and SDR.

3.1.1.3.1 COTS 3GPP equipment integration

The available RUs at the **UC** laboratory are three LiteON FlexFi Sub-6 O-RU supporting 5G Release 15 SA with O-RAN option 7.2 working in n78: 3.3~3.8 GHz. These O-RUs will be the only WATs that will be connected to the O-RAN system. They will be used for the connectivity to the UEs while playing a key role in several integration activities, such as the one included next in section 3.1.1.3.2.

3.1.1.3.2 Handover-based sensing integration

This work presents an ISAC use case involving handover control built on top of the BubbleRAN MX-RIC platform, demonstrating how real-time radio measurements can be leveraged to enable intelligent and dynamic mobility management in an O-RAN architecture. The system showcases a closed-loop workflow in which low-layer measurements (e.g., I/Q samples) are collected, processed in near real-time, and used to trigger control decisions via xApps. The primary objective is to demonstrate a data-driven decision-making workflow within the xApps ecosystem, where real-time radio measurements are collected, processed, and translated into control actions. Specifically, uplink channel quality derived from Sounding Reference Signal (SRS) measurements is used as an example signal to illustrate how such decisions, e.g., handover triggering, can be implemented in a programmable RAN environment.

Experimental Setup and System Workflow

As shown in Figure 3-5 (see demo video[2]), the scenario consists of a split RAN deployment with one CU and two DUs: DU1 and DU2. A commercial Pixel smartphone acts as the UE. The system follows the O-RAN architecture, where the Near-RT RIC enables communication between the RAN and the xApps.

In total, the system includes three xApps and two Python scripts. Two monitoring xApps are deployed, one per DU, to collect low-layer physical metrics via O-RAN standardised Low Layer Control Service Model (LLC-SM), including SRS I/Q samples, noise measurements, and channel estimates. The third xApp is a handover control xApp, which triggers the F1AP-based handover procedure to move the UE from one DU to a neighboring DU through O-RAN standardised RAN Control Service Model (RC-SM). In parallel, two Python scripts process the real-time data collected by the monitoring xApps and visualize key metrics such as Signal-to-Noise Ratio (SNR) and Channel Impulse Response (CIR).

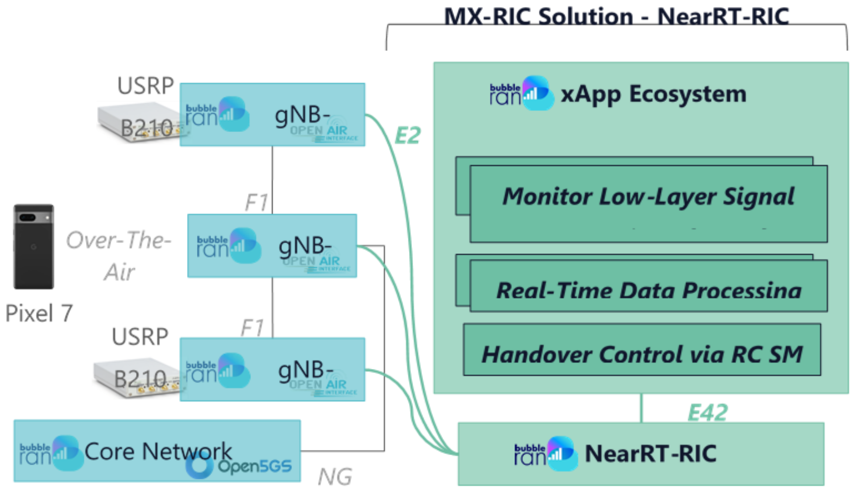


Figure 3-5 Experimental setup and scenario for the handover control based on sensing information

[2] Demo video: https://youtu.be/CGgvUCKy3M4?si=69rfKQH6iWXmwTVz

Initially, only DU1 is active, and the UE connects to it after disabling airplane mode. DU2 remains inactive until a handover is triggered.

Once the UE is connected to DU1, the first monitoring xApp is deployed to collect low-layer measurements. At the same time, a Python script processes the incoming data stream and visualises the real-time SNR and CIR. From the observed plots, the SNR exhibits significant fluctuation of up to ±20 dB, indicating an unstable channel condition.

Based on this observation, DU2 is activated, and the handover control xApp is launched to trigger the handover procedure from DU1 to DU2. The handover is completed without service interruption. After the UE is successfully handed over, a second monitoring xApp is deployed for DU2, along with the corresponding Python script to visualise the metrics.

Post-handover results show that the SNR fluctuation is reduced to approximately ±5 dB, indicating a more stable and reliable channel in the target cell.

In this experimental setup, the xApps are executed manually to clearly demonstrate the decision-making workflow, from data collection, to real-time processing, to control action. In practice, this pipeline can be fully automated, and the decision logic (e.g., detecting unstable SNR conditions) would directly trigger control actions, enabling intelligent and autonomous mobility management.

xApp Design and Execution

Two types of xApps are used in this experiment: monitoring xApps and a control xApp.

- Monitoring xApp. The monitoring xApp is responsible for collecting physical layer measurements from the DU. The data is formatted according to the O-RAN LLC Service Model (LLC-SM) and transmitted from the DU to the Near-RT RIC via the E2 interface, and then forwarded to the xApp through an E2-compliant interface (E42).

  It provides a continuous stream of signal-related data, including SRS I/Q samples, noise measurements, and channel estimates. This xApp enables real-time observability of radio conditions and serves as the primary data source for downstream processing and decision-making.

- Control xApp. The control xApp implements the handover logic for mobility management. It is triggered when the monitoring pipeline detects unstable channel conditions. The xApp formats control messages according to the RAN Control Service Model (RC-SM) and specifies the target handover action, i.e., moving the connected UE from the source DU to a neighboring DU. It interacts with the RAN through the E2 interface to execute the handover procedure.

This design demonstrates how control logic can be modularised, decoupled from the underlying RAN infrastructure, and deployed as independent xApps.

3.1.1.3.3 SDR-based gNB with radar capabilities

As introduced in section 2.1.2.1 of deliverable **D3.2** [6], another alternative to a radar-based WAT is the implementation of a Sub-6 SDR-based gnB with the capability of featuring radar capabilities. The setup depicted in Figure 3-6 represents the communication between a gNB with a UE in a TDD duplexing mode (**green** antenna); in addition, the gNB is able to receive the reflected signals simultaneously via the Uniform Linear Array (ULA) (**blue**) acting as a monostatic radar. The gNB is based on a modified version of OAI and an SDR platform (Ettus N321) to perform Over-The-Air (OTA) transmission/reception. The use of digital beamforming, described in section 3.2.2.2 of deliverable **D3.1** [5], is used to perform Angle of Arrival (AoA) estimation. This sensing system is configured to operate at band n46 (5150-5925MHz) with a bandwidth of 100 MHz and numerology 1 (SCS of 30 kHz), used for both communication and sensing.

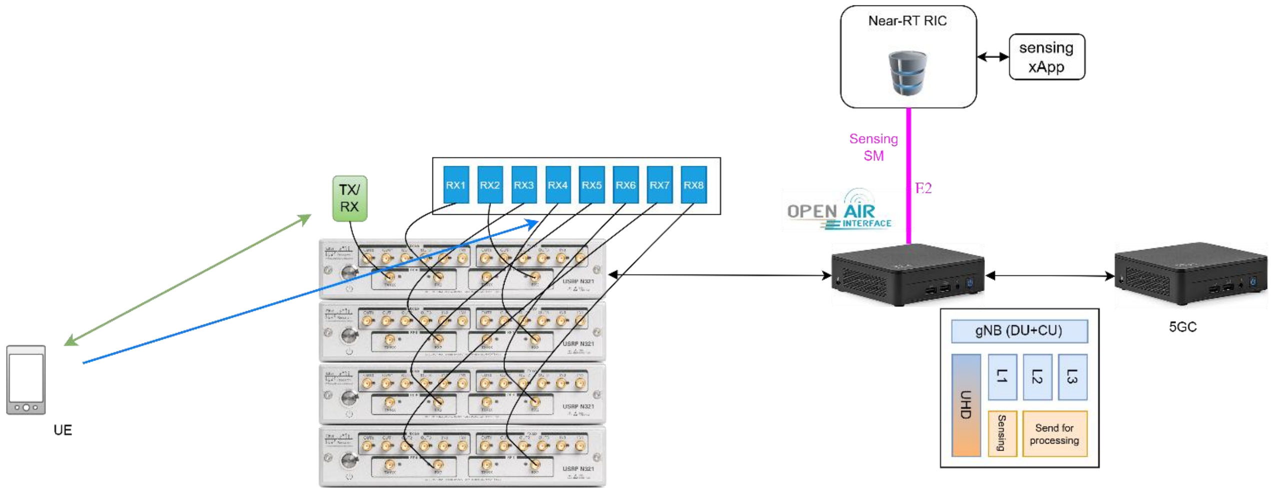


Figure 3-6 5G SA architecture with SDR-based sensing devices

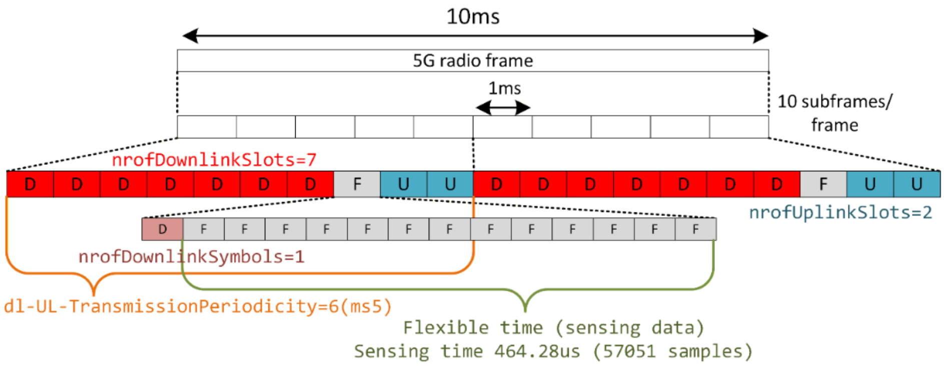


Figure 3-7 NR frame configuration for sensing integration

Although the setup allows capturing the reflected signals of transmissions, it presents two limitations, due to implementation and actual system operation. As can be observed in Figure 3-6 the setup embraces one TX and eight RX antennas. The real time processing of the sample flows from the 8 antennas with the given bandwidth (100 MHz) would require very high computation capability to keep the strict processing timing of the gNB. On top of that, the low usage of PRBs implies that many sub-carriers do not transport any data, thus hindering the sensing capability. Having those potential limitations in mind, a more flexible integration has been implemented, taking advantage of the NR frame structure configuration options. Figure 3-7 depicts the adopted NR frame configuration. As can be seen, it has a transmission periodicity of 0.5 ms embracing 10 slots. The TDD pattern is configured to have 7/2 downlink/uplink slots, respectively. Then, the flexible slot is setup according to the slot formats defined in TS 38.213 (Table 11.1.1-1). In particular configuration #16 is adopted where the first OFDM symbol of the flexible slot is used for downlink and the rest remain flexible. During the 13 flexible symbols, corresponding to 464.28 µs for the adopted numerology ($\boldsymbol{\mu} = \mathbf{1}$), sensing signal is sent using the gNB radio setup. This sensing time period allows processing the reflected signal from the multiple RX antennas without affecting the gNB operation.

In particular, synthetic 5G signals with full usage of subcarriers are used for sensing, although the integration would allow exploring other alternatives.

Figure 3-8 shows the running system, where the two antennas in the upper N321 SDR system are the ones in charge of communicating TDD with the UE, while the reflected signals are picked up by the 8 RX antennas of the ULA. Figure 3-9 shows a graphical representation of a heatmap plotted from an xApp when integrating the sRU with the SM referred to in sections 3.1.1.1 and 3.1.1.2.1.

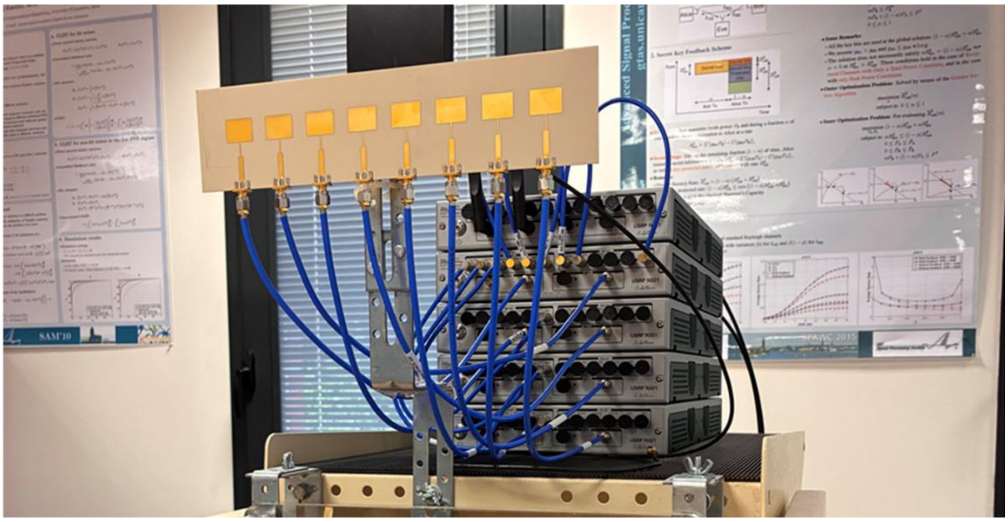


Figure 3-8 SDR-based gNB at Sub-6 with radar capabilities

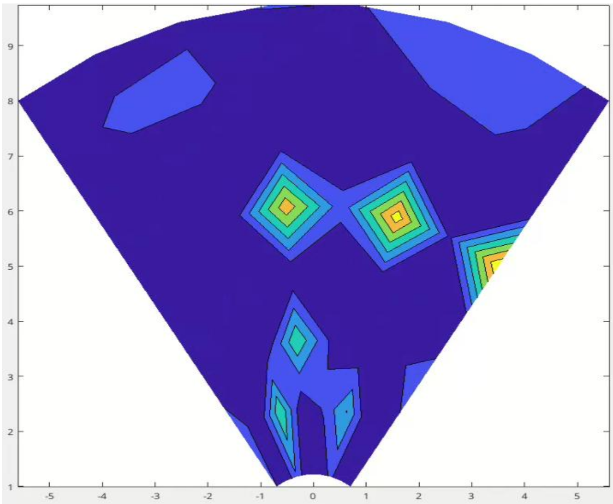


Figure 3-9 Example heatmap extracted from the Sub-6 sRU

3.1.1.3.4 MAC scheduler

The MAC scheduler implementation is composed of three main components: the OpenAirInterface (OAI) gNB hosting the RB allocation at the MAC layer, the FlexRIC-based Near-RT RIC hosting an extended MAC E2 SM and xApp execution environment, and the DRL xApp that computes scheduler behaviour updates. The details of the xApp algorithm are discussed in deliverable D4.3 [9], so the description herewith focuses on the software integration. The interaction among these components enables a practical realisation of Near-RT scheduler reconfiguration over an O-RAN-compliant control framework**.** The reconfiguration trigger is done based on sensing information, for instance gathered by the corresponding xApp exploiting the SM described in Section 3.1.1.1.

The MAC scheduling logic is implemented in the DU, where the RB allocation behaviour is defined. At this level, scheduling decisions can be based on several metrics available at the MAC layer, such as the current RLC queue backlog, channel quality, and Quality of Service (QoS) requirements, among others. Figure 3-10 depicts the monitoring and control loop established between the OAI MAC scheduler and the Near-RT RIC through the extended MAC E2 SM. This implementation allows the gNB to adjust its scheduling behaviour at runtime according to control parameters received from the Near-RT RIC, while preserving the native timing constraints of the radio stack. Within OAI, the scheduler integration is designed to fit the existing MAC processing pipeline. Scheduling is organised into a pre-processing and a post-processing stage, and the xApp-derived parameters are applied during the pre-processing step, where UE priority is determined according to the algorithm selected. After the UEs are sorted according to the coefficients provided by the scheduler, the post-processing stage performs the final RB mapping and Downlink Control Information (DCI) generation.

On the control side, the implementation relies on FlexRIC as the Near-RT RIC framework. FlexRIC provides the O-RAN-compliant control environment through which xApps interact with the RAN. In this implementation, FlexRIC is extended to support the scheduler monitoring and reconfiguration functions required for xApp-based scheduler reconfiguration. In particular, the FlexRIC MAC E2 SM is extended so that the gNB can expose, through the Indication Message, the per-UE measurements required by the xApp. In addition, the implementation of a Control Message enables the reception of the xApp control parameters needed to update scheduler behaviour. Table 3-7 summarizes the parameters included in the extended Indication and Control Messages of the E2 MAC SM, which enable the dynamic reconfiguration for the drift-plus-penalty (DPP) scheduler defined in deliverable D2.2 [4].

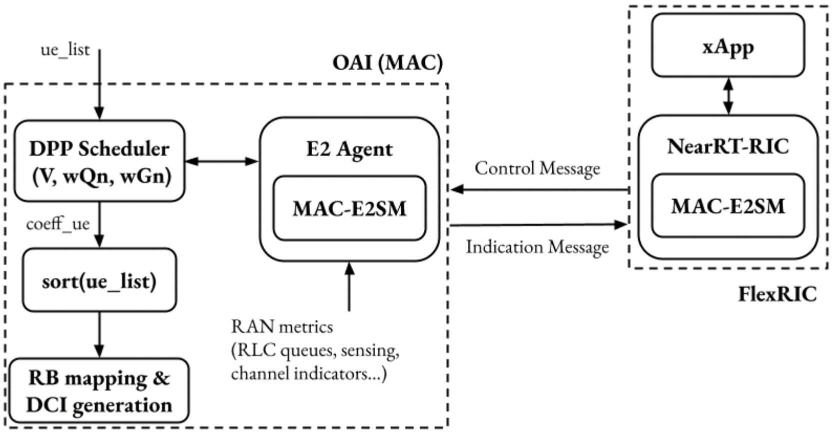


Figure 3-10 Functional architecture of the sensing supported MAC scheduler

Table 3-7 Extended MAC E2 SM

Parameter	Description
Indication Message	
`MCS`	MCS reported for each UE.
`Q`	Occupancy of the RLC buffers.
`G`	Occupancy of the virtual queues used by the DPP scheduler to track QoS requirement fulfilment.
`total_bytes`	Cumulative count of bytes transmitted.
`allocated_RBs`	Cumulative number of RBs allocated.
`GFBR`	QoS requirements.
`max_RBs`	Total number of RBs available for allocation in the cell.
`sensing`	Sensing-related information.
Control Message	
`V`	DPP parameter regulating the stability-utility trade-off.
`w_Q`	Weights assigned to the RLC queue stability.
`w_G`	Weights assigned to the virtual queue stability.

