Co-funded by the European Union

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

D5.1 Testing Methodologies and Testbed Setup

November 2025

6G-SENSES project has received funding from the Smart Networks and Services Joint Undertaking (SNS JU) under the European Union's Horizon Europe research and innovation programme under Grant Agreement 101139282

Project Start Date: 2024-01-01 **Duration**: 30 months

Call: HORIZON-JU-SNS-2023 **Date of delivery**: 2025-11-09

Topic: HORIZON-JU-SNS-2023-STREAM-B-01-02 **Version**: 1.0

Dissemination Level: Public (PU)

Grant Agreement Number:	101139282
Grant Agreement Number:	101139282
Project Name:	SEamless integratioN of efficient 6G WirelesS tEchnologies for Communication and Sensing
Project Acronym:	6G-SENSES
Document Number:	**D5.1**
Document Title:	Testing Methodologies and Testbed Setup
Version:	1.0
Delivery Date:	2025-08-31 (**2025-11-09**)
Responsible:	Sapienza, University of Rome (**UNIROMA1**)
Editor(s):	Federico Trombetti, Salvatore Pontarelli (**UNIROMA1**)
Authors:	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, Ramón Agüero, Ignacio Santamaría, Jesús Ibáñez (**UC**), Xi Ding, Nils Hildebrand, Eduard Jorswieck (**TUBS**), Germán Castellanos, Simon Pryor (**ACC**), Ioanna Mesogiti (**OTE**), Markos Anastasopoulos, Anna Tzanakaki (**IASA**), Yazhou Zhu, Jessica Sanson, Valerio Frascolla (**INT**), Muhammad Saadi, Shahid Mumtaz (**NTU**).
Keywords:	6G, Testing Methodologies, Testbed, Setup, Proof of Concept.
Status:	Final
Dissemination Level	Public (PU)
Project URL:	https://www.6g-senses.eu

Revision History

Rev. N	Description	Author	Date
0.1	Draft Table of Contents (ToC)	Federico Trombetti (UNIROMA1)	2025-06-21
0.2	Small sections update after first weekly meeting	Federico Trombetti (UNIROMA1)	2025-07-04
0.3	Updated Chapter 3	Federico Trombetti (UNIROMA1)	2025-07-10
0.4	Added Sections 3.3 and 3.4	Federico Trombetti (UNIROMA1)	2025-07-11
0.5	Updated PoC#2 Updated Introduction	Xi Ding, Nils Hildebrandt (TUBS), Jesús Ibáñez, Ignacio Santamaría (UC), Federico Trombetti (UNIROMA1)	2025-07-18
0.6	Updated PoC#1 in Chapter 4 Updated Chapter 2	Jesús Gutiérrez (IHP), Luis Díez (UC), Ioanna Mesogiti (OTE)	2025-07-25
0.7	Updated PoC#2 in Chapter 5	Xi Ding (TUBS), Jesús Ibáñez, Ignacio Santamaría (UC),	2025-09-12
0.8	Updated PoC#1 Updated Chapter 2	Jesús Gutiérrez (IHP), Ioanna Mesogiti (OTE)	2025-09-22
	Updated PoC#3 in Chapter 6	Luis Díez (UC), German Castellanos (ACC)	2025-10-07
	Updated PoC#3	German Castellanos (ACC)	2025-10-14
0.9	Final Revision	Ignacio Santamaría (UC), German Castellanos (ACC), Valerio Frascolla (INT)	2025-10-15 2025-10-17 2025-10-20
1.0	Last revision and submission of the document	Jesús Gutiérrez (IHP)	2025-11-09

Table of Contents

List of Figures

List of Tables

Executive Summary

6G-SENSES Work Package 5 (**WP5**) is designed to build a series of prototypes that validate and demonstrate the project concept. These demonstrations serve to verify the technologies developed in **WP3** and **WP4**, while ensuring the future-proof impact of the architecture defined in **WP2**.

Deliverable **D5.1** provides the detailed specifications and concepts of the use cases and demonstrations to be carried out during the project, including the infrastructures and technologies underpinning each Proof of Concept (PoC). Together, these PoCs illustrate the feasibility, scalability, and added value of the 6G-SENSES approach across multiple dimensions.

- **PoC#1: Multi-Technology Integrated Sensing and Communication (ISAC) Platform**

  This PoC develops a small-scale end-to-end (E2E) prototype to demonstrate performance gains in a multi-technology ISAC environment. By leveraging multiple Wireless Access Technologies (WATs) as sensing inputs, and integrating them with real-time Radio Access Network (RAN) and Core Network (CN) extensions, the PoC validates the ability of 6G-SENSES to dynamically and intelligently adapt network behaviour.

- **PoC#2: Cell-Free MIMO (CF-MIMO) Prototype**

  The second PoC delivers a cell-free MIMO (CF-MIMO) physical layer prototype, enhanced with real-time control capabilities. Implemented on representative Software Defined Radio (SDR) hardware, it demonstrates the feasibility of distributed signal processing, tight synchronization, reciprocity calibration for Time Division Duplexing (TDD) operation, and efficient fronthaul/backhaul integration. This PoC provides strong evidence of how advanced PHY innovations can translate into tangible performance gains in 5G Advanced and 6G networks.

- **PoC#3: Network Digital Twin (NDT) via RAN Sensing**

  The third PoC makes use of the sensing functionality of the RAN to build up a Network Digital Twin (NDT) that is emulated thanks to the telemetry data provided by the Open RAN (O-RAN) Radio controllers. The demonstrator comprises the use of three technologies: Sub-6, millimetre wave (mmWave) and 5G NR, as sensing information sources to be pushed to the O-RAN framework for carrying out an assessment of the current network planning. The generated data sets are then used for network optimization purposes, mainly focused on energy efficiency.

Together, these demonstrations confirm the technical soundness of the 6G-SENSES architecture and its potential to support next-generation services. The outcomes of **WP5** will serve as a crucial step toward validating the vision of the project of intelligent, energy-efficient, and future-ready 6G networks.

1 Introduction

The 6G-SENSES project aims to go beyond the capabilities of current 5G networks, by addressing the anticipated surge in mobile data traffic and the stringent performance demands of emerging services. These include ultra-low latency, high device and traffic densities, extreme mobility, and service reliability requirements that exceed what current 5G technologies can support.

6G-SENSES adopts a paradigm shift from traditional network-centric architectures [1]. This shift involves moving away from rigid, abstract service provisioning models, towards a more dynamic, fine-grained model, tailored to the specific needs of applications. Moreover, 6G-SENSES embraces a departure from monolithic network designs by promoting modular and multi-layered architectures, enabling service-driven deployments across heterogeneous network segments. This architectural evolution, detailed in [2], supports the transformation of service provisioning models and the broader ecosystem, encouraging openness, interoperability, and innovation among different network operators.

Technologically, 6G-SENSES integrates advanced wireless communication and networking techniques [3] (e.g., RIS, advanced RAN architectures), edge computing capabilities, and Artificial Intelligence (AI)-driven network management and orchestration. Seamless coordination across these layers is obtained through service-aware network slicing and automated orchestration mechanisms. These innovations are brought together within a unified, E2E evaluation framework that supports the design, testing, and validation of future 6G services under realistic deployment scenarios.

Ultimately, 6G-SENSES aims to establish a holistic and future-ready architectural foundation that can efficiently support distributed, low-latency, and high-performance service delivery, meeting the evolving needs of the next generation of applications and stakeholders.

This document serves as an introduction to the testing methodologies and testbed procedures carried out in 6G-SENSES, focusing on planning and defining the testing methodologies and procedures that will be used to evaluate the 6G-SENSES wireless solutions. Three types of testing procedures and requirements will be specified:

i) Lab-scale tests of individual technological blocks and network segments (e.g., RAN, RIS).
ii) Small-scale demonstration zones focusing on the evaluation of use cases and applications.
iii) Demonstration of 6G-SENSES infrastructure through live demonstrations of verticals. Emphasis is given to ensure a common-well defined measurement methodology among partners to facilitate collaboration, as well as to align with existing standards for conducting and reporting measurements of Key Performance Indicators (KPIs) for 5G and 6G networks.

Evaluation scenarios are also identified and associated with the types of tests. Emphasis is given to the definition of a test suite for O-RAN specifications in order to validate specific 6G-SENSES blocks.

Organisation of the document

This deliverable is structured as follows:

- **Chapter 2** details the KPIs employed in the evaluation of the project.
- **Chapter 3** outlines the 6G-SENSES evaluation framework, including the formal definitions of key concepts, testing methodologies, testing cycles, and descriptions of the use cases of the project.
- **Chapter 4**, **5** and **6** provide detailed insights into PoCs #1, #2, and #3, respectively.
- **Chapter 7** provides a description of the datasets and data used to carry out the experiments.
- **Chapter 8** concludes the document and identifies the next steps towards the realization of the 6G-SENSES concept.

2 KPI Defined in the Standards

Three main use cases have been identified in the context of 6G-SENSES along with relevant KPIs. The selected 6G use cases – as reported in deliverable **D2.1** [1] – take into consideration both the various service provisioning roles and stakeholders of future 6G ecosystems, and the envisioned 6G end-user (vertical or individual) application services. The 6G-SENSES use cases put emphasis on: a) the 6G-SENSES technical targets and vision towards supporting 6G vertical services and the associated KPIs, and b) the technology-related functionalities and capabilities that can untap new service provisioning paradigms in 6G ecosystems. In brief, the use cases envisioned within 6G-SENSES [1] are the following:

- **Use Case #1: Sensing-enabled Services**, which focuses on two scenarios: #1 to exploit sensing information to improve communication services (sensing-aided communication), and #2 to enable active sensing with Wi-Fi and provide Wi-Fi sensing standardization design. This use case highlights the work of the project on ISAC and, in particular, on WAT sensing and integration in a 6G RAN.
- **Use Case #2: Ubiquitous Connectivity for Hyper Reliable and Low-Latency Communication (HRLLC) & Immersive Services**, which focuses on storylines exploiting the CF-MIMO and RISs capabilities and their combination with sensing. This use case highlights the work of the project on RIS-assisted CF-MIMO for improved coverage and increased spectral efficiency.
- **Use Case #3: Network Digital Twin**, which focuses on two scenarios: #1 to achieve network optimisation and #2 to foster energy saving, exploiting network intelligence. This use case highlights the work of the project on network digital twinning to optimize capacity, availability and energy efficiency via AI / Machine Learning (ML) at Orchestration, Network and User layers.

These use cases pose specific requirements and KPIs and are mapped to corresponding PoCs, as detailed in the following chapters. This chapter summarizes the main 6G-SENSES KPI targets related to the three use cases and maps these to the global 6G landscape and, especially, on the latest KPIs definitions and targets by ITU-R (shown in Figure 2-1).

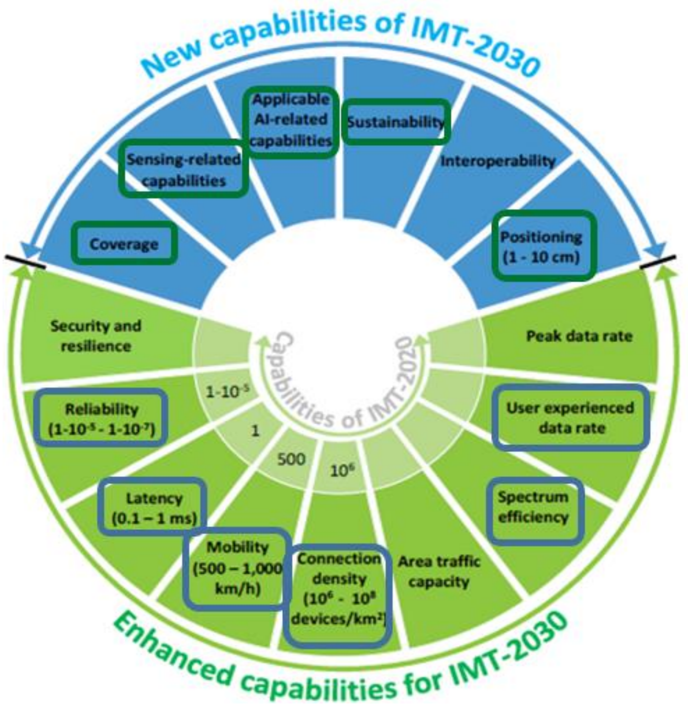

Figure 2-1 Overview of ITU-R KPIs addressed by 6G-SENSES

On the one hand, 6G-SENSES goes beyond the ITU-R "Enhanced Capabilities" part, corresponding to KPIs with (legacy) standardised definitions by elaborating on contextual definitions and new target values, namely:

- User Experienced Data rate.
- Spectrum Efficiency.
- Connection Density.
- Mobility.
- Latency.
- Reliability.

On the other hand, items of the "New Capabilities of IMT-2030" part – currently not defined or simply defined as targets for Research and Innovation – are addressed by proposing new KPIs to technically interpret and evaluate them, namely:

- Positioning.
- Sustainability (Energy Efficiency).
- Coverage.
- Applicable AI-related capabilities.
- Sensing-related capabilities.

A detailed list of the main KPIs and target values set by 6G-SENSES is provided in Table 2-1 and Table 2-2.

Table 2-1 6G-SENSES view on ITU-R Enhanced Capabilities

Enhanced Capabilities	
KPIs	KPIs Target values
User Experienced Data Rate	Context Based; >50% improvement in throughput with the 6G-SENSES solution as compared to the 5G network
Spectral Efficiency	SE: 5x improvement in 95%-likely per-user throughput over small-cell systems (under uncorrelated shadow fading conditions) improved compared with 5G (i.e., >30b/s/Hz)
Connection Density	Intelligent connectivity density (& massive random access): >20% connection density compared with existing systems based on non-intelligent connectivity
Mobility	Same as ITU
Latency	Context Based: Similar targets as IMT-2030; 0.1-1 ms
Reliability	Context Based: Similar targets as IMT-2030; 10^{-5}-10^{-7}

Table 2-2 6G-SENSES view on ITU-R New Capabilities

New Capabilities			
	KPIs	KPIs Definitions	KPIs Target values
Sustainability	Energy Efficiency		>15% enhanced resource usage efficiency for use cases with extreme performance requirements
Positioning	Positioning Latency	Time to acquire position of objects	<10 ms to comply with E2E service latency of <1 – 10 ms.
	Accuracy		<1-10 cm (in 2D or 3D)
Applicable AI-related capabilities	Network/Appl. Layer based; Large field to be further explored		
Coverage	Sensing area Coverage	Percentage of Radio Covered area where network sensing (ISAC) is available	Optimally 100% of coverage area; Target >50% of radio coverage area
Sensing related capabilities	Range resolution (3GPP)	Level of detail sensed at distance	Theoretical minimum accuracy of 2.4 m
	Range resolution (Active Sensing using Wi-Fi)	Range resolution is the ability of the sensor to resolve two closely spaced objects in distance. The finer the range resolution is, the better the sensor can separate targets at a distance.	< 1 m at 160 MHz BW
	Range resolution (Passive Sensing), non-3GPP non-Wi-Fi	Range resolution is the ability of the sensor to resolve two closely spaced objects in distance. The finer the range resolution is, the better the sensor can separate targets at a distance.	< 1 m at 200 MHz BW < 10 cm at 2 GHz BW
	Range Accuracy (Active Sensing)	The accuracy of distance measurements between the sensor and the single point object. This metric reflects the ability of the system to measure distances with high precision.	<40 cm at 30 dB SNR
	Orientation accuracy	The precision in determining the orientation or angle of an object relative to the sensor. This metric is crucial for applications requiring accurate angular positioning.	Less than 10% of the measured value
	Velocity Resolution (Active Sensing)	Velocity resolution refers to the minimum difference in radial velocity between two moving point targets that a sensor can separate in Doppler domain	< 0.1 m/s

	Velocity accuracy (Active Sensing)	The accuracy in measuring the velocity of movement of an object. This metric is essential for applications that track the velocity and direction of moving with high precision.	<0.1 m/s at 30 dB SNR
	Angular Resolution	Angular resolution is the minimum angle between two point targets at the same range that can be distinguished by the sensor.	20 º with ULA 8x1 @ Sub-6 1,5º @ 60 GHz 16x4 array 8.7º with 8x4 Array @cm-band (14.8-15.35GHz)
	Sensing Latency	Time to obtain sensing information from ISAC - measured from initiation of request	< 10 ms stipulated by O-RAN
	Sensing Bandwidth	Bandwidth needed for transmitting sensing information	in the order of MB/s.
	Sensing update rate	Time between two different samples of sensed data	> 25 ms between Wi-Fi Channel State Information (CSI) frame interval
	Active Sensing: Sensing accuracy of motion detection	Full duplex operation on active sensing with self-interference mitigation enables detection of human movement	within 2 m from the sensor
	Active Sensing: Sensing accuracy of motion detection	Hand Motion Doppler detection distance	< 50 cm
	Passive Sensing: Sensing accuracy of motion detection	Detection of human movement	within 4 m from the sensor (human walking/ crossing the line between Wi-Fi devices)

3 Overall Testing Methodologies

The 6G-SENSES project is dedicated to pioneering innovations that go far beyond the capabilities of current 5G technologies, targeting a new generation of intelligent, immersive, and sustainable communication systems. These technological breakthroughs are integrated into a unified, E2E framework designed to meet the demanding performance, intelligence, and user-experience requirements set by next-generation applications and service ecosystems.

To validate its vision, 6G-SENSES results will be demonstrated across a series of strategically selected use cases, including next-gen network services and sector-specific verticals such as autonomous systems. Innovations will be assessed across multiple layers of the architecture, from individual components to full-scale deployments, throughout all project phases: design, development, integration, and operational testing.

Live demonstrations and trials will take place in the labs at **UC** and **TUBS**. The **UC** will host test cases for PoC#1 and PoC#3, while **TUBS** premises will host the test case for PoC#2. The PoCs will be permanently hosted at the premises of these 6G-SENSES partners. Besides, parts of the PoC will be demonstrated in public events such as conferences and/or 6G-related events.

To ensure consistency, a harmonized experimentation framework has been established from the outset, encompassing:

- Standardization of concepts and terminology across the consortium.
- A unified roadmap for testing and validation activities.
- Clear identification and alignment of evaluation stages and their interdependencies.
- Formalized procedures for test planning, execution, and post-analysis.
- Agreed objectives, KPIs, and benchmarks for performance and impact assessment.
- A common template approach for documenting testing and experimentation processes.

3.1 Formalization of Concepts & Terminology

As a foundational step toward the definition of the 6G-SENSES evaluation methodology, it is essential to establish a unified and consistent terminology that is adopted across all testing and validation activities. This shared vocabulary ensures clarity and coherence throughout the project lifecycle, particularly as it spans multiple partners, facilities, and experimental domains. The following definitions represent the agreed-upon terms for use in all testing and evaluation efforts within 6G-SENSES.

Device Under Test (DUT): The DUT refers to the specific hardware or software component subjected to testing. In the context of 6G-SENSES, DUTs may include advanced sensors, AI-based modules, transceivers, or edge processing units.

System Under Test (SUT): An SUT is a broader configuration consisting of multiple interconnected DUTs. It represents a complete functional setup under evaluation, such as a 6G-enabled immersive environment or an integrated AI-native communication stack.

Testing vs. Evaluation:

- **Testing** involves the execution of specific operations or procedures aimed at gathering results. In a narrower sense, it refers to checking whether a particular DUT demonstrates an expected behaviour or meets predefined technical requirements — typically resulting in a pass/fail outcome.

- **Evaluation** is the analytical process of interpreting testing outcomes to assess the extent to which a system or capability meets performance goals or functional criteria. It often involves comparing observed metrics against KPIs or benchmarks defined by the project.

Testing/Evaluation Phases: These refer to the structured periods during which defined testing or evaluation activities are performed. Each phase may serve as a prerequisite for subsequent phases and contributes specific insights, data, or validation outcomes essential for the progression of the experimentation flow.

Measurement System: comprises one or more instruments and associated components that are configured to perform complete and accurate measurements. This includes data collection, signal capture, and timing synchronization where relevant.

Test Case: It is a formally defined procedure describing how a specific test is to be executed. In 6G-SENSES, each test case outlines:

- The objective of the test (what is being assessed).
- The SUT configuration.
- The sequence of steps and procedures to be followed.
- The metrics and measurements to be collected.
- The calculations and analysis applied to those measurements.
- The KPIs or success thresholds used to determine test validity.

Test Scenario: It comprises one or more test cases that are executed under specific real-world or simulated contextual conditions, such as mobility, environmental interference, or service configurations. Scenarios represent E2E workflows and may mimic field deployments or operational behaviours. The terms “test case” and “test scenario” may be used interchangeably for simplicity, unless further distinction is required.

Experimentation: In the scope of 6G-SENSES, experimentation is the structured execution of multiple test cases under varying configurations and environments, to conduct a comprehensive assessment of the SUT's behaviour, performance, and reliability across diverse conditions and use cases.

