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

# D2.2 System architecture and preliminary evaluations

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| **Editor(s):** | Anna Tzanakaki (IASA) |
| **Authors:** | Markos Anastasopoulos, Ilias Floudas, Anna Tzanakaki (IASA), Vladica Sark, Mert Özates, Batuhan Sütbas, Arzu Ergintav, Jesús Gutiérrez (IHP), Jesús Ibáñez, Ignacio Santamaría, Luis Díez, Ramón Agüero (UC), Xi Ding, Nils Hildebrandt, Eduard Jorswieck (TUBS), Mikel Irazabal, Navid Nikaein (BR), Muhammad Umar, Sajjad Ahmad, Padmanava Sen (BI), Yazhou Zhu, Jessica Sanson, Valerio Frascolla (INT), Muhammad Saadi, Shahid Mumtaz (NTU), Federico Trombetti, Salvatore Pontarelli (UNIROMA1), German Castellanos, Simon Pryor (ACC). |
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# Executive Summary

**6G-SENSES** aims to develop a next-generation 6G architecture that integrates communication and sensing capabilities. This system is designed to enhance network intelligence, improve sensing accuracy, and support applications such as object tracking, environmental monitoring, and digital twin (DT) technology. This report outlines the system architecture, discusses the technologies adopted and developed in the framework of the project and presents preliminary evaluations of the proposed 6G infrastructure.

The proposed architecture relies on a multi-layer structure, inspired by the 3GPP and Open Radio Access Network (O-RAN) standards. It also adopts a disaggregated network approach that separates Radio Access Network (RAN) and Core Network (CN) functions for flexibility and scalability and enhances network flexibility by enabling Virtual Network Functions (VNFs).

In terms of the RAN user plane (UP), it integrates multiple Radio Access Technologies (RATs), combining 3GPP (5G NR) and non-3GPP, such as Wireless Fidelity (Wi-Fi), millimeter wave (mmWave), Sub-6 GHz technologies supporting Integrated Sensing and Communication (ISAC) capabilities enabling networks to use existing signals available for communication purposes to sense objects and the surrounding environment. It also takes advantage of Reconfigurable Intelligent Surfaces (RISs) to improve network efficiency, sensing accuracy, and energy optimization and distributed Multiple-Input Multiple-Output (MIMO) technology to improve network coverage, spectral efficiency (SE), and latency as well as reduce energy consumption and optimize network resources dynamically. To support sensing capabilities, 6G-SENSES exploits 5G NR-based sensing, Wi-Fi-based sensing, Sub-6 GHz sensing and mmWave sensing.

This document also describes the 6G-SENSES control plane (CP) giving emphasis on the extensions required with respect to the capabilities of existing CN functions to support ISAC services and incorporates Near-Real-Time (Near-RT) and Non-Real-Time (Non-RT) RAN Intelligent Controllers (RICs) to dynamically adjust network behavior. Taking into consideration the 6G-SENSES multi-RAN/multi-technology environment, several innovations for the control of the RAN, the transport network and the CN functions are proposed.

6G-SENSES also adopts the O-RAN Service Management and Orchestration (SMO) for managing, automating, and optimizing the RAN. It also leverages Artificial Intelligence (AI) and Machine Learning (ML) techniques to perform AI-driven automation and optimization of network operations in support of resource allocation, and sensing functionalities and also aims to support predictive analytics for real-time decision-making. Overall, the SMO plays a critical role in enabling ISAC by providing centralized intelligence, automation, and real-time data processing ensuring efficient management, coordination, and optimization of ISAC-enabled functionalities. In addition, the benefits of Multi-access Edge Computing (MEC) in end-to-end (E2E) service delivery are discussed.

Finally, preliminary studies have started being performed with the target to validate the feasibility of the proposed architecture. However, the final evaluation and benchmarking is planned to be reported as part of deliverable **D2.3** “6G-SENSES architecture evaluation and benchmarking”.

# 1 Introduction

6G services will be associated with a wide spectrum of vertical applications with greatly varying requirements and will offer advanced features beyond connectivity spanning from sensing to monitoring and positioning. To address these requirements, 6G will feature Integrated Sensing and Communication (ISAC) capabilities, performing sensing through the mobile communication infrastructure. The sensing data collected and processed by the network can then be leveraged to enhance the operations of the network, augment existing services such as eXtended Reality (XR) and digital twinning, and enable new services, such as object detection and tracking, along with imaging and environment reconstruction. This potential has already attracted a lot of attention from 3GPP, which has initiated a preliminary study on use cases and ISAC requirements, making it a promising candidate to optimize both communications and sensing systems [1].

Sensing and communication functions can be performed taking different approaches: (a) adopting separate and dedicated infrastructures for sensing and communications, where information acquired from one infrastructure is used to assist the other; (b) sensing and communication capabilities are supported by common hardware (HW) sharing the available spectrum, with the constraint that sensing and communication signals are transmitted over different time slots; and (c) adopting integrated systems fully sharing both spectrum and time domains. Although some early prototypes are available validating concepts (a) and (b), implementations of 3GPP-compliant ISAC systems – concept (c) – are still at a very early stage. These systems demand additional complexity in signal processing but require collection and aggregation of huge volumes of synchronized In-phase and Quadrature (IQ) reflected (echo) streams that need to be processed to extract information on the sensed environment. This processing can only be performed at edge servers, introducing the need to transport the IQ streams over flexible high-capacity transport networks.

6G-SENSES proposes a 6G architecture that interconnects a multi-technology Radio Access Network (RAN) able to offer sensing functionalities (3GPP and non-3GPP) with Core Network (CN) domains through an advanced transport network, to facilitate joint support of sensing and communication services. The novel 6G RAN technologies proposed by the project include Cell-Free massive MIMO (CF-mMIMO) and ISAC to support the 6G vision inspired by the current (and future) architectural framework based on 3GPP and Open-RAN (O-RAN). The project considers a multi-technology RAN ecosystem with technologies that are able to offer sensing functionalities (3GPP and non-3GPP). These technologies include Sub-6, Wi-Fi, mmWave and 5G NR, which will coexist in an ISAC framework. This framework will make use of new physical (PHY) layer technologies to increase their cooperation and inherent capabilities with the aim to improve precision/accuracy of the sensing capabilities. To further strengthen communication and sensing functionalities, 6G-SENSES leverages Reconfigurable Intelligent Surfaces (RISs).

6G-SENSES adopts a disaggregated architectural approach, where RAN network functions (NFs) are separated and can be placed at different locations according to their resource requirements and delay constraints. The CN also adopts Control and User Plane Separation (CUPS), leveraging virtualization and softwarization. The overall CN architecture follows the paradigm of the Service-Based Architecture (SBA) involving a set of key Virtual Network Functions (VNFs). The integration of novel and advanced RAN technologies in 6G-SENSES brings also the need for extension in their control and management requirements and features as well as the relevant interfaces.

The heterogeneity and dynamicity of these complex environments that the project is concentrating on, as well as the need to process sensing data generated by the 6G-SENSES infrastructure, pose new challenges in terms of management and performance optimization for these advanced systems. In this context, Artificial Intelligence (AI) and Machine Learning (ML) will play a key role. More specifically AI/ML tools will facilitate exploitation of the huge volume of sensing data in support of services such as object/obstacle detection and tracking, imaging and environment reconstruction towards XR services and digital twinning. In addition, AI/ML techniques will be adopted to enable intelligent automation, proactive network management and optimization in resource allocation and overall network operation and performance. In this environment, end-to-end (E2E) services are provisioned with the support of SMO.

This deliverable presents the initial work carried out in the context of 6G-SENSES Work Package 2 (**WP2**), to provide a functional description of the overall system architecture and a preliminary evaluation of the proposed architecture. The requirements of the proposed architecture have been derived by the work performed and reported in the context of deliverable **D2.1** [2] "*Report on 6G-SENSES use cases, network architecture, KPIs and supported RAN functions*". This deliverable has been used as input for deliverable D2.2 to provide the specification framework of the proposed 6G-SENSES architecture. In addition, deliverable **D3.1** [3] "*Initial report on the development of 6G-SENSES infrastructure building blocks*" has provided input to D2.2 defining the PHY layer elements that were adopted in the 6G-SENSES architecture. Moreover, Wireless Edge Caching initially investigated in deliverable **D4.1** [4] can be supported by the Edge Cloud functionality envisioned in the 6G-SENSES architecture located at the Multi-access Edge Computing (MEC) nodes.

Taking these inputs, this document summarises the overall functional architecture proposed by the project and details its multilayer structure, key elements and interfaces. In addition, some initial description and preliminary results produced as part of the architecture evaluation have been reported. The refined and final architecture proposal of 6G-SENSES will be reported in deliverable **D2.3** "*6G-SENSES architecture evaluation and benchmarking*" together with a detailed evaluation of its performance.

## 1.1 Organisation of the document

This document comprises eight (8) chapters. Following the Executive Summary and Introduction sections:

Chapter 2 is briefly listing the 6G use cases that the project will concentrate on and summarises the requirements of the 6G-SENSES architecture from the perspective of the user, the technology and the service provisioning.

Chapter 3 provides an overview of the 6G-SENSES functional architecture and a detailed discussion of the multi-layer architecture proposed by the project including the user plane (UP), the control plane (CP) as well as the orchestration and management plane. The discussion involves identification of relevant technologies and functional blocks and the required interfaces as well as proposed extensions and innovations.

Chapter 4 focuses on UP technologies that the project is focusing on, addressing 3GPP (5G NR) and non-3GPP (Sub-6, Wi-Fi and mmWave) RAN related technologies, CF-mMIMO, RIS as well as ISAC solutions. In addition, this chapter discusses transport network and MEC solutions suitable for ISAC.

Chapter 5 focuses on CP aspects of the 6G-SENSES architecture giving emphasis on the extensions required with respect to the existing technology capabilities to support ISAC services. Taking into consideration the 6G-SENSES multi-RAN/multi-technology environment, several innovations for the control of the RAN, the transport network and the CN functions are proposed.

Chapter 6 discusses end-end service provisioning over the 6G-SENSES infrastructure and the role of the O-RAN SMO for managing, automating, and optimizing the infrastructure. AI/ML techniques are also leveraged in support of E2E service provisioning, while MEC is also discussed.

Chapter 7 provides an overview of some initial efforts towards the evaluation of the proposed technologies and the overall 6G-SENSES architecture, while some preliminary results of the relevant evaluation studies.

Finally, Chapter 8 summarises the document.

# 2 6G-SENSES Service Requirements

In deliverable D2.1 [2], a set of 6G use cases have been defined, including both 6G service requirements and 6G business concepts that the 6G-SENSES vision, architectural solution and deployment paradigms will be able to support. To this end, the 6G trends and vision of 6G ecosystems were initially studied, and in parallel the 6G-SENSES system functionalities and capabilities were analysed to identify the value created for the various roles / layers of the 6G ecosystem to be shaped. On this basis, a concrete set of use cases to be enabled by 6G-SENSES was specified, along with the KPIs and the requirements to be met.

The selected 6G use cases address both the various service provisioning roles and stakeholders of future 6G ecosystems and the envisioned 6G end-user (vertical or individual) application services. The use cases also highlight 6G related requirements with 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 are the following:

- **Use Case #1: Sensing enabled Services**. This use case focuses on exploiting sensing information to improve communication services (sensing-aided communication) and on enabling active sensing with Wi-Fi system and Wi-Fi sensing standardization design. This use case highlights the work of the project on ISAC and, in particular, on Multi-Wireless Access Technology (WAT) sensing and integration in a 6G Radio Access Network (RAN).
- **Use Case #2: Ubiquitous Connectivity & Immersive Services**. This use case focuses on storylines exploiting CF-mMIMO and RIS capabilities combined with sensing. This use case highlights the work of the project on RIS-assisted CF-mMIMO for improving spectral and energy efficiency (EE) KPIs, coverage and localisation.
- **Use Case #3: Network Digital Twin (DT)**. This use case focuses on storylines enabling Network Optimisation and Energy Saving, exploiting Network Intelligence. This use case highlights the work of the project on network digital twinning serving for optimising capacity, availability and EE via AI/ML at Orchestration, Network and User layers.