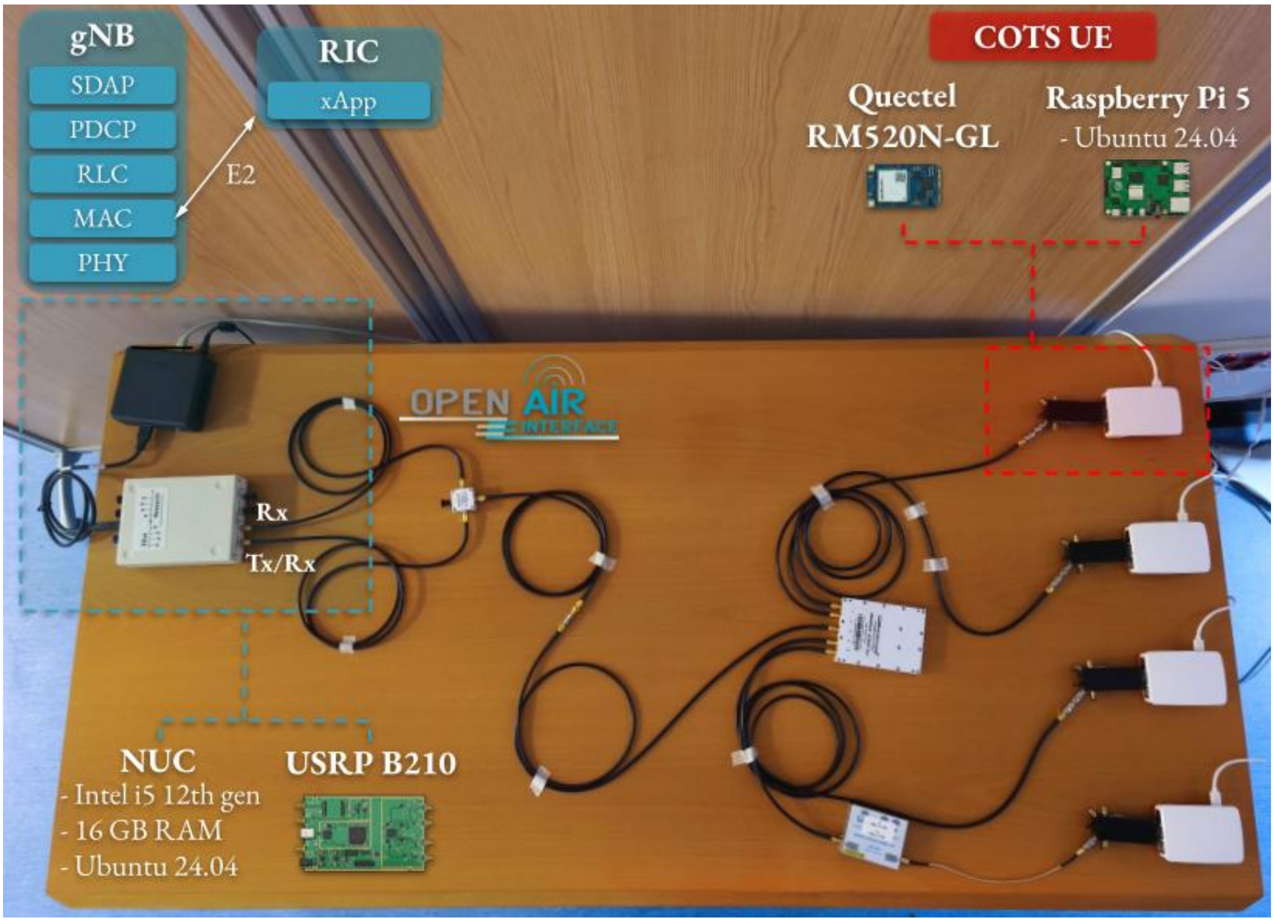


Figure 3-11 Validation testbed for the MAC SM extension

As a result, the proposed implementation establishes a closed functional loop between the gNB and the xApp. The gNB reports RAN metrics through the FlexRIC-integrated E2 agent, the DRL xApp subscribes to the MAC E2 SM with configurable reporting periods ranging from 10 to 1000 ms, and consumes the information to infer an updated scheduler configuration. The resulting control parameters are then sent back to the MAC layer to bias subsequent scheduling decisions. This design choice is relevant from the implementation standpoint because it keeps the intelligence-driven adaptation outside the most time-critical scheduling operations while still influencing the effective scheduling outcome. In other words, the xApp does not replace the MAC scheduler execution path; instead, it tunes the scheduler behaviour by controlling the parameters that shape the prioritisation logic executed inside OAI. This is consistent with the timing constraints of 5G scheduling, which must be completed in less than 1 ms depending on subcarrier spacing.

The implementation in OAI and FlexRIC has been validated on a 5G testbed using a USRP B210 as radio front-end, Quectel RM520N-GL modems acting as commercial UEs, and a remote Open5GS core instance carrying real traffic, thereby confirming the correct e2e operation of the scheduler reconfiguration loop. Figure 3-11 shows the testbed setup.

3.1.1.4 mmWave Analogue Front-End (AFE) integration

Within the 6G-SENSES project, a mmWave modular and low-power front-end of low capable to support MIMO and digital beamforming applications in ISAC is in the last stages of implementation. This front-end comes as a replacement of a COTS front-end from Sivers Semiconductors, currently operating in IHP's 60 GHz ISAC platform.

The integration of the **IHP**-developed transceiver chipset into the front-end module is achieved via a wirebond interface. The chipset provides a differential interface at its RF (60 GHz) and LO (30 GHz) interfaces with a 100 µm pitch. Hence, an appropriate chip-to-PCB transition is required. To address the inherent parasitic inductance, various electromagnetic structures are investigated, including defective ground structures (DGS) and an auxiliary wirebond loop to achieve an Inductor-Capacitor-Inductor (LCL) configuration. The initial evaluation of the strategies is conducted using a simplified single-ended interface.

Building on these results, a differential transition was selected and optimised through full-wave EM simulations. The end design of the front-end module is projected to be on a four-layer PCB stack-up. The DGS approach is affected by the presence of a dielectric stack-up and also complicates the board routing in the bottom layer. Consequently, the matching network is adopted using an auxiliary bondwire, which, although involves additional wirebonds, guarantees the isolation of the RF routing in a mixed-signal routing. The layout of the adopted transition is given in Figure 3-12.

Characterisation of the designed transition, prototyping is performed in a back-to-back configuration, i.e., PCB-to-chip-to-PCB transition, using a dedicated test chipset on the same substrate with paired pads for thru connections. Both ends of the transition are equipped with 60 GHz baluns on the PCB to enable laboratory measurements with single-ended equipment. The baluns' single-ended interface terminates into GSG probes with 300 µm pitch.

To achieve the shortest wirebond length and hence reduce the associated parasitics, the chip is embedded in a cavity in the PCB, with a depth equal to the chip height (200 µm). The 3D rendering of the interface shows that the wire pair originating from the chip pads has a tight pitch to cancel the inductance effects of the individual oppositely directed current-carrying conductors. On the other hand, the auxiliary pair is intentionally placed with a wider pitch to achieve the maximum inductance from the pair, enabling the desired LCL behaviour.

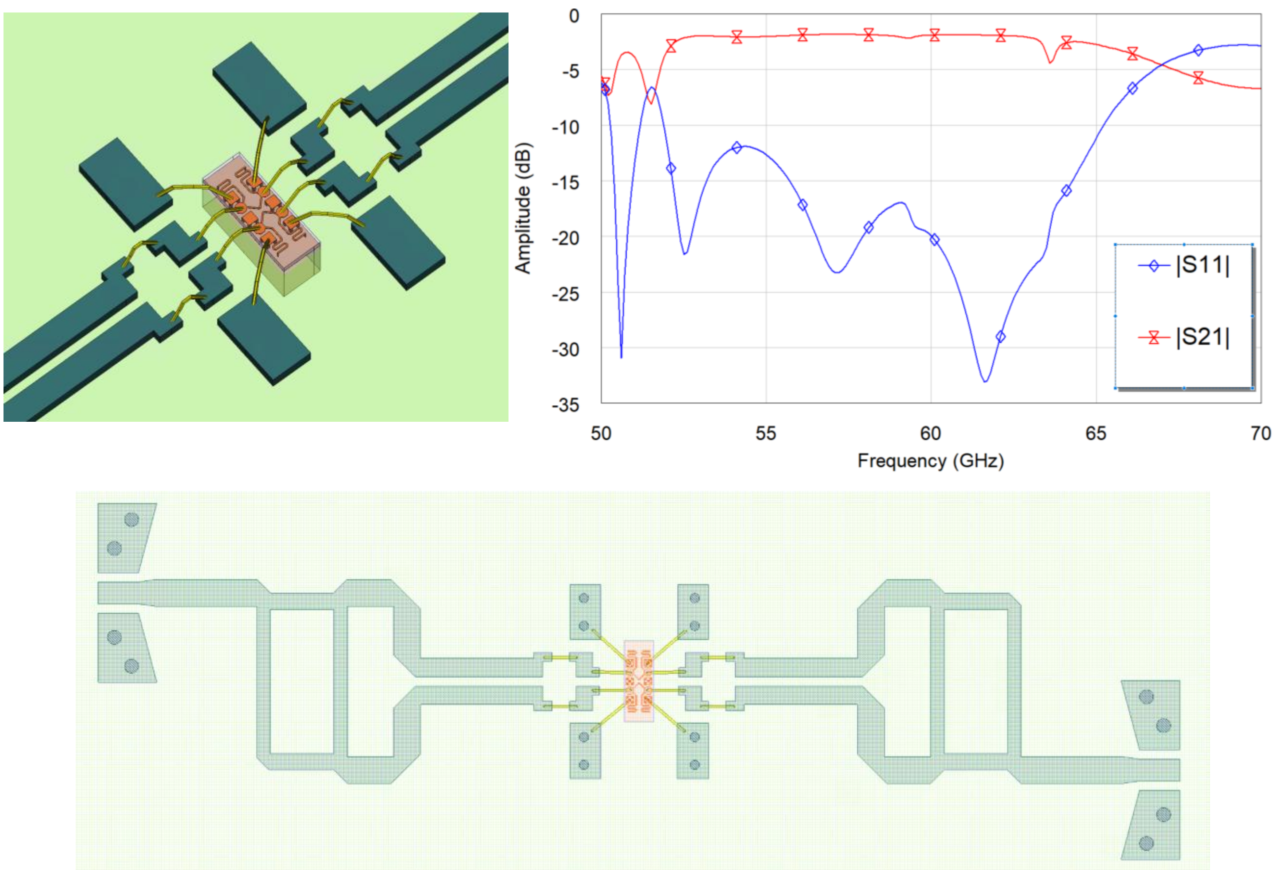


Figure 3-12 Layout for PCB-chip-PCB differential wirebond transitions, 3D rendering and full wave simulation results

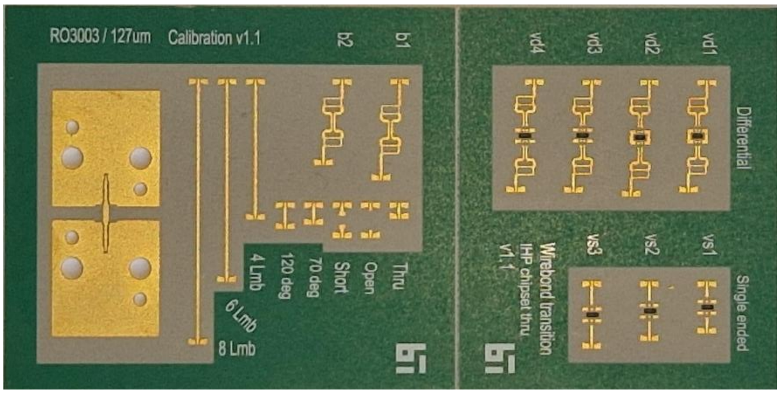


Figure 3-13 Developed PCB prototype for chip-to-PCB transition characterisation

Full-wave simulation results indicate that the design achieves a matching range of 53 GHz to 65 GHz, i.e., a 20% fractional bandwidth. The bandwidth margin ensures additional robustness against the manufacturing tolerances in PCB production and wirebond loop profiles. A variety of transitions, both single-ended and differential, are manufactured on a PCB stack with RO3003-FR4-RO3003 configuration. Each RO3003 has a 127µm thick dielectric with 35 µm of copper. Each design is implemented with minor variations for experimentation. Successful measurements of the transitions will ensure the performance of the chip-to-PCB transition in the front-end module. The photograph of the test PCB is shown in Figure 3-13.

3.1.1.4.1 Analog front-end hardware Integration with Baseband system

The chip-to-PCB transition, together with two 4x1 microstrip antenna arrays (10 dBi gain each), is integrated on a 4-layer PCB stack-up. The 3D rendering of the 60 GHz frontend module is shown in Figure 3-14.

The baseband generation and processing for the intended sensing system are planned to be provided by an RFSoC system developed by **IHP**. The interface between the used TRx chipset and the RFSoC system needs special attention regarding impedance standards and the number of bulky connectors. The transceiver chip's receiver circuitry provides downconverted baseband signals at 1 kΩ differential interfaces, which are not directly compatible with the RFSoC's 100 Ohm differential interface ports.

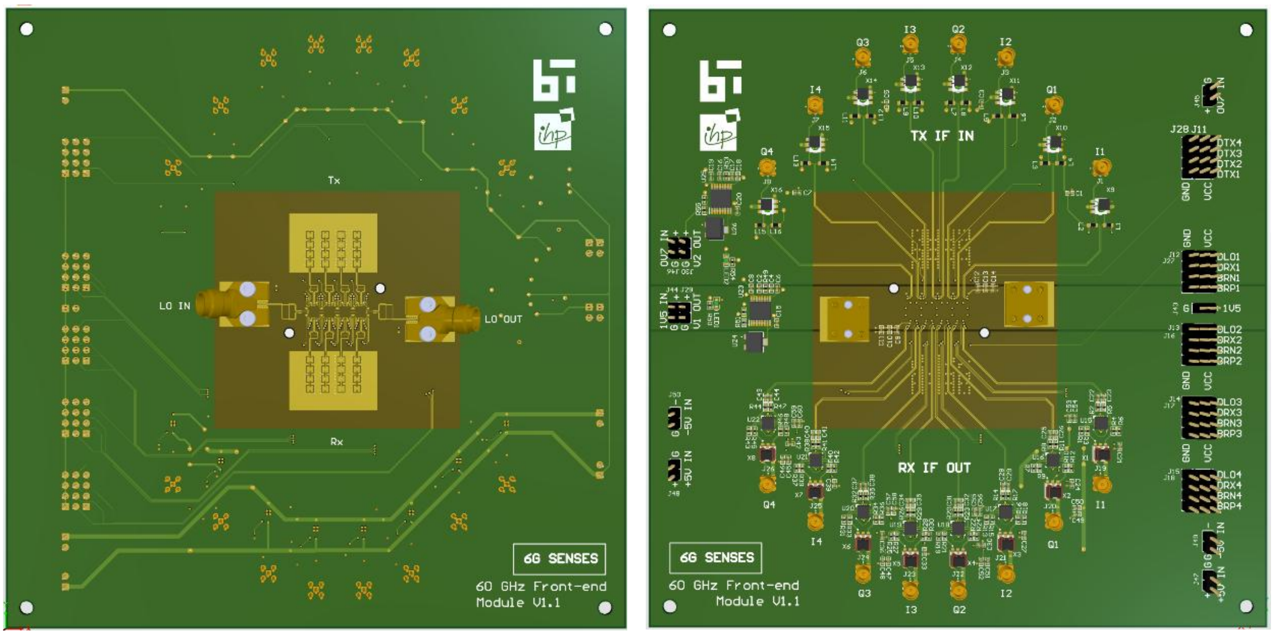


Figure 3-14 3D rendering of the 60 GHz AFE, (a) Front-side with IHP chipsets, wirebond transitions and antenna arrays, and (b) backside with baseband and digital connections.

Additionally, the number of bulky connectors for differential interconnects is a downside. Pairwise length matching, routing complexity, mechanical overhead, and higher susceptibility to mismatch are associated with increased connector count. To mitigate these issues, on-board signal-end conversion is adopted, and compact Micro-Miniature Coaxial (MMCX) connectors are used. For the RFSoC differential interface, IHP is designing an intermediate board to convert the signal to a differential interface before it enters the baseband system.

Since conventional distributed RF matching networks are not practical for receiver 1 kΩ impedance matching, eight fully differential baseband amplifiers (TI THS4509) are provided on the frontend module. The amplifier circuits enable

1. High impedance matching to the standard 100 Ω.
2. Conversion from differential to single-ended, hence reducing the cabling.
3. A voltage gain of 2 V/V.

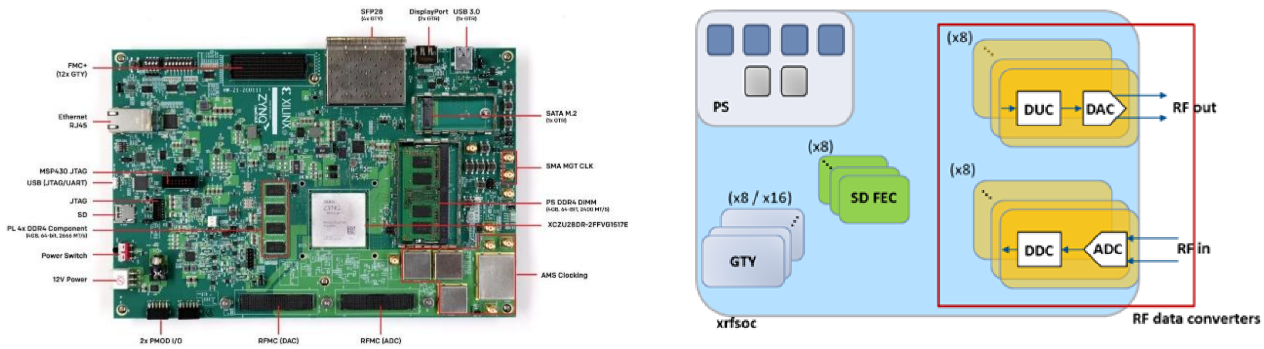
In this way, the amplifier outputs are available to the RFSoC system via eight MMCX connectors, as shown in Figure 3-14, labeled "RX IF OUT".

On the transmitter side, the chipsets accept a differential 100 Ω source at their baseband interface. Although RFSoC can support the same standard, on-board RF transformers (TCM2-33X+) provide a single-ended interface, reducing the connector count from 16 to 8. The Tx baseband interface for the RFSoC system is labeled "RX IF OUT," as shown in Figure 3-14.

3.1.1.4.2 Baseband Adapter Board

The Xilinx Ultrascale+ RFSoC ZCU111 evaluation board – see Figure 3-15 a) – was chosen to implement the radar signal processing. This hardware platform was used by IHP to develop the mmWave OFDM ISAC solution, based on commercial beamforming modules, as described in section 3.2.3 of deliverable **D3.2** [6]. The RFSoC-Field Programmable Gate Array (FPGA) solution is powerful and consists of a quad-core ARM Cortex-A53, a dual-core ARM Cortex-R5, eight analogue-to-digital converters (ADCs), eight digital-to-analogue converters (DACs), and abundant programmable logic resources.

Furthermore, the mmWave ISAC solution in [6] implements not only real-time communication and sensing using broadband OFDM waveform, but also proprietary SDR functionality, enabling the evaluation of different *comm+sensing* waveforms. The basic SDR solution supports the use of four DACs and four ADCs, allowing for two IQ transmit and two I/Q receive paths.



a) b)

Figure 3-15 a) ZCU111 evaluation board w/o addon board (source: Xilinx), b) key features of the RFSoC FPGA. PS – processing system, DUC – digital up-conversion, DDC – digital down-conversion, SD FEC – soft-decision forward error correction

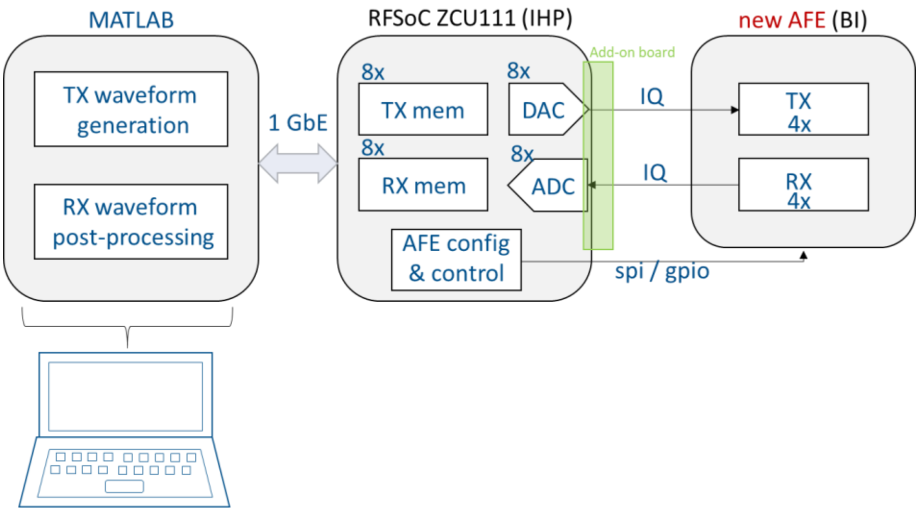


Figure 3-16 SDR 60-GHz MIMO RADAR system with signal processing in software

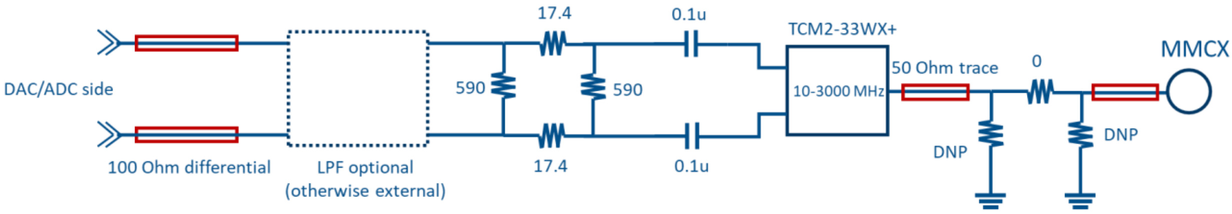


Figure 3-17 Balanced to unbalanced signal transformation

In this implementation, the existing 60 GHz Analogue Front-End (AFE) with COTS modules will be replaced with 60 GHz analogue front-end (AFE) developed by BI. In addition, due to the special features of the new AFE regarding the baseband interface and the number of baseband inputs and outputs, it is necessary to modify the SDR design, i.e., increase the number of memory channels from 4 to 8. This way, four IQ transmit and four IQ receive baseband signal paths will be supported for MIMO radar. The SDR MIMO radar system with radar signal processing implemented in software is illustrated in Figure 3-16.