3.2 Testing Activities – Planning, Definition and Testing

The planned technical activities adopt a systematic and iterative approach built around three core phases: **Design**, **Implementation**, and **Testing**. This methodology ensures consistency, reproducibility, and depth across diverse testing environments and use cases. The process is structured into the following stages:

Experimentation Design

This initial phase involves collaborative coordination among project partners to establish the overall experimentation strategy. Key planning activities include:

- Defining the overarching testing framework and cycles.
- Establishing test objectives in line with project ambitions and vertical requirements.
- Identifying the necessary SUTs and DUTs.
- Determining how to simulate or generate testing conditions (e.g., AI-driven scenarios, extreme edge cases, immersive environments).
- Selecting and specifying complementary tools/equipment needed to support test execution.
- Developing a timeline and task breakdown for site preparations.
- Aligning partner responsibilities for infrastructure readiness at each test testbed/facility.

Experimentation Implementation

This stage involves a detailed breakdown of the experiments at the level of individual test scenarios, tailored to each testing site. It includes:

- Mapping to technical and functional requirements derived from 6G use cases.
- Defining vertical applications and services to be tested, such as DTs.
- Establishing target KPIs and evaluation metrics.
- Specifying the full network configuration.
- Outlining the test flow based on service behaviour, user interactions, triggering of network functionalities, and real-time decision-making.
- Using standardized templates for documenting each experiment to ensure uniformity across sites and scenarios.

Experimentation Testing

This final stage covers the real-time implementation and operation of the experiments. It includes:

- Executing preparatory activities, such as SUT configuration, validation, and environment setup.
- Conducting testing procedures based on defined scenarios.
- Capturing and storing measurements and telemetry from various components and layers.
- Performing post-processing, correlation, and analytics on the data collected.
- Evaluating results against defined KPIs.
- Documenting and sharing results for cross-site and cross-use case evaluation.

This structured methodology ensures that experimentation in 6G-SENSES not only validates its cutting-edge innovations but also provides a coherent and repeatable path toward building trust in 6G technologies at scale.

3.3 Testing/Evaluation Cycles

We illustrate the overall testing methodologies and evaluation cycles employed in the 6G-SENSES project in Figure 3-1. We divide the cycles in three main stages: Solution Development, Component Integration & Evaluation, and Vertical Apps & Services Life Cycle Management (LCM). Each stage represents a key phase in the testing and evaluation of the novel 6G technologies.

In the first stage, *Solution Deployment*, we focus on the fundamental aspects of the system creation. This stage is conveyed by the development of the components, followed by their integration, to build a more cohesive system. This stage is then concluded with the Complete Solution Integration & Operation, where the integrated system is tested to ensure that all components of the system work together seamlessly.

The second stage, *Component Integration & Evaluation*, builds upon the developed solutions to validate and test their performance. It starts with the validation of the baseline functionalities, then proceeds to perform the same kind of validation to more complex functionalities; finally, the validation is carried out across the whole proposed general solution.

The third stage, *Vertical Apps & Services LCM*, addresses the adaptation and deployment of the solutions in a real-world application context. This stage aims at providing an iterative approach to the development of the applications and services developed in the project. Starting from a description of the services provided, then followed by the deployment of the app, and their performance evaluation.

Figure 3-1 illustrates a comprehensive and iterative testing methodology.

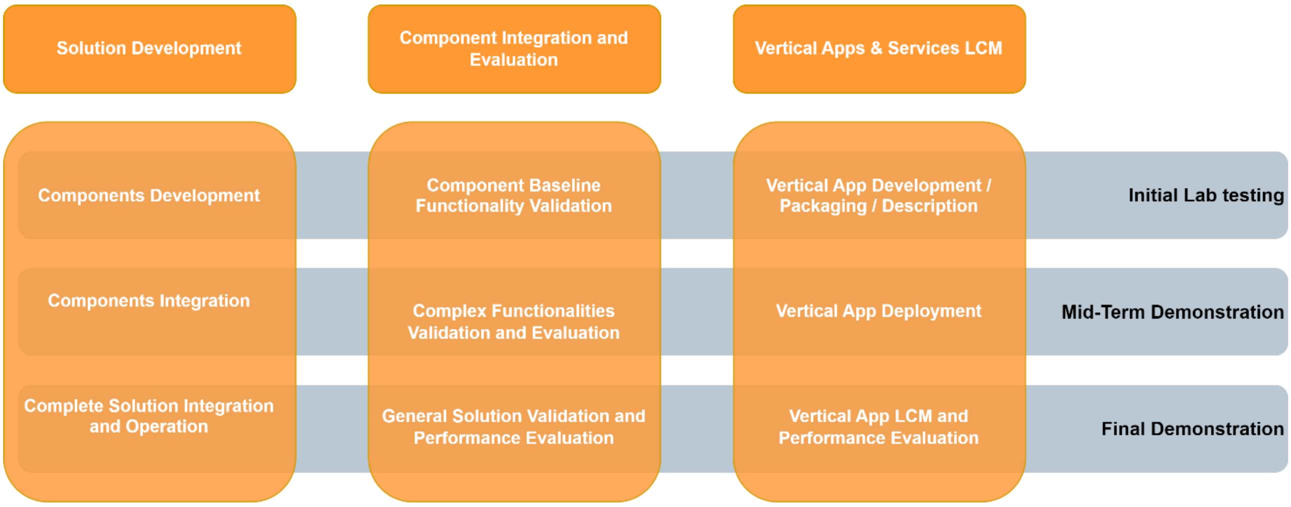

Figure 3-1 6G-SENSES Testing and evaluation cycles

3.4 Test Cases Description

The assessment of the solutions that play a role in the PoCs are structured in tabular format, whose fields and description are shown in Table 3-1. This structure will be afterwards followed when depicting these solutions for each of the PoCs in the following chapters.

Table 3-1 Test Case Definition in Tabular Format

<Test Id>	<Test Case Title>
Phase	*<Definition of Phase when the test case will be performed>*
Description	*<The 'Description' field contains the description of the test case including high-level objective, whom it concerns, etc.>*
Target UCs	*<Reference to the UCs in the context of which this test case will be performed.>*
Requirements	*<This field provides the link to the requirements sections of D2.1 / The ref. IDs of the requirements that are validated/evaluated by the test case are needed.>*
KPIs	*<This field contains:* • ***for measurable requirements (performance or measured properties of functionalities):*** *the definition of the parameters to be measured towards determining whether the requirements are achieved, and the associated target values against which evaluation will be based.* • ***for non-measurable requirements (functionalities):*** *the qualitative criteria (or designed/deployed functionalities) to indicate the satisfaction of these requirements; and information related how these can be verified and evaluated.>*
PoC	*<Define the testbed/ test facility to be used.>*

4 PoC#1 – Multi-Technology ISAC Platform

PoC#1 builds an E2E small-scale prototype to demonstrate potential performance gains 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 an operated Radio Unit (RU), 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. 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.

4.1 Mapping to architecture

In PoC#1, the provision of these functionalities extends throughout the 6G-SENSES network architecture proposed in deliverable D2.2 [2]. This way, Figure 4-1 depicts the baseline 6G-SENSES multi-layer architecture with the highlighted components that do provide additional functionalities – hence playing a role in PoC#1.

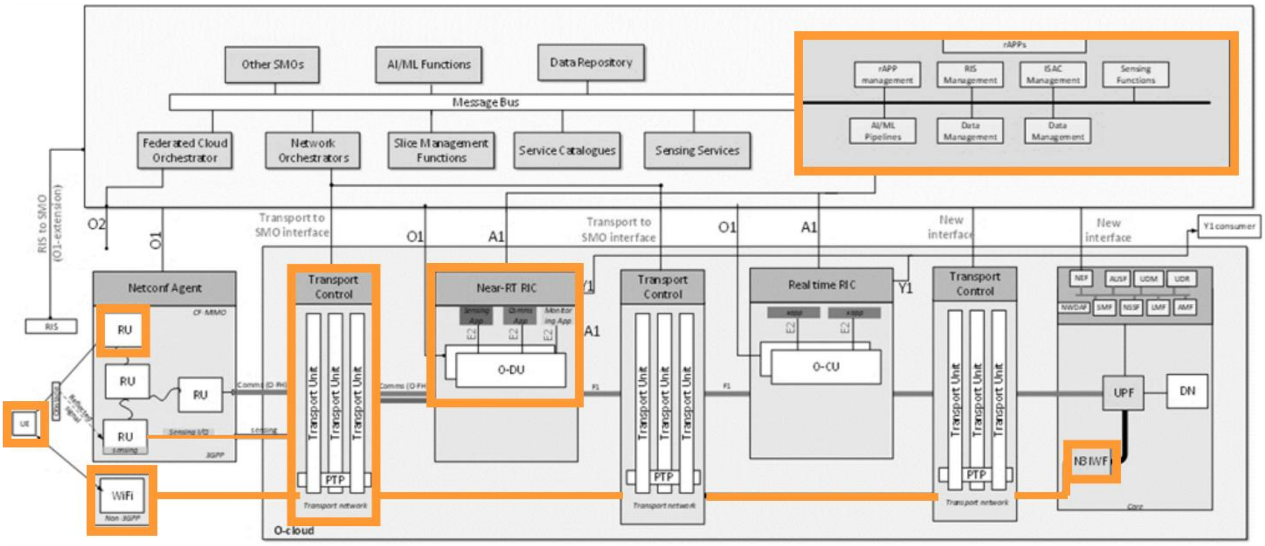

Figure 4-1 Multi-layer 6G-SENSES Architecture with highlighted components belonging to PoC#1

Figure 4-2 depicts the relation between the technical components developed in **WP3** and **WP4** and their mapping to PoC#1 activities.

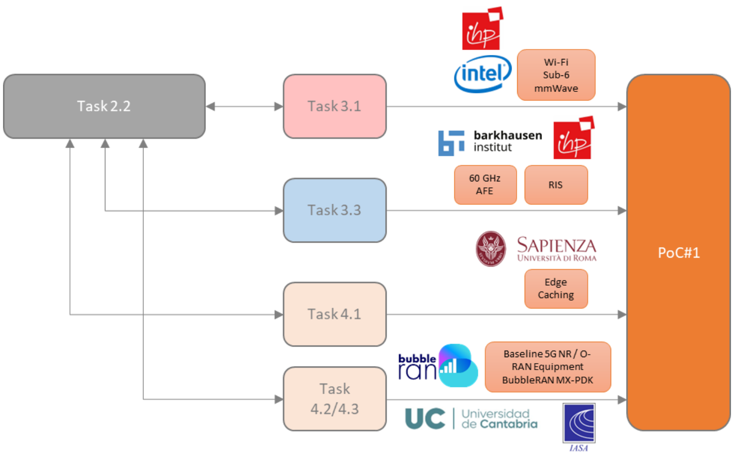

Figure 4-2 PoC#1 Task Workflow

The WATs and components involved in PoC#1 (cf. deliverables **D3.1** [3] and **D4.1** [4]) and their role are explained below:

- User Equipment (UE) (see Table 4-1 for additional details)
  - Types of UEs: commercial UEs, Quectel modules, SDR-based UE implementations, such as OpenAirInterface (OAI) and srsRAN.
  - Commercial units can equip both 5G and Wi-Fi modems.
  - Options to send positioning information to the O-RAN system:
    - direct reporting from the UE through the E2 interface to the RIC.
    - sensing capabilities of non-3GPP network nodes can be exposed to the RIC through an extended version of a Non-3GPP Interworking Function (N3IWF) supporting the E2 interface or exposed to the CN through the N2 interface.
- O-RU (see Table 4-2 for additional details)
  - Types of O-RUs: commercial O-RUs, SDR-based R&D O-RUs that leverage Ettus devices, e.g., N321, with 5G RAN implementations (OAI, srsRAN), Commercial SDR-based O-RUs (Massive Beams [8]).
  - 6G-SENSES extends O-RAN specifications to enable O-RU sharing for communications and sensing services.
  - Intention to move from conventional, typically "black box", commercial O-RU to a more research-oriented O-RU using SDR-based O-RUs (e.g., Massive Beams [8]).
- Wi-Fi (see Table 4-3 for additional details)
  - Explore the usage in Wi-Fi in active sensing technology, where one of the antennas is used to transmit while the remaining antennas are used for simultaneous reception.
- Non-3GPP non-Wi-Fi (see Table 4-4 for additional details)
  - Use of non-3GPP non-Wi-Fi technologies that support ISAC as a source of sensing data to be pushed to the O-RAN framework.
  - Improved performance capabilities (range, angle) compared to Wi-Fi and 3GPP, sometimes leading to an increased combined performance when fusing both sensing data sets.
- Extensions to the Open DU (O-DU) (see Table 4-5 for additional details)
  - Compression and downsampling of I/Q signals before transmitting them to the RIC.
  - O-DUs may need to coordinate between themselves.
  - Implementation of dApps and ISAC (as presented in section 5.3.3 of D2.2 [2]), through direct interaction with O-DU functions. dApps can implement spectrum sensing, interference detection, and proactive network adjustments, significantly improving network efficiency in dynamic environments.
  - Custom Medium Access Control (MAC) scheduler to exploit sensing information for network optimization (OAI based).
- Extensions to the RIC (see Table 4-6 for additional details)
  - Sensing Service Models: Two different sensing service models will be implemented 1/ **BubbleRAN**, 2/ **UC**.
  - MAC scheduler Service Model.
  - xApp able to consume sensing service models and exploit MAC scheduler service model for scheduler reconfiguration.

  - Means to tackle the increased computational burden on the Near-RT RIC due to real-time sensing data processing.
  - Configuration and monitoring of the Non-RT RIC for additional components, e.g. RISs.
  - xApp for resource block scheduling and beamforming using sensing information.
  - xApp for positioning combining 3GPP and non-3GPP sensing information.
- Extended N3IWF (see Table 4-7 for additional details)
  - 6G-SENSES will adopt and extend N3IWF (with a new E2 interface) to provide the necessary access and authentication protocols with new features that allow Wi-Fi networks to securely expose sensing data to the RIC.
  - Architectural integration detailed in deliverable **D2.2** [2], cf. Sec. 5.2.
- Transport extensions (seeTable 4-8 for additional details)
  - Sensing information would need to be shared among different entities, traversing the underlying transport networks interconnecting the RAN units, where various techniques and algorithms should be used to appropriately address the information flows.
  - Optimization of the transport network and the impact that sensing data may have over other traffic flows.

4.2 KPI Identification and Testing Methodologies, Capabilities and Functionalities

In this section, we present the different Test Cases tables that describe how the elements and components defined in section 4.1 can be tested, as well as the KPIs associated to these tests.

Table 4-1 Extensions to the UE

Test 1.1	Extensions to the UE
Phase	Initial lab testing @ IASA
Description	• One of the sensing approaches followed in PoC#1 with respect to monostatic sensing relies on the connectivity established between the BS and the UE to estimate channel conditions and extract information for the Angle of Arrival (AoA) and the Time Difference of Arrival (TDoA). No changes are required at the UE. • Sensing information collected at UE level from non-3GPP networks can be exposed to the O-DU through extensions in Physical Uplink Control Channel (PUCCH)/ Physical Uplink Shared Channel (PUSCH). To implement this, modifications in the uplink (UL) protocol stack are needed. The relevant implementation is carried out using SDR-based UEs.
Target UCs (taken from D2.1)	**Use Case #1: Storyline #1**: UEs are used to perform a sensor fusion functionality collecting data from external sensors that are embedded into the uplink control channel. This information is extracted at the O-DU and is fused with network measurements to create an enhanced dataset that is shared with the device and other devices increasing scalability. Given that sensing information flows are terminated at the O-DU and managed by a dApp, low sensing latency (in the order of ms) is expected.
Requirements	**P/VU -FUNC- #1** – Capturing object positioning and motion information with required accuracy. **P/VU -PERF- #3** – Sensing latency components.
KPIs	N/A
PoC	IASA testbed

Table 4-2 Extensions to O-RU

Test 1.2	Extensions to the O-RU
Phase	Initial lab testing @ UC Mid-term integration @ UC Final demonstration @ UC
Description	Provision of monostatic radar functionalities to a gNB based on OAI implementation using an SDR platform (N321). Use of digital beamforming as in section 3.2.2.2 (D3.1) to perform AoA estimation. The sensing system features a 100 MHz BW for sensing.
Target UCs (taken from D2.1)	**Use Case #1: Storyline #1**. An SDR based O-RU (gNB) provides 5G NR communication to a UE based on a Quectel module. While performing downlink (DL) transmissions the O-RU receives and processes reflected signals to sense the environment. The sensing information consists on the detection of changes in the surroundings, as compared with a reference situation, thus enabling obstacle detection, and such information is sent up directly to the near RT-RIC through an E2 interface using the defined sensing service model (SM) (see Test 1.6 for more details). Afterwards such information can be exploited by xApps to detect the presence of obstacles.
Requirements	**P/VU-FUNC-#1**, Capturing object position and motion information with required accuracy (see Table 4-5 in D2.1 [1]). **S- FUNC- #21**, 3GPP RAN Enhanced Capabilities (see Table 5-31 in D2.1 [1]). **S- FUNC- #24**, Sensing Data for RIC xApps/rApps (see Table 5-34 in D2.1 [1]).
KPIs	Measurable requirements: • Angular resolution: 20º with 8 antennas. • Range resolution: 1,5 m. Non-measurable requirements: • Added E2 functionality for direct gNB – RIC interfacing to transport sensing information (see Test 1.6).
PoC	UC testbed

Table 4-3 Extensions to Wi-Fi

Test1.3	Extensions to Wi-Fi
Phase	Initial lab testing @ INT Mid-term integration @ UC Final demonstration @ UC
Description	The architecture for Wi-Fi active sensing on sub-7 GHz bands leverages standard client/user device transmission, reception, and processing. In this PoC, a commercial laptop transmits standard 802.11 Orthogonal Frequency-Division Multiplexing (OFDM) waveforms and simultaneously receives the echoes of its own transmissions. By extracting Channel State Information (CSI) from the received signals and applying a 2D Fast Fourier Transform (FFT) (over both range and Doppler), the device generates a radar-like map of its surroundings, providing real-time range–Doppler heatmaps that visualize the movement of targets.
Target UCs (taken from D2.1)	**Use Case #1: Storyline #2**. The system can reliably perform gesture recognition at close range—detecting hand and arm movements at distances less than 50 cm from the device. This capability enables fine-grained interaction scenarios and demonstrates the potential of ISAC technologies for sensing applications.

Requirements	**P/VU -PERF- #4**, **P- FUNC- #6**, **P-FUNC- #7**, **P-FUNC- #8**, **P-FUNC- #9**
KPIs	**Measurable requirements** 1. Full duplex operation on active sensing with self-interference mitigation enables detection of human movement within a distance smaller than 2 m from the sensor. 2. Hand Motion Doppler detection at smaller distance of 50 cm. **Non-measurable requirements:** 1. The device can indicate when a person is present or absent in the monitored area, shown through a presence status overlay. 2. Users can adjust sensing and processing parameters (such as sensitivity or mode selection) through the graphical interface, with immediate effect. 3. All sensing, processing, and visualization is performed on a single commercial laptop, with no need for specialized external hardware.
PoC	UC testbed

Table 4-4 Extensions to Non-3GPP non-Wi-Fi

Test1.4	**Extensions to Non-3GPP non-Wi-Fi**
Phase	Initial lab testing @ IHP Mid-term integration @ UC Final demonstration @ UC
Description	The 6G-SENSES WATs that are considered for providing sensing information to the 6G control fabric are the Sub-6 ISAC system presented in D3.1 sec. 3.2.2 [3] and the mmWave ISAC system presented in deliverable D3.1 sec. 3.2.3 [3]. Both solutions follow the modality of monostatic sensing, i.e., as a radar, to obtain the channel coefficients to be sent to the RIC using the SM for sensing presented in D2.2 [2] and detailed in Table 4-6 in this document. The intended PoC for 60 GHz ISAC front-end leverages IHP BiCMOS technology for mmWaves. The key innovation is the capability to support ISAC for communication users, i.e., positioning the potential users while simultaneously serving existing users. Designed for ultra-low power consumption and using low supply voltage, the frontend is optimized for battery-operated devices. The chipset will be packaged into an Antenna-in-Package (AiP) type Printed Circuit Board (PCB) module integrating four Radio Frequency (RF) chains and a 4x1 array for transmission and 4x1 array for reception. This configuration supports beamforming and MIMO operations. The packaging approach is scalable, provisioning for future expansion to additional RF chains. Baseband modulation and system control will be hosted through an RFSoC platform, ensuring flexible signal processing.
Target UCs (taken from D2.1)	**Use Case #1: Storyline #1**
Requirements	**P/VU -PERF-#4**

KPIs	**Measurable requirements:**
	• Sub-6 ISAC system:
	    ○ Angular resolution: 15º
	    ○ Range resolution: 0.7 m

	• 60 GHz ISAC system:
	  ○ Angular resolution: 6º
	  ○ Range resolution: 6,7 cm
	• 60 GHz Front-End
	  ○ Power consumption: < 100 mW per TRX chipset from 1.5 V.
	Non-measurable requirements:
	• Added E2 functionality for direct O-RU – RIC interfacing.
	• ISAC Front-End: MIMO integration, 4-channel with scalability provision.