These use cases pose various requirements and KPIs to the 6G-SENSES system, to be subsequently translated into system level requirements (a.k.a. system/technical specifications) and KPIs, which the 6G-SENSES architecture and technology developments need to meet. The main technical requirements are summarised in Table 2-1 – Table 2-3.

**Table 2-1 End-User and Performance related Requirements**

| Requirement | Specification and KPIs |
|---|---|
| **User Maximum Data rate** | User Maximum Data rate depends on specific applications. The target is to achieve >50% improvement in throughput with the 6G-SENSES solution as compared to the 5G network. ~250Mbps is considered the max. target value for the use cases. |
| **Latency** | 6G-SENSES considers E2E latency reduction towards the 0.1 - 1 ms target |
| **Connection Density** | 6G-SENSES considers intelligent connectivity density for the use cases; aiming to achieve >20% connection density compared with existing systems based on non-intelligent connectivity (target for the use cases ranging between $10^6$-$10^8$ devices/km$^2$). |

| Requirement | Specification and KPIs |
|---|---|
| **Energy Efficiency (EE)** | Enhanced EE is the key objective for Use Case #3. The target is to achieve at least 15% enhanced resource usage efficiency while supporting use cases with extreme performance requirements. |
| **Coverage area** | In 6G-SENSES use cases coverage KPI is considered in two ways:<br>a. Communication services coverage area; aiming to achieve >20% improvement in coverage as compared to the 5G network using 6G-SENSES innovations at the RAN.<br>b. Wireless sensing coverage area; which constitutes new KPI for 6G networks and corresponds to the area where sensing information can be obtained and where sensing-related services can be provided. Ideally it shall be possible to be the same as the communication coverage area. |
| **Sensing related** | It shall be possible to capture positioning and motion information with required accuracy. A number of sensing services related KPIs are posed by the use cases (such as range resolution or level of detail sensed at distance) – (to meet application demand), Location accuracy – (to meet application demand), Orientation accuracy, Angular resolution, Motion rate accuracy, etc., reported in deliverable D2.1, which in turn pose a number of requirements to be met by the system. These are requirements are:<br>• Sensing latency.<br>• Sensing update rate.<br>• Sensing precision/accuracy.<br>• Sensing availability/ coverage. |
| **Mobility** | 6G-SENSES use cases pose a set of requirements related to mobility in different ways. Apart from the traditional definition of mobility in terms of speed of a user device, 6G-SENSES considers mobility in terms of motion of the parts of the body of human/ object (robot), in terms of gestures recognition, etc. |

**Table 2-2 Technology Specific Requirements**

| Requirement | Specification |
|---|---|
| **RAN** | Key high-level technical (RAN-related) requirements deriving from the 6G-SENSES use cases are:<br>• Incorporation of sensing in the RAN segment to capture and process environment information in order to: 1. Provide sensing-enabled services, 2. Optimize service coverage, 3. enable resources optimization.<br>• Incorporation of multi-WAT platform to exploit various technologies' advantages in different environments.<br>• Dynamic adaptation of the user's connection to the most suitable RAT based on factors such as user location, network conditions, and application requirements.<br>These requirements imply the adoption of novel technologies such as ISAC, CF-mMIMO and RIS in 6G networks, which pose numerous new requirements in the RAN, associated with supporting: Proximity services, time synchronization between |

| Requirement | Specification |
| --- | --- |
| | the User Equipment (UE) and gNB, PHY and Medium Access Control (MAC) designed to support sensing functions, coordinated interference management, etc. |
| **O-RAN** | 6G-SENSES solution needs be compliant with the latest advancements in O-RAN and 3GPP RAN. Therefore, sensing-related innovations need to be incorporated to O-RAN and future 3GPP RAN systems. To this end:<br>1. 6G-SENSES envisions sensing related functionalities of ISAC enabled by a Multi-WAT (Sub-6, mmWave, Wi-Fi and 5G NR technologies) platform assisted by RIS that ingests cross-technology sensing to evolved O-RAN RICs. This requires: the capability to ingest and process sensing data from multiple sources in O-RAN RICs, coordination of O-DUs, and the expansion of O-RAN interfaces to support with CF-mMIMO and ISAC RIC-assisted devices.<br>2. 6G-SENSES addresses network optimization assisted by RAN sensing and O-RAN digital twinning. This requires: xApps/rApps receiving telemetry from multiple nodes. The data can be processed to steer the traffic, improve the EE as well as increase the SE and save on CApital EXpenditures (CAPEX) and OPerational EXpenditures (OPEX). |
| **Wi-Fi** | Passive and active sensing based on Wi-Fi is needed, to support use case scenarios requiring active recognition, gesture recognition/hand tracking, human presence detection and breathing rate, etc. |
| **mmWave/THz** | mmWave/THz wireless units can be used to enable ISAC services. This comes with a set of technical requirements related to: improvement in the frontend EE, support of Continuous Wave (CW)/ Frequency-Modulated Continuous Wave (FMCW) radar and low/medium-speed communication functionality, higher angular and range resolution in localization capabilities for enabling sensing services, EE and radar lateral resolution improvement, compliance with Electromagnetic field (EMF) human exposure limits. |
| **CF-mMIMO** | 6G-SENSES considers a CF user-centric radio access structure, going beyond the classical network-centric ones, where each user is served by the closest base station (BS). These structures aim to achieve the target spectral and energy efficiencies and optimize coverage probability compared to traditional ones. The requirements set for the CF system are:<br>• SE: 5x improvement in 95%-likely per-user throughput over small-cell systems (under uncorrelated shadow fading conditions)<br>• EE: power savings > 10% (including RAN, front-haul and processing) over small-cell systems for low spectral efficiencies (e.g. 1.25 bit/s/Hz).<br>• Coverage probability: 5x coverage probability improvements for 95% of users achieving a certain rate<br>• User-centric clustering: number of Access Points (APs) serving each user device is flexible, but there is an upper quota determined by the number of antennas at the RU.<br>• Fronthaul signaling load: The amount of signaling data transmitted between O-RUs and the O-DU/O-CU depends on the functional split. |

| Requirement | Specification |
|---|---|
| | • Incorporation of distributed algorithms for the phase synchronization of the different antennas of each AP (intra-AP reciprocity calibration), as well as between the different APs composing the CF-mMIMO (inter-AP reciprocity calibration).<br>• Timing Synchronization between APs, in addition to phase and frequency. Timing offsets should be less than 100 ns to enable effective coherent combining in indoor scenarios. |
| **RIS** | RIS is considered as an enabler for 6G-SENSES use cases in two ways:<br>1. To enhance the quality of communication channels in ISAC systems. This aspect of integration requires utilizing RIS to enhance the quality of communication channels based on sensing from the ISAC systems.<br>2. To enhance the sensing capabilities of ISAC systems. By strategically modifying the propagation characteristics of electromagnetic waves, RIS can improve the accuracy, resolution, and range of sensing and detection systems. This requires a collaborative approach where the RIS, communication devices, and sensing systems work in conjunction to achieve optimal performance.<br>In any case, a set of technical requirements are posed on RIS:<br>For (1) RIS-assisted communication links optimization the targets are:<br>• RIS-assisted SNR gain: >20% SNR gain due to the assistance of RISs with respect to systems without RIS in LoS environments with blocked direct links.<br>• RIS-enabled throughput: > 10% in rate due to the assistance of RIS.<br>• Performance of traditional communication systems with poor direct path conditions has a 30% -40% improvement with RIS.<br>• RIS-reduced interference: Reductions up to 20 dB in interference-to-noise ratio levels in RIS-assisted MIMO-ICs.<br>• RIS-improved coverage: coverage to blocked users or users in blind spots.<br>• RIS-optimized EE: average max-min EE >50% for optimized RIS designs with static power consumption < 1 dBm.<br>For (2) RIS-assisted sensing the main target is:<br>• RIS-optimized sensing accuracy: 3dB Mean-Square Error (MSE) reduction in azimuth and elevation angles with RIS-assisted ISAC systems. |
| **Sensing Service Model (SM)** | Integration of sensing with O-RAN requires to develop a Service Model (SM) based on O-RAN specifications (i.e., E2AP) and within the FlexRIC framework, which should consider the large amount of data to transmit between the E2 Node and the xApp, and the latency constraints inherited from the PHY layer. The SM needs to be implemented within the E2AP protocol, to maintain its portability among different nearRT-RICs and following O-RAN principles. It also needs to consider the number of listening antennas, as they are essential for the sensing algorithms.<br>It will enable writing sensing algorithms in an xApp, rather than embedding them into the RU, facilitating its portability moving the implementation from L1 to L7. |
| **Orchestration** | Placement of RAN entities RU/DU/CU and integration with APs and RIS, along with ISAC functionalities, requires flexible placement schemes depending on various |

| Requirement | Specification |
|---|---|
| | changing factors such as the throughput required for communication and sensing data links, the fronthaul (FH) and backhaul (BH) capacities, etc.<br>An Intelligent Plane, able to orchestrate the placement of disaggregated RAN entities, and optionally to manage sensing data and non-sensing traffic flows exploiting AI/ML techniques is needed. |

**Table 2-3 Network Operation and Service Provisioning related Requirements**

| Requirement | Specification |
|---|---|
| **Scalability** | The network elements shall be easily scalable to deal with large-scale deployments. |
| **Interoperability** | Interoperability between network elements with B5G/6G network interfaces shall be ensured. |
| **Harmonization of sensing data (by Multi-WAT sources)** | Capturing and processing of sensing data by different WAT sources shall be harmonized in order to ensure same/similar service availability over the coverage area of a multi-WAT RAN environment. |
| **Sensing data management practices** | Effective sensing data management practices shall be followed, adhering to general data management principles. |
| **E2E System Efficiency / Sustainability** | The system shall be efficient in terms of performance and sustainable in terms of resource utilization and cost. |
| **Cost Efficiency of E2E Solution** | Each network element and the E2E solution shall provide a cost-efficient solution, i.e. low Total Cost of Ownership (TCO), CAPEX, OPEX, for a given performance/functionality implementation. |

These requirements have been taken under account in the development of the 6G-SENSES system architecture specified in the following chapters.

# 3 6G-SENSES Network Architecture

## 3.1 Functional 6G-SENSES architecture

6G services will be associated with a wide spectrum of vertical applications with greatly varying requirements and will offer advanced features beyond connectivity spanning from sensing to monitoring and positioning as well as sensing and reconstructing the DT of the surrounding environment. To address these requirements, 6G will feature ISAC capabilities, performing sensing through the mobile communication infrastructure. This can be achieved adopting either a Channel State Information (CSI) or a passive radar approach. The CSI sensing approach 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). This information can be then used to support a set of applications [7] including human localization and tracking, presence detection, activity recognition, healthcare, etc. In the "radar" sensor approach, the network exploits its own radio signals to sense and comprehend the surrounding physical world. The echoes (reflections) and scattering of wireless signals predominately transmitted for communication purposes, provide information related to the characteristics of the environment and/or objects therein [1]. The sensing data collected and processed by the network can then be leveraged to enhance the operations of the network, augment existing services such as XR and digital twinning, and enable new services, such as object detection and tracking, along with imaging and environment reconstruction. This potential has already attracted a lot of attention from 3GPP, which has initiated a preliminary study on use cases and ISAC requirements, making it a promising candidate to optimize both communications and sensing systems [1].