Add-on board

BI's AFE board, with **IHP**'s radar chips, integrates a single-ended baseband interface to digital converters on the baseband board (ZCU111 evaluation board) to reduce the number of connector count and make the board compacter. The connection to the board is made via MMCX connectors. The data converter interface on the FPGA board is differential, and commercially available add-on boards for ZCU11 have differential inputs and outputs. A new add-on board is required to connect the AFE board to the baseband board. The new add-on board comprises circuits made of surface mount devices (SMDs) for converting balanced to unbalanced signals and vice versa. Exemplary transformation circuit for a single DAC / ADC is shown in Figure 3-17. This conversion must be made for 8 DAC and 8 ADC to interconnect 4 TX quadrature (I and Q) inputs and 4 RX quadrature outputs at the AFE, respectively.

On the DAC side, the interface is 100-Ohm, with differential signaling. Balanced signal is first filtered by a low-pass filter (LPF) of the 5-th order, as shown in Figure 3-18. The pi-attenuator has a dual role: attenuating the signal by 3 dB, as well as reducing any reflections from the transformer. The series capacitors together with the TCM2-33WX+ transformer form a High-Pass Filter (HPF) to remove common mode, where the latter transforms the differential signal into a 50-ohm single-ended signal, which is further fed to the MMCX connector. For ADC the whole procedure is reversed, from single-ended to differential. The connection between the add-on board and the AFE board is made using MMCX cables.

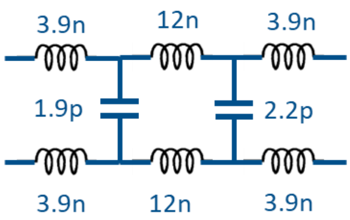


Figure 3-18 5-th order LPF with 1 GHz cutoff

The implementation of the add-on board is currently underway and the resulting board will be described in deliverable **D5.3**.

3.1.2 Implementation at IASA

The PoC#1 implementation at IASA aims to demonstrate two key capabilities of the multi-layer, multi-technology 6G-SENSES architecture, as illustrated in Figure 3-19:

i. **Transport interconnect**: how the transport network supports both sensing and communication flows, and

ii. **Integration and delivery of non-3GPP sensing information** to O-RAN xApps through the O-RAN orchestration framework.

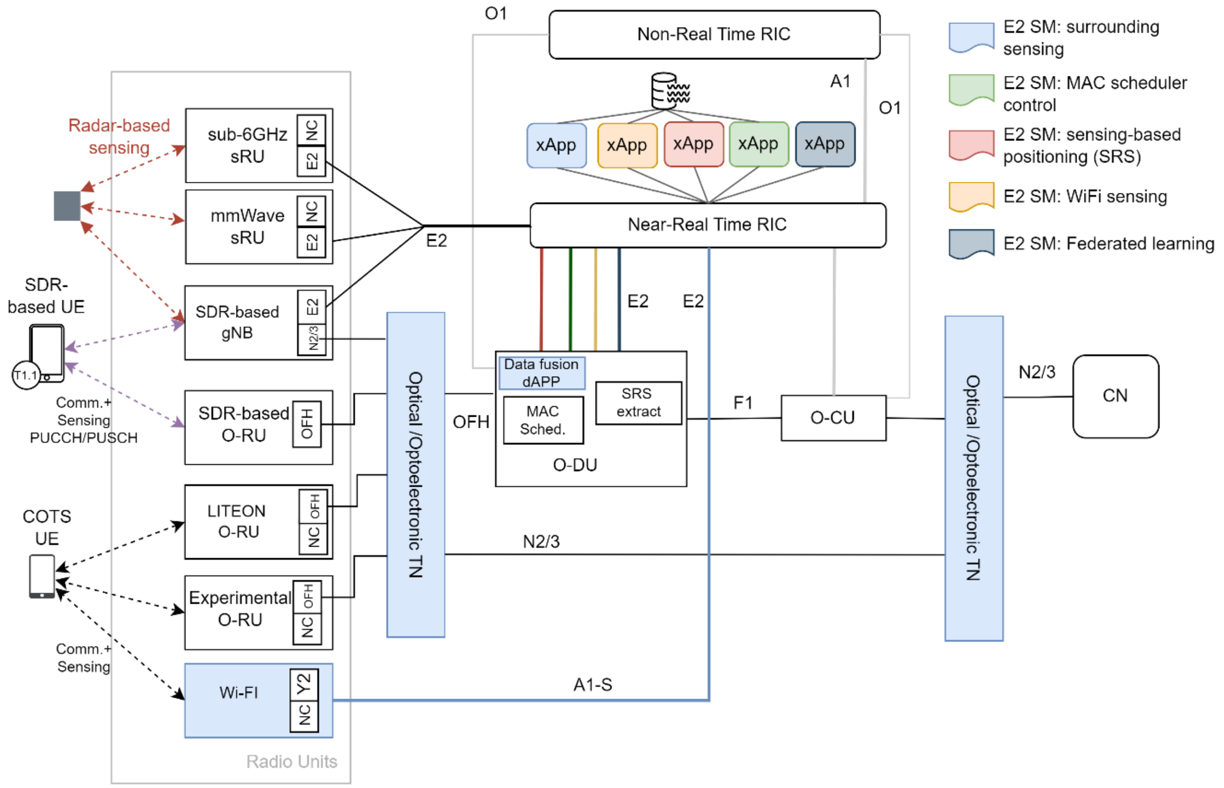


Figure 3-19 Platform Implementation of the 6G-SENSES architecture for PoC#1 at IASA

3.1.2.1 Transport interconnect

The main goal is to experimentally demonstrate and validate a multi-technology transport network architecture capable of jointly supporting communication and sensing services in O-RAN-compliant ISAC deployments. The implementation aims to show how heterogeneous traffic generated by multiple O-RUs with different communication and sensing requirements can be efficiently transported and dynamically orchestrated over a multi-technology transport network. More specifically, it demonstrates:

- E2e support of ISAC services over O-RAN-compliant infrastructures.
- Dynamic transport and orchestration of traffic streams associated with communication and sensing services.
- Integration of packet-switching and all-optical switching technologies under a unified SDN-enabled transport control framework.
- Dynamic allocation of network resource (capacity, routing) according to the bandwidth and latency requirements of sensing and communication flows.
- Experimental validation of flexible service provisioning and resource utilisation across multi-technology transport domains.
- Demonstration of how sensing-related and communication traffic can coexist over shared transport resources while maintaining logical isolation and service differentiation.
- Evaluation of transport-network programmability and reconfigurability using OpenFlow, RESTCONF, NETCONF/YANG, and optical switching control mechanisms.
- Validation of the feasibility of integrating USRP-based O-RAN RUs with multi-technology transport infrastructures, supporting both communication and sensing services.

We consider a multi-layer, multi-technology network architecture compatible with O-RAN and 3GPP specifications supporting ISAC. Figure 3-19 illustrates the overall system architecture, highlighting the main functional components and interfaces and showing how the transport network supports both sensing and communication flows in O-RAN environments. In particular, the transport network interconnects the disaggregated RAN components and the CN. Each O-RU encapsulates baseband I/Q samples, typically transported using eCPRI over Ethernet, and assigns them to Virtual Local Area Network (VLAN)-tagged flows, enabling traffic separation per RU, antenna port, beam, sensing stream, or service type. At the O-DU side, a single O-DU can simultaneously serve multiple O-RUs by demultiplexing and extracting the incoming VLAN-tagged I/Q streams. These flows are subsequently mapped to internal processing pipelines according to the O-DU scheduling and resource-allocation policies. To support this type of connectivity, we consider the multi-technology transport network shown in Figure 3-19.

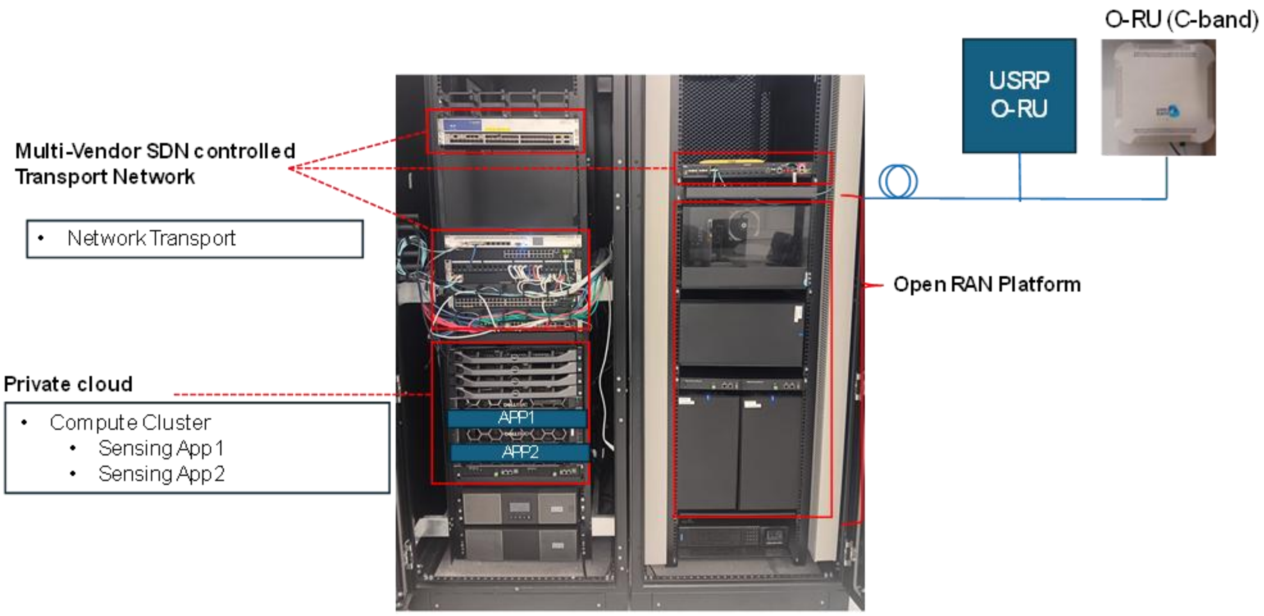


Figure 3-20 Multi-technology transport network PoC

The demonstrator setup consists of multiple O-RUs connected through a multi-technology fronthaul and transport infrastructure interconnecting RAN and CN domains. The radio infrastructure is implemented using USRP N310 platforms equipped with 10G SFP+ interfaces, enabling direct integration with the transport network using Ethernet/eCPRI connectivity. Different O-RUs can be configured to support communication-only, sensing-only, or joint communication-and-sensing services. The generated I/Q streams are encapsulated into VLAN-tagged Ethernet flows, enabling logical separation of radio resources according to service type, sensing modality, beam, or processing requirements.

The transport network combines: i) an optoelectronic packet-switching segment implemented using OpenFlow-capable Aruba 3810M switches; ii) an all-optical switching segment implemented using a Polatis 6000 optical switching fabric, and iii) a centralised SDN-based orchestration framework coordinating packet and optical resources.

The packet-switching infrastructure is controlled through the OpenDayLight (ODL) SDN controller using RESTCONF APIs and OpenFlow forwarding rules, while the optical segment is dynamically configured through SCPI/Telnet-based control of the Polatis optical switch. The transport orchestration framework maintains visibility of VLAN mappings, forwarding paths, optical cross-connections, wavelength assignments, and transport resource utilisation across the different technology domains.

The demonstrator considers the following representative scenarios:

Scenario 1 – Joint Communication and Sensing Transport

This scenario evaluates the simultaneous transport of communication and sensing traffic generated by ISAC-enabled O-RUs over the shared multi-technology packet-optical transport infrastructure. Communication-related streams with sensing-related data streams are dynamically transported toward the corresponding processing entities. The scenario validates the ability of the transport network to dynamically allocate packet and optical resources while simultaneously supporting connectivity between RAN and CN for communication services, as well as between RAN and distributed sensing applications for sensing-related processing and analytics.

Scenario 2 – Multi-O-RU Sensing Aggregation

This scenario evaluates the aggregation of sensing-related traffic generated by multiple O-Rus, transported toward centralised sensing applications over the shared transport infrastructure. Multiple O-RUs simultaneously transmit sensing measurements, which are time- multiplexed and forwarded toward the sensing-processing domain. The scenario demonstrates how sensing information originating from geographically distributed O-RUs can be jointly collected and processed to support cooperative and multi-static sensing applications.

Scenario 3 – Transport Reconfiguration and Resilience

This scenario evaluates the resilience and dynamic reconfiguration capabilities of the proposed multi-technology transport infrastructure under changing traffic conditions and link failures. The orchestration framework continuously monitors the state of the packet and optical transport domains and dynamically updates policies to maintain e2e service continuity for both communication and sensing traffic flows. Upon detection of transport link failures, the framework automatically re-establishes connectivity by selecting alternative packet and/or optical paths and reconfiguring the underlying transport resources in real time.

3.1.2.2 Integration and delivery of non-3GPP sensing information

The goal is to demonstrate the integration and delivery of non-3GPP sensing information toward O-RAN xApps through the O-RAN orchestration framework. In particular, we aim to validate how sensing data generated by external sensing platforms and – such as Wi-Fi Channel State Information (CSI) – can be ingested to the network in a secure way through the Service Management Orchestrator (SMO) using the A1-S and delivered toward Near-RT RIC xApps for real-time sensing-aware optimisation and control. More specifically, the following functionalities are demonstrated:

- Ingestion of sensing-related information into the SMO through broker-based interfaces and A1-S mechanisms.
- Delivery of sensing information toward sensing-aware xApps operating in the Near-RT RIC.
- Real-time exploitation of external sensing information for communication and sensing optimisation functions.
- Fusion of non-3GPP sensing information with 3GPP sensing data (fusion dApp).

In the proposed architecture, sensing information generated by external sensing platforms, such as Wi-Fi-based sensing systems or other non-3GPP sensing technologies, is collected through gateway and broker-based mechanisms connected to the SMO. The sensing information is subsequently exposed through the A1-S interface, enabling delivery of sensing-aware information toward xApps and rApps operating within the O-RAN ecosystem. The framework supports transport of sensing-related information across the multi-technology packet-optical transport infrastructure interconnecting the sensing domain, O-RAN components, and orchestration entities. The transport network dynamically forwards sensing data streams toward the SMO and the Near-RT RIC while maintaining logical traffic separation and coordinated resource allocation. Within the Near-RT RIC, sensing-aware xApps consume the non-3GPP sensing information to support real-time optimisation and control functions.

3.2 Small-Scale Demos for PoC#1

3.2.1 Wireless Edge Caching

PoC#1 features a small-scale demonstration designed to showcase the Wireless Edge Caching (WEC) capabilities developed in the 6G-SENSES project [7][8]. The proposed solution is implemented through an ad-hoc xApp deployed on top of the RIC. This xApp executes Robot Operating System (ROS) code to collect sensing data from the Radar Sensor and seamlessly integrate it into a ROS workspace. The overall application workflow is illustrated in Figure 3-21.

Data collected from the real system is handled by a dedicated xApp capable of communicating through ROS topics that share the same namespace as the Gazebo[3] simulation environment, which creates a unified connection between the physical architecture and its simulated counterpart.

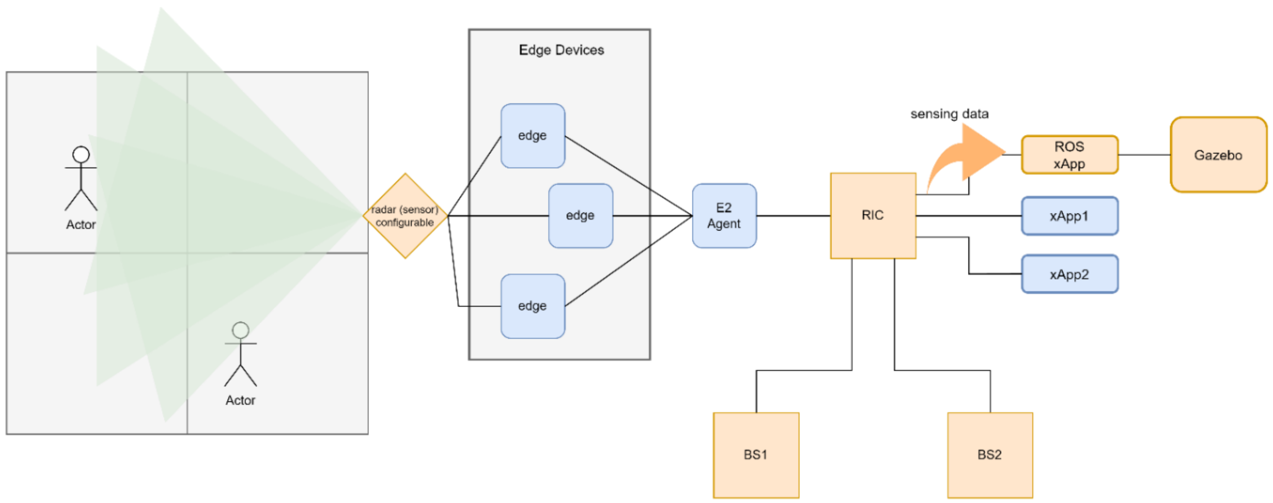


Figure 3-21 WEC demonstration using sRUs for sensing data provision to the ROS workspace

[3] https://gazebosim.org/home

As a result, the solution provides a tightly integrated framework for testing more advanced scenarios in which intelligent caching decisions can significantly enhance sensing applications, while reducing the need for expensive physical hardware deployment. We provide the WEC xApp specifications in the sequel.

3.2.1.1 RIC and ROS Bridge

The xApp operating on the RIC executes ROS Python code that continuously listens for sensing data from the RIC. Upon receiving data, the application publishes it to ROS topics, effectively transferring all sensing information into the ROS environment in real time. This behaviour is achieved through a dedicated ROS node responsible for processing and distributing the data across the ROS workspace.

3.2.1.2 ROS and Gazebo Bridge

The sensing data collected within ROS is subsequently sent to Gazebo with the use of ros_gz_bridge, a package which is used to establish the communication layer between the two frameworks.

Developed as part of the ROS–Gazebo integration ecosystem, ros_gz_bridge is a software package that converts and relays messages between ROS Interfaces and Gazebo Transport messages, allowing the two systems to exchange data seamlessly. This allows a mixture of real hardware data and simulated one inside the Gazebo environment, thus allowing for more complex scenarios to be simulated effortlessly. This setup makes it possible to efficiently evaluate caching policies in more suitable and complex environments, that would otherwise require deploying multiple physical hardware components.

Figure 3-22 depicts an experiment that connects both real and virtual world (Gazebo) making use of the mmWave sRU for movement tracking. A real user is monitored in real time with the mmWave sRU and it is represented real-time in a virtual ROS environment.