PoC	**UC** testbed

Table 4-5 Extensions to the O-DU

Test1.5	**Extensions to the O-DU**
Phase	Initial lab testing @ **BR**, **UC**, **IASA** Mid-term integration @ **UC** Final demonstration @ **UC**
Description	1/ **BubbleRAN**: The way 5G measures the UL channel is primarily using the Sounding Reference Signal (SRS), which can be transmitted periodically or not, depending on the configuration. A pilot Reference Signal is generated in the UE and transmitted in UL, permitting noise inference and channel estimation and equalization in the gNB. A natural choice for an application in this regard (an xApp) is to retrieve the received SRS signal, as well as the noise, to infer the channel and act accordingly. 2/ **UC**: The O-DU is provided with techniques to better manage the radio resources based on sensing information. Particularly, it incorporates a multi-objective MAC scheduler able to manage traffic flows with different characteristics and requirements, whose operation can be tweaked from a sensing xApp through the near RT-RIC using a dedicated E2 Service Model (E2SM). 3/ **IASA**: The O-DU is extended with the capability to perform inference of lightweight Neural Network (NN) models processing sensing streams coming from the O-RUs.
Target UCs (taken from D2.1)	**1/ Use Case #1: Storyline #1.** A UE transmits SRSs that are forwarded through the gNB to a low-latency xApp in real time (i.e., < 1 ms) using the newly defined Lower Layer Control (LLC) O-RAN SM. Utilising this information, the xApp infers the UE position correlating the signals received from different antenna ports, enabling services related to the UE location. **2/ Use Case #1: Storyline #1:** A UE implemented with a Quectel module is served by a gNB based on commercial O-RU and the modified O-DU. A sensing xApp continuously receives sensing information about the scenario and, based on such information, it triggers a change on the scheduler operation. For instance, based on the scenario information (i.e. user location, obstacle detection) future communication impairment is detected, and the MAC scheduler is reconfigured increasing the number of allocated PRBs to ensure that certain granted bit rate (GBR) achieved according to the configured 5G Quality of Service (QoS) Identifier (5QI) parameters. 3/ **Use Case #1: Storyline #1.** This scenario considers the case of an O-DU processing incoming I/Q data received by the O-RU. A pretrained ML model is used to extract sensing information (i.e., from UL PUSCH DMRS), which combined with geolocation information can expose a heatmap of possible UE geographical positions.
Requirements	**P/VU-FUNC-#1**, Capturing object positioning and motion information with required accuracy (see Table 4-5 in D2.1 [1]).

	P/VU -PERF-#4, Mobility (see Table 4-8 in D2.1 [1]). **S-FUNC-#21**, 3GPP RAN enhanced capabilities (see Table 5-31 in D2.1 [1]).
KPIs	**Measurable requirements**: • Theoretical minimum accuracy of 2.4 meters. • Max mobility range. • User performance improvement with sensing information. **Non-measurable requirements**: • E2 support at the DU for SRS-based location information to be shared with xApps. • E2 support at the DU for xApp assisted MAC scheduling configuration.
PoC	UC testbed

Table 4-6 Extensions to the RIC

Test1.6	Extensions to the RIC
Phase	Initial lab testing @ **IASA**, **BR**, **UC** Mid-term integration @ **UC** Final demonstration @ **UC**
Description	1. **Sensing SM** (s) from **BubbleRAN**: this RAN function extracts the I/Q samples of received SRS signals from multiple Transmission Reception Points (TRPs) before the Channel Estimation in UL. The data is modelled in two ways: based on the O-RAN LLC E2SM and a custom multi-RAT sensing E2SM to provide more flexibility. These data are gathered on a ms by the RAN function and then transported to the xApp via O-RAN E2AP protocol. 2. **Surrounding sensing SM** (**UC**): this SM provides a heatmap of the surroundings provided by a modified O-RU with radar-based sensing capabilities. It is assumed that the I/Q processing has been already performed. As a result, the sensing information consists of range/angle coordinates around the sensing device. 3. **MAC scheduler SM** (**UC**): this SM provides MAC scheduler configuration information along with metrics used for MAC scheduling, such as buffer occupancy or level of compliance with 5QI parameters. Besides, the SM allows modifying configurable parameters of the scheduler (i.e. weights applied to different parameters). 4. **Federated Learning SM** (**IASA**): The RIC is extended with the capability to coordinate Federated Learning (FL) process selecting entities that are be used to provide sensing da-ta, the agents that are used for FL local training and aggregation.
Target UCs (taken from D2.1)	**Use Case #1: Storyline #1**: (**BR**, **UC**) A radar-based sensing device (i.e. modified O-RU or sensing only RU) equipped with an E2 agent periodically gathers information of the surrounding and sends it to the near RT-RIC. At the same time a gNB tracks user location and notifies such information to the near-RT RIC exploiting the define SM. An xApp subscribed to both data sources fusion the sensing information to predict coming communication conditions and exploit the MAC scheduler SM to adapt the allocation policy. **Use Case #1: Storyline #1**: (**IASA**) An xApp is responsible for managing the FL process collecting and processing sensing information from multiple RAN elements. The corresponding decisions is taken in order to minimize the volume of transmitted sensing information and, therefore, reduce energy consumption, without losing sensing accuracy. Through this approach the served area can be increased. The FL model is trained to predict mobility and take decisions to minimize energy consumption in RAN.

Requirements	**S-FUNC-#22**, O-RAN RICs sensing capabilities (see Table 5-32 in D2.1 [1]). **S-FUNC-#24**, Accuracy of sensing data for RICs sApps/rApps (see Table 5-34 in D2.1 [1]). **S-FUNC-#36**, Sensing service Model (see Table 5-46 in D2.1 [1]).
KPIs	**Measurable requirements**: • Precision of the developed sensing algorithm for detecting potential users. **Non-measurable requirements**: • Capability to ingest sensing data from multiple sources in O-RAN RICs. • Definition of E2SMs for general sensing information collection.
PoC	UC testbed

Table 4-7 Extensions to N3IWF

Test1.7	**Extensions to N3IWF**
Phase	Initial lab testing @ IASA Mid-term integration @ IASA Final demonstration @ IASA
Description	6G-SENSES proposes to adopt and appropriately extend N3IWF to provide the necessary access and authentication protocols with new features that allow Wi-Fi networks to securely expose sensing data to the RIC (see section 4.2.1.2 in D2.2 [2]).
Target UCs (taken from D2.1)	**Use Case #1: Storyline #2**: (IASA) The corresponding scenario focuse on the exposure of sensing information from Wi-Fi through N3IWF to RIC in a secure way. A Wi-Fi network connected to the 5G network through N3IWF collects sensing and channel quality measurements. Thus, it extends the functionality of the N3IWF to support the E2 agent. Since the N3IWF already serves as the main interworking point between non-3GPP networks and the 5G Core, enhancing it with E2 support would allow it to act as a bridge between non-3GPP positioning sources and the RIC. This structural alignment suggests that the N3IWF could be extended to support E2-based interactions, enabling non-3GPP positioning data to be exposed to the near-RT RIC for further processing and optimization. Additionally, to minimize latency, the N3IWF could be co-located with the near-RT RIC, ensuring faster transmission of positioning data.
Requirements	**P/VU -PERF-#4**
KPIs	**Measurable requirements**: • Latency: Reduced latency to expose sensing information from Wi-Fi to RIC. • Sensing accuracy: combination of sensing data coming from Wi-Fi and 3GPP networks. **Non-measurable requirements**: • N3IWF could be extended to support E2-based interactions, enabling non-3GPP positioning data to be exposed to the near-RT RIC for further processing and optimization.
PoC	IASA testbed

Table 4-8 Extensions to the Transport Network

Test1.8	Extensions to the Transport Network
Phase	Initial lab testing @ IASA Mid-term integration @ IASA Final demonstration @ IASA
Description	6G-SENSES proposes and has experimentally validated an architecture (c.f. deliverable D2.2 section 5.4) exploiting an optical transport network that interconnects RAN and CN domains, to facilitate joint support of sensing and communication services. These I/Q echo streams are transmitted in the form of UL FH streams and are redirected to a Multi-Access Edge Computing (MEC) node for storage and processing. A sensing dApp, deployed at the DU, can analyse the quality of the I/Q echo streams at the MEC and decide which I/Q streams can be used to support the required sensing.
Target UCs (taken from D2.1)	**Use Case #1: Storyline #1**, The main objective of this UC is to transfer sensing information to the suitable compute nodes for processing, applying suitable control policies in the transport nodes. It is known that by increasing the number of frames collected and processed by sensing xApp, higher sensing accuracy can be achieved. However, increasing bandwidth increases also the volume of sensing I/Q streams that are transported and processed by the sensing app. To address these requirements, optical splitters are employed at the RUs duplicating I/Q streams creating two separate paths for comms and sensing. This allows comms streams to be forwarded through a combination of optoelectronic switches supporting the Common Public Radio Interface (CPRI)/ extended CPRI (eCPRI) protocols for further processing at the DUs/CUs whereas sensing streams can be transferred and terminated at the edge server hosting the sensing app. The eCPRI compliant optoelectronic switches can aggregate I/Q streams from multiple RUs maximizing the utilization of network resources. Aggregation of sensing flows from the RUs is performed adopting all optical switching technologies with switching times in the order of 25 ms-75 ms. This enables the collection of the necessary number of OFDM frames per tracked area allowing the sensing app to achieve the required sensing accuracy level. The corresponding policy reduces the volume of transmitted information while, at the same, time increases sensing range and accuracy.
Requirements	**P/VU -PERF-#4** **P/CU - PERF #5**
KPIs	N/A
PoC	IASA testbed

4.3 PoC#1 implementation

Figure 4-3 depicts the implementation of the 6G-SENSES architecture in the context of PoC#1. The figure highlights the network components, extensions to O-RAN through new SMs, as well as the system component over which each of the aforementioned tests is mainly implemented.

One or more UEs are expected to pass through an indoor environment, where the different radar-based sensing and active sensing technologies are deployed. While communicating with the UEs, the radar-based sensing technologies can sense the environment and provide sensing data with different granularities to the RIC. The *comm+sensing* technologies maintains the communication while inferring the position of the UEs. This way, the xApps behind the RIC can exploit *comm+sensing* merged data to anticipate communication impairments, and react optimizing the usage of radio resources by reconfiguring the MAC scheduler.

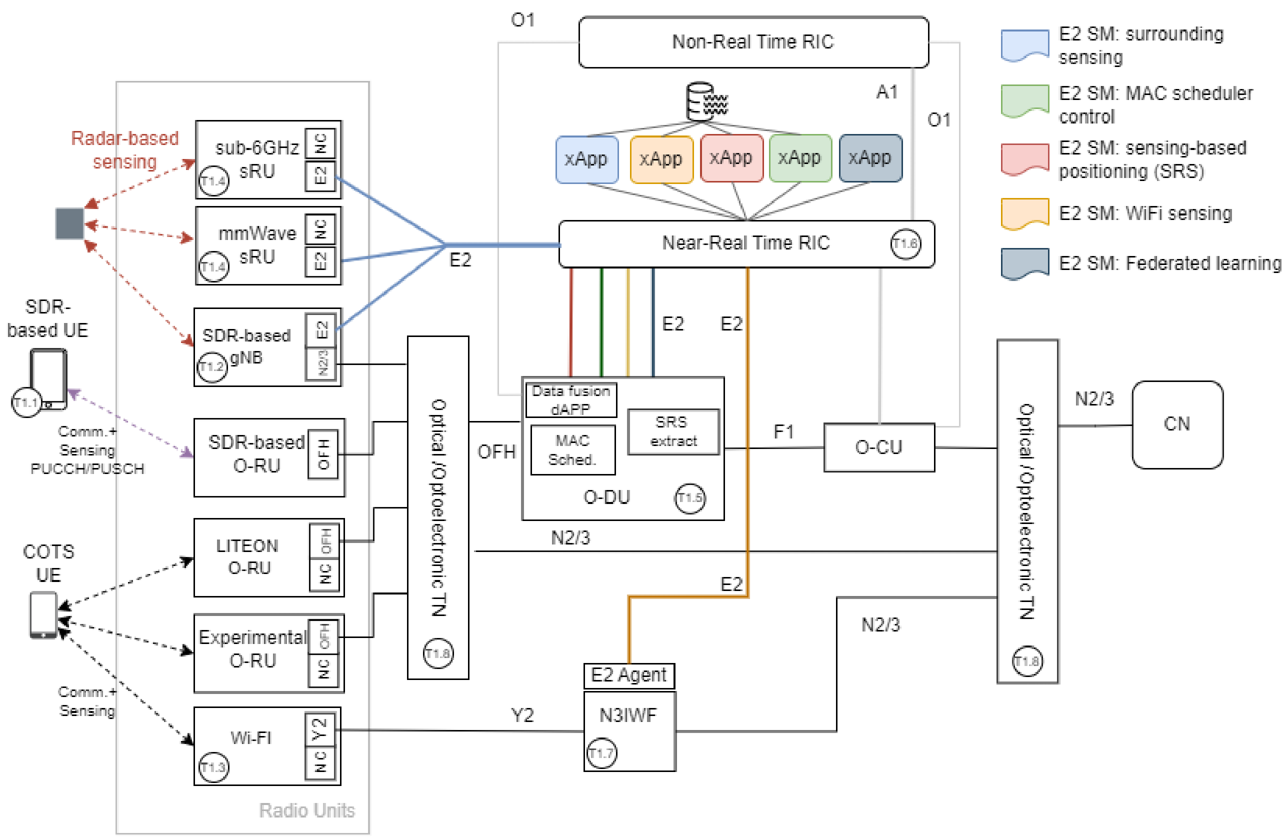

Figure 4-3 Implementation of the 6G-SENSES architecture for PoC#1

4.4 Initial planning for PoC#1

Table 4-9 describes the different PoC#1 versions and the envisioned planning.

Table 4-9 Initial Planning for PoC#1

PoC#1 Version	Description	Functionalities	Required Developments	Month
v1	Sensing Service Model extension to Sub-6	E2SM integration, sensing information passed to the RIC	RIC extended capabilities to support sensing	20
	Sensing based MAC scheduler	OAI implementation with basic functionality	Extensions to the DU	
v2	Sensing Service Model extension to mmWave	E2SM integration, sensing information passed to the RIC	RIC extended capabilities to support sensing	21
v3	MAC scheduling SM	First version with reporting functionalities	Extensions to RIC	22
v4	Sensing Service Model extension	E2SM integration, bi-directional interaction with the WATs (Sub-6, mmWave)	RIC extended capabilities to support sensing	23

v5	Sensing Service Model extension to Wi-Fi	E2SM integration, sensing information passed to the RIC	RIC extended capabilities to support sensing	24
	gNB with monostatic radar functionalities	Reception of reflected 5G NR transmissions	Extension to O-RU	
	Sensing based MAC scheduler	Development xApp control	Extensions to the DU	
	MAC scheduling SM	Integration in DU and near RT-RIC	Extensions to RIC	
	Scalable 60 GHz ISAC hardware	Beamforming and MIMO links link to mobile user and tracking	BiCMOS chipset testing	
v6	MAC scheduling SM	Addition of control functionalities	Extensions to RIC	26
	Scalable 60 GHz ISAC hardware	Chip-to-module interface	Chip-to-module interface	
v7	gNB with monostatic radar functionalities	Evaluation of processing options	Extension to O-RU	27
v8	Sensing based MAC scheduler	Integration and validation	Extensions to the DU	28
v9	Scalable 60 GHz ISAC hardware	Antenna design and module integration	Antenna design and module integration	
v10	gNB with monostatic radar functionalities	Full integration with other components	Extension to O-RU	30
v11	Final Integration	ALL	-	

4.5 Small-Scale Demos for PoC#1

4.5.1 Wireless Edge Caching

Wireless Edge Caching (WEC) [5], [6] refers to a novel distributed architecture for storing contents at the wireless edge networks, such as BS and UE, to efficiently accommodate the proliferation of mobile devices and new data-hungry applications.

In order to efficiently deploy a WEC solution, multiple challenges need to be addressed with different and specific application requirements. Achieving efficiency in WEC requires joint optimization of network-layer caching and physical-layer signal transmission.

For application-specific use-cases, dynamic content popularity [5], [6] needs to be addressed to be able to deploy an efficient caching policy. This approach differs significantly from traditional caching models, where standard algorithms typically store data based on historical access patterns.

By considering content popularity, caching can move beyond simply retaining previously accessed data. Since content popularity fluctuates over time, maintaining an up-to-date view of requests enables caching to anticipate future access rather than relying solely on past data.

Although caching strategies for traditional Internet applications have been widely explored in the past, the unique characteristics of 6G applications drive the need for developing new caching mechanisms that consider these distinct features.

With this PoC, we aim to demonstrate the applicability of novel caching strategies in the context of WEC, by iterating over different simulation instances.

1. **Custom Simulation:** this is the first set of iteration, which focuses on delivering a solid caching mechanism in terms of numerical evaluation. The main focus of this first iteration it is to provide a lightweight simulator which is able to compare caching strategies in a more abstract environment, without taking into consideration the physical characteristics of the RAN sensing use case.
2. **ROS-Gazebo Simulation:** the second set of testing iterations, which brings a more realistic environment to the simulation. With the addition of ROS and Gazebo, the simulation is now executed in a more standardized environment, with physically accurate objects taking part in the simulation. This allows us to simulate real scenarios, with multiple actors taking part into the simulation, creating a more realistic environment to test the caching solutions.
3. **ROS-Gazebo + RAN Signal Simulation:** the final set of testing iterations, which extends the work to also simulate the RAN wireless sensing signal, and the cache data produced by the sensing use case; aligning with the objectives of the 6G-SENSES project by providing solutions directly tied to the PoC use case.

These phases allow us to deliver a comprehensive simulation environment, validating and strengthening our proposed solution through multiple progressive steps. The work of **D4.1** [4] has covered the first two phases of the work so far, while the remaining work for the last phase will be addressed in **D4.2**.

4.5.2 Wi-Fi PoC

This PoC demonstrates a robust real-time sensing pipeline using commodity Wi-Fi hardware, closely following the approach introduced in [9] and incorporating optimizations for practical deployment on standard devices. The system processes streaming CSI data from Wi-Fi signals, using advanced signal processing techniques for human presence, gesture, and vital sign detection.

The pipeline begins with precise time-phase synchronization of incoming frames. This involves a multi-stage process: cross-correlation for coarse alignment, sub-sample refinement, and per-frame phase unwrapping, using the dominant transmitter–receiver leakage as a stable phase reference. After synchronization, self-interference and static clutter are suppressed by removing the direct current (DC) component per subcarrier over a sliding window, which reveals dynamic motion signatures and enables tracking of moving objects.

Range–Doppler processing is performed by applying a Discrete Fourier Transform (DFT) across subcarriers and a FFT over time. Doppler estimation and range profiling are triggered once a buffer of M frames is available. The system then estimates the signal-to-noise ratio (SNR) and detects peaks above a configurable threshold, allowing reliable identification of human presence, movement, and gestures in real time.

All signal processing and synchronization steps operate continuously on streaming data, with Doppler and range calculations performed in real time as new data arrives. The implementation supports flexible adjustment of buffer sizes and operational parameters to accommodate different sensing tasks and hardware capabilities, inspired by recent developments in Wi-Fi 6/7 and integrated sensing [9], [10].

Three primary operational modes are supported:

1. **Gesture mode** for short-range, high-accuracy hand gesture recognition via enhanced interpolation.
2. **Presence mode** for longer-range occupancy detection.
3. **Efficiency mode** for resource-limited scenarios.

The demo utilizes 160 MHz Wi-Fi bandwidth in the 6 GHz band, with 512 subcarriers and 25 ms frame intervals (32-frame Doppler batches). This configuration yields a theoretical range resolution of 0.94 m and Doppler resolution of 0.03 m/s, with a maximum range of 5 m and a velocity span of ±0.5 m/s. Through coherent integration, phase compensation, and adaptive interpolation, centimetre-level tracking accuracy is achievable on commercial off-the-shelf (COTS) hardware, as shown in [9].

A lightweight Python-based GUI (see Figure 4-4) allows interactive adjustment of sensing and processing parameters, and displays live range–Doppler maps, subcarrier statistics, and presence detection overlays. During demonstration, participants can observe live tracking as they move towards or away from the device, with real-time visualizations of their distance and radial velocity. Hand gestures performed within a 50 cm range are also recognized.