Depending on the level of integration of the sensing functionality into the communication network, different approaches can be adopted including:

(a) Fully separated infrastructures performing sensing and communications functionalities. Based on this approach, information acquired from one infrastructure is used to assist the other.

(b) Common hardware supporting sensing and communication capabilities. This approach is implemented by sharing the available spectrum, with the constraint that sensing, and communication signals are transmitted over different timeslots.

(c) Fully integrated systems sharing both spectrum and time domains.

Depending on the number and roles of devices involved in sensing several options also exist including:

(a) The monostatic case, where a single device is used for transmitting and receiving sensing signals

(b) The bi-static/multi-static sensing, where a single transmitter and physically separated single or multiple receivers are used to acquire the sensing signals.

(c) The passive sensing approach, where signals transmitted primarily for communication purposes can be also used by other devices for sensing.

Although some early prototypes are available validating these concepts, these are mostly available in non-3GPP networks (i.e., Wi-Fi), whereas implementations of 3GPP-compliant passive radar-based ISAC systems are still at a very early stage. The main reason is that these systems demand additional complexity in signal processing and require collection and aggregation of huge volumes of synchronized IQ reflected (echo) streams that need to be processed to extract information on the sensed environment. This processing can only be performed at edge servers, introducing the need to transport the IQ streams over flexible high-capacity transport networks.

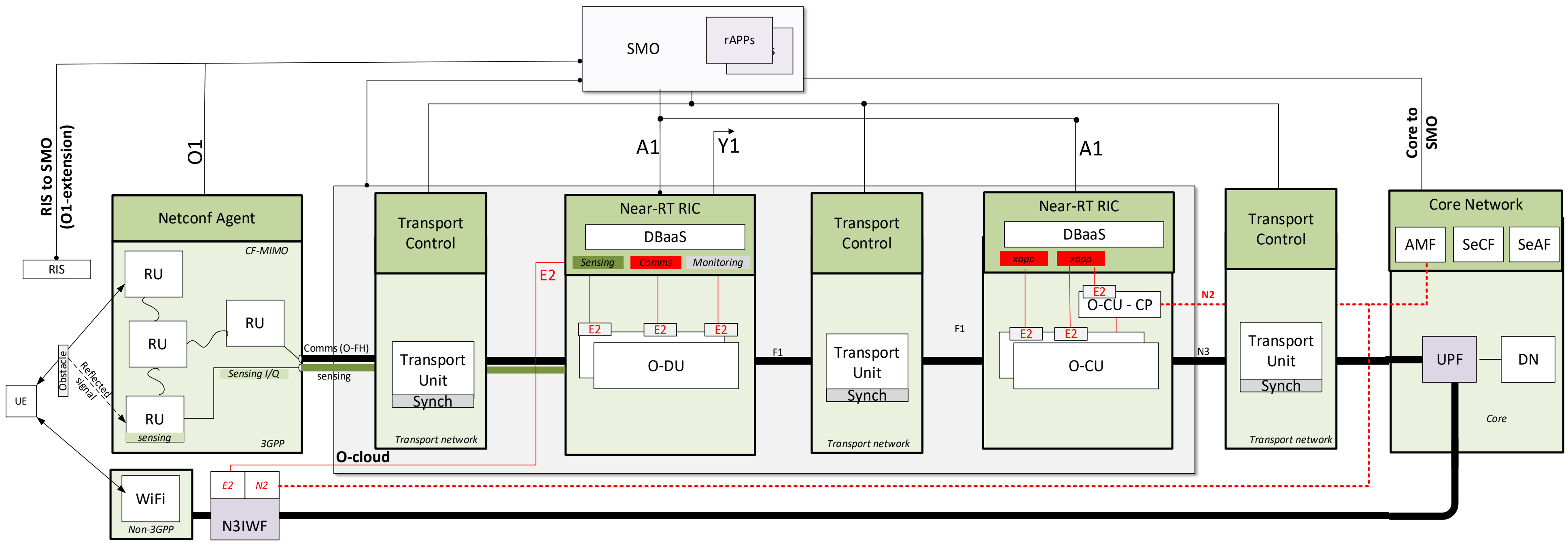



**Figure 3-1 Generic 6G-SENSES architecture**

6G-SENSES proposes a 6G architecture that interconnects a multi-technology RAN able to offer sensing functionalities (3GPP and non-3GPP) with CN domains, to facilitate joint support of sensing and communication services, as shown in Figure 3-1. The RAN technologies of interest include non-3GPP (Sub-6, Wi-Fi, mmWave) and 3GPP-based (5G NR) networks, which coexist in an ISAC framework to obtain accurate representation of the surrounding environment.

Non-3GPP based sensing is performed adopting Wi-Fi networks that are extended to operate as monostatic and multistatic radars. The output of the sensing information from non-3GPP networks is exposed to the RAN segment in a secure way through suitable extensions of the E2 interface of the RAN Intelligent Controller (RIC). To achieve this, there is a need to enable Wi-Fi networks to expose their sensing related data in a secure way. Addressing this requirement, 6G-SENSES proposes the use of the non-3GPP Inter-Working Function (N3IWF), which is responsible for interworking between untrusted non-3GPP networks and the 5G CN. 6G-SENSES, therefore, proposes to adopt and appropriately extend N3IWF to provide the necessary *access and authentication protocols with new features that will allow Wi-Fi networks to securely expose sensing data to the RIC.*

3GPP-based sensing is performed based on the principle of a distributed passive wireless radar. According to this, 6G BSs generate communication signals reflected on "objects" located in the surrounding area, creating IQ echo streams. These IQ echo streams are transmitted in the form of uplink FH streams to the O-RAN Distributed Units (O-DUs), where they are compressed/downsampled and transmitted through the E2 interface to the RIC. Purposely developed sensing xApps fuse the incoming sensing streams (IQ echo streams and Wi-Fi sending data), analyse their quality and cache data to a fast in-memory database. These data can be then exploited internally by the system to optimize the operational parameters of the various building blocks of the RAN segment (e.g. beamforming design, codebook selection, beam steering, power control, etc.), or they can be exposed to the vertical applications through the Y1 interface.

The sensing output is also passed to the SMO, who decides the optimal network resource configuration to support both communication and sensing services. To perform this, the SMO provides mechanisms supporting automated lifecycle management (LCM) for ISAC services instantiating and automatically reconfiguring E2E slices considering both communication (i.e. FH, BH) and sensing services requirements. A first concept demonstration of this architectural approach is detailed in [8].

### 3.2 Multi-layer 6G-SENSES architecture

6G-SENSES adopts a multi-layer/ multi-technology approach compatible with O-RAN and 3GPP specifications to provide ISAC services and expose sensing data both internally and externally (3rd party exposure). Figure 3-2 illustrates the overall 6G-SENSES architecture, highlighting key components and interfaces that facilitate connectivity within the RAN system and the CN. This architecture is aligned with the O-RAN framework that disaggregates traditional RAN functions, introducing software-defined intelligence and advanced control mechanisms. At the radio level, the Radio Unit (RU) handles transmission and reception of radio signals, interfacing with the DU via the FH link. The DU is responsible for real-time baseband (BB) processing and connects to the Centralized Unit (CU) over the F1 interface, which is divided into a CP (F1-C) managing signalling and mobility control, and a UP (F1-U) handling user data transmission. The CU itself is split into the CU-Control Plane (CU-CP), responsible for network signaling and mobility procedures, and the CU-User Plane (CU-UP), which manages user data traffic.

At the O-RU level, 6G-SENSES extends O-RAN specifications to enable O-RU sharing for communications and sensing services. The shared O-RU reference architecture is shown in Figure 3-3, where a shared O-RU can share its resources (e.g., i.e., spectrum) with the O-DUs blocks used to process sensing and communication signals. The Shared O-RU framework can be used in scenarios when a new O-RU is deployed to perform passive sensing (i.e., monitor spectrum for sensing tasks).