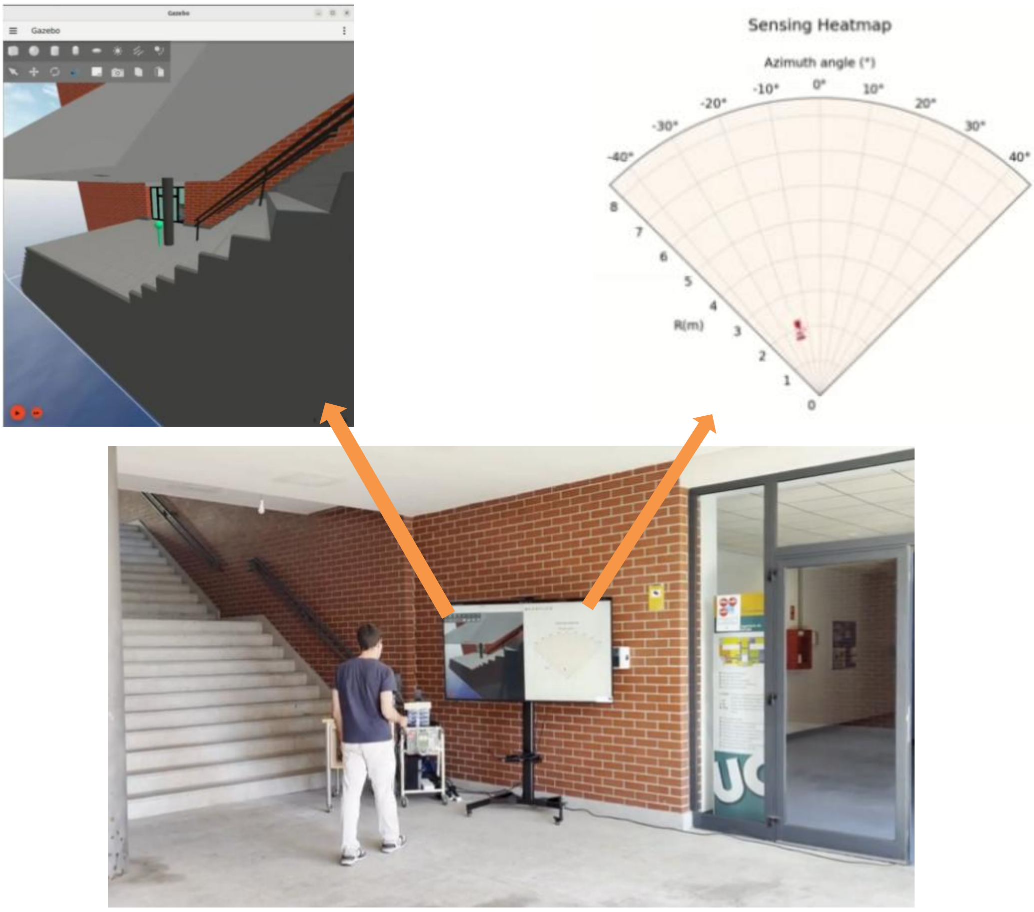


Figure 3-22 Experiment connecting both real and virtual world (Gazebo) making use of the mmWave sRU for movement tracking

3.2.2 Wi-Fi PoC

The main objective of the Wi-Fi demo is to assess the operation of the LIVESENSE platform, which transforms a COTS laptop's Wi-Fi Network Interface Card (NIC) into a centimetre-level Range-Doppler sensor. This demonstrator validates monostatic Integrated Sensing and Communication (ISAC), ensuring that the device can perform high-accuracy environmental sensing while simultaneously preserving standard Wi-Fi communication and internet connectivity.

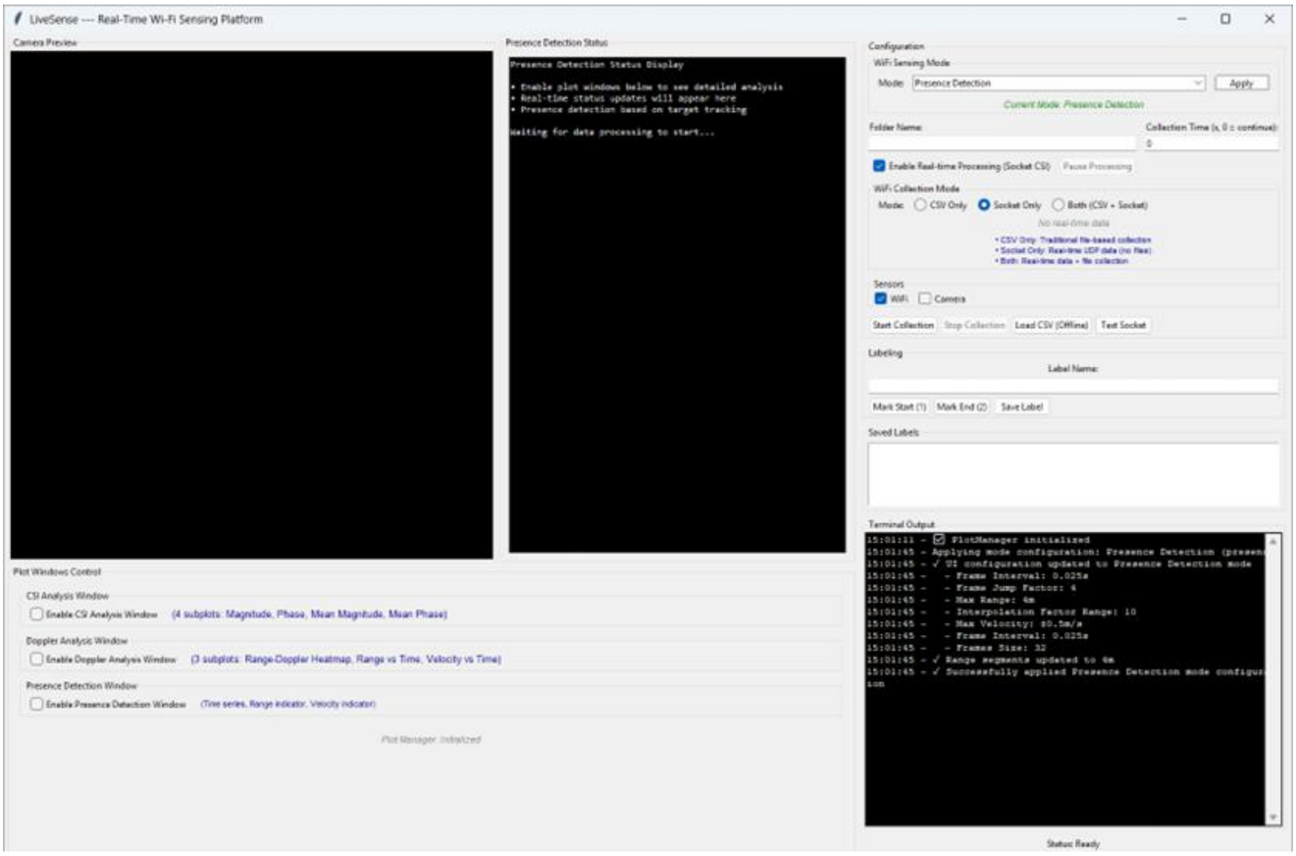


Figure 3-23 LiveSense user interface

Demonstrator Scenarios & Setup

Hardware Deployment: The setup utilizes a single, unmodified COTS laptop equipped with an Intel AX211 (Wi-Fi 6E) or Intel BE201 (Wi-Fi 7) NIC.

Monostatic Topology: The platform operates monostatically, using one antenna as the transmitter (Tx) and another antenna on the same device as the receiver (Rx). This eliminates the need for bistatic separated Tx/Rx pairs and environment-specific calibration.

Use Cases: The demonstrator showcases several sensing capabilities within a few metres of the device: detecting the distance and radial velocity of attendees, monitoring micro-motions like human respiration, and performing sub-decimetre and-gesture ranging.

Interference & Coexistence: The sensing operates in the 6 GHz band utilizing a 160 MHz bandwidth with 512 subcarriers. By leveraging this wide bandwidth, the system achieves a processing gain of >25 dB, providing a high SNR against environmental interference. Furthermore, it maintains a stable sensing sampling rate of 40 Hz without packet loss, even under heavy communication loads like simultaneous HD video streaming and video calls.

Processing Pipeline & Implementation: The LIVESENSE real-time pipeline is implemented in Python and performs several key steps on-device:

Synchronisation & Self-Interference Mitigation: It extracts fully synchronised CSI by applying real-time time-phase alignment. It also performs adaptive self-interference cancellation via background subtraction to remove static clutter and Tx-Rx coupling.

Range-Doppler Generation: A two-dimensional Fast Fourier Transform (2D-FFT/DFT) is applied across subcarriers (range domain) and temporal frames (Doppler domain) to generate accurate Range-Doppler maps.

Operational Modes: The platform provides interactive configuration through three modes: i) ***Gesture mode*** for high range accuracy via advanced interpolation, ii) ***Presence mode*** to maximize detection range, and iii) ***Efficiency mode*** to reduce computational overhead on the host.

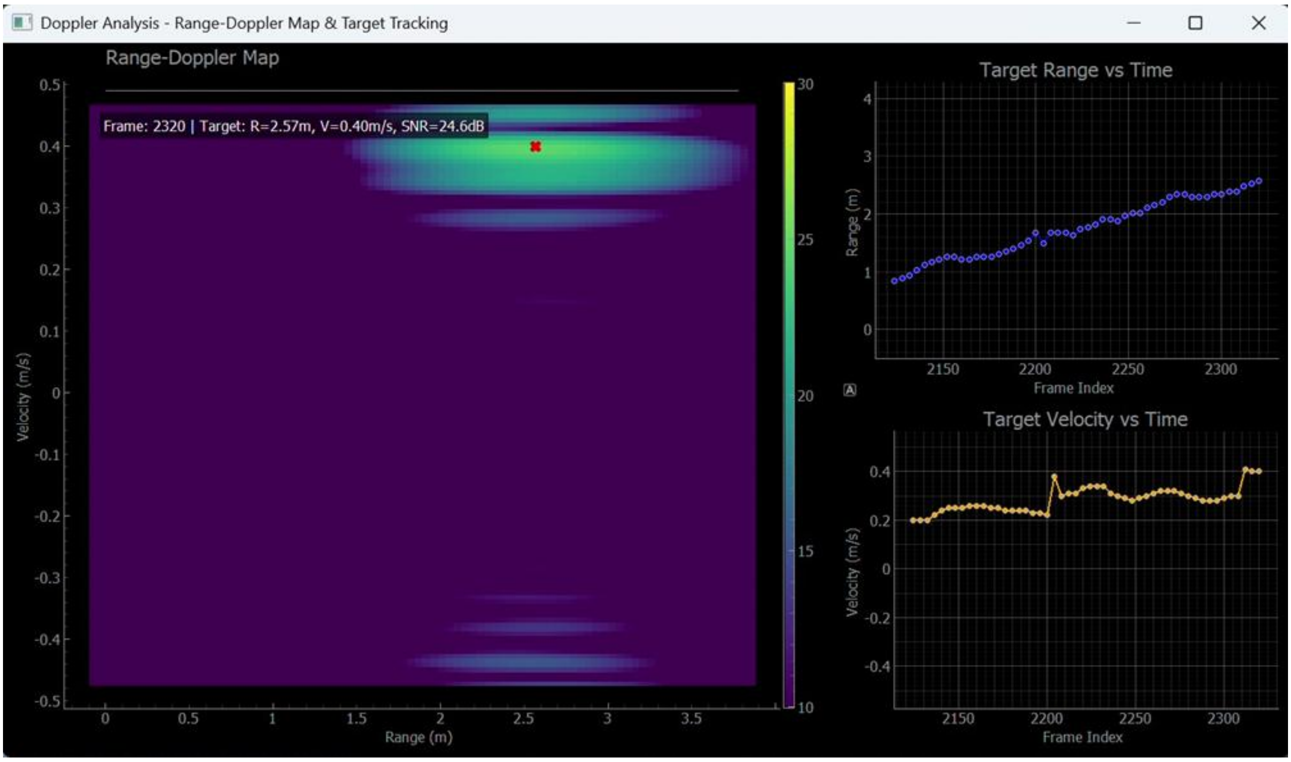


Figure 3-24 Live sense Demo Visualisation

Demonstrator Outputs / KPIs: The system streams real-time data to a custom Python/Qt Graphical User Interface (GUI). The expected outputs and key performance indicators (KPIs) include:

- **Real-time Visualisations:** Streaming of Range-Doppler maps, historical tracking of target range and velocity versus time, sub-carrier magnitude/phase, and presence-detection overlays.
- **Tracking Accuracy:** The platform maintains a median range error of less than 5 cm for hand gestures (under 0.6 m). It also maintains an error of less than 20 cm for whole-body motion (up to 3 m), with a maximum detection range of 4 m.
- **Multi-target Resolution:** The system successfully distinguishes multiple targets, such as separating a stationary user performing gestures at 0.2 m from a moving target 1 m away. This multi-target tracking remains robust even in uncontrolled, crowded environments like cafes with heavy background Wi-Fi traffic.

3.3 Risks and mitigation measures for PoC#1

This section provides an overview of the risks that are being identified as part of PoC#1 development and integration activities. Table 3-8 shows the risks that have been considered throughout the evaluation of the PoC, which are considered as "Unforeseen risks" to the Project, i.e., not defined in the Description of Work (DoW).

Table 3-8 Unforeseen risks for PoC#1

Unforeseen Risk №	Description of the risk	Severity of the risk	Likelihood of the risk	Mitigation Measures
1	Logistical or travel constraints impacting the ability to present or integrate the Wi-Fi platform in the project PoC (e.g., travel delays, equipment not arriving on time, venue issues)	Medium	Medium	Prepare remote/virtual demonstration materials.
2	Real-time processing or latency/delay when running ML models on COTS laptop devices, impacting user experience or demo results	High	Medium	Optimize signal processing and ML pipelines; pre-load/test all demos; reduce model complexity where needed; keep fallback non-ML demo modes available.
3	The RU extension to support sensing does not provide required range resolutions using 5G-NR signals	High	Medium	Adoption of signals tailored for sensing exploiting the flexibility of the 5G frame and slot configuration.
4	Integration of the 60 GHz Analog Front-end for sensing more complex than expected	Low	Medium	Use of the alternative (existing) commercial Analog Front-End from Sivers Semiconductors.
5	The integration of chip and antenna are severely delayed due to 4 months and more delay by the PCB Manufacturer. Due to the complexity of the design, there is very limited options for reliable manufacturer found given the low volume production.	Medium	High	Use of the alternative (existing) commercial Analog Front-End from Sivers Semiconductors to showcase in the demonstration for EUCNC 2026. The partners involved continued with the PCB verifications and the delayed packaging schedule. The work will continue beyond June 2026 to make sure the results are available before the final review timeline. Also, expedited packaging schedule is proposed and followed up by BI (partner developing antenna and the integration with chip from IHP).
5	5G-NR signals may not attain the required range resolutions	Medium	Medium	Extend the bandwidth using subband "stitching", as has already been proposed. Another possibility would be to use optimal signals for sensing, such as those already used in the existing Sub-6 device.

4 PoC#2 – CF-MIMO Prototype

PoC#2 delivers a CF-MIMO PHY prototype and extends it to support a RT control loop. The algorithms related to this implementation are deployed on top of representative real-time SDR hardware components to demonstrate the feasibility of the concept as well as achieving high network performance. All relevant aspects of an operational CF-MIMO network are demonstrated, including tight timing synchronisation, OTA reciprocity calibration for TDD operation, distributed signal processing for channel estimation and beamforming, and fronthaul/backhaul data plane traffic exchange.

4.1 PoC#2 integration and demonstration activities

Initially, the objective of the PoC#2 platform was to realize distributed CF-MIMO transmission schemes as proposed in deliverable **D5.1** [1], including independent transmission, joint transmission on shared resource blocks (RBs), and coordinated multi-beam transmission with synchronisation and phase compensation between distributed RUs. The long-term objective would be to integrate custom distributed beamforming strategies into the OAI PHY processing chain to realise explicit control over the beamforming and precoding weights applied to distributed antenna groups.

From a PHY-layer perspective, these transmission modes require coordinated generation and real-time distribution of I/Q sample streams across multiple synchronised RF frontends. The applied beamforming weights determine the activation, phase, and amplitude of the individual antenna branches and so directly influence coherent transmission and spatial focusing performance.

The current implementation is based on OAI and a multi-USRP SDR platform operating at 3.6 GHz. The platform leverages 16 antenna elements distributed across four synchronised USRP devices, thereby providing the basis for scalable distributed beamforming experiments. A larger configuration of antennas will be feasible.Although the software currently exposes the setup as one logical RU/gNB instance, the RF frontend is already physically partitioned across multiple SDR nodes, representing an intermediate distributed antenna architecture.

The practical realisation of fully customised distributed beamforming inside OAI proved significantly more complex than initially expected, particularly due to the tightly integrated real-time PHY processing, synchronisation requirements across multiple USRPs, and the internal precoding and I/Q-sample scheduling mechanisms.

Therefore, instead of immediately implementing a fully customised distributed CF-MIMO precoding framework, we focused on assessing the behaviour of the beamforming functionality already available within OAI. The near-field experiments are used to evaluate coherent transmission, synchronisation stability, RF-chain coordination, and spatial focusing effects under synchronised multi-USRP OTA conditions. Consequently, the near-field experiments are considered an intermediate validation step toward the distributed CF-MIMO concepts proposed in deliverable **D5.1** [1] and the future integration of custom distributed beamforming algorithms.

4.1.1 CF-MIMO test platform for near-field beamforming

In the context of this deliverable, the implementation at **TUBS** focuses on the realisation of a scalable CF-MIMO test platform for near-field beamforming investigations based on OAI and SDR hardware. In contrast to a purely simulated setup, the platform operates as a real OTA system and is designed to support distributed transmission with a large number of synchronised antenna elements (see the sketch in Figure 4-1). The main objective is to investigate spatial focusing effects in static indoor scenarios using distributed antenna arrays and to evaluate the achievable signal concentration at a dedicated user position. Particular attention is paid to the comparison between independent transmission from separated antenna arrays and joint transmission from multiple arrays serving the same user.

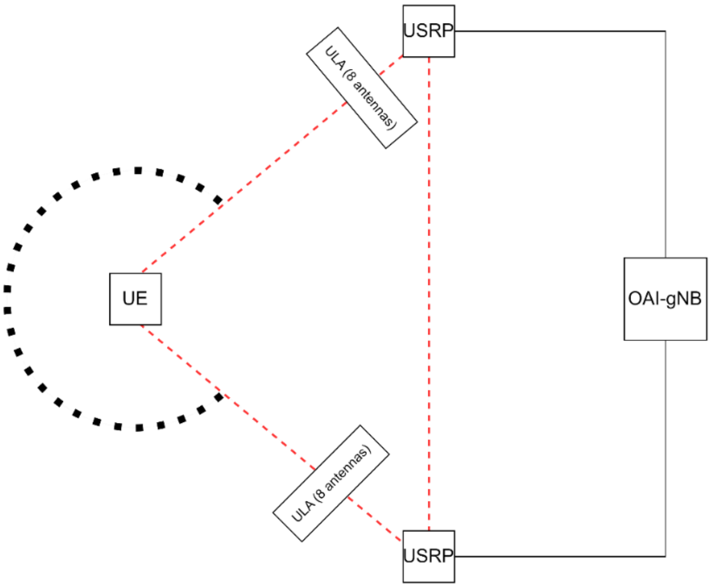


Figure 4-1 Experiment 1 physical setup

a)

b)

Figure 4-2 a) Multi-USRP X410 based gNB platform with 16 synchronised RF chains, b) UE implementation based on a USRP 2974 platform used as the receiving node in the OTA setup

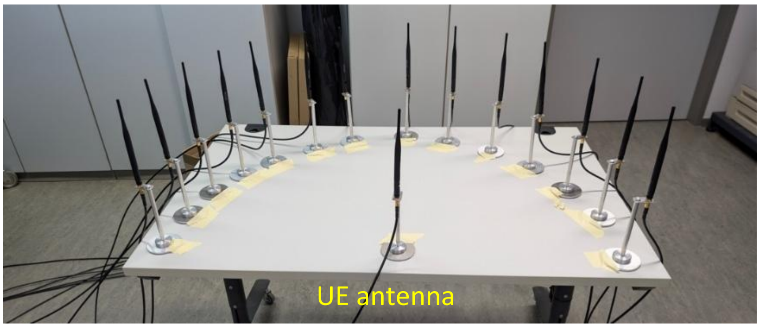


Figure 4-3 Top view of the antenna arrangement showing the spatial distribution of transmit antennas and measurement receivers (front view)

Figure 4-4 Semi-circular antenna deployment around the UE position for near-field spatial measurements (side view)

The gNB implementation is based on four USRP X410 devices providing a total of 16 antenna ports, as shown in Figure 4-2 a). Within OAI, all antenna branches are configured as a single Radio Unit (RU), allowing centralised processing and coherent operation across all transmit chains. Depending on the considered scenario, the system can be operated either as a single uniform linear array (ULA) with 16 antenna elements or as two physically separated ULAs with eight antenna elements each. Each antenna branch is connected to an individual RF frontend, while synchronisation across all devices is ensured using external reference distribution via OctoClock, providing a common 10 MHz reference clock and PPS synchronisation.

The user side is implemented using an OAI UE running on a USRP 2974 platform, as shown in Figure 4-2 b). The corresponding antenna is located at the center of the surrounding antenna arrangement, as illustrated in Figure 4-3. The system operates in 5G NR band n78 at a carrier frequency of 3.6192 GHz using the same numerology across gNB and UE. The UE performs standard uplink and downlink procedures, including uplink pilot transmission required for channel estimation and downlink beamforming operation at the gNB.