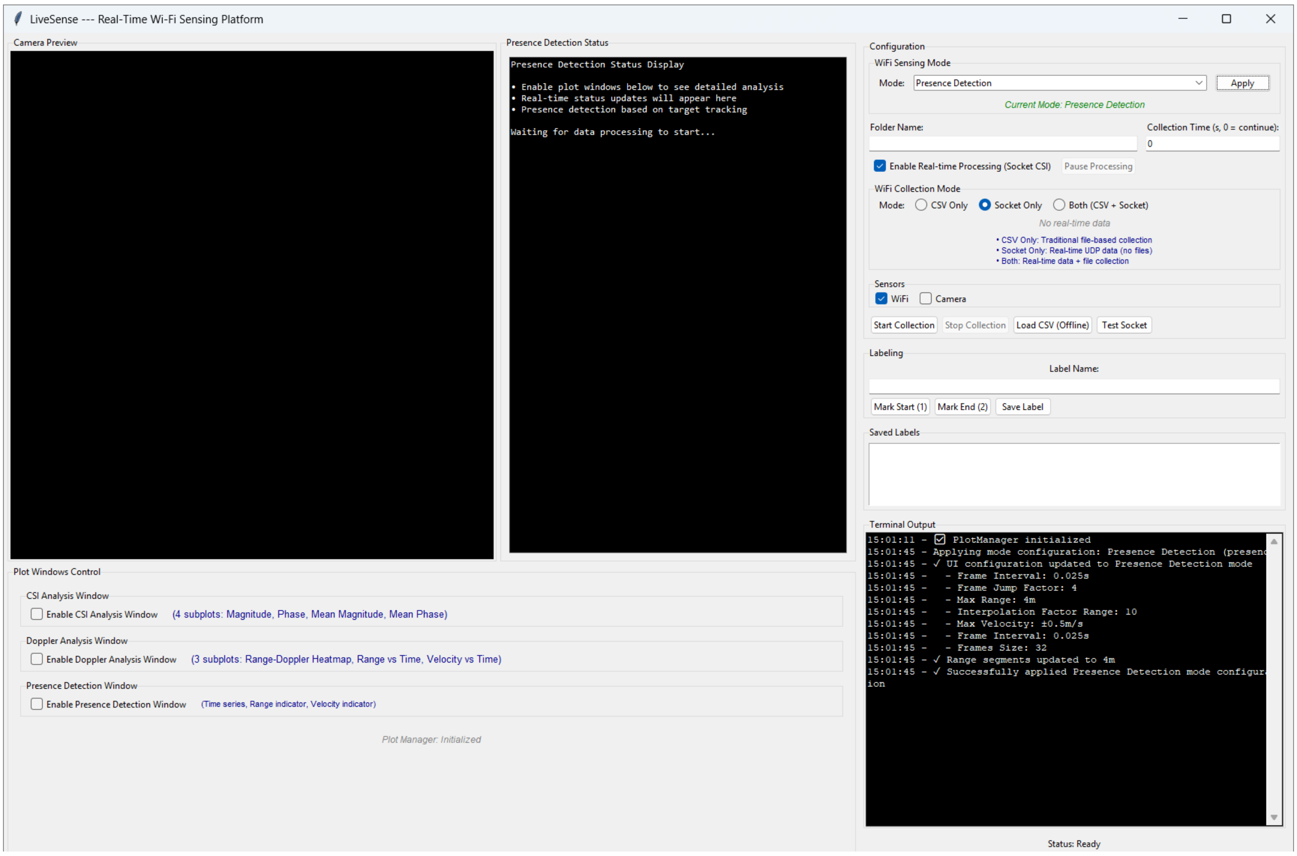

Figure 4-4 Wi-Fi PoC Platform

4.5.3 Transport interconnect PoC

This PoC demonstrates how optical/optoelectronic transport networks can facilitate 6G-SENSES sensing services. To facilitate 6G ISAC services exploiting the capabilities of optical transport networks we propose the system architecture illustrated in Figure 4-5 a). This architecture adopts an optoelectronic transport network to interconnect the RAN with the core functions located at edge and central cloud compute resources. The hierarchical structure of the proposed architecture offers RAN connectivity and collects and aggregates communication and sensing traffic streams from the RUs, while transporting these to edge and central cloud servers for processing. For the RAN segment, we consider a typical 5G compatible MIMO-OFDM waveform. The primary objective of the system is to successfully establish connections for communication purposes between the 5G RUs and the UEs. However, the OFDM waveforms transmitted for communication purposes are reflected by obstacles in the environment and are received by the RUs. These echo signals can then be processed to sense the surrounding environment and detect moving targets. In this PoC moving targets are provided from an emulated environment. The Doppler OFDM radar functionality is supported by a suitable sensing app hosted at the edge cloud as show in Figure 4-5.

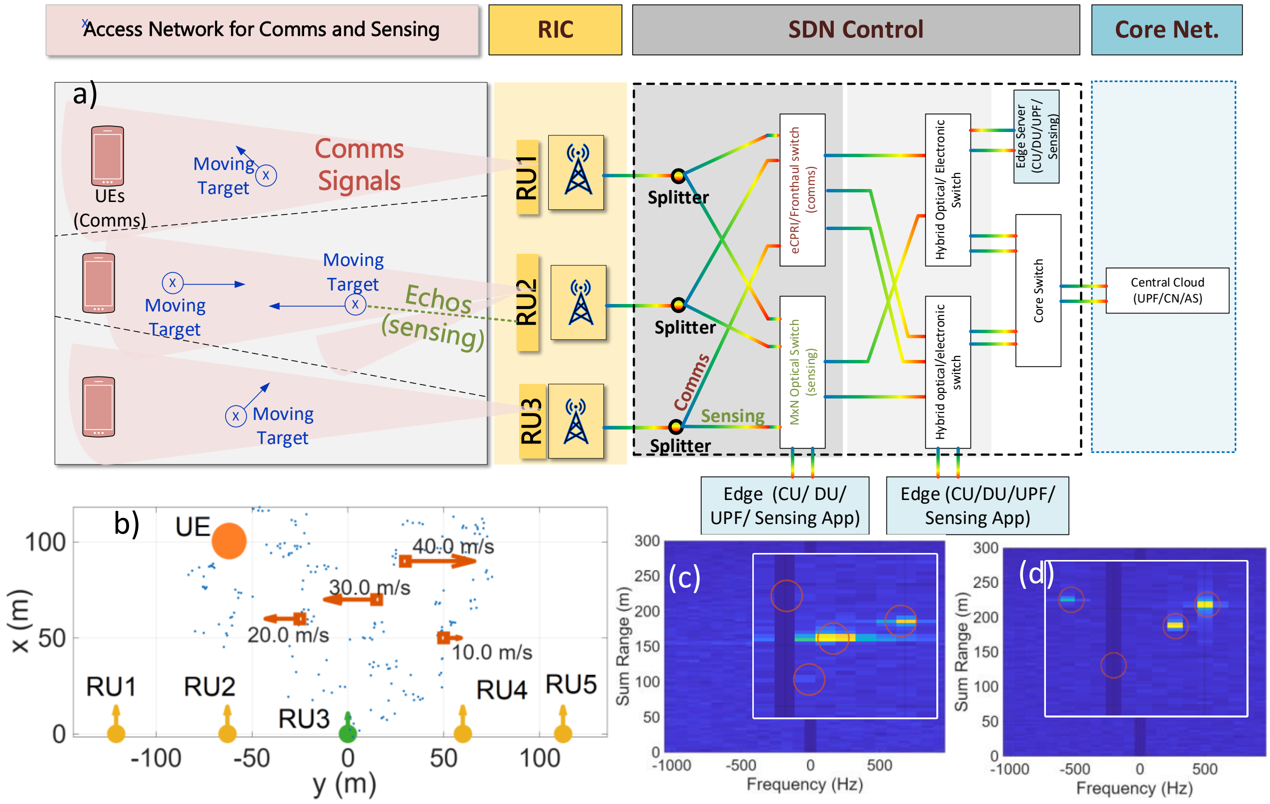

Figure 4-5 Implementation of the 6G-SENSES transport network for PoC#1

The OFDM waveform is organized into frames with 10 ms duration each comprising ten subframes of 1 ms. The bandwidth (in MHz) allocated per RU i is denoted as W_i. The main parameters characterising the performance of the OFDM Doppler radar are distance and velocity resolution, Δd_i and Δv_i, respectively. By increasing the number of frames collected and processed by the OFDM radar, higher sensing accuracy can be achieved. However, increasing the bandwidth increases also the volume of sensing I/Q streams, which are transported and processed by the sensing app implementing the Doppler OFDM radar. Given the characteristics of the sensing flows described above their aggregation from the RUs can be performed adopting all optical switching technologies with switching times of the order of 25ms-75ms. This enables collection of the necessary number of OFDM frames per tracked area allowing the sensing app to achieve the required sensing accuracy level transparently. Therefore, transparent optical switching plays a key role in supporting the functionality of the Doppler OFDM radar. The proposed solution offers an elegant and simple implementation eliminating the need of optoelectronic conversions.

The proposed concept is demonstrated in Figure 4-6. As can be seen, appropriate scheduling policies are applied at the optical switches to perform the required aggregation and transfer the optimal number of frames from the RUs (sufficient to detect the moving targets) to the sensing apps.

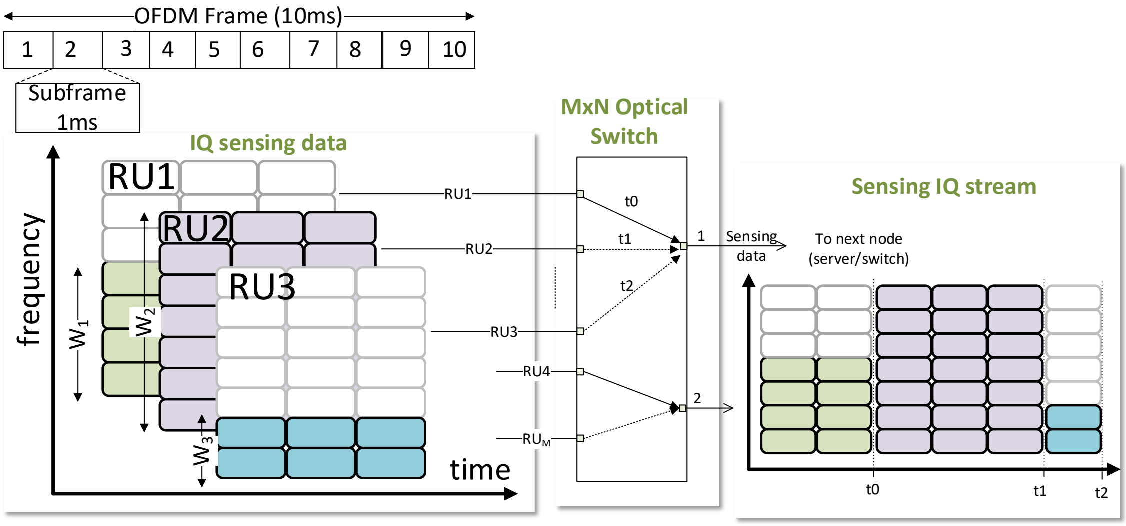

Figure 4-6 All optical transport network for aggregation of sensing flows PoC#1

4.5.4 Integration of non-3GPP technologies (Wi-Fi) via N3IWF

A key challenge in 6G-SENSES is determining how the necessary sensing metrics from non-3GPP access networks can be collected and provided to the 5G/6G network in a way that allows the near-RT RIC to leverage them effectively. The xApp responsible for real-time positioning that is hosted in near-RT RIC requires continuous updates regarding user location from both 5G/6G and non-3GPP networks. The primary issue that arises is how non-3GPP access networks can report their metrics through the 5G/6G system in a standardized and efficient manner.

Three potential approaches can be considered for collecting and transmitting non-3GPP positioning data to the RIC.

The first approach involves direct reporting from the UE through the E2 interface. In this case, the UE would be responsible for gathering Wi-Fi-based positioning data and transmitting it directly to the RIC. While this method eliminates the need for additional network elements, it places a higher dependency on the UE's capabilities and may lead to increased signalling overhead.

A second approach is to introduce a dedicated control element within the non-3GPP access node, embedding an E2 agent that communicates directly with the RIC. This would allow the Wi-Fi or other non-3GPP access points to handle positioning information independently of the UE and transmit the necessary data to the xApp. However, this approach requires the development of a new network element, along with the implementation of all the necessary background protocols, making it a more complex and resource-intensive solution.

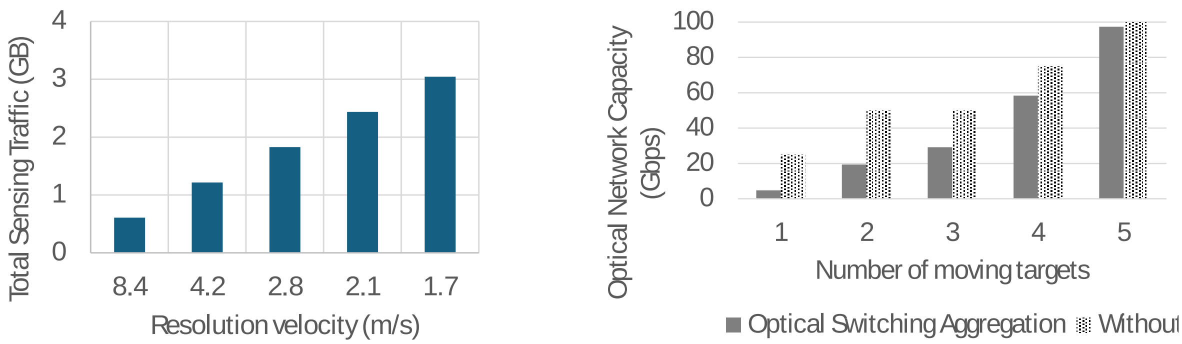

Figure 4-7 a) Volume of sensing traffic vs resolution velocity b) Optical transport network capacity allocated for sensing with and without optical network switching

A third approach, which presents a more practical and scalable solution, is to extend the functionality of the N3IWF to support the E2 agent. Since the N3IWF already serves as the main interworking point between non-3GPP networks and the 5G Core, enhancing it with E2 support would allow it to act as a bridge between non-3GPP positioning sources and the RIC. This approach benefits from the alignment of the transport protocols between the N3IWF and the E2 interface, simplifying the integration process. The N3IWF control plane protocol stack includes NGAP over SCTP, operating above IP and Ethernet or Wi-Fi at the lower layers. Similarly, the E2 interface, which facilitates communication between the near-RT RIC and RAN nodes also employs SCTP over IP, with E2AP handling control signalling at the application layer. This structural alignment suggests that the N3IWF could be extended to support E2-based interactions, enabling non-3GPP positioning data to be exposed to the near-RT RIC for further processing and optimization. Additionally, to minimize latency, the N3IWF could be co-located with the near-RT RIC, ensuring faster transmission of positioning data.

In this context, the proposed PoC considers a multi-RAT environment that integrates both 5G RAN and non-3GPP connectivity. Sensing signals from both Wi-Fi and 3GPP networks are exposed in a secure way to Near RT-RIC providing the necessary physical information to perform multi-technology positioning.

4.6 Risks and mitigation measures

This section provides an overview of the risks that are being identified as part of PoC#1 development and integration activities. Table 4-10 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 Description of Work (DoW).

Table 4-10 Unforeseen risks for PoC#1

Unforeseen Risk Nº	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	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.

5 PoC#2 – CF-MIMO Prototype

PoC#2 delivers a 6G CF-MIMO PHY prototype and extend it to support 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 synchronization, over-the-air (OTA) reciprocity calibration for TDD operation, distributed signal processing for channel estimation and beamforming, and fronthaul/backhaul data plane traffic exchange.

5.1 Mapping to Architecture

The provision of these mentioned functionalities extends throughout the 6G-SENSES network architecture proposed in deliverable D2.2 [2]. This way, Figure 5-1 depicts the baseline 6G-SENSES multi-layer architecture with the highlighted components that do provide additional functionalities – hence playing a role in PoC#2. Figure 5-2 depicts the relation between the technical components developed in **WP3** and **WP4** and their mapping to PoC#2 activities.

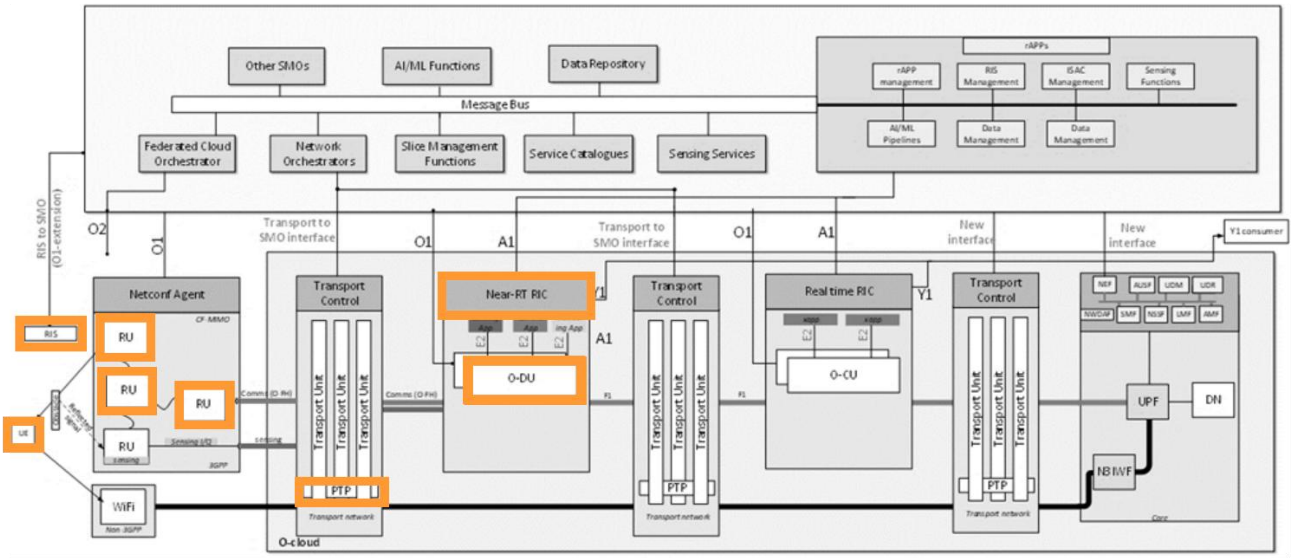

Figure 5-1 Multi-layer 6G-SENSES Architecture with highlighted components belonging to PoC#2

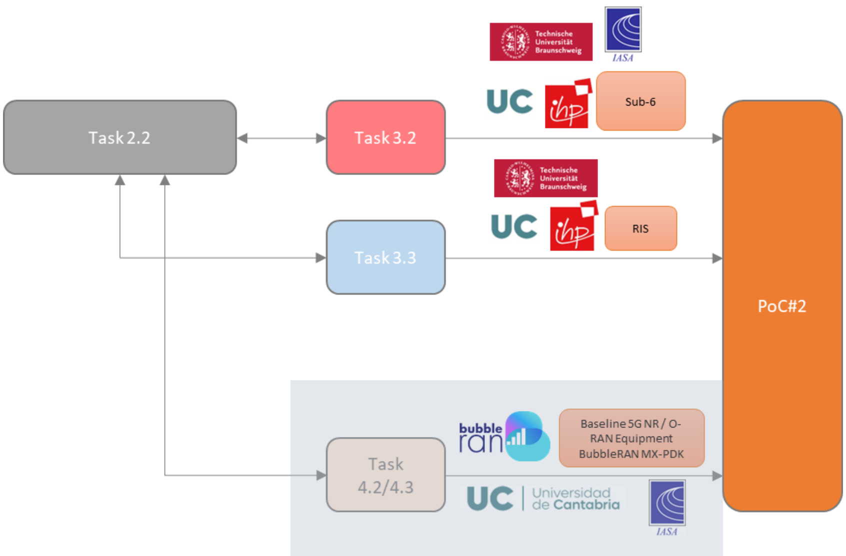

Figure 5-2 PoC#2 Task Workflow

The WATs and components involved in PoC#2 and their role are explained below[1].

- User Equipment (UE)
  - Types of UEs: OAI/srsRAN-based UE implementation using Ettus/NI devices, commercial 5G UEs.
  - Functions: Support multi-AP connectivity in CF-MIMO; mobility testing across Sub-6.
  - Extensions: Interfaces for feedback of CSI, synchronization, and real-time control monitoring.
- Sub-6 GHz Antenna Arrays (MIMO)
  - Types: SDR-based USRP X310/X410 devices forming centralized massive MIMO arrays, based on an OAI/SRS implementation of a 5G SA gNB using Ettus/NI USRPs for the RF front-end.
  - Functions: Provide high-capacity, coherent beamforming and joint transmission at Sub-6.
  - Extensions: Support synchronization (Table 5-3), reciprocity calibration (Table 5-6), and joint processing in a single-DU centralized setup.
- RIS Panels
  - Type: 16x16 elements @ 5.5 GHz[2] with 1-bit resolution.
  - Functions: Enhance coverage, capacity, and energy efficiency.
  - Extensions: Controlled by RIC; dynamically reconfigured according to user mobility and traffic demand.
- DU Extensions
  - Functions: Distributed channel estimation, joint precoding, beamforming.
  - Extensions: Compression of fronthaul traffic, coordination among multiple DUs, algorithms for pilot assignment and mobility tracking.
- RIC Extensions
  - Near-RT RIC: Real-time user-RU assignment, beamforming updates.
  - Non-RT RIC: Long-term optimization of RIS configuration and energy efficiency.
- Time Synchronization
  - Functions: Provide system-wide frequency and time alignment across USRPs and distributed RUs to enable coherent CF-MIMO operation.
  - Implementation: Each subsystem uses an OctoClock for local REF/PPS distribution. All OctoClocks are disciplined by a central Master OctoClock, which in turn is synchronized by a Meinberg GNSS clock generator with optional Precision Time Protocol (PTP) support.
- Reciprocity Calibration
  - Functions: Ensure channel reciprocity in TDD operation by compensating for hardware non-reciprocities across distributed APs. This enables coherent joint precoding and beamforming in CF-MIMO.
  - Extensions: Implementation and validation of reciprocity calibration algorithms (from **WP3**) on USRP-based platforms. In PoC#2, feasibility is assessed on a small-scale setup at **UC**; in future extensions, the approach is scalable to large-scale CF-MIMO deployments at **TUBS**.