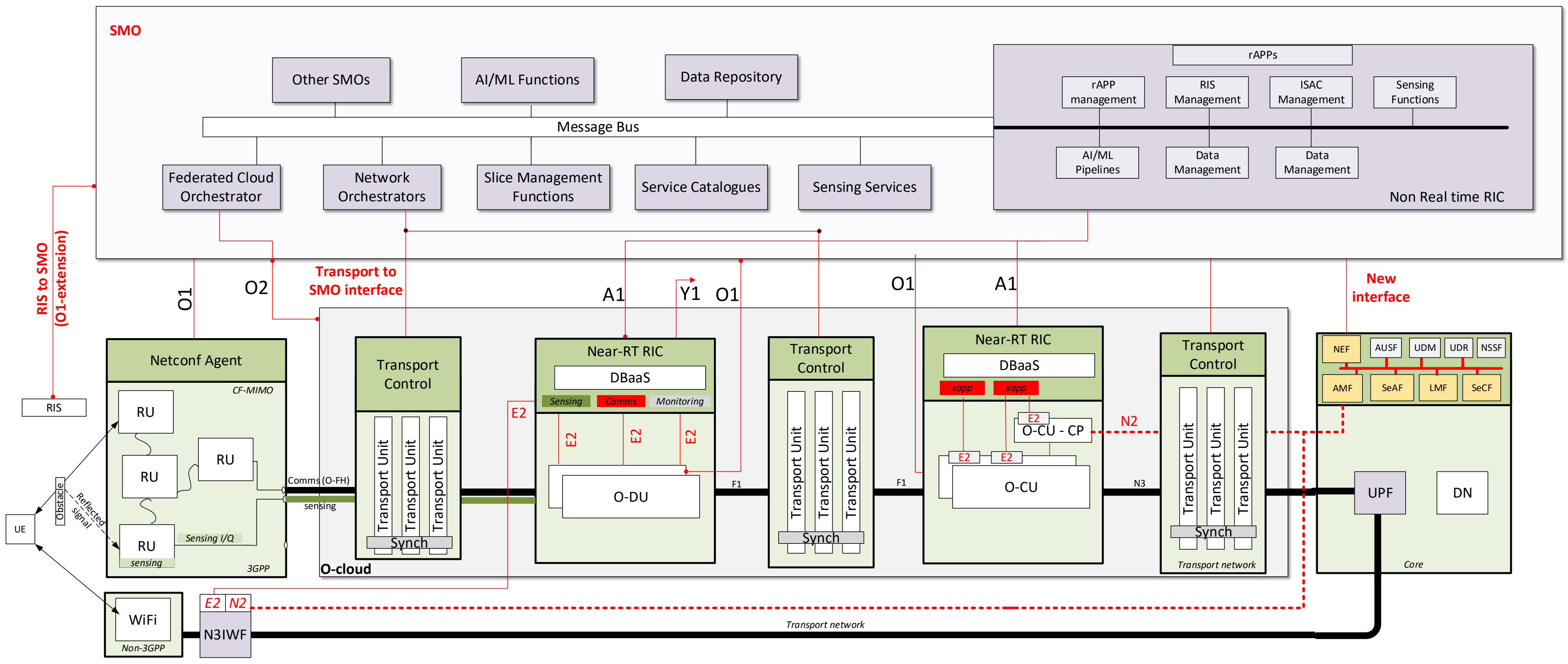



**Figure 3-2 Multi-layer 6G-SENSES Architecture**

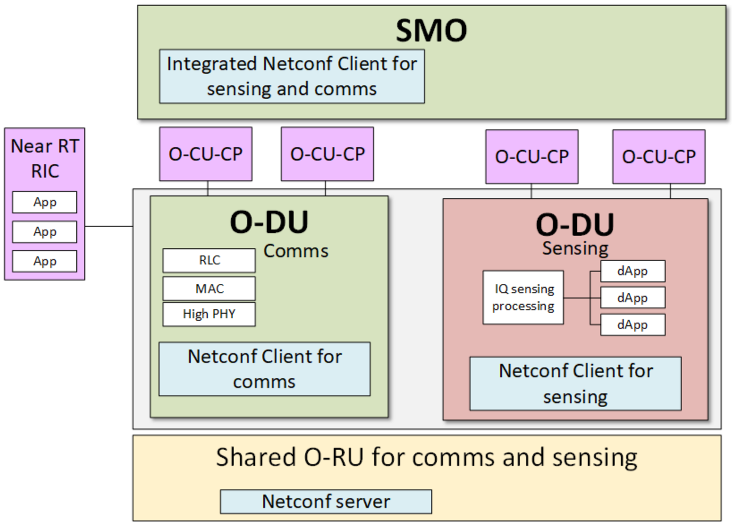



**Figure 3-3 O-RU sharing for comms and sensing**

To introduce network intelligence, the O-RAN architecture incorporates two key controllers: the Near-Real-Time RIC (near-RT RIC), which operates on timescales of milliseconds to seconds and optimizes RAN behaviour via the E2 interface, and the Non-Real-Time RIC (Non-RT RIC), which provides long-term policy control, resource optimization, and analytics. The E2 interface establishes a connection between the near-RT RIC and E2 nodes, such as DUs, CUs, and O-RAN-compliant gNBs, utilizing a publish-subscribe mechanism to facilitate data exchange between xApps and RAN functions. Communication between the non-RT and near-RT RIC is facilitated by the A1 interface. The non-RT RIC is part of the SMO framework, which coordinates RAN resources through the O1 interface, ensuring efficient configuration and performance management. The two RICs open the road for the integration of AI and ML techniques in the RAN, with AI models being trained in the non-RT RIC and then executed in the near-RT RIC to dynamically adjust network behaviour. Caching and data storage in the RIC is performed through the deployment of an in-memory DataBase as a Service (DBaaS) platform. An in-memory database is a specialized database designed to store data primarily in internal memory, rather than on traditional disk drives (i.e., SSDs). This allows to meet the extremely fast response times required by RIC as it eliminates the need to access disk storage. In 6G-SENSES, DBaaS is used to store sensing data exposed the 3GPP and non-3GPP sensing elements, vector supporting AI/ML training and inference as well as geospatial indices used by edge caching applications.

Beyond the RAN, the 5G CN serves as the backbone for multi-access integration, supporting both 3GPP and non-3GPP connectivity. The Access and Mobility Management Function (AMF) handles user authentication, registration, and mobility management, while the Session Management Function (SMF) is responsible for session establishment and Quality of Service (QoS) enforcement. The User Data Management (UDM) stores subscriber information, and the Policy Control Function (PCF) applies policies related to service access and data prioritization. The Network Exposure Function (NEF) can be used to act as a mediator between external applications and the 5G CN, when they are not authorized to access NF functions of the 5G CN directly. The Network Repository Function (NRF) stores a record for all 5G existing elements in the network, as well as their supported services, so that NFs can discover, subscribe and get notified about each other's events. The Network Data Analytics Function (NWDAF) collects, analyses, and provides insights from network data to support decision-making, optimization, and predictive analytics. To enable access of sensing devices in the RAN, 6G-SENSES introduces a set of CN functions that are responsible to authorise and manage sensing service connections, expose sensing data to 3rd parties and provide sensing analytics services. The responsible CN entities for these functionalities extend the 3GPP TR 33.713 and, specifically, introduce:

- the Sensing Control Function (SeCF) that is used to support sensing services, with some AMF's functionalities integrated, which enables:

- Connectivity for external sensors used to complement ISAC services.
- Inventory handling and device context management.
- Authentication and authorization for sensing devices.
- Exposing sensing data via NEF to the AF.

- The sensing analytics function (SAF), which provides high level analytic services for sensing services that are exposed through NEF.

Finally, The User Plane Function (UPF) routes user data traffic, ensuring low-latency communication between the network and external services over the N6 interface.

To support multi-access connectivity, the architecture integrates non-3GPP technologies such as Wi-Fi and mmWave networks through the 5G CN Non-3GPP Interworking Function (N3IWF). This function ensures seamless authentication, encryption, and tunnelling between non-3GPP devices and the 5G CN. Connectivity is established through the Nwu interface, which links non-3GPP devices to the network, while the N2 interface handles control signalling between the N3IWF and the 5G CN, and the N3 interface facilitates user plane data exchange between non-3GPP networks and the 5G CN. The data flow in this architecture ensures seamless connectivity. UEs can access the network either through O-RAN or non-3GPP technologies, with traffic processed at the RAN level before being forwarded to the 5G CN over the N2 (CP) and N3 (UP) interfaces. For non-3GPP access, the N3IWF enables secure interworking, ensuring a unified connection with the 5G CN. To expose sensing data from non-3GPP APs to O-RAN compliant elements, 6G-SENSES extends N3IWF with a new E2 interface. This will allow instantiation of secure tunnels towards the RIC protecting the E2 traffic with IPsec tunnels and reusing certificate-based authentication implementations that are already available at the N3IWF as defined by ETSI TS 133 210 and ETSI TS 133 310. The UPF then routes user data between the network and external applications over N6, supporting low-latency applications and location-based services.

# 4 User Plane Key Components

### 4.1 The 6G-SENSES Multi-Wireless Access Technologies (3GPP/non 3GPP)

A variety of WATs are adopted and developed by the project with the aim to optimally support the ISAC solutions targeted. These are presented in the sections below.

#### 4.1.1 5G New Radio (NR)

While 5G technology has revolutionized wireless communication with high-speed, low-latency, and ultra-reliable connectivity, its capabilities extend beyond data transmission. As already discussed, in this context a key emerging application is wireless sensing, where 5G networks can be leveraged to detect, track, and analyse objects and environments, effectively enabling applications in autonomous systems, smart cities, industrial automation, and beyond.

The 5G-enabled sensing utilizes the existing radio signals exchanged between the BS and users/devices to extract environmental and motion-related data—transforming wireless networks into intelligent radar-like systems. Radio wave reflections, Doppler shifts, phase variations, and round-trip measurements are used to derive meaningful insights about the surroundings. The core principles include:

- **CSI Analysis**: 5G BSs continuously track CSI, which describes how signals propagate through the environment. Variations in CSI patterns, caused by moving objects, obstructions, or environmental changes, can be analysed for sensing applications.
- **Round Trip Time (RTT):** measures how long it takes for a signal to travel from a transmitter to a receiver and back. This helps in precise localization, enabling applications like indoor positioning and tracking of moving objects.
- **Doppler Shift Analysis**: The frequency shift in radio waves caused by moving objects (similar to how a siren changes pitch as it moves) can be used to detect velocity and movement direction. This is crucial for autonomous vehicles, drone navigation, and robotic automation.
- **Angle-of-Arrival (AoA) and Beamforming:** 5G's advanced mMIMO and beamforming capabilities allow BSs to estimate the direction from which a signal arrives. This can be used for localization, tracking, and environmental sensing in smart infrastructure and industrial settings.

Despite its potential, 5G-based sensing faces two main challenges. First, interference and noise combined with environmental variations and external signals can introduce errors in sensing data. Second, data processing that introduces a high level of complexity as analyzing massive real-time data streams requires advanced AI schemes and edge computing.

To address these challenges, 6G-SENSES RUs, DUs and CUs are redesigned and enhanced with new capabilities providing communication and sensing services over a single unit. The extended 6G RUs can, in addition to RF and Low-PHY layer processing, collect sensing data (RF waveforms), pre-process the collected waveforms (i.e., synchronize, timestamp and compress signals) to keep only the useful information and aggregate waveforms (fuse data coming from multiple sources) so that the 6G DUs can at a later stage estimate the parameters of interest (position, speed, obstacle detection environmental monitoring, etc). These parameters can be further processed by the 6G CUs to estimate more complex metrics (e.g. trajectory of a moving device) that can then be either exposed to external vertical users (i.e., extending UPF with match action rules to handle sensing data) or even used by the 6G platform to optimize its protocols (i.e., PHY-layer protocol optimization such as beam steering, beamforming, CF-mMIMO optimization or even upper layer protocols).

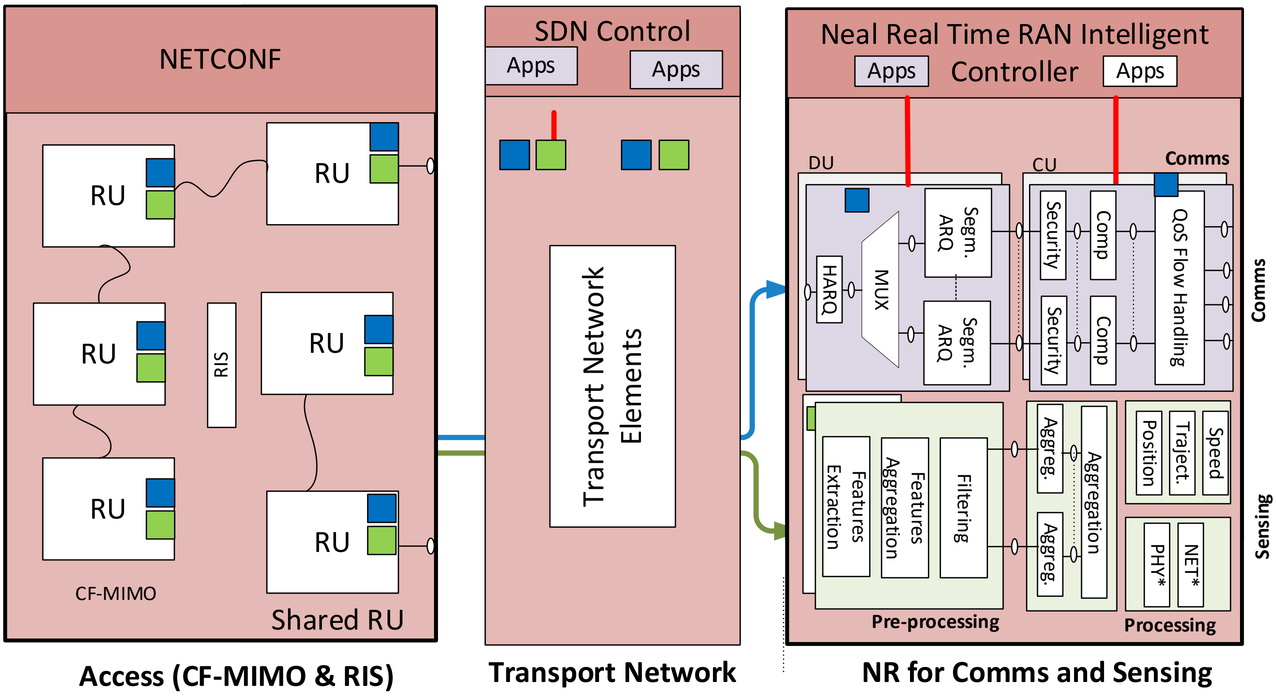



**Figure 4-1 6G-SENSES elements supporting communications and sensing**

A high-level view of the redesigned RU/DU/CU elements supporting communications and sensing services is shown in Figure 4-1, where the various sensing functionalities performed at the DUs (i.e., IQ stream processing for feature extraction, aggregation, filtering, estimation of the position of the target object) can be implemented as will be discussed in the following subsections in the form of distributed applications (dApps) [9] that can provide sensing services based on analysis and inference of UP data, including IQ samples and data packets[1].