To enable the 16-antenna deployment, the standard OAI implementation was extended to support the full number of transmit and receive chains required by the setup. In addition, modifications were introduced in the OAI USRP interface to support TDD operation using the shared TX/RX RF port instead of separated transmit and receive ports. This behaviour is required by the practical RF setup and can be activated through a dedicated configuration flag in the SDR parameters of the OAI configuration files. The implementation has been validated in OTA operation, confirming successful synchronisation, UE attachment, and stable communication between gNB and multiple UEs.

The main experimental activity currently under preparation is referred to as **Experiment 1** and focuses on near-field beamforming with two separated ULAs. In this setup, both arrays are statically positioned with a defined spatial separation and are oriented toward a fixed UE position. The antenna deployment used for the experiment is shown in Figure 4-3 and Figure 4-4. Due to the array aperture, carrier frequency, and the limited laboratory dimensions, the considered operating region lies within the radiative near-field region, making near-field focusing effects relevant for the evaluation.

To characterize the spatial beam focusing, additional synchronised measurement receivers based on USRP X310 platforms are placed behind the UE position along one or more semicircular measurement trajectories, as illustrated in Figure 4-3, Figure 4-4 and Figure 4-5. These reference receivers are configured with the same carrier frequency and numerology as the UE and are used to evaluate the spatial distribution of the received signal quality around the intended focal point. Depending on the final implementation of the measurement software, the evaluation will be based on metrics such as SINR and CQI, or alternatively on received signal strength measurements if passive signal-quality estimation proves more robust for the reference receivers.

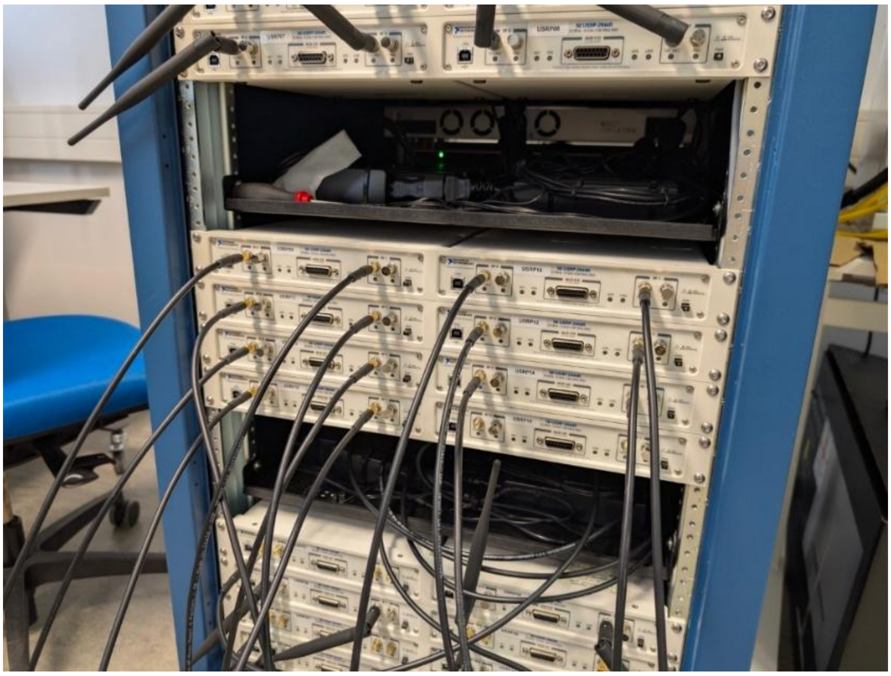


Figure 4-5 Synchronised USRP X310-based measurement receivers used for spatial signal measurements

Three transmission cases are considered for the comparison. In the first case, only the first ULA is active and serves the UE. In the second case, only the second ULA is active. In the third case, both ULAs jointly transmit toward the same UE position with the objective of achieving stronger spatial focusing and constructive signal combination at the intended target location. The measurement receivers are used to verify that the beam maximum is concentrated at the UE position while signal levels decrease at surrounding observation points.

At the current stage, the OAI platform with 16 antenna support has been implemented and validated, and the OTA communication between gNB and UE has been successfully established. The corresponding link quality indicators, including RSRP and BLER, are shown in Figure 4-6. The system operation statistics are shown in Figure 4-7.

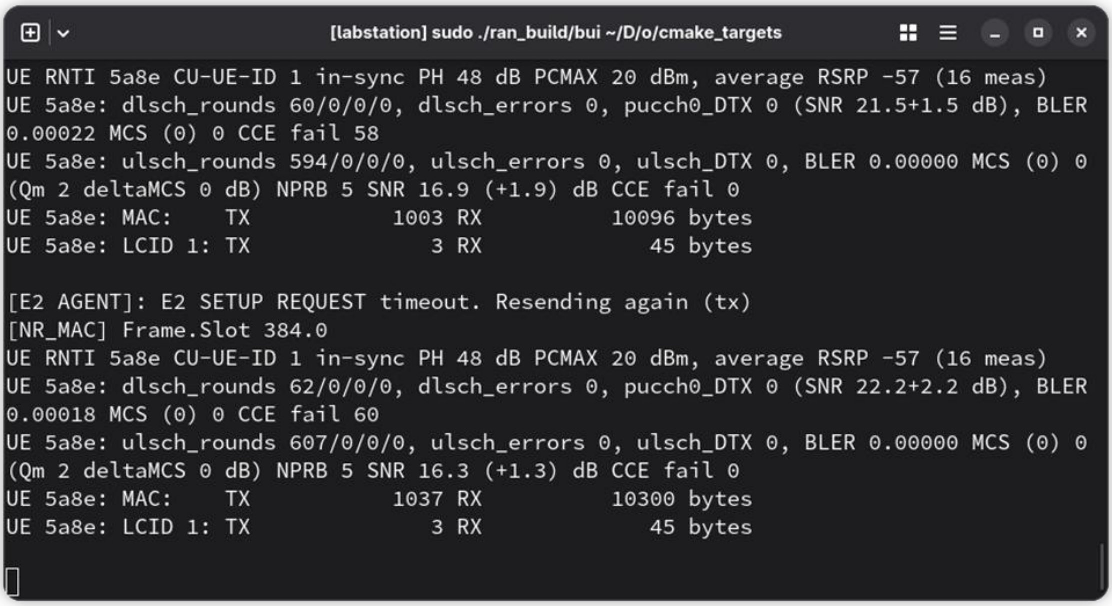


Figure 4-6 Real-time console output showing MAC layer statistics and HARQ operation during OTA experiments

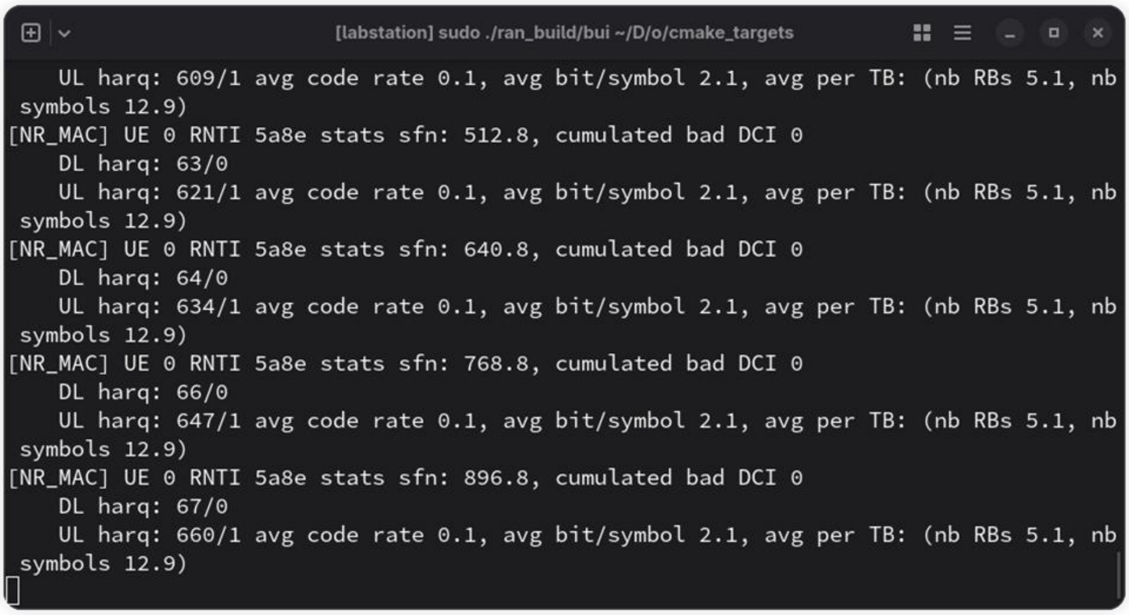


Figure 4-7 Real-time console output illustrating link quality indicators, including RSRP, SNR, and BLER

4.1.2 Output Metrics and Data Collection

The performance evaluation of the implemented scenarios is based on measurable system-level metrics that can be obtained directly from the OAI framework. The primary output considered in this work is the achievable data rate, which is derived from the effective throughput observed at the user side. In addition, other relevant indicators, such as signal quality and link performance, can be monitored depending on the configuration. These include, for example, received signal strength or scheduling-related metrics provided by OAI.

To enable reproducibility and structured evaluation, all relevant output data is collected and stored via a network-based interface. Each UE instance is associated with a predefined IP address, which allows external access to the transmitted and received data streams. This setup enables real-time monitoring as well as offline analysis.

From an implementation perspective, the data collection process is realised as follows:

- Each UE is assigned a fixed IP address within the experimental network.
- Data traffic is generated and received over standard IP-based connections.
- Performance metrics such as throughput (data rate) are measured at the IP layer.
- The collected data is stored for further evaluation and comparison across scenarios.

This approach allows a consistent comparison of the different transmission schemes under identical conditions. Furthermore, it reflects a realistic deployment scenario, where performance is evaluated based on e2e data transmission rather than purely theoretical metrics.

4.1.3 Implementation at UC

In addition to deploying, at UC premises, a small-scale distributed multi-user MIMO demonstrator, composed of two single-antenna UEs (one of them mobile) and one 6-antenna AP based on USRP B210 devices, the UC research team is carrying out the necessary tasks to port the multi-antenna and multi-carrier reciprocity calibration procedure to the CF-MIMO testbed at TUBS facilities.

Specifically, an OAI-based RU gNB has been implemented using the same 5G NR numerology as that employed by the TUBS prototype, but running on simpler hardware available at UC (USRP N310, USRP N321, and an OctoClock). It has been verified that OAI manages all RU antennas using a single UHD streamer for transmission and a single UHD streamer for reception. This prevents the native execution of the reciprocity calibration procedure, since the latter requires one RU antenna to transmit while the remaining RU antennas receive (and vice versa).

For this reason, the **UC** RU includes an extra antenna (an additional USRP) whose sole purpose is to act as a reference antenna in the OTA reciprocity calibration procedure. This procedure takes as input the OAI structures *openair0_cfg_t* and *usrp_state_t*, along with a pointer to a vector where the calibration results are returned. In the procedure, a *uhd::usrp::multi_usrp* object is created for the USRP dedicated to calibration, along with its corresponding RX and TX streamers. The feasibility of this solution has been validated through the tests conducted at **UC**.

The Argos OTA reciprocity calibration algorithm [6], extended to support multicarrier communications, has been integrated into and validated on an OAI RU gNB deployed at the **UC**.

The **UC** experimental setup, shown in Figure 4-8 and Figure 4-9, consists of one USRP N310 operating as a four-antenna gNB and one USRP N321 acting as the external calibration device. The gNB runs OAI version 2025.w32 and is configured with the following parameters:

- Number of antennas: 4.
- Band: 78.
- Number of resource blocks: 51.
- Subcarrier spacing: 30 kHz.
- Center frequency: 3619.20 MHz.
- Sample rate: 30.72 Msps.

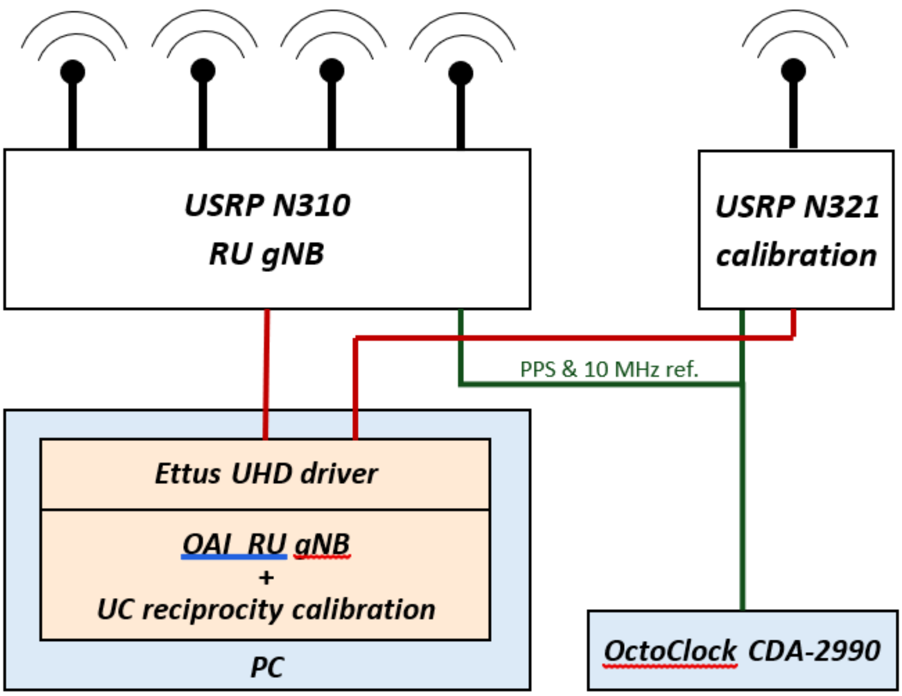


Figure 4-8 Block diagram of UC setup for reciprocity calibration integration in OAI RU gNB

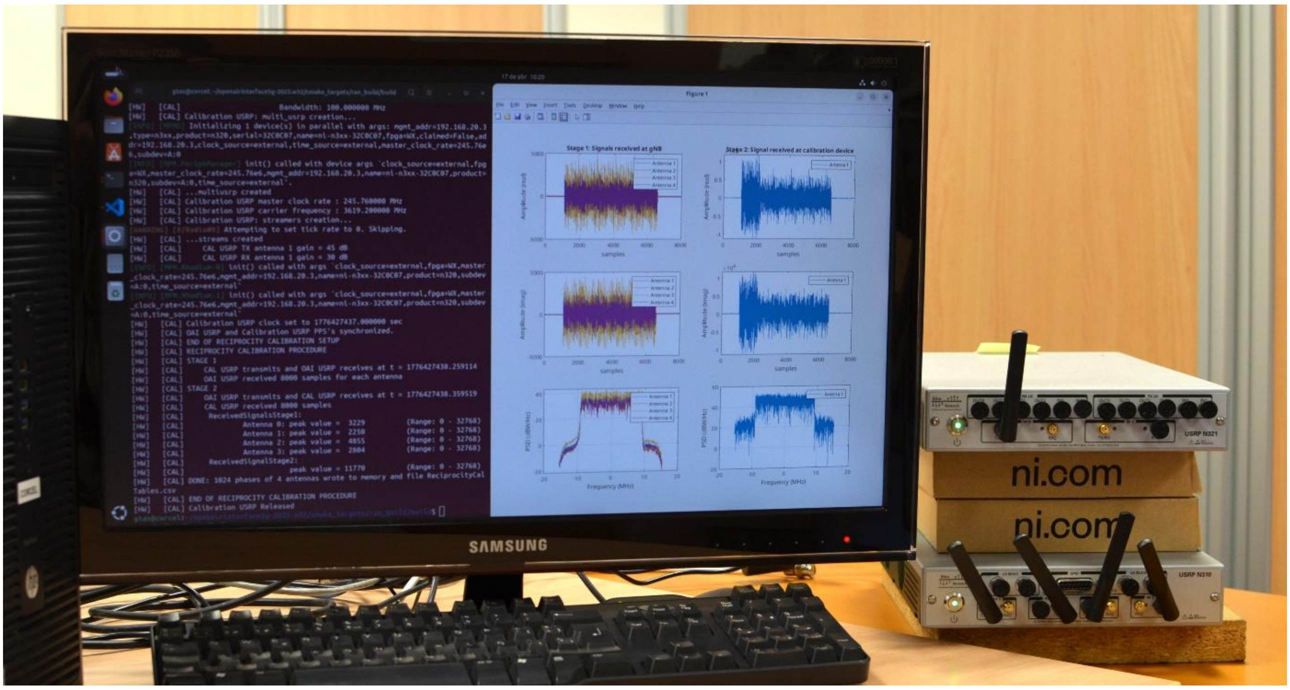


Figure 4-9 Picture of reciprocity calibration integration in OAI gNB at UC lab

UC has developed dedicated C++ software to control the RF hardware, including both the gNB USRPs and the additional calibration USRP, through the Ettus UHD driver. This software implements the reciprocity calibration algorithm and has been fully integrated into the standard OAI gNB C++ codebase. The integrated solution has been successfully tested using the **UC** setup.

Figure 4-10 presents a screenshot of the running gNB, displaying the reciprocity calibration log messages. These logs include:

- Reciprocity calibration setup: initialisation and configuration of the calibration USRP.
- Reciprocity calibration procedure, comprising:
  - Stage 1: The calibration USRP transmits five OFDM symbols, which are received by the gNB USRP through its four antenna RF chains, as illustrated in the left panel of Figure 4-11.
  - Stage 2: Each gNB antenna transmits five OFDM symbols using frequency-domain multiplexed pilots, enabling simultaneous reciprocity calibration of four (or more) antennas. The corresponding received signal at the calibration USRP is shown in the right panel of Figure 4-11.
  - Phase estimation: linear regression–based estimation of the phase drift as a function of frequency (subcarrier index) for each gNB RF chain. The resulting phase characteristics are presented in Figure 4-12.