---

[1] Please note that we are using the terminology from 3GPP, e.g. RU, DU, CU, RIC. In the actual implementation, we use the OpenAirInterface (OAI) protocol stack. The RIC functionalities are implemented with a proper interface inside the OAI.

[2] Open Source RIS, https://novoflect.de/en/5-5-ghz-ris-2/

5.2 KPI Identification and Testing Methodologies, Capabilities and Functionalities

In this section, we present the tables of different test cases, which illustrate the metrics defined in subsection 5.1 and their corresponding KPIs.

Table 5-1 Extensions to the UE

Test 2.1	Extensions to the UE
Phase	N/A
Description	The UE in PoC#2 consists of OAI/srsRAN-based UEs at Sub-6 GHz, used for testing multi-AP connectivity and mobility in a CF-MIMO setup.
Target UCs (taken from D2.1)	**Use Case #2**: multi-AP connectivity and AP assignment in CF-MIMO systems (referenced from D2.1 definition of use cases).
Requirements	**S- FUNC- #31**, UEs must support TDD operation, Sub-6 GHz band, and logging of channel and performance metrics.
KPIs	Signal-to-Interference-plus-Noise Ratio (SINR), Channel Quality Indicator (CQI), achievable data rate.
PoC	TUBS testbed

Table 5-2 Extensions to the DU

Test 2.2	Extensions to the DU
Phase	Initial lab testing @ TUBS Mid-term integration @ TUBS Final demonstration @ TUBS
Description	In the single-DU CF-MIMO setup, the DU centralizes channel estimation and joint precoding/beamforming across multiple RUs. While inter-DU coordination is not required in this PoC, the design is scalable to larger multi-DU deployments.
Target UCs (taken from D2.1)	**Use Case #2**: multi-AP connectivity in CF-MIMO systems (D2.1), with current PoC focusing on single-DU centralized processing and future scalability to mobility and multi-DU scenarios.
Requirements	**P-PERF-#10** (Capacity): The DU shall support centralized processing across multiple RUs to increase per-user outage capacity and reliability (outage probability reduced by >10× compared to baseline). (see Table 4-16 in D2.1 [1]) **P-NFUNC-#11** (Cost Efficiency): The DU shall enable cost-efficient CF-MIMO operation (low TCO solution), with potential OPEX reduction compared to conventional small-cell deployment. (see Table 4-17 in D2.1 [1]) **S-FUNC-37**: Support for TDD reciprocity-based channel estimation and coherent joint precoding/beamforming. **S-FUNC-38**: Synchronization of phase and time alignment across RUs to ensure coherent combining.
KPIs	Measurable requirements: • SINR gain, throughput, outage probability, sync error, latency. Non-measurable KPIs: • Cost efficiency, energy efficiency, scalability, reliability.
PoC	TUBS testbed

Table 5-3 Extensions to Time Synchronization

Test 2.3	Extensions to Time Synchronization
Phase	Initial lab testing @ **TUBS**, **UC** Mid-term integration @ **TUBS**, **UC** Final demonstration @ **TUBS**, **UC**
Description	In PoC#2, synchronization across distributed USRPs is ensured using a hierarchical scheme: each MIMO rack is synchronized via OctoClock devices distributing REF/PPS signals, and all racks are aligned through a central GNSS-disciplined clock generator. This setup enables coherent channel estimation, joint precoding/beamforming, and reciprocity calibration in TDD operation.
Target UCs (taken from D2.1)	**Use Case #2**: Multi-AP connectivity in CF-MIMO (Sub-6 GHz) with coherent joint transmission enabled by system-wide time synchronization.
Requirements	**P-PERF-#10** (Capacity): Ensure coherent combining gain through tight time and frequency alignment (see Table 4-16 in D2.1). **P-NFUNC-#11** (Cost efficiency): Low-cost synchronization using commercial OctoClock and GNSS-disciplined clocks (see Table 4-17 in D2.1).
KPIs	**Measurable KPIs:** • Measurement of packet error rate. • Measurement of data rates. • Measurement of SINR / CQI or similar. • Measurement of latency times (during data transmission). **Non-measurable KPIs:** • Before calibration and after calibration (with UC algorithm). • With State-of-the-Art (SotA) beamforming and with distributed beamforming. • With cellular user association and with cell-free user association. • For different scenarios (antenna geometries and antenna spacings).
PoC	**TUBS** testbed

Table 5-4 Extensions to RIS Panels

Test 2.4	Extensions to RIS Panels
Phase	Initial lab testing @ **TUBS** Mid-term integration @ **TUBS** Final demonstration @ **TUBS**
Description	Six RIS panels (16×16 elements, 5.5 GHz) are be integrated into the CF-MIMO testbed. The panels are network-controlled via Raspberry Pis with Power over Ethernet (PoE), supporting both manual GUI configuration and programmable APIs (Python/C++). In PoC#2, RISs are arranged in a (1+1+4) configuration and jointly optimized with MIMO beamforming. Scenarios also include cascaded RIS deployments, where up to six RIS panels (16×16 elements, 5.5 GHz) are integrated into the CF-MIMO testbed. Scenarios also include cascaded RIS deployments, where the signal is first reflected by one RIS panel and then by a second RIS panel before reaching the receiver, enabling evaluation of double-reflection paths.
Target UCs (taken from D2.1)	**Use Case #2**: RIS-assisted CF-MIMO with multi-AP connectivity (Sub-6 GHz), enabling coverage, capacity, and energy-efficiency enhancements.
Requirements	**P-PERF-#10** (Capacity): RIS to enhance SINR and user data rates (see Table 4-16 in D2.1 [1]).

	P-NFUNC-#11 (Cost efficiency): Network-controlled RIS for low-cost reconfigurable coverage extension (see Table 4-17 in **D2.1** [1]).
KPIs	**Measurable requirements:** • SINR gain with RIS vs. baseline. • CQI and achievable data rate improvements. • Coverage uniformity with single vs. multiple RIS panels. **Non-measurable KPIs:** • Cost efficiency (via centralized control). • Flexibility of integration (network-based RIS control). Flexibility of integration (network-based RIS control).
PoC	**TUBS** testbed

Table 5-5 Extensions to Sub-6 GHz Antenna Arrays

Test 2.5	Extensions to Sub-6 GHz Antenna Arrays
Phase	Initial lab testing @ **TUBS** Mid-term integration @ **TUBS** Final demonstration @ **TUBS**
Description	The Sub-6 GHz antenna arrays in PoC#2 consist of OAI/SRS-based USRP X310/X410 devices, forming centralized MIMO arrays for high-capacity, coherent transmission at Sub-6 GHz.
Target UCs (taken from D2.1)	**Use Case #2**: Multi-AP connectivity and mobility support in CF-MIMO systems (referenced from D2.1 definition of use cases).
Requirements	Arrays must support TDD operation, synchronization, and reciprocity calibration across distributed antennas for coherent joint processing.
KPIs	SINR, CQI, achievable data rate, phase synchronization accuracy.
PoC	**TUBS** testbed

Table 5-6 OTA reciprocity calibration in an CF-MIMO platform

Test 2.6	OTA reciprocity calibration in an CF-MIMO platform
Phase	Initial lab testing @ **UC** Mid-term integration @ **TUBS** Final demonstration @ **TUBS**
Description	**Implementation of distributed reciprocity calibration algorithms in a TDD CF-MIMO system**: Real-time implementation of distributed reciprocity calibration algorithms on a CF-MIMO platform based on USRP B210 nodes. The platform consists of 3 APs, with 2 antennas each, beamforming 5G-NR frames coherently to a maximum of two UEs. Both intra-AP calibration algorithms (using one of the antennas of each AP as a reference) and inter-AP calibration algorithms (using one of the APs as a reference) are implemented. The OTA calibration algorithms are based on bidirectional pilot transmissions between the antennas of an AP or between the APs.
Target UCs (taken from D2.1)	**Use Case #2 (Ubiquitous connectivity & Immersive services)***:* A CF-MIMO composed of up to 3 APs sends 5G-NR signals to a UE. The 5G-NR frames are beamformed by the APs using CSI obtained in the UL phase after a reciprocity calibration phase. The UE moves within a specific area (approximately 1 m x 1 m), performing SNR, EVM, and SNDR measurements on the DL. The objective is to achieve improved coverage compared to the case where the UE is served by a single AP.

Requirements (taken from D2.1)	**S- FUNC-#32**, Requirement #32, Synchronization requirements (see Table 5-41 in D2.1 [1]).
KPIs	**Success criteria:** • Demonstration of the feasibility of OTA calibration algorithms. • Improved SNR and improved coverage in the UE service area with respect to DL transmissions without calibration. **Measurable requirements:** • SNDR: improvements > 4 dBs wrt to uncalibrated systems. • Outage probability: EE improvement >8 dB for an uncoded BER of 1e-3. • SNR maps: improved uniform coverage in the measurement area. • Phase synchronization error (in degrees) < 2º.
PoC	TUBS testbed

5.3 PoC#2 implementation

In this PoC, the small-scale CF-MIMO demonstration validates the interaction of several functional components within the 6G-SENSES multi-layer architecture. The experiment bridges lower-layer testbed implementations with higher-layer near-real-time control, demonstrating the integration of CF-MIMO and RIS technologies.

From Figure 5-3 we can distinguish different layers:

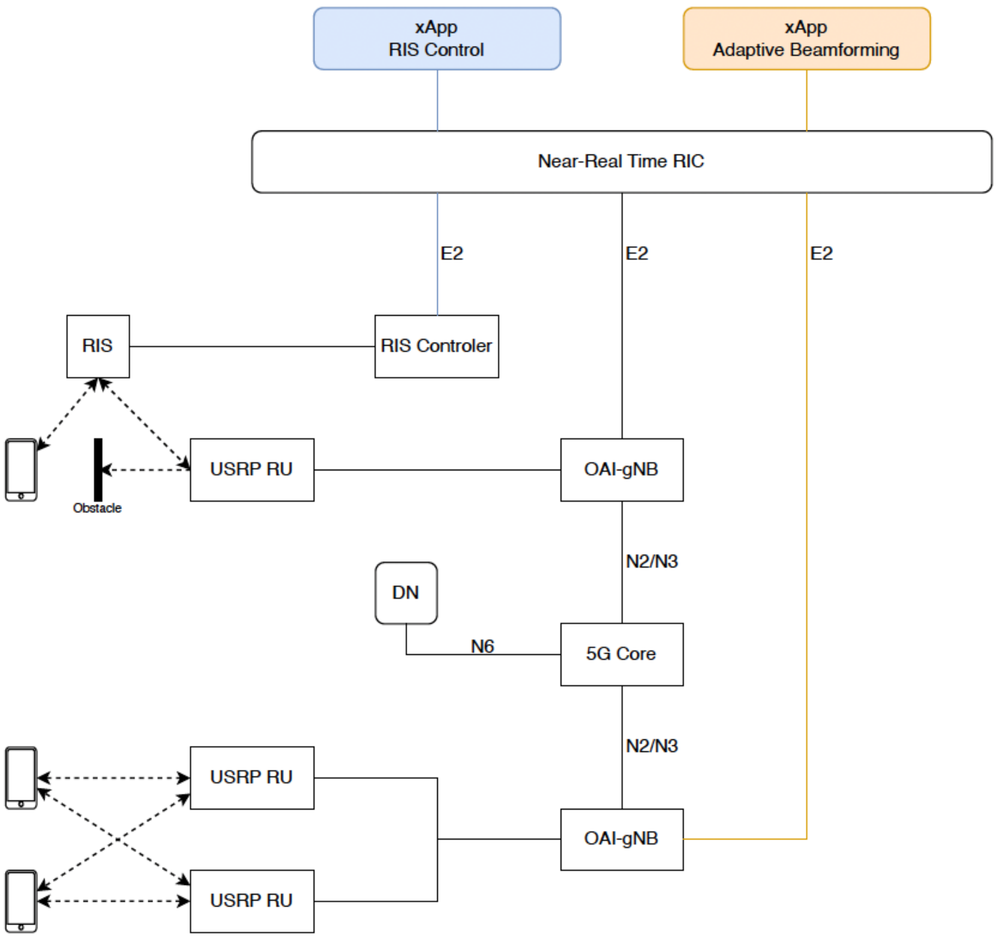

Figure 5-3 Implementation of the 6G-SENSES architecture for PoC#2

1. RU/UE Layer: A (distributed) CF-MIMO testbed is implemented with two (or more) USRP RUs and two (or more) UEs, validating both independent and joint transmission modes. Experimental measurements, including SINR, CQI, and achievable data rates, are collected to evaluate different beamforming strategies.
2. RIS Integration (E2 Interface to Near-RT RIC): Between two and six RIS panels are deployed, each managed by a Raspberry Pi-based controller and connected via a RIS Controller to the Near-RT RIC. This setup demonstrates the feasibility of RIS integration and supports both algorithm-driven configuration and manual control via a GUI interface, including series RIS operation.
4. Near-RT RIC Layer (E2 Interface): Two xApps—RIS Control and Adaptive Beamforming—are deployed on the Near-RT RIC. They communicate with the OAI-gNB and RIS Controller via the E2 interface, enabling KPI-based (SINR, CQI, throughput) monitoring and optimization.
5. Core and Data Network (DN) Layer (N2/N3/N6 Interfaces): The OAI-gNB connects to the 5G Core through N2/N3 interfaces, while the 5G Core connects to the DN through the N6 interface. This layer ensures E2E data flow and control, supporting upper-layer RIC and xApp operations.

5.4 Initial planning for PoC#2

Table 5-7 describes the planning of the main tasks necessary for the implementation of PoC#2.

Table 5-7 Initial Planning for PoC#2

PoC#1 Version	Description	Functionalities	Required Developments	Month
v1	Evaluation of OTA reciprocity calibration	Feasibility of OTA recip. Calibration algorithms. SNR EVM performance assessment in small-scale platform at UC	Small-scale CF-MIMO platform integration. TDD protocol implementation with USRP-B210 nodes. Extension to OFDM 5G-NR signals	M18
	Hardware setup ready	USRP platform, synchronization, network and compute nodes deployed and ready	Network and compute tested	M18
v2	Software components deployed	OAI RAN components and core network ready	OAI modification for TX/RX with same antenna	M20
	Experimental platform for cell-free massive MIMO at Sub-6 GHz	CF-MIMO testbed with 24 USRPs (48 antennas) enabling PHY-layer experiments on synchronization, high-throughput networking, and independent/joint beamforming for 2 UEs	Preparation for v2 by enabling mobile target integration and extending control functions for sensing.	M20
	RIS ready	RIS hardware in the lab. Control framework developed.	Development of software components	M20
	Experimental integration of RIS panels for CF-MIMO enhancement at Sub-6 GHz.	6 RIS panels (16×16 elements, 5.5 GHz) with network-based control via Raspberry Pis; support for manual/automated beam configuration, multi-RIS chaining (e.g., RU→RIS1→RIS2→UE), and	Development of RIS optimization algorithms (beam steering, cascaded RIS operation); integration with CF-MIMO testbed for joint evaluation of SINR,	M20

		joint optimization with AP beamforming.	CQI, throughput improvements	
v3	Final Hardware setup ready	RIS mounted on frames. Powered and controlled by Raspberry Pis	Mechanical work	M23
v4	Integration of reciprocity calibration module at TUBS platform	Performance evaluation of coherent beamforming schemes with and without rec. calibration.	Code/protocol adaptation for increased numbers of APs (up to 48 Tx antennas). Implementation of coherent beamforming (e.g., MRT)	M24
	Expanded RU to 48 antennas	Use gNB with more antennas	Modified OAI to use more antennas for beamforming	M24
v5	Algorithms integrated	RIS is controlled by an xApp	E2 an RIS controller, implementation of algorithms in xApp	M26
v6	Beamforming control implemented	Beamforming controlled by xApp	Add E2 to gNB, deploy RIC and xApp	M28
v7	Distributed Beamforming integrated	Cooperative beamforming of multiple RUs		M28
v8	Final version	Full version integrated	All above	M30

5.5 Small-Scale Demos for PoC#2

5.5.1 Scalable experimental environment for CF-MIMO

The main goal of this small-scale demonstration is to provide a flexible and scalable experimental environment for CF-MIMO and mobile scenarios. It enables the evaluation of centralized and distributed synchronization methods, supports high-throughput and low-latency networking, and integrates both fixed and mobile units to facilitate coherent MIMO operations and distributed processing experiments.

5.5.1.1 Overall Testbed Architecture

The overall testbed architecture integrates fixed and mobile infrastructures with centralized and distributed synchronization, as well as high-speed networking across all units. The system is composed of a MIMO rack, a mobile rack, three movable tables, and a server room hosting the central computing and network core. The interconnection and synchronization framework of the entire platform is illustrated in Figure 5-4, which shows how all subsystems are linked through a fiber patch panel and synchronized by the Master OctoClock.

The MIMO rack consists of three independent subsystems, each comprising eight USRP X310 devices. Within each subsystem, synchronization is provided by a dedicated OctoClock distributing reference (REF) and pulse-per-second (PPS) signals to all USRPs. Each group of USRPs connects to an aggregation switch via sixteen 10G Ethernet links, and the switches UL to the server core through four 25G Ethernet connections. This setup ensures precise time alignment and low-latency, high-throughput data transfer large-scale MIMO operations. The detailed configuration of the MIMO rack is shown in Figure 5-5.

The mobile rack (see Figure 5-6) contains three USRP X410 devices synchronized by an OctoClock. Data transmission is supported by three 100G Ethernet links, while control traffic is handled through three 1G Ethernet links. In addition, three movable tables are available, each equipped with a USRP 2974 connected through dual 10G Ethernet links, allowing flexible placement and experimentation at the network edge. All

OctoClocks across the fixed and mobile infrastructures are fed by a central Master OctoClock, which distributes four REF and four PPS outputs to maintain system-wide synchronization.