### 4.1.2 Wi-Fi (Sub-6, 60 GHz)

#### *4.1.2.1 Wi-Fi – Sub-6 GHz - System Architecture for Monostatic Active Sensing*

One of the pillars of 6G-SENSES is the adoption of non-3GPP technologies for sensing including Wi-Fi operating in the sub-6 GHz band. The most common deployment scenario in Wi-Fi sensing is the monostatic active sensing approach in which a single client device performs the roles of transmitter, receiver, and signal processor. In this architecture, the sensing signal is generated, transmitted, received, and processed entirely at the client side. This “radar-like” operation uses Wi-Fi CSI derived from 802.11 packets to extract key sensing parameters such as range, Doppler (velocity), and motion/presence detection. The Wi-Fi sensing operation follows a structured procedure similar to traditional Wireless Local Area Network (WLAN) protocols:

- **Sensing Session:** The client (acting as the sensing initiator) begins by exchanging capabilities with any other sensing-capable devices (if involved). This phase establishes the session parameters and assigns measurement setup IDs for subsequent operations.

[1] https://www.techplayon.com/dapps-oran-distributed-applications/

- **Sensing Measurement Setup:** The client configures the operational attributes (such as waveform parameters) that will govern the sensing measurement. In monostatic active sensing, both the transmit (Tx) and receive (Rx) chains are co-located on the client device.
- **Sensing Measurement Instances:** During this phase, the client transmits Wi-Fi packets that include training sequences (used for channel estimation) and then receives the echoes. The CSI data captured from these echoes is analyzed to extract environmental information such as range, Doppler shifts, and motion characteristics.
- **Measurement and Session Termination:** Once the sensing data has been collected, the client can optionally transfer processed information to third-party applications or other devices. The sensing session is then formally terminated.

This sequence of operations mirrors traditional radar sensing—using the echo of a transmitted signal to determine the characteristics of objects in the environment. The system architecture is divided into:

- **Client Device:** The system uses a client device (e.g., Lenovo TS / ThinkPad L Laptop) equipped with an Intel® Wi-Fi module. This device is responsible for initiating the sensing procedure, transmitting the signal, receiving the echoes, and processing the CSI data.
- **Antennas**: In the monostatic configuration, both the Tx and Rx antennas are integrated into the client's transceiver. Their co-location is critical to achieving a radar-like sensing functionality.
- **RF Modules:** The Intel® Wi-Fi module handles RF transmission and reception over the Sub-7 GHz band, with support for 160 MHz channels. Its design facilitates both high-speed communication and high-resolution sensing.
- **Processing Units:** Embedded processors on the client device execute the sensing algorithms. These algorithms (implemented in environments such as Python) process the raw CSI data to derive range, Doppler, and movement information. The system is designed to provide both simple outputs (e.g., range/velocity and presence detection) and optional advanced outputs such as complex range-Doppler maps.

After receiving the Wi-Fi CSI data, the client device processes the information to extract:

- Range Estimation: Determining the distance of objects based on time-of-flight or echo delay measurements.
- Doppler Estimation: Measuring velocity through the analysis of frequency shifts in the returned signals.
- Motion/Presence Detection: Identifying movement or occupancy in the scene through variations in the CSI magnitude and phase.

The processed data can be utilized directly by the client for local applications (such as gesture recognition or indoor localization) or forwarded to third-party applications and other devices, enabling a variety of interactive and ambient sensing scenarios. In the context of 6G-SENSES suitable interfaces will be developed exposing the outcome of Wi-Fi sensing in O-RAN RIC allowing, at a later stage, this information to be combined with 3GPP sensing improving detection accuracy. A high-level description of possible Non-3GPP/3GPP sensing information integration options along with some preliminary results are summarized in subsection 4.2.1.2.

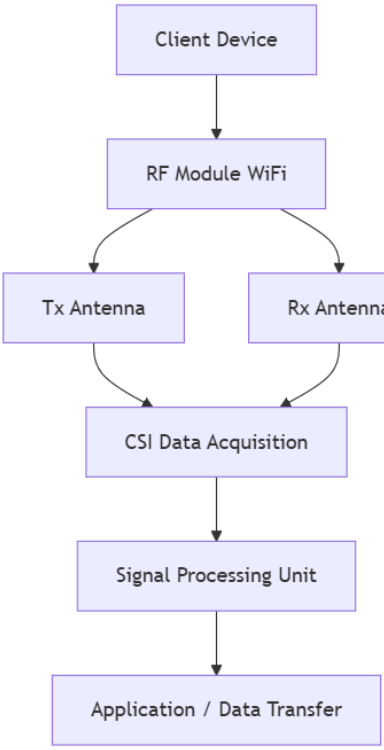



**Figure 4-2 Monostatic active sensing architecture.**

The overall monostatic active sensing architecture is shown in Figure 4-2 comprising the following components:

1. The Client Device integrates the RF Module, which handles both transmission (Tx) and reception (Rx) via co-located antennas.
2. The transmitted Wi-Fi packets propagate into the environment, and the echoes are captured as CSI data by the Rx antenna.
3. The Signal Processing Unit processes this CSI data to extract range, Doppler, and motion information.
4. Finally, the processed data can be used locally or forwarded to other applications/devices.

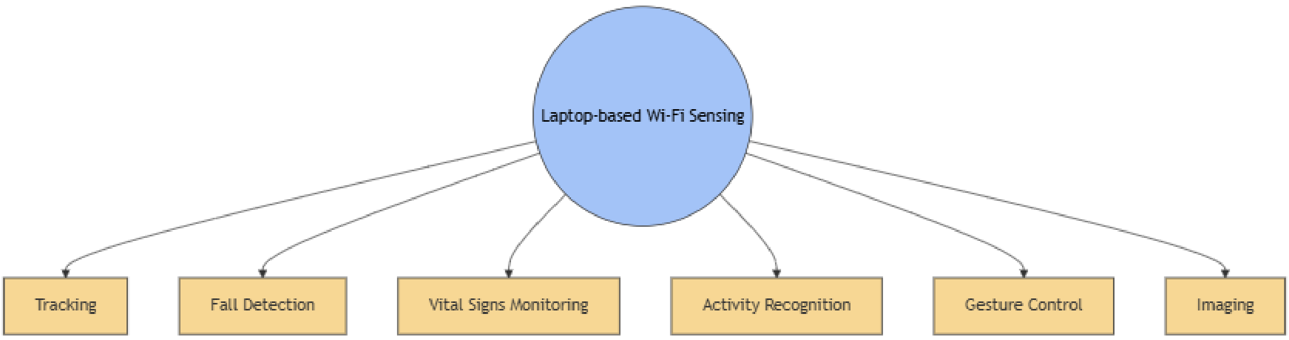



**Figure 4-3 A monostatic active Wi-Fi sensing architecture using a single laptop as both transmitter and receiver (up). Possible applications include (down): Tracking, Fall Detection, Vital Signs Monitoring, Activity Recognition, Gesture Control, and Imaging.**

#### 4.1.2.2 Wi-Fi – 60 GHz

Wi-Fi sensing can be implemented in the 60 GHz band. Specifically, to investigate novel mmWave active Wi-Fi sensing, the following signal processing techniques/approaches are used:

- **Waveform**: The legacy Single Carrier (SC)- Enhanced directional multi-gigabit (EDMG)-CEF-based 11ay PHY layer [10] is extended to the Orthogonal Frequency-Division Multiplexing (OFDM)-based counterpart.
- **Indoor Monostatic Sensing Scenario**: The Q-D channel model proposed by IEEE TGay [11] and the human Boulic model [12] are employed to implement an indoor monostatic sensing scenario, where the transmitter and receiver are co-located at the same position.
- **Channel Estimation**: Channel estimation algorithms are utilized to extract sensing information from OFDM EDMG PPDU signals.
- **Inherent Offset Mitigation**: Synchronization techniques are developed to mitigate time, carrier, and phase offsets.
- **Radar-like Sensing Algorithms**: The classic monostatic radar sensing algorithm is applied to capture the time-frequency profile (2-D radar map). The Short-Time Fourier Transform (STFT) is used to analyze time-varying signals.

An initial experimental validation of a Wi-Fi system operating at 60 GHz performing sensing is presented in Subsection 7.4.

### 4.1.3 Non-3GPP non-Wi-Fi

The definition of the WATs (Sub-6 and mmWave) has been provided with a considerable level of detail in deliverable D3.1 [3]. More concrete details related to ISAC for these technologies are included in section 4.2.2 of this document.

## 4.2 Integrated Sensing and Communication (ISAC)

In the 6G-SENSES ISAC approach sensing can be performed either actively or passively. A discussion on the active and passive sensing options examined and developed is provided.

### 4.2.1 Active sensing

For active sensing, we consider the transmitter and receiver to be co-located, meaning that they can be conveniently synchronized at the clock level [13], [14]. Unlike for active sensing, for passive sensing the transmitter and receiver are spatially separated and asynchronous, which results in timing offsets (TOs) and carrier frequency offsets (CFOs), thus leading to degradation of sensing accuracy with respect to ranging and velocity measurements.

#### 4.2.1.1 Wi-Fi sensing

A summary of the Wi-Fi sensing approaches adopted within the project are summarised in the subsections below.

##### 4.2.1.1.1 Sub-6 GHz Wi-Fi sensing

The architecture concept for the Wi-Fi active sensing on Sub-6 GHz is based on client/user device transmission/reception and processing, where single device (ex. Laptop) transmits standard 802.11 OFDM. The same laptop receives echoes of the transmitted signal, extracting CSI and performing 2D FFT (range and Doppler) to generate a radar-like map of the environment (see Figure 4-4). In standard 802.11 systems, Short Training Sequences (STSs) are often used for coarse packet detection and timing synchronization, while Long

Training Sequences (LTS) are used for fine synchronization and channel estimation. However, in the Sub-7 GHz active sensing Wi-Fi architecture only the LTS is used for both synchronization (coarse and fine) and channel estimation. The STS is not used in any part of the synchronization or channel estimation process. In this context, the relevant system blocks include the following functionalities:

**Transmitter Side (Tx)**

- Signal Generation:
    - The laptop (acting as both transmitter and receiver) generates OFDM packets conforming to the 802.11 PHY layer.
    - Each packet contains a preamble with LTSs, pilot subcarriers, and data subcarriers.
    - The STS portion of the preamble is present in a standard 802.11 packet but is not utilized by our sensing system.
- RF Transmission:
    - The Tx chain sends the modulated RF signal (with the embedded LTS) into the environment.
    - Because this is a monostatic setup, the same device will later receive echoes of this transmitted signal.

**Receiver Side (Rx) and Sensing Processing:**

- Packet Detection & Coarse Synchronization (Using LTS)
    - A coarse timing offset is estimated based on the LTS correlation.
    - Fine Delay and Frequency Synchronization (Using LTS)
    - Using the known structure of the LTS, the receiver refines timing alignment.
- OFDM Demodulation (FFT):
    - A Fast Fourier Transform (FFT) is performed on each OFDM symbol to convert time-domain samples into frequency-domain subcarriers.
    - Pilot extraction and removal.
- Channel Estimation:
    - The channel response (CSI) is computed by correlating against the LTS.
- 2D FFT for Range & Doppler:
    - Range Estimation: A 1D FFT is performed across subcarriers or across repeated OFDM symbols to estimate echo delays (i.e., object distances).
    - Doppler Estimation: Another 1D FFT is performed across multiple transmissions (packets) to detect frequency shifts indicative of object motion/velocity.
    - The outputs of these two FFTs combine into a Range–Doppler Map, enabling radar-like detection and tracking.
- Detection & Post-Processing:
    - From the Range–Doppler Map, the system infers target presence, distance, and velocity.
    - Higher-level algorithms (e.g., thresholding, clustering, or ML) may be applied for specific applications such as gesture recognition, fall detection, or activity monitoring.
    - This architecture highlights a monostatic active Wi-Fi sensing.