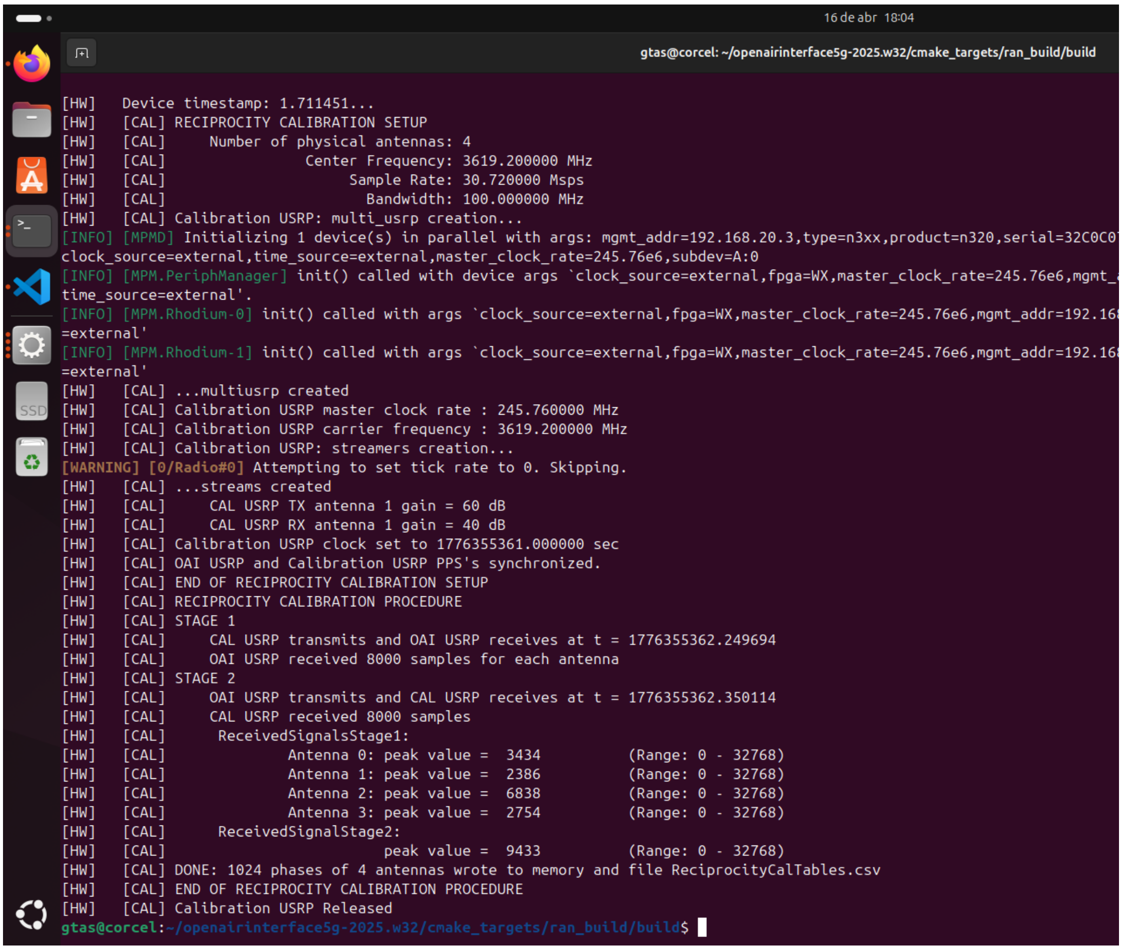


Figure 4-10 OAI gNB running the reciprocity calibration procedure at UC facilities

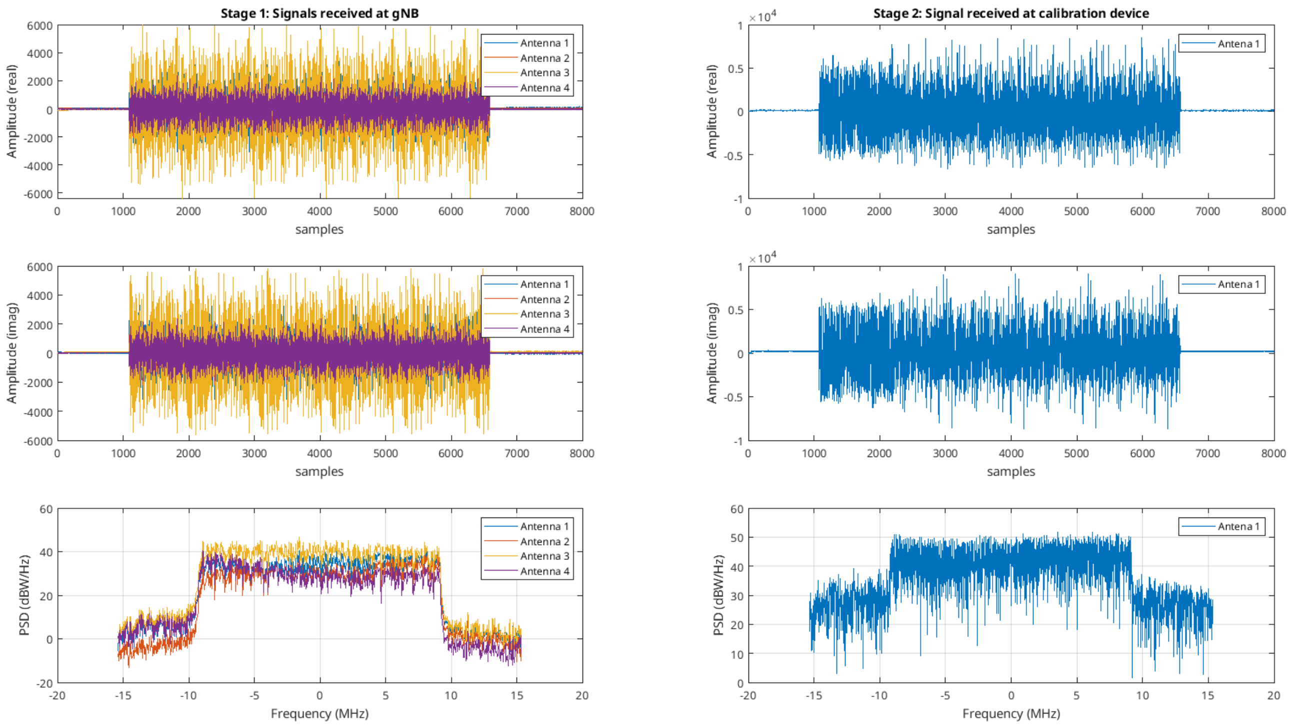


Figure 4-11 Temporal samples (up) and power spectral density (down) of the received signals at Stage 1 (left) and Stage 2 (right)

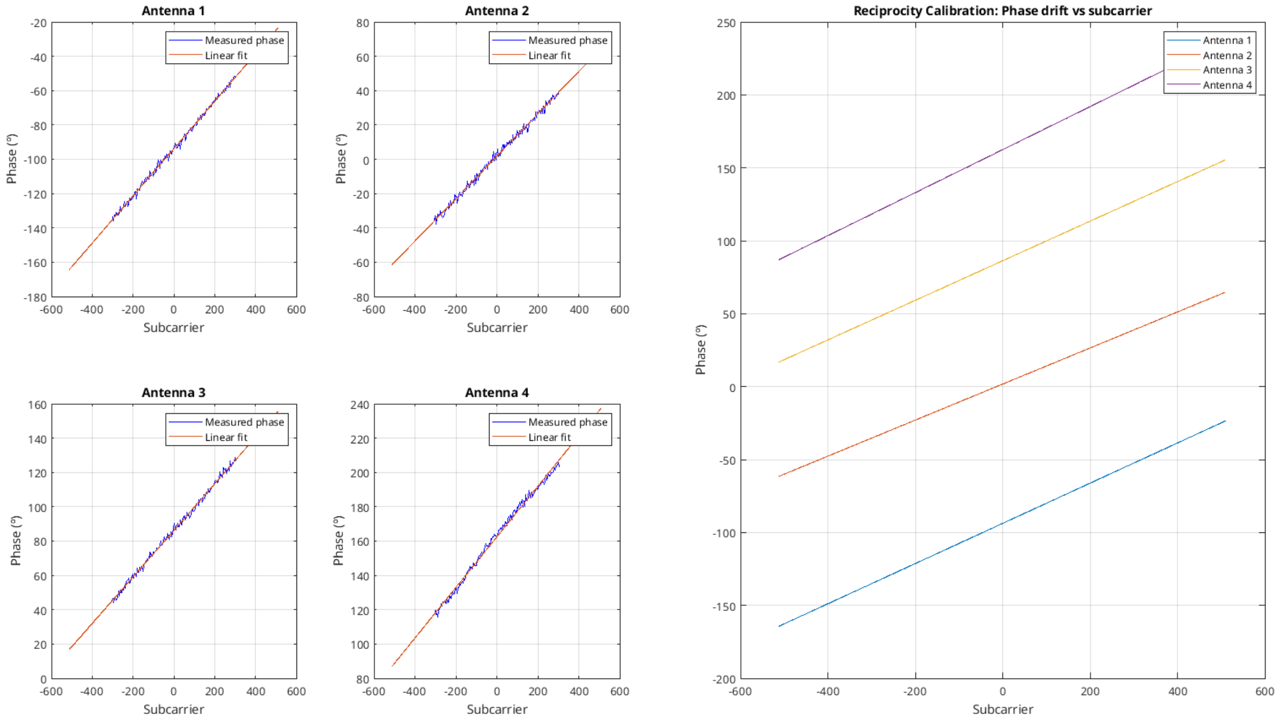


Figure 4-12 Estimated reciprocity phase drift versus OFDM subcarrier for each gNB antenna

4.2 RIS-based PoC Demonstrator

4.2.1 Demonstrator Goal

The main objective of the RIS-based demonstrator is to evaluate the joint optimisation of transmitter beamforming and RIS configuration in a controlled laboratory setup. By integrating multiple RIS panels into the testbed, we aim to quantify the performance gains in terms of signal quality and throughput, and to study the feasibility of more advanced RIS-assisted transmission strategies.

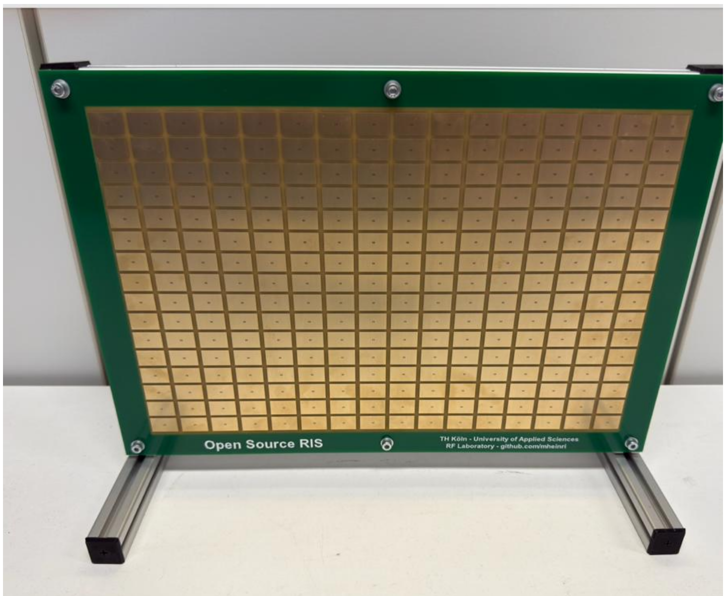


Figure 4-13 Example of RIS panel available at the lab of TUBS

4.2.2 Demonstrator Scenarios

RIS deployment: In total, six RIS panels are available, most likely arranged in a (1+1+4) configuration. Each RIS in Figure 4-13 consists of 256 elements (16×16), designed for 5.5 GHz operation, with elements that can be switched between 0° and 180°.

Integration setup: The RIS panels are connected via USB to Raspberry Pis mounted on the rear side of the panels. The Raspberry Pis are powered and networked via PoE, running the server software component, which automatically detects RIS and publishes them in the network via Zeroconf. A single Pi can manage up to four RIS units.

Client-side control: Two control approaches are provided:

- **GUI-based application:** A graphical interface (see Figure 4-14) allows manual or semi-automatic RIS configuration. Users can set transmitter/receiver azimuth, elevation, and distance parameters. Based on these inputs, the RIS updates its configuration, visualised in real time on the RIS control panel (Figure 4-14), where blue cells represent active elements and grey cells inactive ones. This provides intuitive monitoring and direct feedback of the RIS state.

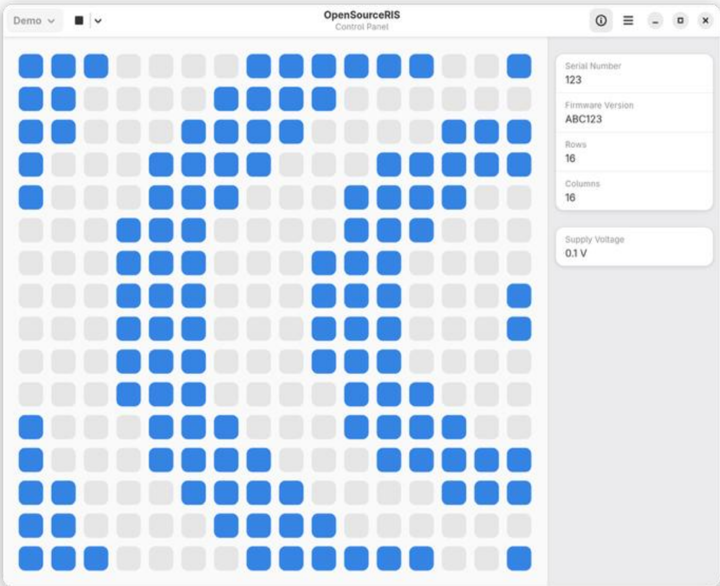


Figure 4-14 RIS Control panel

- **Python library:** A software library (with a C++ version under development) abstracts RIS as programmable objects, supports uploading configurations, and allows grouping multiple RIS panels into geometric structures for joint control. This enables flexible algorithmic optimisation and integration with higher-layer applications.

Experimental scenario: Besides joint beamforming/RIS optimisation, one specific test case involves cascading RIS panels in series (**BS** /**RU** (in Figure 4-15) → **RIS1** → **RIS2** → **UE**) to study the feasibility and impact of multi-hop RIS-assisted transmission.

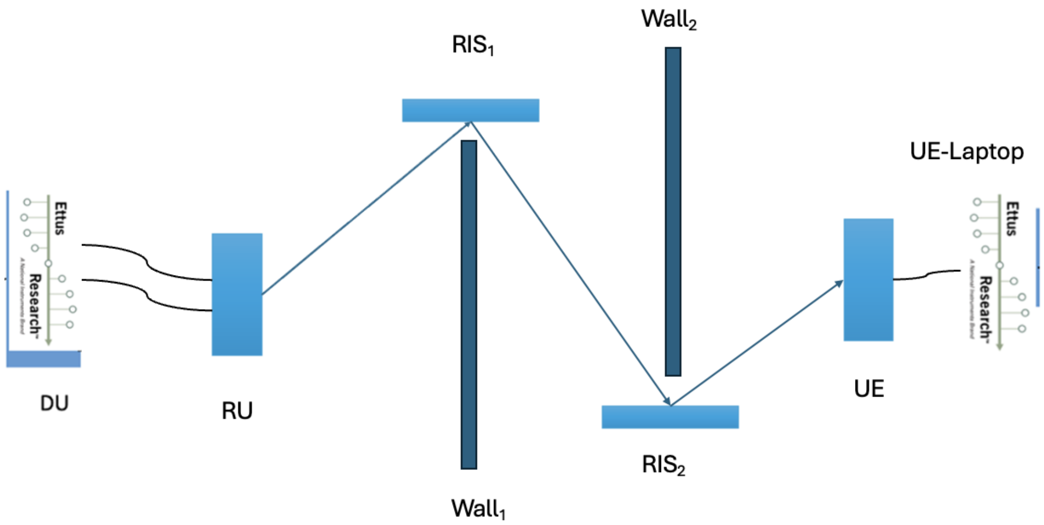


Figure 4-15 Massive MIMO System for RIS – Setup

4.2.3 Demonstrator Outputs

The demonstrator assesses the practical feasibility and benefits of RIS integration. The expected outputs and KPIs include:

- **SINR, CQI, and data rate measurements**: Quantifying the performance gain of RIS-assisted transmission compared to baseline (without RIS).
- **Coverage analysis**: Evaluating improvements in uniformity of coverage when multiple RIS panels are jointly configured versus individual usage.
- **Cascaded RIS impact**: Measuring achievable performance when using two RIS in series, providing insights into the limits of multi-hop RIS operation.

4.3 Risks and mitigation measures for PoC#2

This section provides an overview of the risks that are being identified as part of PoC#2 development and integration activities. Table 4-1 shows the risks that have been considered throughout the evaluation of the PoCs and that are considered as "Unforeseen risks" to the Project, i.e. not defined in the DoW.

Table 4-1 Unforeseen risks for PoC#2

Unforeseen Risk Nº	Description of the risk	Severity of the risk	Likelihood of the risk	Mitigation Measures
1	Hardware failure of USRPs, RIS panels, or synchronisation units (e.g., OctoClock, GNSS clock)	Medium	Medium	Keep spare hardware modules; establish rapid replacement procedure; regular maintenance and calibration.
2	Software integration issues between SDR (OAI/SRS), RIS control, and RIC interfaces	High	Medium	Early integration testing; modular API design; fallback to simplified configuration scripts if automated control fails.
3	Measurement inaccuracy due to interference/noise in the lab environment	Medium	High	Shield critical links; run experiments in controlled lab conditions; apply statistical averaging across measurement runs.

4	Software bugs or crashes in SDR stack (OAI/SRS) or RIS control software	High	Medium	Early debugging and modular testing; maintain backup software version.
6	Software bugs or crashes in OAI implementation	Medium	Medium	Early debugging and modular testing; maintain backup software version.
7	Software integration issues between OAI and RIC	High	Medium	Early integration testing; modular design

5 PoC#3 – Network Digital Twin (NDT) via RAN Sensing

PoC#3 leverages the sensing capabilities of the RAN to optimise network performance and energy efficiency with the support of an NDT. The NDT is being developed based on network planning information and network performance/telemetry data, and is implemented as an xApp associated with the O-RAN RICs. The demonstrator is currently integrating three complementary technologies—Sub-6 GHz, mmWave, and 5G NR—as sensing information sources, which are being fed into the O-RAN framework. Within this framework, we improve network planning processes, enabling dynamic re-configuration decisions that enhance network performance and energy efficiency. These assessment and optimisation functions rely on network performance datasets that are continuously being collected and processed by the NDT application. A general implementation architecture is presented in Figure 5-1. This architecture, focused on integration and implementation activities, is an extract of the architecture defined for PoC#3 in deliverable **D5.1** [1].

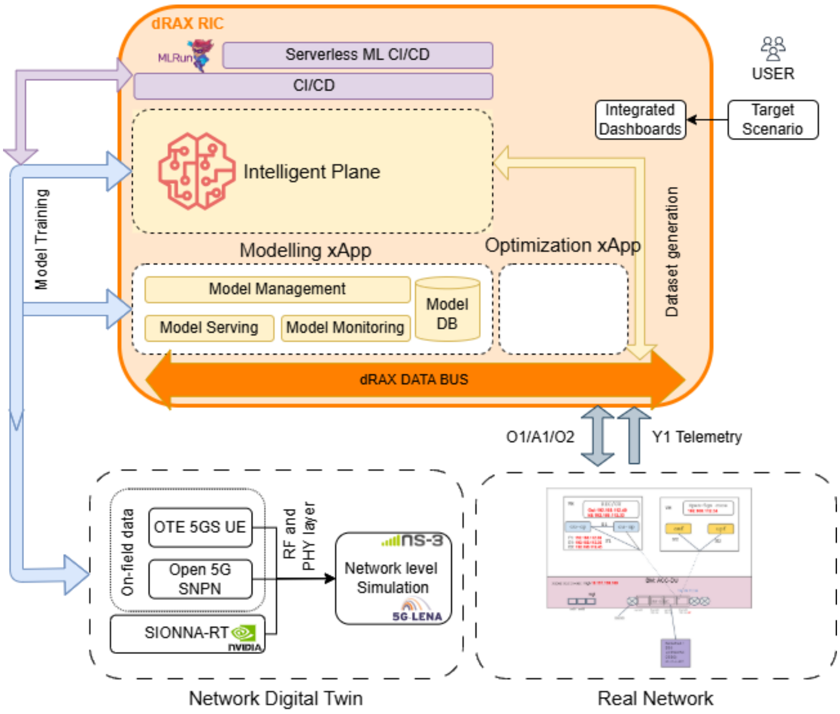


Figure 5-1 PoC#3 implementation Architecture

5.1 Architecture Overview

The PoC#3 architecture is structured around two main application components, two network environments, an Intelligent Plane serving AI capabilities to the applications and a user-driven optimisation interface, collectively enabling the creation, validation, and deployment of Network Digital Twin (NDT) models.

At the core of the system lies the **Modelling xApp**, which encapsulates the full lifecycle management of NDT models. This xApp comprises four key functional blocks:

- **Model Management**, responsible for model creation, versioning, and lifecycle control.
- **Model Serving and Implementation**, which translates NDT model outputs into actionable network configurations.
- **Model Monitoring**, which evaluates model performance and accuracy against real network conditions and triggers update model capabilities.
- **Model Database (Model DB)**, acting as a repository for storing generated and validated models.

Complementing this component is the **Optimisation Control xApp**, which orchestrates the decision-making process. This application receives high-level **target scenarios** defined by the user and translates them into optimisation objectives. Based on these objectives, it interacts with the Modelling xApp to select, evaluate, and deploy appropriate models.

The architecture interfaces with two distinct environments:

- The **Real Network**, which provides live telemetry data and acts as the execution environment where optimisation actions are applied. Depending on the Use Case, this real network can use an external sensing device to integrate sensing capabilities into the model training.
- The **NDT and Simulator Environment**, which enables the generation and evaluation of models through simulation-based analysis.

The Intelligent Plane provides AI/ML services to the xApp to support their life cycle. In this implementation, it provides the data set generation capabilities from data metric collected from the real network, to create the models. Additionally, it will provide update capabilities, so that the model be improved based on NDT and real data.

Finally, a User Interface layer enables the definition of target scenarios, which drive the optimisation process through the Optimisation Control xApp.

This architecture enables a closed-loop system where data-driven models are continuously created, refined, and applied to optimise network performance and energy efficiency. To define the operation of the PoC, a set of operational cycles are needed.

5.2 Model Cycles

The system operation is organised into three interrelated cycles: Model Creation, Model Actualisation and Validation, and Model Implementation. These cycles collectively enable continuous learning, adaptation, and optimisation of the network.

5.2.1 Model Creation Cycle

The Model Creation cycle is responsible for generating initial NDT models based on real network observations. Figure 5-2 depicts the flow diagram of this cycle.