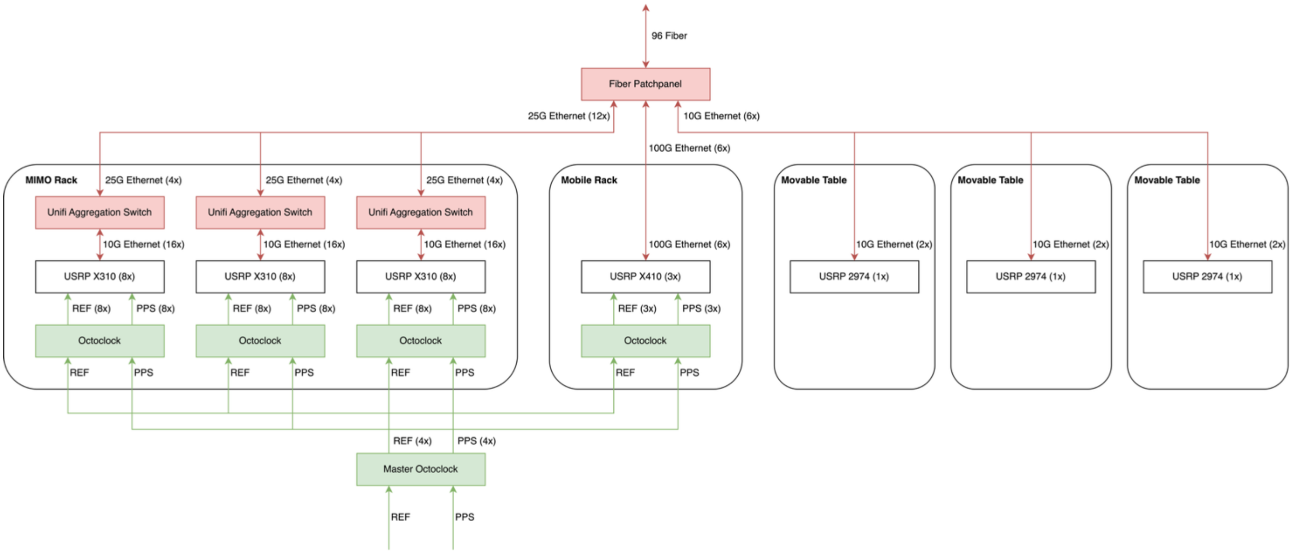

Figure 5-4 Lab Networking & Synchronisation

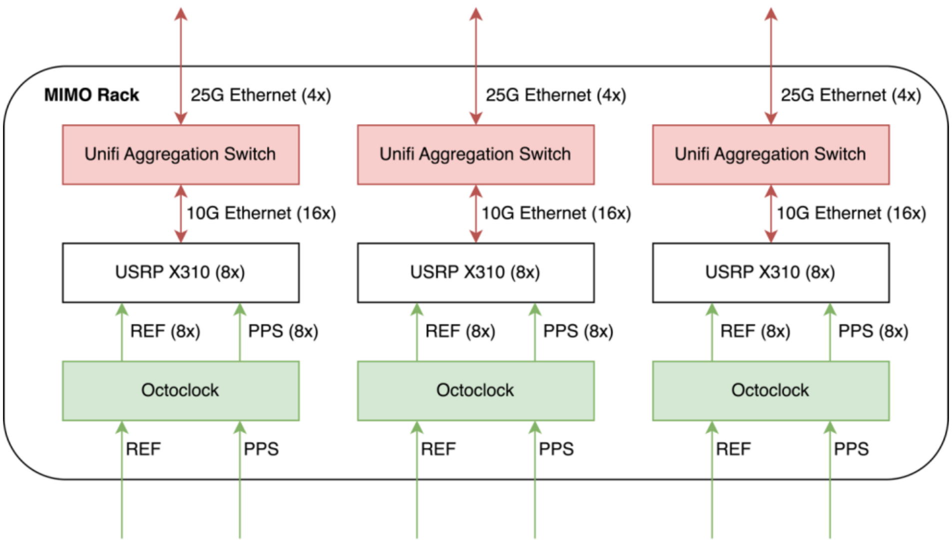

Figure 5-5 MIMO Rack

Figure 5-6 Mobile Rack

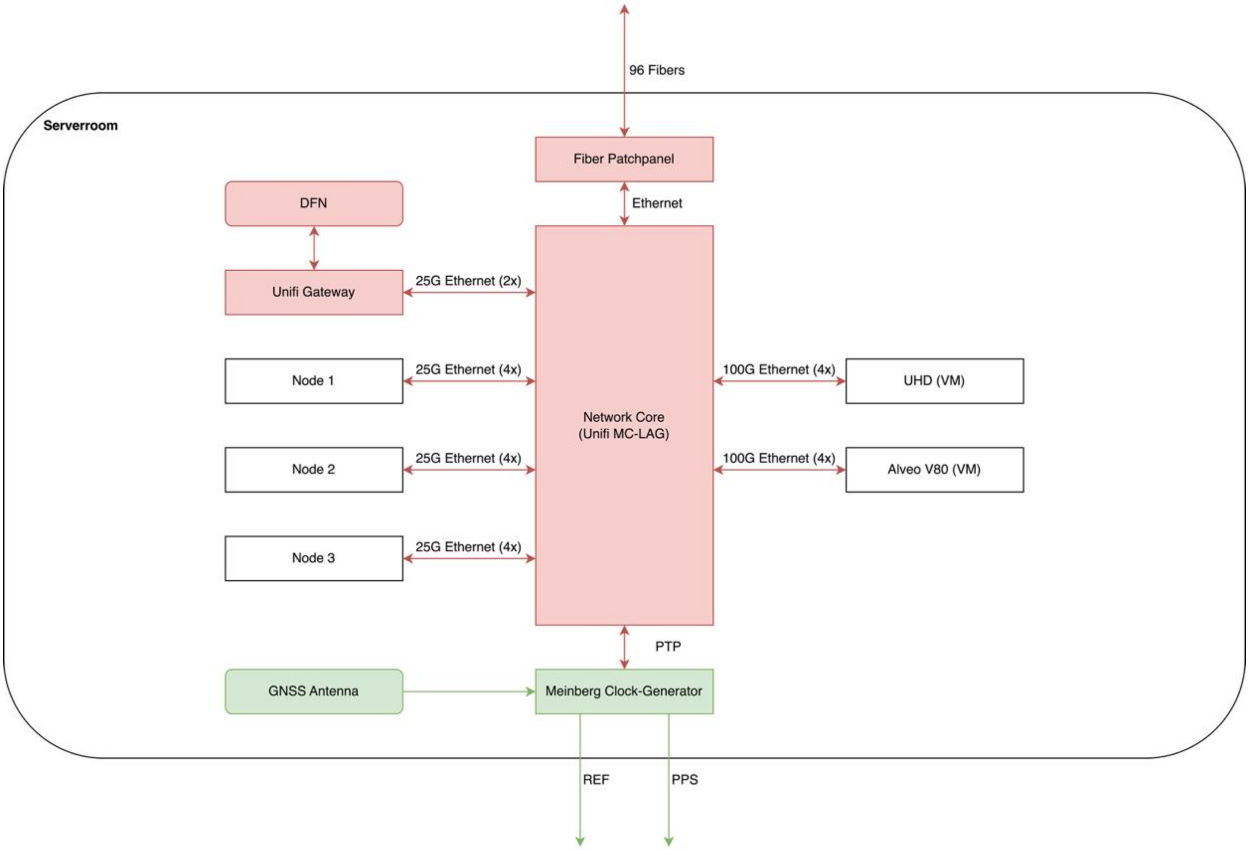

Figure 5-7 Overview of the Server infrastructure

At the heart of the testbed lies the server room, which provides the computing and networking backbone. The network core is built using a Unifi Multi-Chassis Link Aggregation Group (MC-LAG) configuration, aggregating traffic from all subsystems via a 96-core fiber patch panel. Three compute nodes are connected through four 25G Ethernet links each, while USRP Hardware Driver (UHD) (VM) and Alveo V80 (VM) servers are equipped with four 100G Ethernet interfaces to support ultra-high-speed data processing. Time synchronization is guaranteed by a Meinberg clock generator, which receives the global reference from a GNSS antenna and distributes REF and PPS signals, with optional PTP support for further alignment. The layout of the server infrastructure is depicted in Figure 5-7.

5.5.1.2 Configurations of the CF-MIMO platform

The overall architecture of the CF-MIMO platform was initially introduced in deliverable D3.1 [3]. In this deliverable, the setup is revisited with a focus on its experimental validation within PoC#2, targeting distributed beamforming and time synchronization aspects in the 6G-SENSES context.

The experimental platform is based on Ettus Research's USRP hardware (UHD) and GNU Radio-compatible software frameworks for baseband signal processing and visualization. A DU is connected to two RUs via a fronthaul network, enabling real-time coordination and evaluation of different beamforming strategies in Figure 5-8. This smaller-scale setup is dedicated to PHY-layer experimentation, focusing on distributed massive MIMO with synchronization, reciprocity calibration, and real-time control functionality.

The system supports multiple communication modes that allow comparison of different coordination levels between RUs. These configurations are used in PoC#2 to validate the impact of synchronization accuracy and calibration on coherent joint transmission. For now, two initial communication modes are supported:

1. Independent mode – each RU applies a different beamforming technique to serve its associated UE individually.

2. Joint mode – both RUs employ the same beamforming strategy to jointly serve multiple UEs.

This platform therefore acts as a bridge between the general testbed infrastructure and the specific PHY-layer experiments, allowing us to verify the feasibility of suitable beamforming methods and prepare for more advanced CF-MIMO configurations in subsequent evaluations. The physical setup would comprise 24 USRPs with 48 antennas in total, which are used to form 2 RUs with 12 USRPs each, and 24 antennas each to facilitate communication with 2 UEs. Each UE is connected to a corresponding laptop for signal processing and data exchange.

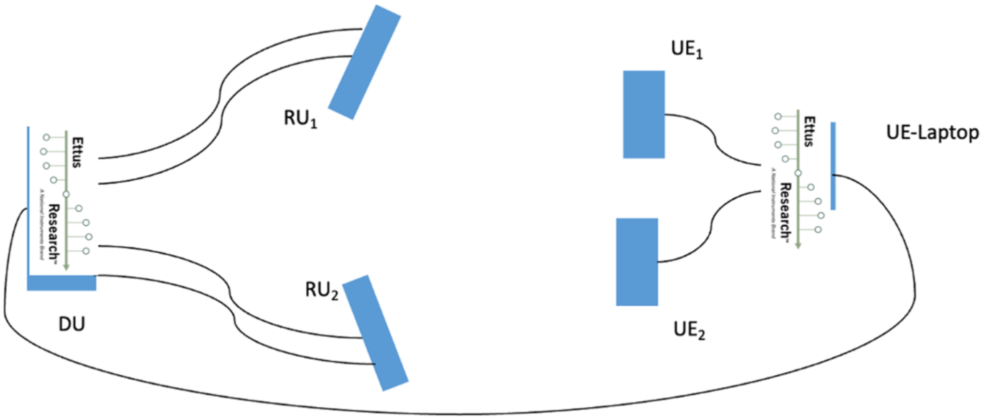

Figure 5-8 Massive MIMO System for CF-MIMO – Setup

The baseline configuration, shown in Figure 5-9, involves each RU independently serving a different UE through separate beamforming. Here, RU1 exclusively serves UE1, while RU2 exclusively serves UE2, each using its own beam. This setup is technically straightforward, as it requires no coordination or synchronization between the RUs. Each RU simply performs beamforming based on the CSI of its assigned UE, making implementation relatively simple. Additionally, this configuration imposes no specific similarity requirements between the channels from each RU to each UE, making it robust to varying channel conditions and suitable for fast-changing or heterogeneous environments.

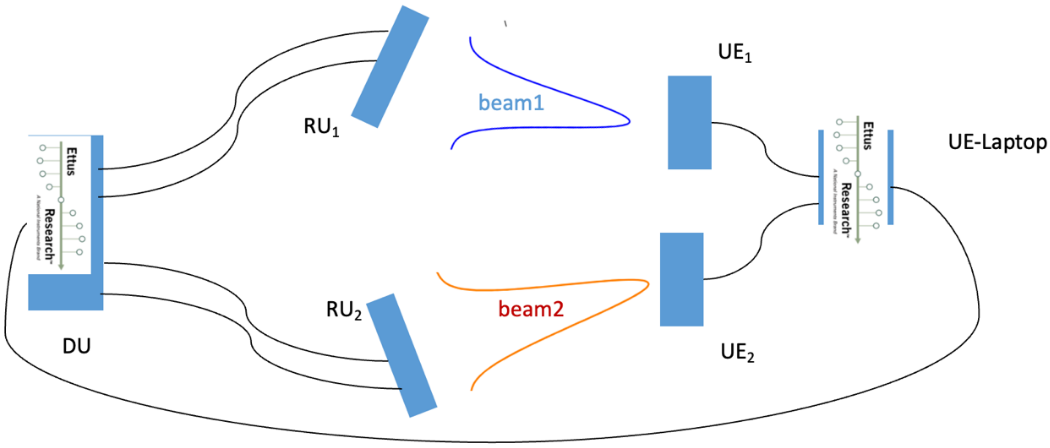

Figure 5-9 Baseline: Two RUs serve two different UEs separately through beamforming

In the second configuration (Figure 5-10), both RUs serve both UEs on the same RB. In this mode, RU1 and RU2 simultaneously serve UE1 and UE2 using the same RB. This approach demands a high level of coordination to avoid destructive interference, as both RUs are transmitting over the same frequency and time resources. To maximize signal strength and ensure coherent reception at the UEs, the RUs must synchronize their transmission timing and possibly adjust their beamforming strategies. This configuration requires channels between each RU and UE to be sufficiently similar or compensated for in real-time, and it places stringent demands on synchronization and CSI sharing, particularly in dynamic channel conditions.

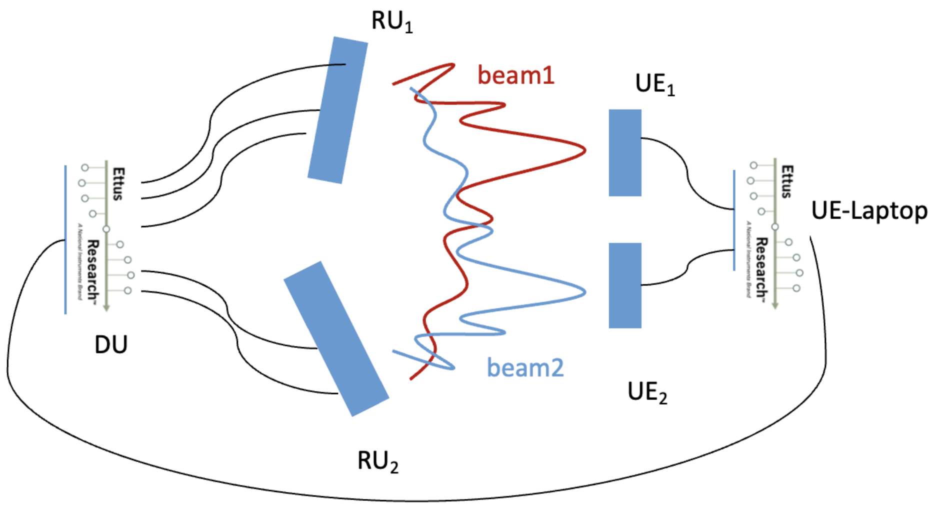

Figure 5-10 Second configuration: both RU1 and RU2 are serving UE1 and UE2 on the same RB

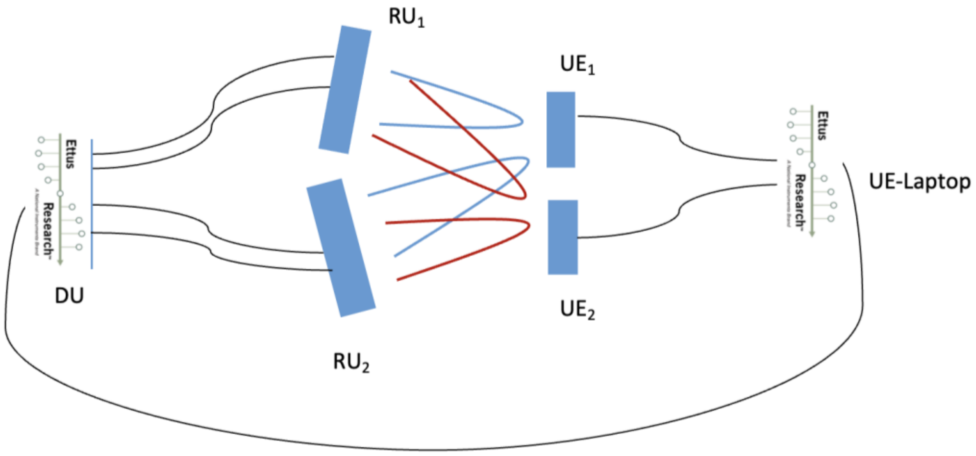

Figure 5-11 Third configuration: both RUs serve both UEs with different beams, accounting for synchronization and phase offsets

The third configuration shown in Figure 5-11 involves both RUs serving both UEs with different beams, accounting for synchronization and phase offsets. In this setup, each RU uses distinct beams to communicate with both UEs, taking into consideration any phase offsets between the RUs. This setup is technically challenging, as it requires sophisticated signal processing and synchronization mechanisms to adapt the beamforming for each RU-UE link while compensating for phase mismatches. It demands a detailed understanding of the channel characteristics and precise adjustments for phase alignment, which may require stable, low-latency fronthaul links to support real-time synchronization and CSI updates. This configuration is highly sensitive to variations in channel phase and amplitude, making it technically complex but potentially valuable for achieving flexible and adaptive communication.

5.5.1.3 Output of the CF-MIMO Small-Scale Experimental Platform

The small-scale CF-MIMO experimental platform provides a controlled environment for studying the fundamental challenges of distributed MIMO operation.

Main outputs include:

1 Validation of testbed integration: Demonstrated that the 6G-SENSES testbed can successfully host a distributed CF-MIMO setup, integrating DU–RU fronthaul connections, synchronization mechanisms, and real-time processing.

2 Feasibility of multi-mode operation: Verified both independent transmission mode and joint transmission mode, showing that the platform can support flexible RU–UE mapping strategies.
3 Beamforming insights: Collected experimental data on the performance of different beamforming strategies under distributed RU conditions, highlighting the trade-off between robustness (independent mode) and performance gains (joint mode).
4 Synchronization assessment: Quantitatively evaluated synchronization accuracy across distributed RUs, identifying critical requirements for phase alignment and CSI exchange in real-time operation.
5 Baseline for advanced configurations: Established a foundation for extending experiments towards more complex setups (e.g., multi-beam coordinated transmission with phase compensation), which will be explored in the next stages of PoC#2 activities.

Expected KPIs:

1 SINR measurements across independent and joint transmission modes.
2 CQI reporting to evaluate link adaptation performance.
3 Data rate measurements to quantify throughput under different beamforming and synchronization conditions.

5.5.2 RIS-based PoC Demonstrator

5.5.2.1 Demonstrator Goal

The main objective of the RIS-based PoC is to evaluate the joint optimization 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.

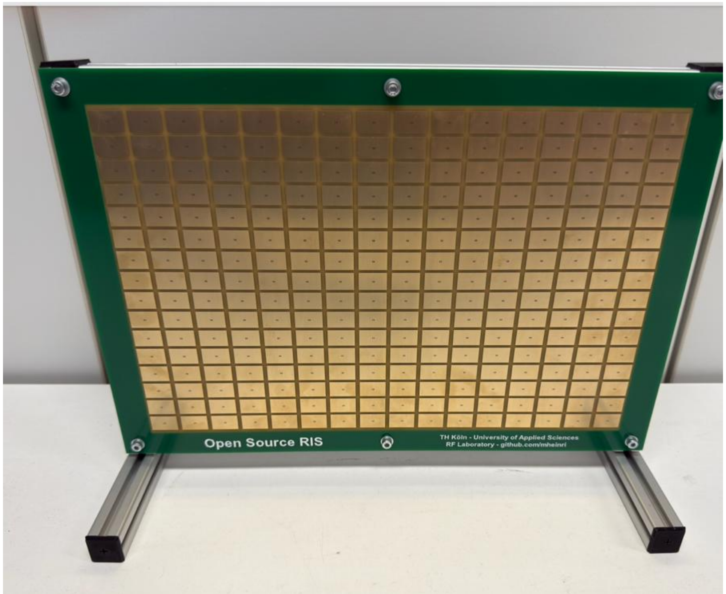

Figure 5-12 Example of RIS panel available at the lab of TUBS

5.5.2.2 Demonstrator Scenarios

RIS deployment: In total, six RIS panels are available, most likely arranged in a (1+1+4) configuration. Each RIS in Figure 5-12 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 5-13) 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, visualized in real time on the RIS control panel (Figure 5-13), where blue cells represent active elements and grey cells inactive ones. This provides intuitive monitoring and direct feedback of the RIS state.

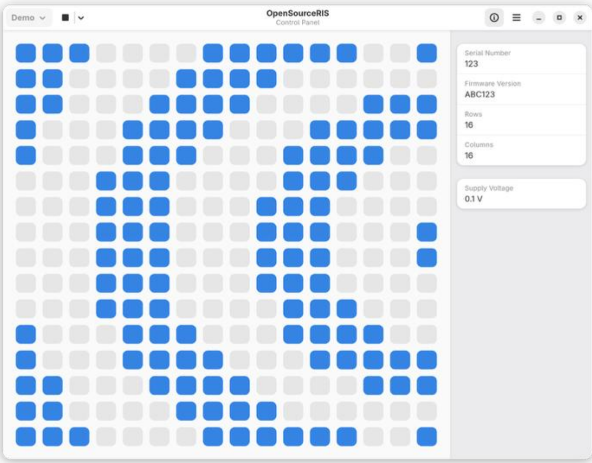

Figure 5-13 RIS Control panel

- **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 optimization and integration with higher-layer applications.

Experimental scenario: Besides joint beamforming/RIS optimization, one specific test case involves cascading RIS panels in series (**BS** /**RU** (in Figure 5-14) → **RIS1** → **RIS2** → **UE**) to study the feasibility and impact of multi-hop RIS-assisted transmission.

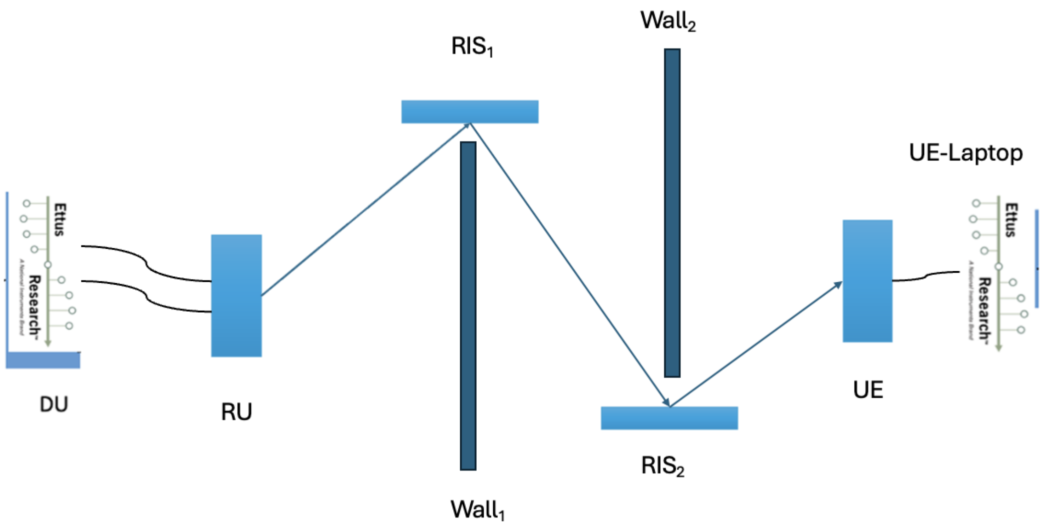

Figure 5-14 Massive MIMO System for RIS – Setup

5.5.2.3 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.