**Figure 4-4 Active Sensing sub-6 GHz processing steps**

#### *4.2.1.1.2 mmWave Wi-Fi sensing*

Within the 6G-SENSES project, the following research directions are being pursued to integrate active mmWave sensing-based environmental awareness as a built-in feature of next-generation Wi-Fi communication systems:

- **Integration with IEEE 802.11bq System**: Extend the mmWave sensing framework to work with next-generation IEEE 802.11bq Wi-Fi communication systems.
- **Standardization**: Collaborate with IEEE 802.11bq standards organizations to support mmWave sensing in next-generation IEEE 802.11bq Wi-Fi systems.

By developing novel mmWave active Wi-Fi sensing capabilities and features for ISAC, higher sensing bandwidths, and finer sensing applications can be achieved. To accomplish this, major changes in radar-like sensing signal processing, waveform design such as OFDM, and protocol modifications are required.

### *4.2.1.2 CSI based 3GPP/non-3GPP positioning*

6G-SENSES considers multi-RAT environments that integrate both 5G-RAN and non-3GPP connectivity, as illustrated in Figure 4-5. A key challenge is determining how the necessary CSI metrics from non-3GPP access networks can be collected and provided to the 3GPP network in a way that allows the near-RT RIC to leverage these effectively. The xApp responsible for real-time positioning that is hosted in the near-RT RIC requires continuous updates regarding user location from both 5G (3GPP) and non-3GPP networks. The primary issue that arises is how non-3GPP access networks can report their metrics through the 5G 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 APs 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.

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 CN, 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 CP protocol stack includes the Next Generation Access Stratum (NGAS) Application Protocol (NGAP) over Stream Control Transport Protocol (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 a suitable protocol for the communication over the E2 interface (E2AP) handling the 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.

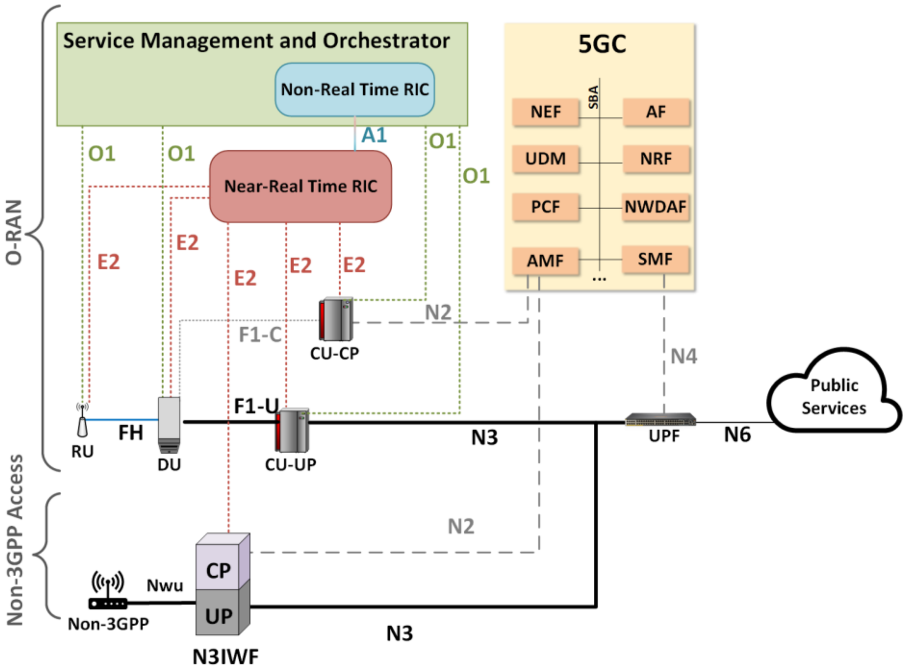



**Figure 4-5 Overall 5G Network architecture, adopting tha O-RAN concept with support for non-3GPP access**

### 4.2.2 Passive sensing – radar-based sensing

#### *4.2.2.1 Sub-6*

The developed sensing system presented in deliverable D3.1 [3] is built of 4 × USRP N321 software defined radios (SDRs). These radios share the same local oscillator and have a common timing source. The channel bandwidth used is 200 MHz. A single transmit antenna with antenna gain of 7 dBi is used. The receiving antenna is a patch array antenna consisting of 8 patches in the form factor of a Uniform Linear Array (ULA). Each patch has an antenna gain of around 3 dBi and a beam width of approximately 60 degrees.

This system outputs the stored signals a so-called heat map. This representation is shown in Figure 4-6. This figure represents the angle and the distance from which the signals arrive to the receiving ULA. In these heat maps, the color scheme symbolize the intensity of the incoming signal (stronger the lightest the color is) at a given angle and from a certain distance. As presented in deliverable D3.1 [3], different algorithms are being used to detect the objects that generate the reflections with their corresponding polar coordinates.

The concepts of angular and range resolutions are depicted in Figure 4-7. The former represents the angle and the distance that provide an insight on the extent the objects “seen” are larger than their actual physical dimensions.

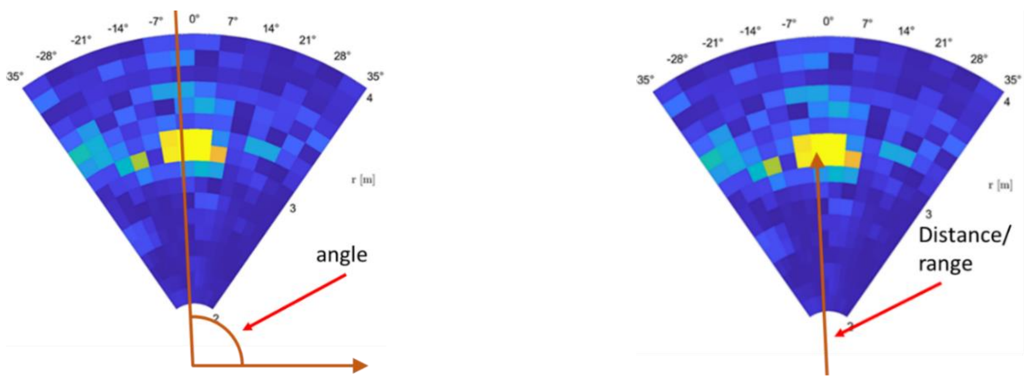



**Figure 4-6 Angle and distance of the detected object in polar coordinates**

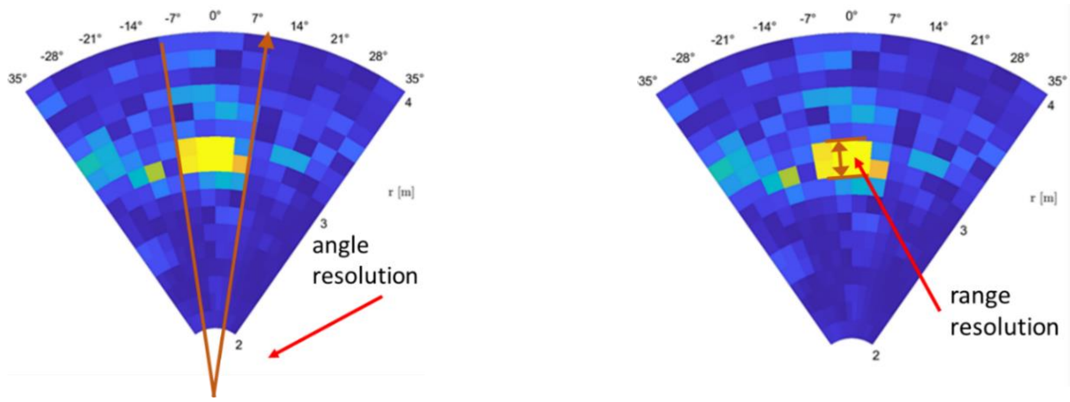



**Figure 4-7 Angular and range resolution**

Featuring a channel bandwidth of 200 MHz, the Sub-6 sensing system is able to detect people and to differentiate them within the surrounding environment. It also provides a reasonable angular resolution that is highly impacted as the distance between the sensing system and the objects increase. This has impact in the required size of the receiving ULA, which would require additional antennas to improve the performance.

The sensing functionality of the radio interface has the potential to improve the beam search and beam tracking functionalities of the PHY layer, making them more attractive for use in the next generation radio networks. This should enable using higher antenna gains which will indirectly improve the power efficiency of the network.

Once the heatmaps are processed, the estimated range resolution is about **0.8** to **0.9** m. The angular resolution, on the other hand, is about **15°**.

#### *4.2.2.2 mmWave (60 GHz)*

The mmWave ISAC system to be used in 6G-SENSES, which was initially presented in deliverable **D3.1** [3], is a joint communication and sensing system, meaning that the radar functionality is realized just by using the components of the communication part, i.e. sensing and communication do not operate simultaneously. The basic SDR platform contains an analog beamforming mmWave antenna frontend, which is designed for communication. The existence of only one RF chain in the antenna frontend module prevents MIMO-based sensing approaches. Instead, a horizontal beam scan is used to obtain a range-angular radar map. The system supports signal bandwidths up to 2 GHz, a sampling frequency of up to 4 GSps, and one-dimensional (1D) sequential beam scanning within a Field of View (FoV) of 90 degrees.

Separate time slots are used for sensing and communication, meaning that, in each slot, either the communication or the sensing functionality is active. In the sensing mode, a full beam scan is performed by sending out a preamble in every beam direction, processing the received frame from every beam and storing the Estimated Channel Coefficients (CHEs) provided by the BB processor. These estimates are transferred to a PC, where the SW-based post-processing consists of an inverse Fast Fourier Transform (FFT) operation to transfer the frequency-domain CHEs into time-domain CIRs. Furthermore, an alignment procedure is applied. The transfer of the CHE data and the post-processing do not need to be performed within a sensing time slot, it can be independently done at any time. Therefore, the duration of the sensing time slot can be shortened.

The project is assessing the option to support bistatic sensing. This would require a small change in the sensing controller (cf. deliverable **D3.1** [3]). In bi-static sensing, one station should either act as transmitter or as receiver, so these individual modes need to be supported by the state machine. Together with this change, the buffer structure to store CHE data could be extended to use cases like PHY layer security.

With this system, as presented in deliverable D3.1 [3], the angular information can best be seen from the 2D angular-range heatmap plot (as in the case of Sub-6). With the mmWave ISAC platform, a range resolution of **6.7 cm** and an angular resolution of **1.45$^{o}$** are achieved.

### 4.3 Cell-Free massive MIMO

As envisioned in 6G-SENSES and discussed extensively in [3], CF-mMIMO networks and their integration into an O-RAN architecture are key enablers for future 6G networks. The benefits of CF-mMIMO systems are manifold [15], allowing to improve: (i) **spectral efficiency (SE)** through coherent joint transmission in the DL, (ii) **energy efficiency (EE)** by dynamically switching the APs (or O-RUs) on and off depending on changing traffic conditions, (iii) **latency** through distributed processing at the O-DU/O-CU and efficient fronthaul links; and iv) most importantly **coverage and reliability** as they can theoretically provide uniform coverage as the number of APs grows. KPIs for these metrics have been put forward in [1] (cf. Table 5-39) with **5x SE** improvements over small cell-based systems, **EE** power savings **> 10%** over small cell-based systems for low spectral efficiencies and up to **5x coverage** probability improvements.

From a system architecture perspective when integrating CF-mMIMO into O-RAN, the following requirements must be considered:

- **Fronthaul capacity**: several Gbps, scalable with the number of APs and UEs.
- **Channel estimation**: APs need to estimate the channels from the users during uplink transmission to perform coherent beamforming in downlink.
- **Assignment of users to APs**: efficient algorithms for user assignment, scalable with number of APs and UEs.
- **Time synchronization**: nanosecond-level accuracy.
- **Phase synchronization**: Precise synchronization among distributed APs is critical for coherent transmission. Continuous calibration is needed to maintain coherence among the APs.
- **Reciprocity calibration**: Real-time, low-overhead, and accurate compensation for HW mismatches.