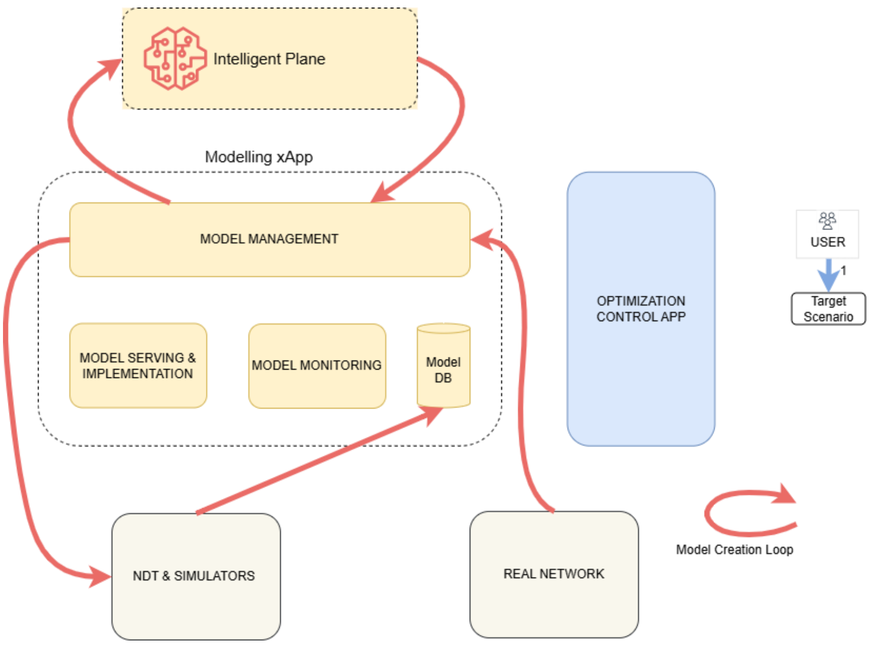


Figure 5-2 PoC#3 Model Creation cycle

Table 5-1 COSMOTOOLs – Parameters/Data Received

Name of Parameter	Description / Data retrieved
GPS	Global Positioning System, used for location tracking
LATENCY	The time it takes for data to travel from source to destination (measured in milliseconds)
DL BITRATE	Download bitrate, the speed at which data is received from a network (measured in Mbps)
UL BITRATE	Upload bitrate, the speed at which data is sent to a network (measured in Mbps)
Reference Signal Received Power (RSRP)	Indicates the power level of the received LTE signal
Reference Signal Received Quality (RSRQ)	Measures LTE signal quality by evaluating interference and power levels
Reference Signal SNR (RSSNR)	Indicates the strength of the LTE signal compared to noise.
Channel Quality Indicator (CQI)	A value used in LTE to adapt transmission rates based on signal conditions
Received Signal Strength Indicator (RSSI)	The total received power including signal and noise

This process begins with the continuous collection of telemetry data from the Real Network, including network performance metrics, configuration parameters, and contextual information. To this end, telemetry data can be collected either from inherent network monitoring functions or from user collected and reported data. An example of such tool can be the "COSMOTools", an **OTE** in-house developed tool that capture and store datasets of network quality and performance metrics over time, location, conditions, etc. as received and reported from UEs registered to the COSMOTools platform.

The datasets to be generated include network-quality related parameters' measurements over time and along routes/ in various locations, such as the ones included in Table 5-1.

These parameters are accompanied by information related to the given network deployment area:

- network planning information (location of gNBs).
- cell reselections locations/info.
- handover locations/info, etc.
- additional info such as the cell-id, LAC/TAC, BS name, user location, terminal brand/model/OS-release, etc.

This information is collected in the form of raw measurements – datasets, while it can be depicted in the form of Heatmaps or Diagrams, as shown in Figure 5-3.

This combined information can clearly be used to construct a realistic twin of the radio-coverage environment instance and can be used to optimise the radio network in a more effective way.

This data is ingested by the Model Management function within the Modelling xApp.

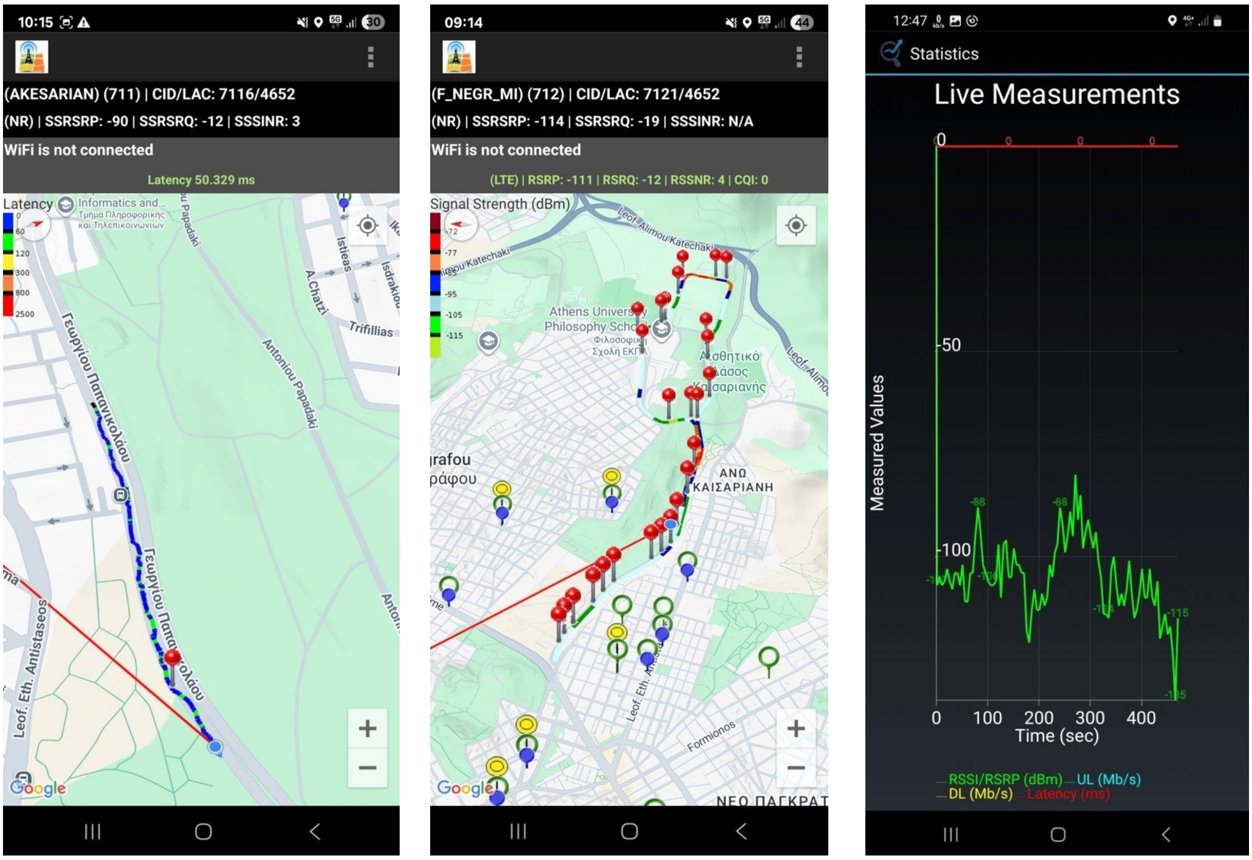


Figure 5-3 Indicative graphical representation of the telemetry information to be collected

Based on this telemetry and network configuration data, the Model Management component constructs a model representation of the radio environment. In this context, a model is defined as a structured description of a specific network scenario, including parameters such as RU and UE locations, radio conditions, and associated performance indicators. This representation is translated into simulator-compatible configuration files, which define the input conditions for the NDT environment. To do so, the Model Management function can connect to the Intelligent Plane to collect data points and help to build the description of the data set generated for the training process.

These configuration files are then forwarded to the NDT and Simulator Environment, where simulations are executed to instantiate the model and generate synthetic outputs corresponding to the defined scenario. The resulting model artifacts, including simulation outputs and derived parameters, are subsequently stored in the Model Database.

It is important to note that, at this stage, the generated model represents an initial approximation of the real network behaviour. Its accuracy depends on the quality of the input data and modelling assumptions, thus requiring further refinement through continuous validation and updating processes.

5.2.2 Model Actualisation and Validation Cycle

The Model Actualisation and Validation cycle ensures the continuous refinement of the NDT models, improving their fidelity and reliability over time.

This cycle operates as a continuous integration and continuous deployment (CI/CD)-like process, where models are iteratively updated based on real-time observations and performance feedback. The Model Monitoring function plays a central role in this process by comparing the outputs of the NDT simulations with actual measurements obtained from the Real Network. Figure 5-4 provides a sketch of this cycle.

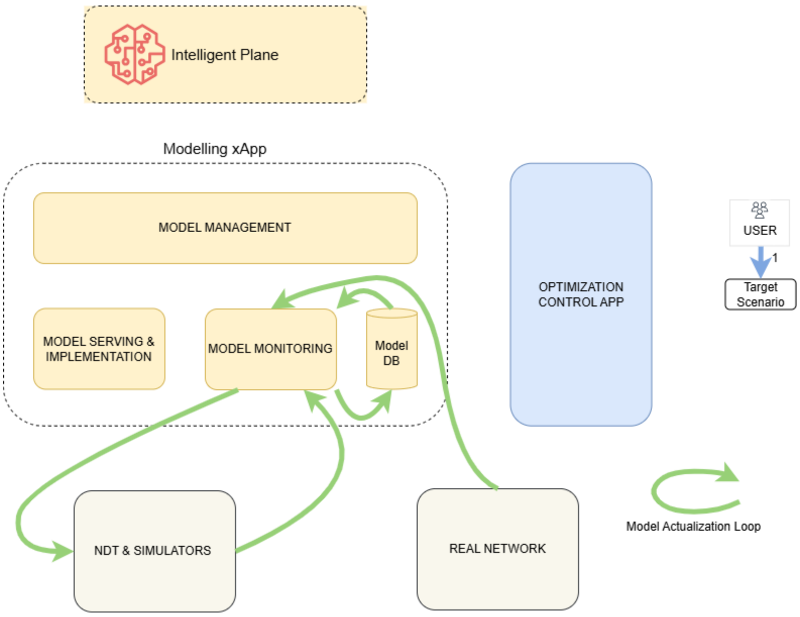


Figure 5-4 PoC#3 Model Actualisation cycle

Through this comparison, the system evaluates the accuracy of each model under varying network conditions. When discrepancies are identified, the system adjusts model parameters and assumptions to improve alignment with observed behaviour. For example, radio propagation models used within the simulation environment may be dynamically modified (e.g., switching between 3GPP, COST, Hata, or other propagation models) to better reflect real-world conditions.

Updated models are re-evaluated through the simulation environment, and their performance is continuously assessed. Once improved accuracy is achieved, the refined models are stored back in the Model Database, replacing or complementing previous versions.

This cycle enables the system to maintain an up-to-date and high-fidelity representation of the network, ensuring that the NDT remains a reliable basis for decision-making and optimisation.

5.2.3 Model Implementation Cycle

The Model Implementation cycle is responsible for applying validated models to optimise the operation of the Real Network. The process is initiated when a user-defined target scenario is provided to the Optimisation Control xApp. This scenario is translated into a set of optimisation objectives, such as improving energy efficiency, enhancing coverage, or maximising throughput.

Based on these objectives, the Optimisation Control xApp queries the Model Database to identify the most suitable model corresponding to the desired scenario. The selected model is then passed to the Model Serving and Implementation function within the Modelling xApp.

This component translates the model outputs into network configuration parameters, effectively mapping NDT-derived insights into actionable control commands. These parameters are then applied to the Real Network, modifying its behaviour accordingly.

Following deployment, the network response is monitored, and the resulting performance is fed back to the Optimisation Control xApp. The system evaluates whether the applied configuration meets the defined optimisation objectives. If the objectives are not achieved, alternative models are selected, and the process is repeated iteratively.

This closed-loop mechanism, shown in Figure 5-5, enables adaptive optimisation, where multiple candidate models can be evaluated and deployed until the desired performance targets are satisfied.

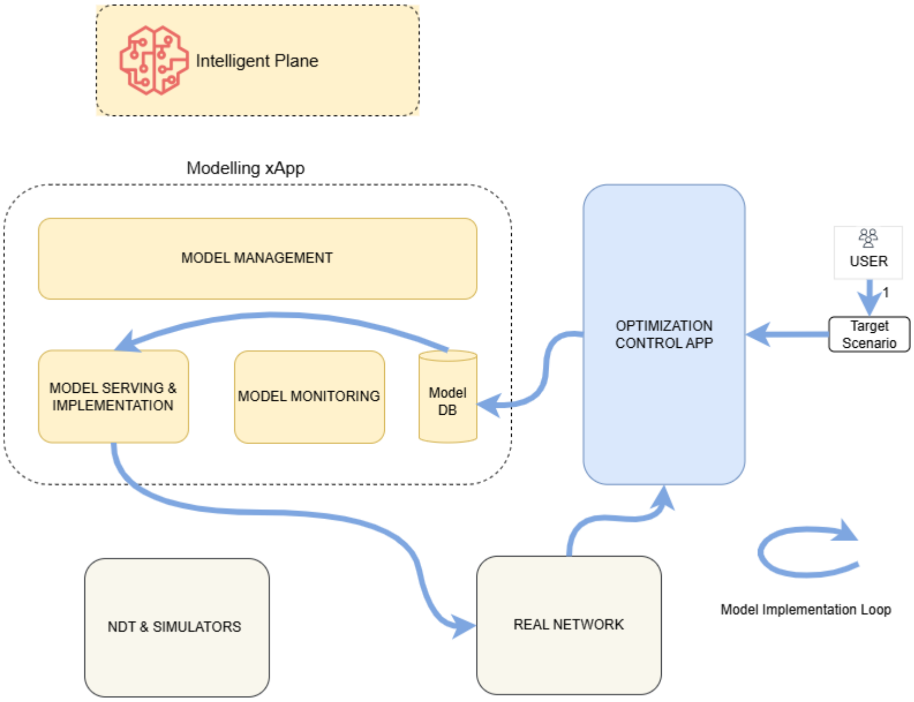


Figure 5-5 PoC#3 Model implementation Loop

5.3 Implementation process

The integration and implementation process, as this application relies on the intelligence of the network, requires a 2-stage process. The first one is intended to collect network information for the NDT to be trained, based on lab information data points that can be exported to the simulator; the second stage entails the selection of already trained functional models or NDT models to provide an accurate view of the real radio environment, which can be easily emulated and tested for optimisation purposes, based on the description of the model cycles described above. Next, some implementation stages for these stages are clarified.

5.3.1 NDT Model Creation

This step is required to create the NDT model, as described in the Model Creation Cycle. It consists on collecting data metrics and KPIs from the real network (lab setup) as well as radio environment information such as the location of UEs, RUs, and potentially objects locations. This is done via RADAR-aided devices, and the data they provide needs to be collected and formatted according to the simulator configuration file requirements. To do so, the integration process involves the following:

- **Real laboratory setup:** this needs to be connected to the dRAX telemetry ingestion data buses. An xApp/rApp is used to collect and process such information. It consists of a series of data places/locations that are known to create the data sets of measurements collected using the COSMOTools telemetry. In principle, 25 location points (see Figure 5-6) will be created to represent the radio environment. A radar device will be used to correlate the sensed location of the UE with the KPI measurements from the 5G setup this needs to be connected to the dRAX telemetry ingestion data buses.

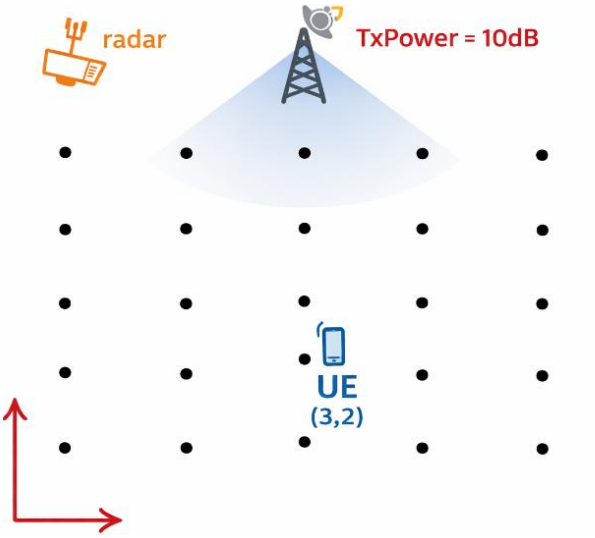


Figure 5-6 PoC#3 Laboratory Set up diagram

- **Simulator framework / NDT setup**: using Sionna/ns-3 and 5G LENA (as shown in Figure 5-7), defining the configuration file format required for future simulations. This part of the work will be reported in deliverable **D5.3**.

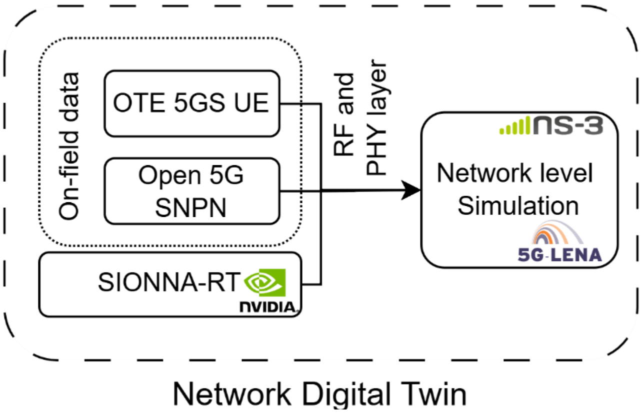


Figure 5-7 PoC#3 Simulation framework and NDT

- **Modelling xApp**: the role of this xApp is to collect telemetry from the real environment and train datasets to generate models, as described above. This xApp provides capabilities for Model Management, Model Monitoring, and Model Serving, as described in **D5.1** [1].

For the model creation, the definition of the model is required. In this implementation, a model is a specific radio environment scenario, consisting of a known RU location, known UE locations, and the associated radio metrics within this environment. As a machine learning (ML) model, it captures the relationship between these three data blocks.

5.3.2 Training phase

The initial training phase is implemented outside the Near-RT RIC time frame. This implies that data collected during the NDT model creation phase is stored locally and subsequently used for offline training outside the dRAX environment. The trained models are then transferred to a model database (DB) within the dRAX SMO.

5.3.3 Execution Phase

After the trained models are stored in the model DB, the optimisation control Modelling xApp, in coordination with the dashboard, selects the optimisation objective and triggers the NDT using real-time network parameters. The optimisation control xApp system then evaluates whether the objective can be achieved, either based on pre-trained scenarios or through direct execution of the simulator framework for fine-tuned results. Upon successful validation of the objective, the resulting network configuration is applied to the real network.

The development and integration of PoC#3 are structured into two interrelated phases:

5.3.4 Pre-Trial of PoC#3 @ OTE

The pre-trial of PoC#3 at **OTE** in Athens aims to pre-test the DT rApp and generate network performance datasets that will be used for estimating the performance of the NDTs. The environment will be the same as the trial to be held in Santander, so that datasets can be portrayed between demo sites as previously described, and the datasets to be collected will entail the afore defined information (in the Model Creation Cycle description). For this purpose, an **ACC** O-RAN gNB is deployed and integrated to the 5GCN of **OTE** Testbed. The configuration of the **ACC** O-RAN gNB is listed in Table 5-2.

Table 5-2 Configuration @ OTE testbed

Parameter	Value
SITE ID	42473 ACCORAN1
cellLocalId	131
EARFCN DL	636666
EARFCN UL	636666
Frequency Band	3500-1
cell Name	N1ACCORAN1E1
ssbFrequency	634080
nRPCI	3
rachRootSequence	66
bSChannelBwDL	100 (MHz)
bSChannelBwUL	100 (MHz)

The **ACC** O-RAN gNB integration has been verified by the 5G CN and **ACC** Management Dashboards as shown in the next figures, while Figure 5-11 provides a photo of the setup at **OTE** premises.