5.5.3 CF-MIMO small-scale demonstrator for reciprocity calibration

5.5.3.1 Demonstrator goal

Frequency synchronization, time alignment, and reciprocity calibration are essential to realize the benefits of coherent processing in a TDD-based CF-MIMO system. These aspects have to be studied in detail before the final solutions are integrated into the final platform at TUBS. Therefore, within WP5 activities, we evaluate the performance and main KPIs related to the reciprocity calibration algorithms developed in WP3 on a small-scale USRP-based platform on the *Universidad de Cantabria* (**UC**) premises. The **UC** CF-MIMO small-scale demonstrator can provide performance metrics using 5G NR Sub-6 GHz signals and evaluate the impact of reciprocity calibration in practical deployments.

5.5.3.2 Hardware Description

The demonstrator, built at the **UC**, is based on low-cost SDR devices, specifically the Ettus USRP B210 for signal transmission and reception, and an Ettus Octoclock-G CDA-2990 for synchronization purposes, allowing to synthesize both carrier frequency and baseband sampling clock and timing. The setup is managed by a central control PC running Matlab under Windows, using the GTEC Testbed Interface Software (GTIS), which is developed by the University of *A Coruña* (UDC) in collaboration with **UC**, for remote control of multiple USRP devices. The control PC communicates via SSH TCP-IP with several Ubuntu PC nodes, each connected to one or more USRP B210 devices via USB3 through the Ettus UHD driver.

Figure 5-15 shows and schematic diagram of the **UC** CF-MIMO small-scale demonstrator, composed of 3 APs with two antennas (two USRP B210s) each and one single-antenna UE.

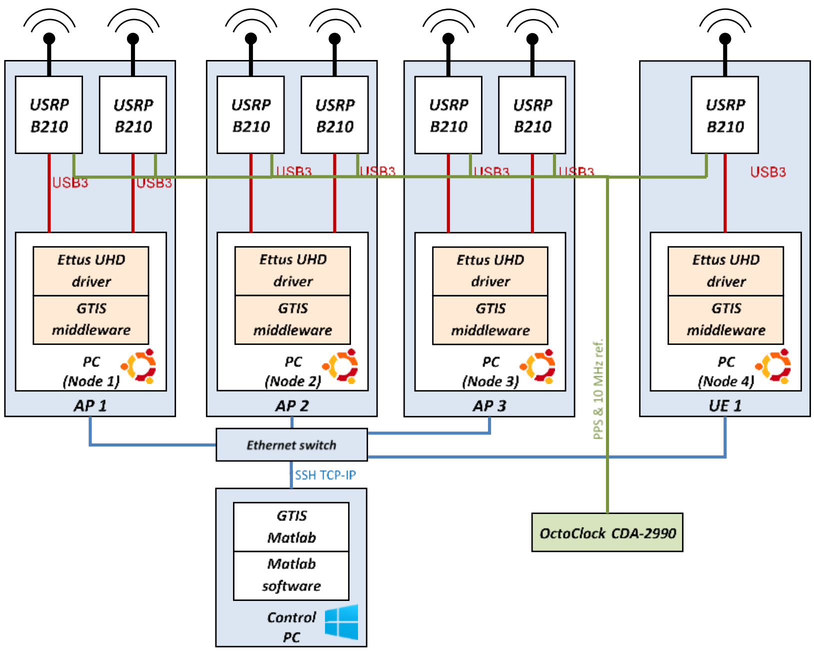

Figure 5-15 UC CF-MIMO small-scale demonstrator diagram

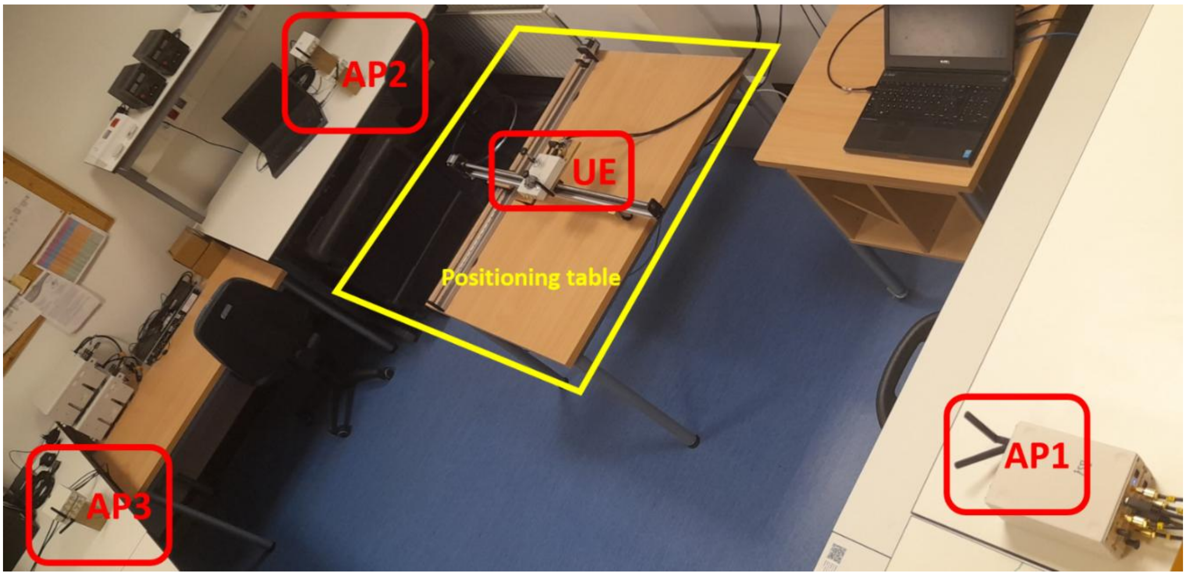

Figure 5-16 UC CF-MIMO small-scale demonstrator setup

A picture of the current demonstrator is shown in Figure 5-16, highlighting the three APs with two antennas each and the single-antenna UE. Additionally, a two-axis positioning table is visible, enabling controlled movement of the UE within a 1x1 meter area in 1 mm steps. This setup allows for measurement campaigns with statistical significance as well as for measuring the spatial distribution of the SNR within the measurement area. This is particularly interesting to evaluate the coverage uniformity achieved by the CF-MIMO architecture versus a small-cell scheme in which the UE is served by a single AP (or even by a single antenna of a single AP). If needed, the reciprocity calibration platform will be upgraded for a fourth AP (total number of 8 antennas) and a second single-antenna UE or a single UE with two antennas.

5.5.3.3 Demonstrator outputs

The main result of the demonstrator is to assess the feasibility of OTA reciprocity calibration in a multicarrier (5G NR style waveforms) CF-MIMO practical deployment using off-the-self commercial transceivers and conventional low-cost synchronization hardware.

The demonstrator measures the performance improvement of the CF-MIMO scheme (with and without proper reciprocity calibration) compared to conventional small-cell schemes. A small cell system is understood for the measurements as a TDD scheme in which the UE is served by only one of the APs (usually the one that provides a higher signal level in the DL).

The main KPIs for this small-scale reciprocity calibration platform will be the following:

- The **signal-to-noise-and-distortion ratio (SNDR)**: measured at the UE in the DL for different number of pilots and OFDM training symbols.
- The **outage probability (Pout)** (for a given BER): estimated as the number of measurements that the (uncoded) BER is below a certain threshold, typically 1e-3. Alternatively, these measures also allow to evaluate the energy efficiency improvement of the CF-MIMO system compared to the small-cell scenario.
- **Phase sync. error in degrees**: The phase synchronization error with respect to the ideal estimated with a sufficiently large number of pilots and OFDM symbols will be evaluated.
- **SNR maps**: SNR measurements in a certain area when the UE is served coherently by all the APs versus when served by a single AP. The spatial variability of these SNR maps allows quantifying the uniformity of coverage provided by the CF-MIMO architecture.

5.6 Risks and mitigation measures

This section provides an overview of the risks that are being identified as part of PoC#2 development and integration activities.

Table 5-8 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 5-8 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 synchronization 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

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

PoC#3 makes use of the sensing functionality of the RAN in order to optimise network performance and efficiency with the assistance of an NDT. The NDT relies on network planning information and network performance/ telemetry data and is implemented in the form of an rApp associated with the O-RAN Radio controllers. The demonstrator comprises the use of the three technologies: Sub-6, mmWave and 5G NR (together with RIS) as sensing information sources to be pushed to the O-RAN framework, which carries out an assessment of the current network planning and decides on network (re)-configuration with the aim to optimise network performance and energy efficiency. The assessment and optimisation rely on captured network performance data sets that are processed appropriately by the NDT application.

The development of the PoC embraces two interrelated phases as follows:

Pre-Trial of PoC#3 @ **OTE**, in Athens:

- **Goal**: pre-testing of DT rApp and generation of network performance datasets to be used for the performance estimation of the NDT(s).
- Using existing **OTE** 5GS UEs and in-house developed tools that capture and store datasets of network quality and performance metrics over time, location, conditions, etc. Indicatively the datasets to be generated include, for a given network deployment area:
  - network planning information (location of gNBs).
  - cell reselections locations/info.
  - handover locations/info, etc.
  - network-related measurements (incl. signal strength (RSSI, RSRQ, RSSNR, CQI, etc.), max upload bitrate, max download bitrate and latency) over time and along routes/ in various locations.
  - Additional info such as the RAT, cell-id, LAC/TAC, BS name, user location, terminal brand/model/OS-release, etc.
- Datasets are used for initial assessment and training of the PoC#3 V2 DT rApp.

PoC#3 at **UC**, in Santander

- **Goal**: Iterated, with AI/ML retraining and improvement, realistic scenarios, adaptive closed-loop, driven by sensing, to improve system energy efficiency.
- Open 5G SNPN (from **ACC**).
- Extended through the integration of 6G-SENSES Intelligent Plane (T4.3).
- Hosting AI/ML PoC#3 O-RAN rApp (T4.2), maintained by **UC**.
- Enriched with sensing telemetry from **WP3** and PoC#1 by **IHP**.
- rApp function: model radio environment, dynamically generating and exporting configuration files and simulation data to the NDT Simulator (Sionna RT).
- **Results**: ray-tracing based NDT system model.

6.1 Mapping to Architecture

Figure 6-1 provides a mapping of PoC#3 into the general 6G-SENSES architecture defined in **D2.2** [2]. The RAN and the radio environment is mapped into the UE-RU relation in the figure. Their metrics and telemetry are generated via the DU and CU in the lower part of the figure which are fed to the message data bus via

O1/E2/A1 interfaces. Once the telemetry is inside the Non-RT RIC, an NDT framework is defined via set of rApps that implement each of the functions of the NDT including Model Monitoring, Model Management, Model DB, Model serving and CI/CD. In particular these can be mapped into the components of the architecture: Model monitoring is a sensing service; Model Management is a service catalogue, Model DB is a data repository, Model Service is also a service catalogue; and CI/CD in connection with the MLRun or other AI/ML life cycle management is part of the AI/ML functions of the architecture. Each function can be considered an rApp that have similar capabilities via intern API supported by the Service Management and Orchestration (SMO)/Non-RT RIC framework.

Figure 6-1 depicts the baseline 6G-SENSES multi-layer architecture with the highlighted components that do provide additional functionalities – hence playing a role in PoC#3. Figure 6-2 depicts the relation between the technical components developed in **WP3** and WP4 and their mapping to PoC#3 activities.

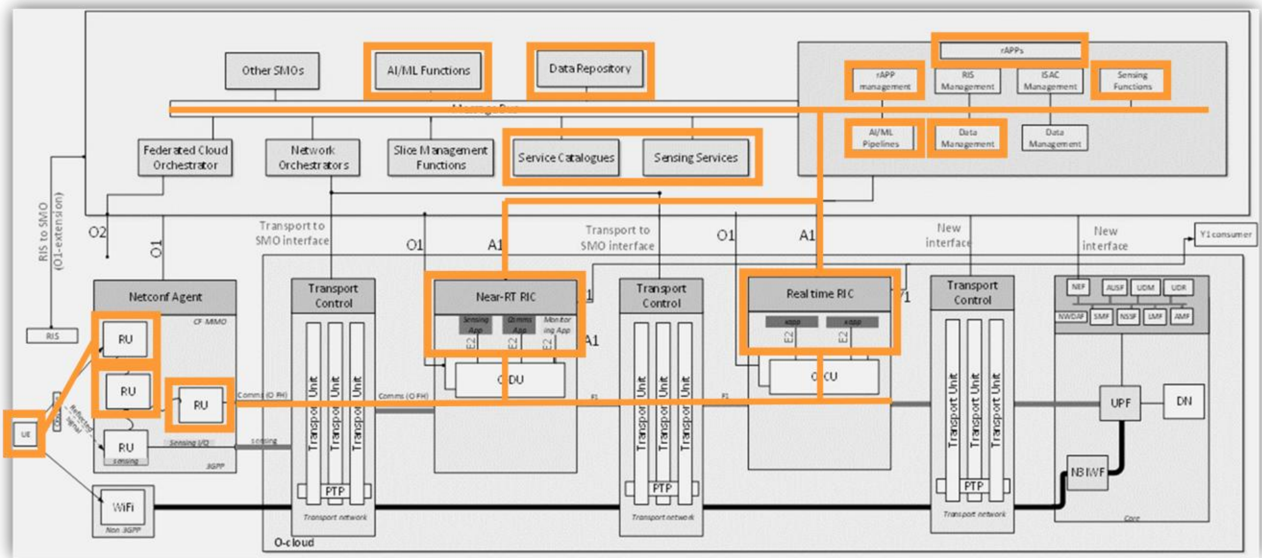

Figure 6-1 PoC#3 description mapped over the 6G-SENSES Architecture with highlighted components belonging to PoC#3

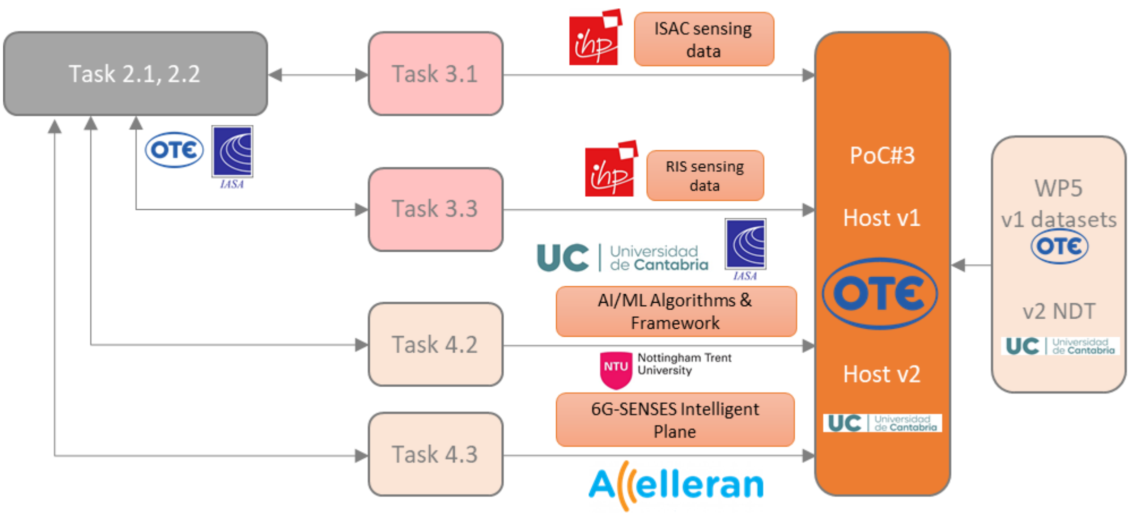

Figure 6-2 PoC#3 Task Workflow

6.2 KPI Identification and Testing Methodologies, Capabilities and Functionalities

In this section, we present the tables of different test cases, which illustrate the metrics defined in subsection 6.1 and their corresponding KPIs.

Table 6-1 Extensions to Open 5G NPN northbound

Test 3.1	Extensions to Open 5G NPN interfaces
Phase	Initial Phase @ ACC Mid-term integration @ **UC**
Description	Enable the integration of the NDT framework with the Open 5G NPN (dRAX) platform to support the ingestion of telemetry, sensing data, and configuration parameters from real or emulated RAN environments. This extension allows the SMO/Non-RT RIC to interact bidirectionally with the NDT—implemented as a set of rApps for Model Monitoring, Management, Serving, Database, and CI/CD—enabling dynamic scenario modelling, performance estimation, and closed-loop optimisation of network configuration. Through standardised O1, A1, and E2 interfaces, the NDT provides realistic representations of network states using data from simulators which are injected northbound into dRAX. This enables the SMO to perform "what-if" analyses and apply optimised configurations to the live RAN, demonstrating adaptive, AI-assisted network optimisation that enhances coverage, and overall operational sustainability.
Target UCs (taken from D2.1)	**Use Case #3: Storyline #1** (**NDT optimization**): Creation and operation of an NDT as a virtual replica of the RAN, continuously updated with telemetry and sensing data from O-RAN components. The goal is to model and predict network performance under varying conditions and enable data-driven optimisation of configuration parameters. By analysing real and simulated datasets, the NDT provides actionable insights to the SMO, supporting coverage extension, interference mitigation, and energy-aware planning in both emulated and real 5G NPN environments.
Requirements	**P-PERF-#12** (Network Coverage Availability); **P-PERF-#13** (RAN EE Optimisation); **P-PERF-#14** (CN EE Optimisation); **P-NFUNC-#15** (Cost Efficiency).
KPIs	• Coverage > 95 %; • RAN EE gain ≥ 15 %; • OPEX reduction up to 2×.
PoC	**UC** testbed

Table 6-2 Extensions to SMO algorithms

Test 3.2	Extensions to SMO algorithms
Phase	Initial Lab Phase@ ACC Mid-term integration @ **UC**
Description	Implement extensions to the SMO algorithms to integrate AI/ML-based decision-making for network optimisation within the NDT loop. These enhancements enable the SMO—through its hosted rApps for Model Management, Serving, and CI/CD—to analyse telemetry and sensing data collected via O-RAN interfaces (O1, A1, E2) and generate adaptive optimisation actions for the real RAN. The algorithms exploit the NDT's continuous feedback cycle, comparing real-network KPIs with simulated outcomes to refine models and policies over

	time focused on energy efficiency. A serverless MLRun framework supports continuous retraining and deployment of updated AI models, while a "what-if" Manager evaluates candidate configurations in the NDT sandbox before their application to the live network.
Target UCs (taken from D2.1)	**Use Case #3: Storyline #2** (**Energy Efficiency**): AI/ML-based optimisation and control mechanisms executed at the SMO level to improve the energy efficiency of RAN and Core components. Using insights generated by the NDT, the SMO's AI algorithms evaluate network KPIs (traffic load, utilisation, power consumption), to reduce energy use while maintaining QoS. The integration of Model Management, CI/CD, and "what-if" rApps enables a closed-loop, self-learning optimisation cycle, demonstrating measurable energy savings and improved sustainability in O-RAN deployments.
Requirements	**P-PERF-#13** (RAN Energy Efficiency), **P-PERF-#14** (CN Energy Efficiency), **S-FUNC-#42** (Scalability), **S-FUNC-#43** (Interoperability).
KPIs	• RAN EE gain ≥ 15 % compared to baseline; • CN EE gain ≥ 20 %; • < 5 % latency increase from AI/ML processing overhead; • Successful closed-loop convergence within ≤ 2 iterations of SMO feedback cycle.
PoC	UC testbed

Table 6-3 Extension to NDT northbound

Test 3.3	Extensions to NDT northbound
Phase	Initial lab testing @ UC Mid-term integration @ UC Final demonstration @ UC
Description	Definition and implementation of interfaces in network level simulator that acts as a component of the NDT to interact with the SMO; in principle ns-3 5G-LENA will be adopted. The simulator exploits the interfaces to report time-referenced telemetry information of different RAN elements (UEs and gNBs). The reported information is be subjected to configuration and covers different layer of the radio access stack, as well as end-user application information (i.e., RTTs). Furthermore, the simulator allows configuration commands from the SMO in order to define the deployment scenario or specific setup. In all cases, the extensions to the simulator are performed so that it is perceived as a real network by the SMO (interoperability).
Target UCs (taken from D2.1)	**Use Case #3: Storyline #1** (**NDT Optimization**). The NDT running on a server is configured to connect with the SMO and to simulate a specific scenario. As the simulation evolves, telemetry information is reported according to a given setup; for instance, it may include RSRP and RSRQ measurements, RLC buffer status or amount of PRBs and MCS indexes used by the gNBs. At a point in time, the NDT receives a configuration command from the SMO and adapts the simulation accordingly.
Requirements	**S-FUNC-#42**, Scalability of interfaces/infrastructure (see Table 5-52 in D2.1 [6]). **S-FUNC-#43**, Interoperability (see Table 5-52 in D2.1 [6]).
KPIs	**Measurable requirements:** • Interface scalability upon different network deployments.