#### 4.3.1 Reciprocity calibration

In the following, we discuss in more detail the key requirements for **reciprocity calibration** in 6G-SENSES, as well as the main conclusions of the studies carried out so far. Reciprocity calibration must compensate for phase (and amplitude) mismatches due to HW asymmetry between Tx/Rx RF chains. Reciprocity calibration must be performed periodically, although infrequently, to compensate for HW drifts due to temperature changes. Therefore, it is important that calibration procedures can be performed by exchanging pilots over-the-air (OTA) between the different PAs. As the calibration is performed at the beginning of the transmission and then repeated rather infrequently, the overhead incurred by reciprocity calibration schemes is low and the impact on the system architecture is minimal. Furthermore, reciprocity calibration should not consume excessive fronthaul bandwidth or processing resources. In 6G-SENSES we have selected two OTA reciprocity calibration schemes: i) **Argos** [16] for the calibration of the antennas of the same AP (called intra-AP or intra-RU calibration), and ii) **BeamSync** [17] for the calibration between different APs. Argos selects a reference antenna on each AP and finds the calibration coefficients (phases) by bi-directionally exchanging pilots between the reference antenna and the others. On the other hand, BeamSync finds the calibration coefficients between APs using a more sophisticated OTA procedure that sends and receives the synchronization signals through the dominant modes of the MIMO channel. BeamSync does not need a reference antenna, which is its main advantage over Argos, especially in scenarios where the antenna selected by Argos might have a very weak channel with some of the other APs.

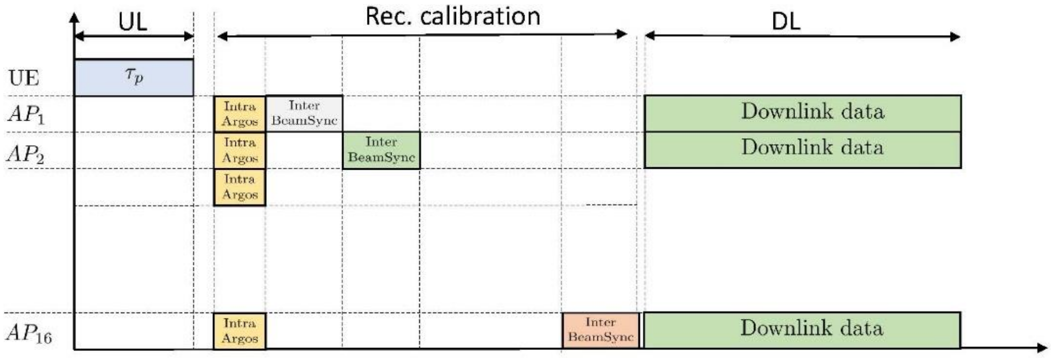



**Figure 4-8 Reciprocity calibration protocol including intra-AP and inter-AP. Each intra-AP (Argos) block requires the bidirectional exchange of pilots between the antennas of the same AP. Each inter-AP block (BeamSync) requires three exchanges of pilots and synchronization signals between two APs.**

It is assumed that the location of the APs is known during the deployment of the CF-mMIMO. The master AP is the central AP (i.e., the one closest to the average of the positions of the different APs), and its position is also known. The positions of the APs can be stored in a database at the edge, consuming negligible radio resources. The DU/CU can access this database and retrieve the positions of the APs when needed. The OTA reciprocity calibration requires a protocol that is illustrated in Figure 4-8. The intra-AP calibration phase can be performed simultaneously for all APs because it involves only the antennas of a single AP and does not generate significant interference to other APs. The inter-AP calibration stage, on the other hand, requires a first broadcast phase in which the master AP sends pilots to all the other APs and then a Time Division Multiple Access (TDMA) phase in which each of the APs is sequentially calibrated with respect to the master AP.

The main conclusions of the studies conducted to date are as follows:

a) The combination of **Argos** as the intra-AP calibration method and **BeamSync** as the inter-AP calibration method provides an effective OTA reciprocity calibration scheme, with low overhead and without consuming excessive fronthaul resources.

b) Simulation results over multiple scenarios show SNR gains with respect to uncalibrated systems between 5 and 10 dB for at 50 % of all user locations.

c) The calibration coefficients remain valid for long periods, on the order of several minutes or even hours, with minimal variations due to temperature changes. Measurements performed on the URSP-based platform at the UC also indicate that the calibration coefficients are not significantly affected by changes in the gain of the amplifiers in the Tx or Rx chains.

To illustrate the performance of the reciprocity calibration procedure we show a simulation result in Figure 4-9. The scenario considers a CF-mMIMO with 16 regularly spaced APs within a 200x200 [m] square. In this case, the master AP is at position [80,80] marked with a square in Figure 4-9 a). The UE position is randomly varied in each simulation, a random realization is depicted in Figure 4-9 a). The main parameters of the scenario are shown in Table 4-1.

The complete protocol is simulated in each realization including UL and DL stages with and without calibration. Figure 4-9 b) compares the Cumulative Density Function (CDF) of the SNR obtained by the UE when conjugate beamforming is applied in the downlink. For comparison, the figure also includes the results obtained when Argos is used for both intra-AP and inter-AP calibration. More precisely, the proposed reciprocity calibration scheme based on Argos for intra-RU calibration and BeamSync for inter-RU calibration guarantees an SNR of 15.9 dB (or higher) at 50 % of all user locations, while the uncalibrated system only guarantees 8.7 dB.

**Table 4-1 Parameters for evaluation of reciprocity calibration algorithms**

| Parameter | Value |
|---|---|
| Number of APs | 16 |
| Antennas per AP (ULAs) | 5 |
| AP Power budget | 20 dBm |
| Number of UE | 1 |
| Number of pilots for uplink channel estimation | 10 |
| Number of pilots for intra-RU cal (**Argos**) | 10 |
| Number of pilots for inter-RU cal (**BeamSync**) | 10 |
| Length of the synchronism sequence (**BeamSync**) | 10 |

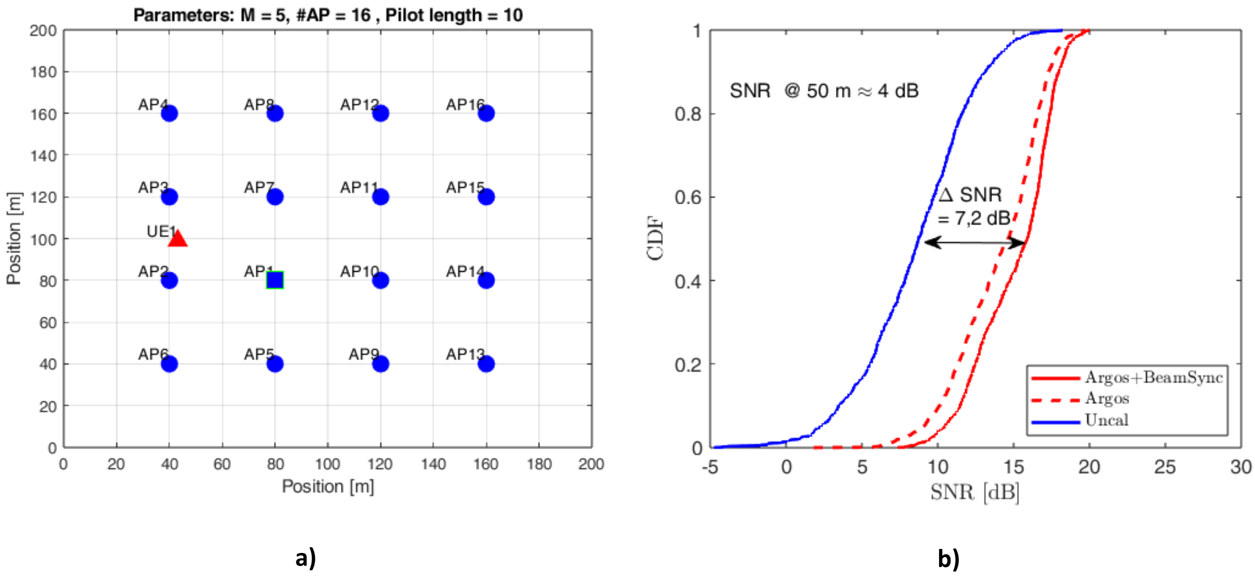



**Figure 4-9 a) CF-mMIMO with 16 APs regularly spaced in 200 x 200 [m] square. The position of the UE the of the UE varies randomly in each realization for the computation of the CDF of the SNR in (b), where the improvement due to the Argos+BeamSync reciprocity calibration stage is shown**

### 4.3.2 Unsourced Random Access

Unsourced Random Access (URA) is a new paradigm proposed in [18] to enable uplink communication of a massive number of users (e.g., millions of users) with a common base station. This scenario is called massive connectivity, being one of the main aspects of 6G communication systems due to the increasing demands in wireless networks. It is particularly important for massive Machine Type Communications (mMTC) applications such that Internet of Things (IoT) or sensor networks. The communication traffic is sporadic, namely, only a small subset of the users is active at any given time. To address this problem, it is suggested in [18] that each user share the same codebook for transmission, hence the system can operate irrelevant of the total number of users and only the number of active users becomes important. Following [18], many low-complexity solutions are developed for the URA setup. Most of these solutions consider either a simple Gaussian multiple access channel, or a fading channel with a single-antenna or a massive MIMO structure with a common centralized base station. However, in cellular massive MIMO, the users at the cell-edges suffer severe large-scale fading, degrading the system performance. This problem is alleviated by distributing the antennas to many APs distributed in a geographical area coordinating to support multiple users.

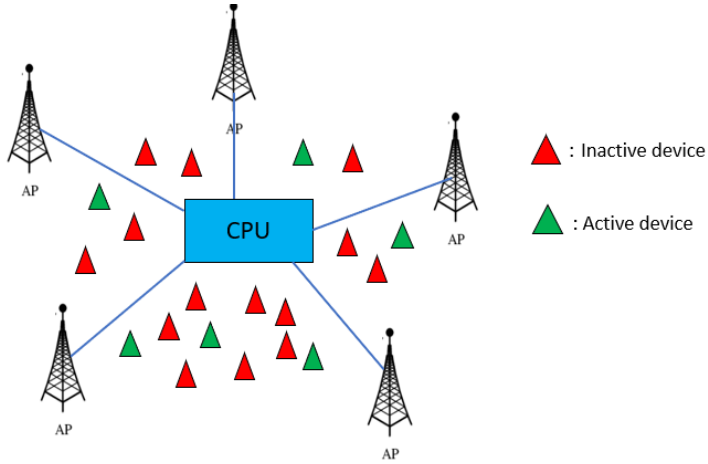



**Figure 4-10 CF-mMIMO URA system with 5 APs and 1 CPU. Active and inactive users are shown by green and red triangles, respectively**

In conventional CF-mMIMO, the number of users is much lower than the number of APs [19]. However, in some applications of next generation communication systems, e.g. massive sensor networks, even the active number of users can be higher than the number of APs, showing the need of developing scalable and distributed signal processing algorithms enabling massive connectivity in CF-mMIMO systems. Therefore, in the context of 6G-SENSES, we develop scalable signal processing algorithms supporting communication of a massive number of users in a CF environment. Since the number of users is high in the URA scenario, the system should be scalable. To keep the system scalable, we aim to recover a subset of the users at each AP. Namely, each AP estimates the uplink channel and transmitted symbols of a subset of the users and pass them to a central processing unit (CPU). Then, the transmitted messages of the users are decoded at the CPU by combining the symbol estimates from different APs. A cell-free URA system with 5 APs and 1 CPU is illustrated in Figure 4-10. Our initial results for cell-free URA are reported in [20].