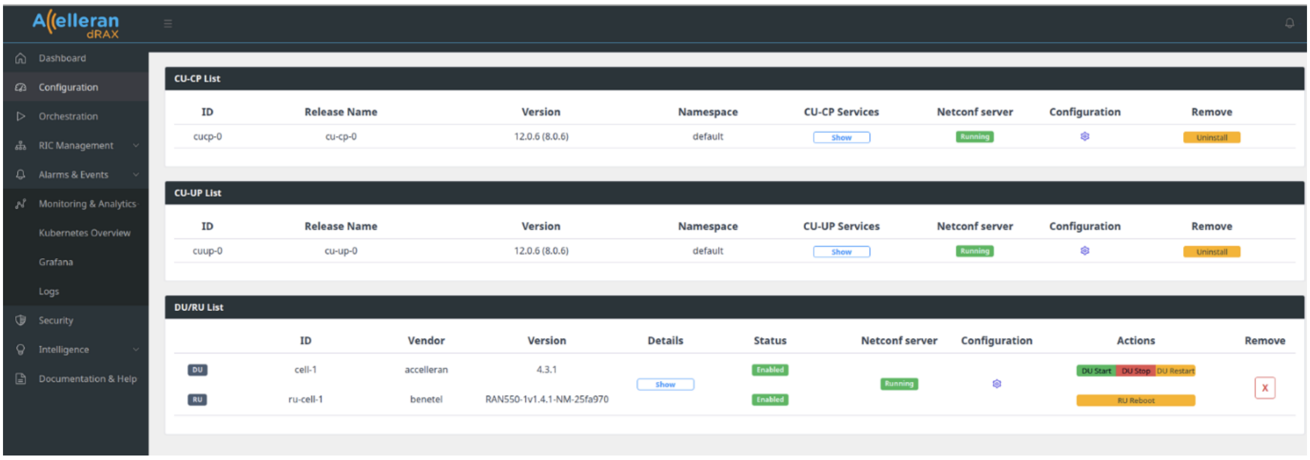


Figure 5-8 Configuration of DU/CU @ OTE testbed's ACC dRAx

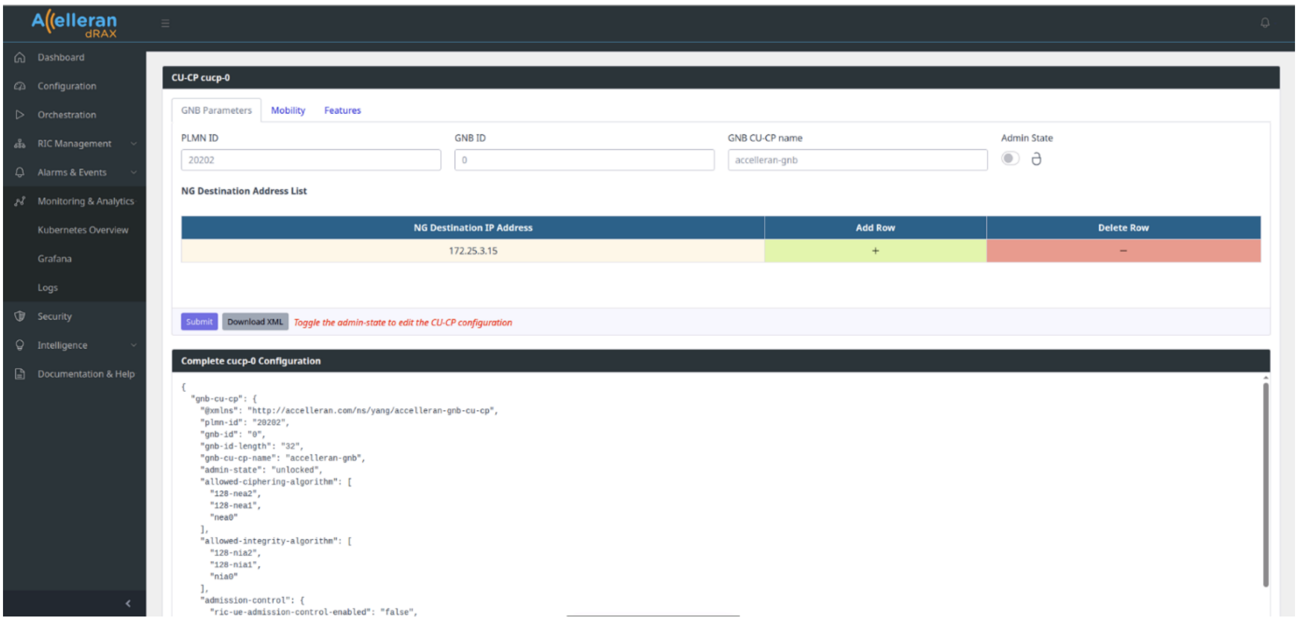


Figure 5-9 Configuration detailed for CU-UP @ OTE testbed's ACC dRAx

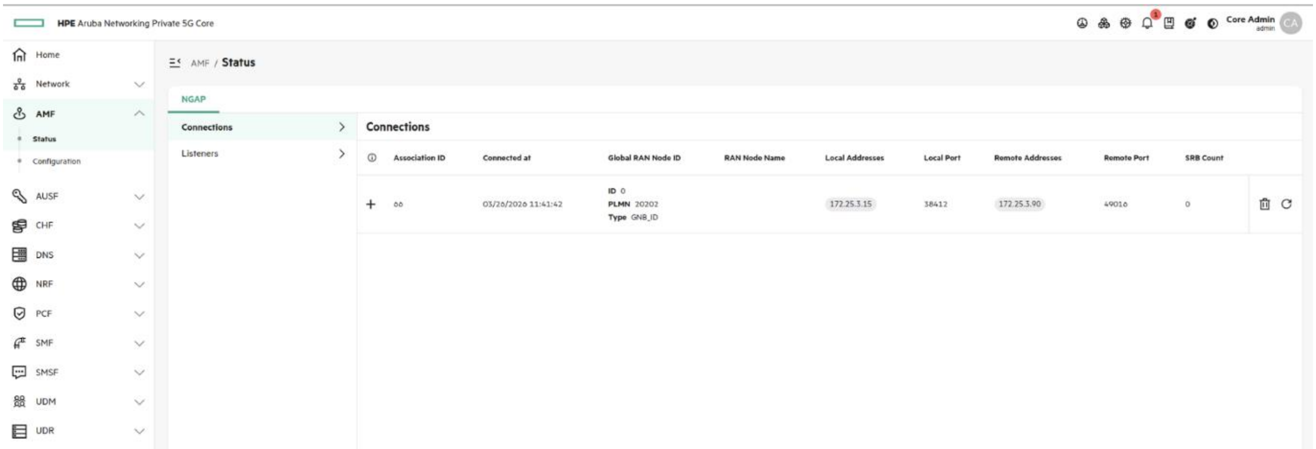


Figure 5-10 Integration of radios and CN @ OTE testbed's HPE 5GCN

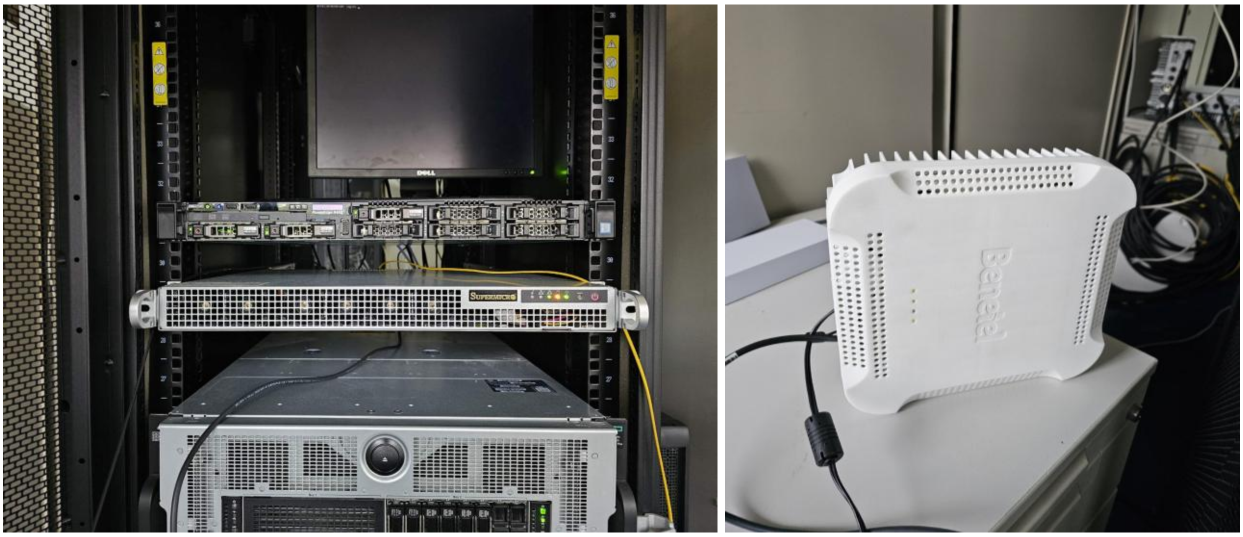


Figure 5-11 Physical installation of ACC O-RAN BS @ OTE testbed

5.4 Risks and Mitigation Measures for PoC#3

This section provides an overview of the risks that have been identified as part of PoC#3 development and integration activities. Table 5-3 shows the risks that have been considered throughout the evaluation of the PoCs and that are considered as "Unforeseen risks" to the Project, i.e., not defined in the DoW.

Table 5-3 Unforeseen risks for PoC#3

Unforeseen Risk Nº	Description of the risk	Severity of the risk	Likelihood of the risk	Mitigation Measures
1	Integration delays between NDT (ns-3 + SIONNA-RT) and the SMO framework due to interface or interoperability mismatches, leading to schedule slippage in UC trials.	High	Medium	Early interface definition and testing using emulated telemetry; maintain a continuous integration (CI/CD) setup across UC and ACC; use mock APIs to validate SMO ↔ NDT communication before full deployment.
2	Insufficient realism of sensing data from OTE pre-trials, causing the trained digital-twin models to underperform when applied to real network scenarios	Medium	Medium	Collect multiple datasets under varying conditions; perform data augmentation; retrain NDT models periodically with new field measurements from OTE and UC
3	AI/ML model drift or instability in rApp decision-making (e.g., what-if optimisation leading to non-optimal or unsafe configurations)	High	Low-Medium	Include rollback policies and guardrails in the SMO; apply model validation pipelines; use sandbox (NDT) simulation before applying policies to the real RAN
4	Limited availability of hardware or lab resources (e.g., Sub-6/mmWave/RIS testbeds or compute resources for simulations) may delay integration or demonstration milestones	Medium	Medium	Establish backup testbeds at partner sites (e.g., partial emulation at UC/ACC labs); plan shared remote access; schedule early procurement and resource booking

6 Summary and Conclusions

This deliverable has presented the current status of the integration of the 6G-SENSES technologies, marking the transition from the design and specification phase (as defined in deliverable **D5.1** [1]) to the practical realisation of interoperable experimental platforms. While significant progress has been achieved, the integration activities reported in this document also highlight the complexity and challenges associated with combining heterogeneous technologies into cohesive e2e systems.

The integration approach adopted in WP5 follows a structured and iterative methodology, enabling progressive consolidation of components across multiple architectural layers, including the RAN, CN, and Intelligent Plane. The use of O-RAN principles has facilitated modularity and programmability; however, full interoperability across components developed by different partners remains a non-trivial challenge, particularly in terms of interface alignment, data model consistency, and timing coordination.

The three PoCs developed within the project provide complementary perspectives on the integration of 6G technologies, although they currently exhibit different levels of maturity and integration completeness.

PoC#1 – Multi-Technology ISAC Platform has reached a relatively advanced stage of integration, demonstrating the feasibility of combining multiple Wireless Access Technologies with sensing capabilities. Initial results confirm the potential of ISAC to enhance network awareness and optimisation. Nevertheless, challenges remain in achieving seamless fusion of heterogeneous sensing data and ensuring consistent behaviour across different technologies, particularly under dynamic conditions. The integration of diverse WATs introduces additional complexity in terms of synchronisation, data alignment, and control coordination, which requires further refinement.

PoC#2 – CF-MIMO Prototype has successfully demonstrated key aspects of distributed radio architectures, including beamforming, synchronisation, and RIS-assisted transmission. However, the integration of PHY-layer innovations with higher-layer control mechanisms is still evolving. Ensuring tight coupling between real-time signal processing and Near-RT control loops remains a critical challenge, especially when scaling the system to more complex scenarios. Additionally, the reliance on SDR-based platforms introduces constraints related to processing latency and system stability, which need to be carefully managed.

PoC#3 – NDT via RAN Sensing represents the most complex integration effort, due to its strong dependence on data-driven modelling and AI/ML processes. While initial integration steps have been achieved, including telemetry collection and model generation, the system is still in an active development phase. Key challenges include ensuring the accuracy and reliability of the NDT models, maintaining consistency between real and simulated environments, and achieving stable closed-loop operation. Furthermore, the integration of the Intelligent Plane introduces additional dependencies related to data availability, model training, and computational requirements, which may impact scalability and real-time applicability.

Across all PoCs, the integration process has revealed several system-level challenges that are critical for the success of the project. These include:

- Interoperability limitations, due to differences in implementation approaches, interfaces, and data formats across components.
- Data consistency and quality issues, particularly when combining real network measurements with simulated or inferred data.
- Scalability constraints, especially in scenarios involving distributed processing, large datasets, or AI/ML-based optimisation.
- Timing and synchronisation challenges, which are particularly relevant for real-time and Near-RT control loops.

While mitigation strategies have been defined and partially implemented, these challenges underline the need for continued integration efforts and iterative validation.

Despite these limitations, the work presented in this deliverable establishes a solid foundation for the subsequent testing and evaluation phase. A common testing framework and methodology have been defined and are being progressively applied across the PoCs, enabling consistent assessment of performance and functionality. Initial testing activities have already started, although full-scale validation is still pending completion of integration activities, particularly for PoC#3.

From an architectural perspective, the integration results provide partial validation of the 6G-SENSES vision, demonstrating that the combination of sensing, communication, and AI-driven intelligence is feasible within a unified framework. However, the status also indicates that further effort is required to achieve full system maturity, particularly in terms of robustness, scalability, and automation.

Looking ahead, the next phase of the project will focus on completing the integration and conducting comprehensive testing and validation campaigns. This will involve:

- Finalising the integration of all components across the three PoCs.
- Extending testing to more realistic and dynamic scenarios.
- Improving the robustness and scalability of the integrated systems.
- Enhancing AI/ML models and optimisation mechanisms, particularly for the NDT framework.
- Validating the end-to-end performance against the defined KPIs.

The outcomes of these activities will be critical for demonstrating the practical viability and impact of the 6G-SENSES technologies and will be reported in subsequent deliverables.

In conclusion, this deliverable represents an important but intermediate step in the project lifecycle. While the progress achieved confirms the feasibility of the proposed architecture, it also highlights the gap between conceptual design and fully operational systems. Addressing this gap through continued integration, testing, and refinement will be essential to realise the full potential of 6G-SENSES in enabling intelligent, adaptive, and energy-efficient 6G networks.

7 References

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[2] 6G-SENSES deliverable D2.3, "Final report on 6G-SENSES network architecture evaluation", January 2026, link

[3] 6G-SENSES deliverable D2.1, "Report on 6G-SENSES use cases, network architecture, KPIs and supported RAN functions", September 2024, link

[4] 6G-SENSES deliverable D2.2, "System architecture and preliminary evaluations", February 2025, link

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[7] 6G-SENSES deliverable D4.1, "Initial SoTA and design of wireless edge caching solutions", January 2026, link

[8] 6G-SENSES deliverable D4.2, "Final design and implementation of wireless edge caching solutions", April 2026, link

[9] 6G-SENSES deliverable D4.3, "AI/ML techniques for enhanced network performance", January 2026, link

8 Acronyms

Acronym	Description
3GPP	3rd Generation Partnership Project
5G NR	5G New Radio
5QI	5G Quality of Service Identifier
ACC	Accelleran (6G-SENSES Beneficiary)
ADC	Analogue-to-Digital Converter
AFE	Analogue Front-End
AI	Artificial Intelligence
AiP	Antenna-in-Package
AoA	Angle of Arrival
AP	Access Point
BiCMOS	Bipolar-CMOS
BI	*Barkhausen Institut* (6G-SENSES Beneficiary)
BR	BubbleRAN (6G-SENSES Beneficiary)
BS	Base Station
BW	Bandwidth
CF-MIMO	Cell-Free MIMO
CMOS	Complementary Metal-Oxide-Semiconductor
CN	Core Network
CI/CD	Continuous Integration/Continuous Deployment
CIR	Channel Impulse Response
COTS	Commercial-Off-The-Shelf
CPRI	Common Public Radio Interface
CQI	Channel Quality Indicator
CSI	Channel State Information
CU	Central Unit
DAC	Digital-to-Analogue Converter
DB	DataBase
DC	Direct Current
DFT	Discrete Fourier Transform
DGS	Defective Ground Structure
DL	Downlink
DN	Data Network

DoW	Description of Work
DPP	Drift-plus-penalty
DU	Distributed Unit
DUT	Device Under Test
e2e	End-to-End
eCPRI	Enhanced CPRI
EPC	Evolved Packet Core
E2AP	E2 Application Protocol
E2SM	E2 Service Model
FFT	Fast Fourier Transform
FL	Federated Learning
FPGA	Field Programmable Gate Array
GBR	Granted Bit Rate
gNB	gNodeB
GNSS	Global Navigation Satellite System
GNU	GNU is Not Unix
GTEC	Communications and Electronics Technology Group
GTIS	GTEC Testbed Interface Software
GUI	Graphical User Interface
PoC	Proof of Concept
HPF	High-Pass Filter
HRLLC	Hyper Reliable and Low-Latency Communication
IASA	Institute of Accelerating Systems and Applications (6G-SENSES Beneficiary)
IHP	*IHP – Leibniz-Institut für innovative Mikroelektronik* (6G-SENSES Beneficiary)
INT	Intel Deutschland GmbH (6G-SENSES Beneficiary)
IP	Internet Protocol
ISAC	Integrated Sensing and Communication
IMT	International Mobile Telecommunications
I/Q	In-phase and Quadrature components
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
KPI	Key Performance Indicator
LAC	Location Area Code
LCL	Inductor-Capacitor-Inductor
LCM	Life Cycle Management

LENA	LTE/EPC Network simulAtor
LLC	Lower Layer Control
LTE	Long-Term Evolution
MAC	Medium Access Control
MC-LAG	Multi-Chassis Link Aggregation Group
MCS	Modulation and Coding Scheme
MEC	Multi-Access Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MMCX	Micro-Miniature Coaxial
mmWave	Millimeter Wave
Multi-RAT	Multiple Radio Access Technology
N3IWF	Non-3GPP Interworking Function
NDT	Network Digital Twin
Near-RT	Near-Real-Time
NGAP	Next Generation Application Protocol
NI	National Instruments
NIC	Network Interface Card
NN	Neural Network
Non-RT	Non-Real-Time
NR	New Radio
NS3	Network Simulator 3
N3IWF	Non-3GPP Interworking Function
NTU	Nottingham Trent University
OAI	OpenAirInterface
ODL	OpenDayLight
O-DU	Open-DU
OFDM	Orthogonal Frequency-Division Multiplexing
O-RAN	Open-RAN
O-RU	Open-RU
OS	Operative System
OTA	Over-The-Air
OTE	*ORGANISMOS TILEPIKOINONION TIS ELLADOS OTE AE* (6G-SENSES Beneficiary)
PCB	Printed Circuit Board
PoC	Proof of Concept

PoE	Power over Ethernet
Pout	Outage Probability
PHY	Physical Layer
PPS	Pulse Per Second
PRB	Physical Resource Block
PTP	Precision Time Protocol
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
REF	Reference Clock
RFSoC	Radio Frequency System-on-Chip
RIC	RAN Intelligent Controller
RIS	Reconfigurable Intelligent Surface
ROS	Robot Operating System
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
RSSNR	Reference Signal Signal-to-Noise Ratio
RT-RIC	Real Time RIC
RTT	Round-Trip Time
RU	Radio Unit
SCTP	Stream Control Transmission Protocol
SDR	Software-Defined Radio
SINR	Signal-to-Interference-plus-Noise Ratio
SMD	Surface Mount Device
SMO	Service Management and Orchestration
SNDR	Signal-to-Noise-and-Distortion-Ratio
SNR	Signal-to-Noise Ratio
SotA	State-of-the-Art
SRS	Sounding Reference Signal
sRU	sensing-Radio Unit
SUT	System Under Test

TAC	Tracking Area Code
TCO	Total Cost of Ownership
TDD	Time Division Duplex
TDoA	Time Difference of Arrival
TLV	Type-Length-Value
TRP	Transmission Reception Points
TUBS	*Technische Universität Braunschweig* (6G-SENSES Beneficiary)
UC	*Universidad de Cantabria* (6G-SENSES Beneficiary)
UDC	University of *A Coruña*
UE	User Equipment
UHD	USRP Hardware Driver
UL	Uplink
ULA	Uniform Linear Array
UNIROMA1	*Sapienza Università di Roma* (6G-SENSES Beneficiary)
UPF	User Plane Function
USB	Universal Serial Bus
USRP	Universal Software Radio Peripheral
VLAN	Virtual Local Area Network
VM	Virtual Machine
WAT	Wireless Access Technology
WEC	Wireless Edge Caching
Wi-Fi	Wireless Fidelity
WP	Work Package