	Non-measurable requirements: • Seamless interoperability with SMO
PoC	**UC** testbed

Table 6-4 Extension to NDT southbound

<Test Id>	Extensions to NDT southbound
Phase	Initial lab testing @ **UC** Mid-term integration @ **UC** Final demonstration @ **UC**
Description	To provide meaningful and realistic information about the network behaviour, the NDT based on ns-3 is extended to admit two additional configurations of the physical layer. The first one is be based on SIONNA-RT simulator that provides ray-tracing calculation and allows the definition of precise 3D environments. The second extension exploits on-field measurements from operator network to mimic real network conditions.
Target UCs (taken from D2.1)	**Use Case #3: Storyline #1**. The NDT is configured with a 3D description of specific scenario. The simulation provides the SMO with information about the expected performance for different configurations to optimise the network setup. According to that knowledge gathered, the NDT is exploited to analyse the impact of the learnt policy over a scenario at scale.
Requirements	**P-PERF-#12**, Network coverage availability (see Table 4-21 in **D2.1** [1]). **P-PERF-#13**, RAN energy efficiency (see Table 4-22 in **D2.1** [1]).
KPIs	Non-measurable requirements (enabler for): • Energy efficiency through optimized network planning • Network planning/network coverage adjusted
PoC	**UC** testbed

6.3 PoC#3 implementation

PoC#3 implementation is depicted in Figure 6-3. The setup is divided in three main entities, i) the Real Network in the bottom right, ii) the Common SMO in the upper part, and iii) the NDT in the bottom left. The Real Network is the one defined in the lab of **UC** where CU/DU/RU are implemented. This one is connected with the Common SMO that collect the telemetry provided via the O1/A1/O2 and Y1 interfaces. The near RT RIC aims to provide the telemetry information toward the SMO Data enrichment subsystem. This entity collects the data via O-RAN standardised interfaces. Inside the Common SMO, the NDT manager system provides the elements to control the NDT. First, the model monitoring is in charge of collecting data from the SMO data enrichment and organise in usable pieces to create usable models, they can be in the form of configuration files or real network entity representations depending on the description of the NDT itself. The models created by the model monitoring are stored on the Model Database. The model management organises them and evaluates how close the models are to the real network via evaluation of KPIs. Additionally, the model management defines which models are sent to the NDT via the model serving entity. The third part, the NDT is composed by the ns3 5G-LENA network level simulator that is integrated with Sionna RT and on the field data from **OTE** 5GS UE and Open 5G SNPN. They are controlled by the model manager which determine the configuration files for each setup and triggers the simulation with the configure values. Results of the simulation are returned to the model management to model evaluation and improvement.

The yellow part of the SMO, i.e., the Model Monitoring, Management, Serving and Database, are the foundation for the creation of an NDT. They oversee creating a replica of the real network and evaluate the accuracy of this replica based on defined KPIs. These elements satisfy the requirement of creating NDT that represent the real network. Still, this is an instantaneous observation of the real work that does not provide update or evaluation of how the real network is evolving or changing. To tackle this, the purple entities handle the Continuous Integration and Continuous Deployment (CI/CD) of the models. They are set as the feedback loop of the NDT to optimise the accuracy of the model via AI techniques. To achieve this, an MLRun serverless mechanism is implemented to continuously look for deviations of the model results and, intelligently, modify network parameters to deploy up-to-date models into the NDT. A clear continuous cycle between the model management and the CI/CD entity is the interconnection between them.

In addition, to use the NDT to evaluate possible changes in the configuration to optimise the network performance, the "what-if" manager is introduced. In this way, optimisation objectives, such as energy efficiency, are evaluated in a sand-box. The same infrastructure of the NDT can be used as a sand-box to evaluate the optimize-to-be configurations. In this way, the "what-if" manager defines network configurations that have the chance to optimise towards a predefined objective. Hence, a set of configurations are sent to the model manager to fire a specific network configuration in the NDT sandbox, and evaluate the results with the objective KPIs. The "what-if" manager then evaluates which is the best configuration and selects the one with the best performance. Then, this configuration is applied to the real network to achieve the desired optimisation goal.

Finally, a user dashboard is presented to show the network and NDT KPIs, and the capabilities to define the "what-if" objectives and how they are selected.

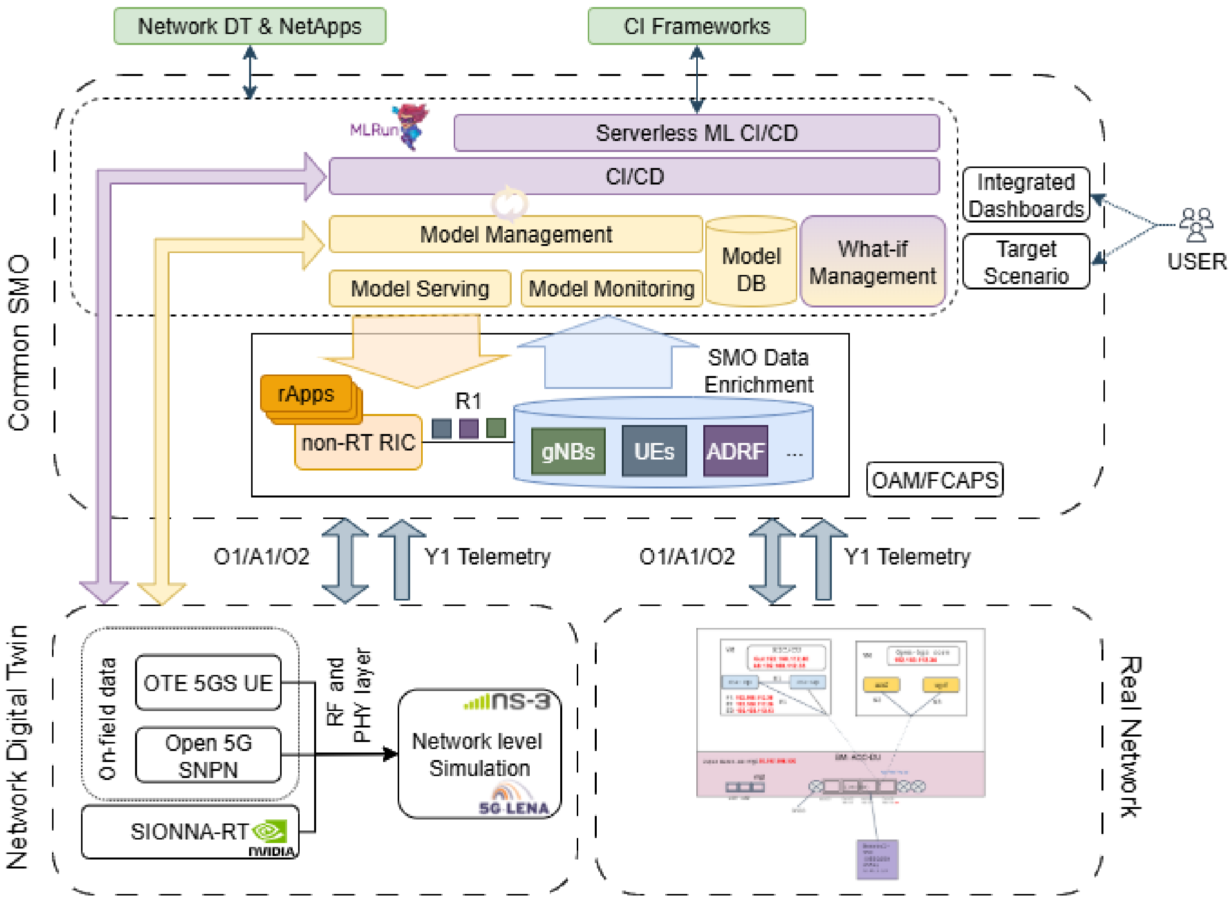

Figure 6-3 PoC#3 demo V2: Located at UC, in Santander (Final demo)

6.4 Initial Planning for PoC#3

Table 6-5 describes the different PoC#3 versions and the envisioned planning.

Table 6-5 Initial Planning for PoC#3

PoC#1 Version	Description	Functionalities	Required Developments	Month
v1	Pre-Trial @OTE: Integration of dRAX with OTE in-house tools	Emulated sensing capabilities and scenario implementation	Interface definition and testing	20
v2	Pre-Trial @ OTE: Modelling network into NDT	Telemetry collecting for the emulated radio, to convert into models (Simulator configuration files)	Model monitoring rApp; Model DB rApp and Dashboard enhancements	21
v3	Pre-Trial @ OTE: Integration to AI/ML modelling	Implementation of AI/ML tools for training and forecasting of NDT models via AI/ML tools	Model Management and AI/ML integration	23
v4	Trial @ UC: integration with real network	Telemetry collected from real network to convert into models, and evaluation process to remain identical to the real-world counterpart	Model management update, Model serving and CI/CD integration	24
v5	Trial @ UC: Network optimization via NDT	Using What-if management for scenario testing via optimisation management	"what-if" function and Model serving update	28
v6	Final demonstration	Final demonstration of PoC#3 objectives	Implementation of optimised model into the real network via E2 interface	30

6.5 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 6-6 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 6-6 Unforeseen risks for PoC#3

Unforeseen Risk №	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	Medium	Medium	Collect multiple datasets under varying conditions; perform data augmentation; retrain NDT models

	when applied to real network scenarios			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

7 Open Data, Datasets

This chapter presents the datasets that will be made Open Access (OA) in Zenodo. Table 7-1 reflects a provisional attempt to enumerate and describe the datasets that will be declared as outputs of the work in 6G-SENSES PoCs.

Table 7-1 6G-SENSES datasets generated in the context of the PoCs

	PoC	Description
Gesture recognition	PoC#1	**Description:** Wi-Fi CSI evolution over time to evaluate gesture recognition solutions. The dataset will also comprise ground truth information and the outcome of the developed solution to be used as benchmark. **Related tests:** Test 1.3 (**INT**)
Monostatic sensing	PoC#1	**Description:** CSI and heatmaps generated by sub-6 and mmWave sensing solutions upon different scenarios and sensing configurations. The dataset will include ground truth information so that it can be used to develop new processing schemes. **Related tests:** Test 1.4 (**IHP**)
Location	PoC#1	**Description:** Algorithmic and NN UE location estimation based in UL SRS signal. The signal will be extracted using O-RAN LLCv1.0 SM. **Related tests:** Test 1.5, Test 1.6 (**BR**)
Resource scheduling	PoC#1	**Description:** Utilization of radio resources over time along with synchronized with surrounding sensing information and network metrics. It can be exploited to define better scheduling schemes; the results yielded by the ones developed in the PoC will be also released for comparison purposes. **Related tests:** Test 1.5, Test 1.6 (**UC**)
Trajectory prediction	PoC#1	**Description:** Trajectory prediction of UEs based on sensing information over time. It will also include ground truth information for evaluation purposes. **Related tests:** Test 1.6 (**IASA**)
Sensing traffic	PoC#1	**Description:** Sensing traffic that will coexist at the transport network with legacy communication traffic flows. Specifically, the dataset will embrace sensing traffic between the RU and DU. It can be further exploited to define traffic management solutions over the transport network. **Related tests:** Test 1.8 (**IASA**)
Evaluation of Distributed Beamforming Strategies	PoC#2	**Description:** Measurements collected from distributed beamforming experiments on the CF-MIMO testbed using OAI. The data includes PHY/MAC-layer parameters such as SINR, CQI, RSRP, MCS, HARQ statistics, code rate, and data rate, extracted from both gNB and UE traces. Independent, joint, and coordinated beamforming modes are compared to assess performance differences in throughput, reliability, and spectral efficiency. **Related tests:** Test 2.1, Test 2.2, Test 2.5 (**TUBS**)
Time Synchronization	PoC#2	**Description:** Dataset collected from time synchronization experiments on the CF-MIMO testbed. The **TUBS** setup provides hardware-based synchronization via OctoClock and GNSS-disciplined clock generators, while **UC** algorithms enable distributed synchronization control using a hierarchical Master and sub-Master AP structure. The dataset includes synchronization logs, phase and frequency offset data, and PHY/MAC-layer metrics (e.g., SINR, CQI, latency, throughput) for evaluating synchronization performance and reciprocity calibration accuracy.

		Related tests: Test 2.3 (**TUBS**)
Joint Beamforming and RIS Optimization	PoC#2	**Description:** Measurements obtained from RIS-assisted CF-MIMO experiments at the **TUBS** testbed. The setup integrates six RIS panels (16×16 elements, 5.8 GHz) controlled via Raspberry Pis and optimized jointly with distributed beamforming strategies. The data include SINR, CQI, and throughput metrics, enabling performance evaluation of RIS-assisted and cascaded RIS configurations. The experiments aim to quantify coverage uniformity, signal quality gains, and the feasibility of chained RIS setups. **Related tests:** Test 2.4 (**TUBS**)
Reciprocity Calibration	PoC#2	**Description:** Reciprocity calibration algorithms are based on bidirectional measurements between antennas of the same RU and between different RUs (or APs). The data set will include measurements obtained in the specific deployment of the small-scale CF-MIMO platform at **UC**, and the calibration coefficients obtained with our implementation. The data set will enable the evaluation of other distributed OTA algorithms. **Related tests:** Test 2.6 (**UC**)
Network telemetry	PoC#3	**Description:** Temporal evolution of network metrics obtained from a real or emulated network during the first integration phases of the PoC. The dataset will include static planning information (e.g., site topology, gNB locations, antenna configurations) to provide better understanding of the network, as well as DU/CU 3GPP/O-RAN compatible telemetry from cells and UEs in diverse scenarios. **Related tests:** Test 3.1, Test 3.2 (**OTE**)
NDT telemetry	PoC#3	**Description:** Temporal evolution of network metrics simulated or predicted by the NDT for specific scenarios. The dataset will include time-referenced simulated measurements (e.g., RSRP, SINR, PRB usage, buffer occupancy) generated by ns-3 5G-LENA and SIONNA-RT tools, complemented by 3D environmental characterisation (ray-traced propagation maps, obstacle models, user mobility traces). It will also contain model versioning information, scenario configuration files, and AI/ML outputs used for model training, validation, and "what-if" evaluations. **Related tests:** Test 3.1, Test 3.2 (**UC**)
Optimisation feedback	PoC#3	**Description**: Dataset generated by the "what-if" Manager and CI/CD rApps containing results from simulated optimisation scenarios. It includes recommended network configurations, predicted KPI improvements (e.g., coverage, throughput, energy savings), and comparisons between NDT predictions and real network measurements. These datasets support the continuous validation and refinement of AI/ML models used for network reconfiguration. **Related tests:** Test 3.2 (model validation and optimisation), Test 3.3 (final integration and closed-loop demonstration) (**ACC**)

8 Summary and Conclusions

This document defines the 6G-SENSES testing and evaluation methodologies and provides a complete roadmap for the project testing and evaluation activities. To summarize, this document provides:

- Formalization of the adopted common terminology.
- Overview of the planning of the testing activities phases of each PoC.
- Association of the testing and evaluation phases with the project activities.
- Identification of the objectives and evaluation KPIs.

With the defined methodology, the 6G-SENSES test objectives have been refined and translated into specific test cases that are executed and evaluated according to a clearly defined set of KPIs. These test cases ensure consistent assessment of performance, functionality, and interoperability across all PoCs:

- **PoC#1: Multi-Technology Integrated Sensing and Communication (ISAC) Platform**

  This PoC develops a small-scale E2E prototype to demonstrate both performance and energy efficiency in a multi-technology ISAC environment. By leveraging multiple WATs as sensing inputs, and integrating them with real-time RAN and CN extensions, the PoC validates the ability of 6G-SENSES to dynamically and intelligently adapt network behaviour.

- **PoC#2: Cell-Free MIMO (CF-MIMO) Prototype**

  The second PoC delivers a CF-MIMO PHY layer prototype, enhanced with real-time control capabilities. Implemented on representative SDR hardware, it demonstrates the feasibility of distributed signal processing, tight synchronization, and efficient fronthaul/backhaul integration. This PoC provides strong evidence of how advanced PHY innovations can translate into tangible performance gains in 6G networks.

- **PoC#3: Network Digital Twin via RAN Sensing**

  The third PoC will make use of the sensing functionality of the RAN to build up an NDT that are emulated thanks to the telemetry data provided by the O-RAN Radio controllers. The demonstrator comprises the use of 6G-SENSES sensing information sources to be pushed to the O-RAN framework for carrying out an assessment of the current network planning. The generated data sets are used for network optimization purposes, mainly focused on energy efficiency improvement.

These tests cases are be executed in the labs at **UC** and **TUBS**.

The **UC** hosts test cases for PoC#1 and PoC#3, while **TUBS** premises host the test case for PoC#2. More information and associated results will be provided in the following **WP5** deliverables, i.e., deliverables **D5.2** and **D5.3**.

This structured approach ensures that all testing and evaluation activities are aligned with the overall project goals, enabling objective validation of the developed solutions and contributing to the successful realization of the 6G-SENSES proposal.

9 References

[1] 6G-SENSES deliverable D2.1, "Report on 6G-SENSES use cases, network architecture, KPIs and supported RAN functions", September 2024, https://6g-senses.eu/wp-content/uploads/2024/10/2024-09-30-6G-SENSES_Deliverable_2_1_vf.pdf

[2] 6G-SENSES deliverable D2.2, "System architecture and preliminary evaluations", February 2025, https://6g-senses.eu/dissemination-communication/deliverables/

[3] 6G-SENSES deliverable D3.1, "Initial report on the development of 6G-SENSES infrastructure building blocks", January 2025, https://6g-senses.eu/wp-content/uploads/2025/07/2025-01-15-6G-SENSES_D3.1_v1_0-FINAL.pdf

[4] 6G-SENSES deliverable D4.1, "D4.1 Initial SoTA and design of wireless edge caching solutions", January 2025, https://6g-senses.eu/wp-content/uploads/2025/02/2025-01-15-6G-SENSES_Deliverable_4.1_MAIN_FINAL.pdf

[5] T. X. Vu, E. Baştuğ, S. Chatzinotas, and T. Q. S. Quek, "Wireless Edge Caching: Modeling, Analysis, and Optimization", in *Cambridge University Press*, 2021.

[6] K. S. Tharakan, B. N. Bharath, V. Bhatia, J. Nebhen, M. Dobrovolny and T. Ratnarajah, "Wireless Edge Caching and Content Popularity Prediction Using Machine Learning," in *IEEE Consumer Electronics Magazine*, vol. 13, no. 4, pp. 32-41, July 2024, doi: 10.1109/MCE.2022.3160585.

[7] P. Yang, N. Zhang, S. Zhang, L. Yu, J. Zhang and X. Shen, "Content Popularity Prediction Towards Location-Aware Mobile Edge Caching," in *IEEE Transactions on Multimedia*, vol. 21, no. 4, pp. 915-929, April 2019, doi: 10.1109/TMM.2018.2870521.

[8] Massive Beams, "A NEW ERA IN THE WORLD OF SOFTWARE-DEFINED RADIOS", 2025, https://www.massivebeams.com/

[9] J. Sanson et al. "Extracting Range–Doppler Information of Moving Targets from Wi-Fi Channel State Information." To appear in Proc. IEEE GLOBECOM (2025). https://arxiv.org/abs/2508.02799

[10] V. Frascolla, D. Cavalcanti, and R. Shah. "Wi-Fi Evolution: The Path Towards Wi-Fi 7 and its impact on IIoT." Journal of Mobile Multimedia 19, 01 (2022). doi:10.13052/jmm1550-4646.19113

[11] J. Gutiérrez et al. "Seamless Integration of Efficient 6G Wireless Technologies for Communication and Sensing Enabling Ecosystems." AIAI 2024 IFIP WG 12.5 Int. Workshops.

10 Acronyms

Acronym	Description
3GPP	3rd Generation Partnership Project
5G NR	5G New Radio
5QI	5G Quality of Service Identifier
ACC	Accelleran
AI	Artificial Intelligence
AiP	Antenna-in-Package
AoA	Angle of Arrival
AP	Access Point
BiCMOS	Bipolar-CMOS
BI	*Barkhausen Institut*
BR	BubbleRAN
BS	Base Station
BW	Bandwidth
CF-MIMO	Cell-Free MIMO
CMOS	Complementary Metal-Oxide-Semiconductor
CN	Core Network
CI/CD	Continuous Integration / Continuous Deployment
COTS	Commercial-Off-The-Shelf
CPRI	Common Public Radio Interface
CQI	Channel Quality Indicator
CSI	Channel State Information
CU	Central Unit
DB	DataBase
DC	Direct Current
DFT	Discrete Fourier Transform
DL	Downlink
DN	Data Network
DoW	Description of Work
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
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
HRLLC	Hyper Reliable and Low-Latency Communication
IASA	Institute of Accelerating Systems and Applications
IHP	*IHP – Leibniz-Institut für innovative Mikroelektronik*
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
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
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
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
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*
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
SMO	Service Management and Orchestration
SNDR	Signal-to-Noise-and-Distortion-Ratio
SNR	Signal-to-Noise Ratio
SotA	State-of-the-Art
SRS	Sound Reference Signal
SUT	System Under Test
TAC	Tracking Area Code
TCO	Total Cost of Ownership
TDD	Time Division Duplex
TDoA	Time Difference of Arrival
TRP	Transmission Reception Points
TUBS	*Technische Universität Braunschweig*
UC	*Universidad de Cantabria*
UDC	University of *A Coruña*
UE	User Equipment
UHD	USRP Hardware Driver
UL	Uplink
UPF	User Plane Function
USB	Universal Serial Bus
USRP	Universal Software Radio Peripheral
VM	Virtual Machine

WAT	Wireless Access Technology
WEC	Wireless Edge Caching
Wi-Fi	Wireless Fidelity
WP	Work Package