### 4.4 Reconfigurable Intelligent Surfaces

RISs are a key technology for future wireless networks such as 6G, as they increase network performance and open up new possibilities for intelligent wireless environments. RIS are cost-effective and energy-efficient devices that improve the performance of wireless communication networks by dynamically changing the radio characteristics of the environment. RIS consist of a large number of elements that can manipulate incoming electromagnetic waves and act as pure, tunable reflectors. They can be used in various scenarios to extend coverage, improve signal quality and avoid obstacles. RIS change the reflection amplitude and/or phase shift of signals.

#### 4.4.1 RIS architectural implications

The requirements for RIS-assisted communications systems must consider the following aspects, among others:

- **RIS deployment (location):** Ideally the RIS should be located close to the Tx or Rx in its area of influence to mitigate the multiplicative fading effect. This has been studied for an interference channel in [3][21]. In addition, the RIS should have a LoS or near-LoS forward (from Tx to RIS) and backward (from RIS to Rx) channel for optimized coverage and improved performance [22].
- **Number of reflecting elements:** The number of reflecting elements depends on the channel conditions and the spectral and energy efficiency requirements. While numbers between 100 and 1000 can be found in the simulation studies, practical RIS panels have a more limited number of elements due to the associated circuit complexity.

- **RIS architecture:** Although existing RIS panels are based on independent reflective elements leading to diagonal scattering matrices, there is great interest in studying architectures with interconnected elements, called beyond-diagonal RIS (BD-RIS) architectures. In 6G-SENSES we have developed new BD-RIS optimization algorithms to improve spectral and energy efficiency KPIs, evaluating the performance of these new architectures. Its performance compared to conventional diagonal RIS has been thoroughly analyzed.
- **Update rate:** the rate at which the RIS coefficients are to be adapted depends essentially on channel coherence time and latency requirements. To provide an example, for a 10x10 RIS panel with 3 bits of resolution per element, deployed in an indoor environment with channel coherence times on the order of milliseconds (ms) the **RIS controller** must complete the computations to update the elements within 10 ms for a total control signaling rate of 30 kbps. This overhead is manageable within an **O-RAN architecture**.

Beyond diagonal RISs (BD-RISs) provide enhanced control over the amplitude and phase of the reflecting elements and thus greater flexibility than diagonal RIS. Therefore, the studies carried out in 6G-SENSES concerning RIS-assisted communications have been mainly focused on the study of the novel BD-RIS architecture and its performance comparison with diagonal RIS. The following is a summary of the main conclusions obtained that guide the design decisions and architecture of these systems.

- **BD-RIS** significantly improves the SE in point-to-point MIMO links over diagonal RIS, especially as the number of reflecting elements, transmit power, or the number of data streams increases. Rate increments of up to 20% over a diagonal RIS are reported in [23] for a 4x4 MIMO system with M=100 elements. The results in [23] also corroborate the need to optimize the BD-RIS (or RIS) position to maximize performance. The importance of having LoS channels is studied in [22] Similar improvements have been reported in [21] for the K-user MIMO interference channel. These results were discussed in detail in [3].
- **BD-RIS,** however, may not always be the most energy-efficient due to its higher static power consumption and its circuitry complexity. The main outcome of [24] is that **EE benefits** of BD-RIS architectures depend heavily on the **static power consumption** of the RIS elements. If the static power is too high, BD-RIS may underperform compared to simpler diagonal architectures.
- The research has been extended to **ultra-reliable and low-latency communications (uRLLC)** multiuser MIMO systems assisted by a BD-RIS in [25]. Short packet lengths are transmitted in URLCC, which makes the first-order Shannon rate an inaccurate performance metric. It is necessary to use more accurate approximations of the achievable rates of Finite Blocklength (FBL) coding regimes that consider the channel dispersion. The results of [25] show that the benefits of BD-RIS are more pronounced in **URLLC systems** compared to systems approaching Shannon capacity, as more flexible architectures help meet stringent **latency** and **reliability** requirements. In this scenario, **BD-RIS** again outperforms diagonal RIS in terms of SE and EE, but its EE performance depends on **static power consumption** of RIS elements.

  The achievable rate region of a BD-RIS-aided uRLLC multiuser broadcast channel (MU-MISO), assuming a FBL coding and treating interference as noise (TIN) as the decoding strategy has been characterized numerically in [26]. It is shown that the **rate region** of BD-RIS-aided systems can be derived from the **SINR region** under the condition that the rate is a monotonically increasing function of SINR. RIS architectures provide higher gains in scenarios with more stringent **reliability** and **latency** constraints, making them particularly suitable for **uRLLC applications**. With a more relaxed globally passive BD-RIS architecture the achievable rate for a decoding probability of error of 1e-5 and short packet length of 256 bits is twice that achieved by a diagonal RIS.

### 4.4.2 RIS architectural implications (interfaces)

In use cases that make use of RISs the goal is commonly coverage extension, which commonly has an impact on energy efficiency (potentially an RU can be switched off given the presence of the RIS), signal enhancement (by using the reflective path of the RIS), deployment costs (related to the former for network planning), etc. The RIS panels may be controlled by the Near-RT RIC for relatively fast operations, such as RIS per-element configuration, and by the Non-RT RIC for more relaxed operations, such as logical split of the RIS or change of static configurations.

Regarding the former, an E2-like interface could be implemented for RIS-specific operations without the need of the involvement of the RUs. RIS-specific E2 SMs should be provided in this case that report RIS-specific information, such as the state (configurations, loaded codebooks, current phase-shifts, RIS energy consumption (if possible), etc.). Tentatively, and if supported by the panel, it might also include the received signal strength indicator (RSSI) at the RIS or the direction of the main signal source (e.g., azimuth and elevation).

The architecture may also provide an interface to locally interconnect gNBs to RIS at cell sites, the F1-x interface. This interface was introduced in the project RISE-6G [27] to cover uses cases with strict time deadlines such as RIS-gNB joint beamforming or use cases that trigger large amount of signalling traffic to control the RIS, such as frequent phase-shift modifications per antenna element.

The specific details of the integration of ISAC and RIS-enabled ISAC solutions are still under discussion. Common ISAC use cases such as people detection can easily be integrated with ISAC rApps/xApps that consume TS28.552 metrics (e.g., L1M.SS-RSRP, L1M.SS-RSRPNrNbr, DRB.AirIfDelayDL, etc.) and E2SM-KPM metrics (e.g., L1M-UL-SRS-RSRP) using the standard E2 interface. Other use cases such as user location based on AoA+ToF [28], [29] in a multi-antenna gNB can leverage ISAC dApps deployed at the O-DU (more details are provided in section 5.3.3), where access to high bandwidth IQ samples is available and RT computations are possible without violating timing deadlines or saturating the monitoring interfaces.

# 5 Control Plane

## 5.1 6G-SENSES Control Plane Overview

The 6G-SENSES architecture aims to expand the capabilities of existing CN functions and introduce new ones, specifically for location and ISAC services. This involves ensuring secure attachment of new sensing devices and RAN elements that have sensing capabilities to the network. To support sensing services in multi-RAN / multi-technology several innovations are envisioned for the control of the RAN, the transport network and the CN functions. These include:

- At the CN the introduction of new functions supporting sensing services and the enhancement of existing ones, i.e., Location Management Function (LMF) for location services.
- The extension of the N3IWF with a new E2 interface allowing the exposure of sensing capabilities from non-3GPP network nodes to the RIC.
- Extensions in the RAN RIC controller for ingesting and processing sensing measurements from 3GPP and non-3GPP networks.
- The development of new SDN-based control policies for the transport network to support the requirements of sensing services.

A detailed description of these elements is provided in the following subsections.

## 5.2 Core Network extensions for ISAC

The 6G-SENSES architecture envisions the extension of existing and the introduction of new CN functions in support of location and ISAC services, respectively. The new functions introduced in the CN ensure that new sensing devices and RAN network elements with sensing capabilities are attached to the network in a secure way.

Specifically, for location-based services the 3GPP 5G CN and protocols can extend ISAC capabilities with the LMF that provides the positioning for each user connected to the network. The 3GPP framework for positioning in 5G networks involves a combination of network components, interfaces, and positioning methods to provide accurate and reliable location information for UEs. The 3GPP standards supporting UL-TDoA positioning are detailed in technical specification TS 38.305, which outline the technical requirements for all location services, including UL-TDOA.

Figure 5-1 illustrates the UE positioning architecture in 5G [30]. The key network components include the UE, Next Generation Radio Access Network (NG-RAN), AM), the LMF, and the Location Service (LCS) entity. While LMF is responsible for location service and calculates the final position of the UE by coordinating the collection of TDOA measurements, the LCS manages the delivery of location-based services by processing positioning requests from LCS clients.

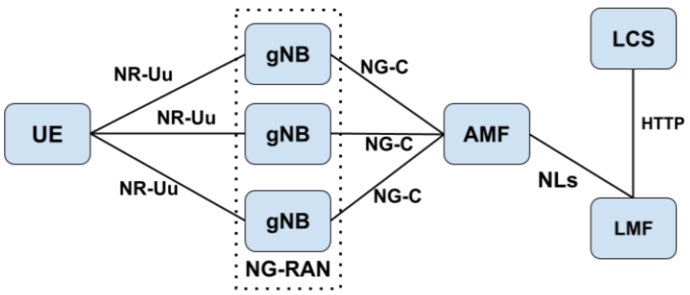



**Figure 5-1 UE Positioning Architecture applicable to NG-RAN [30]**

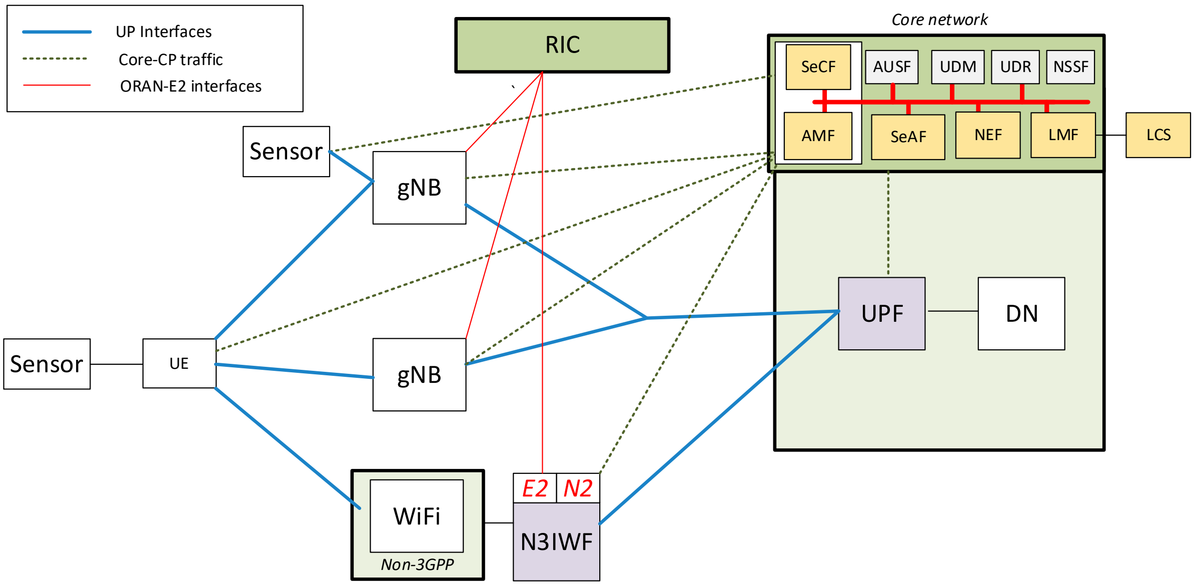



**Figure 5-2 CN extensions for sensing services**

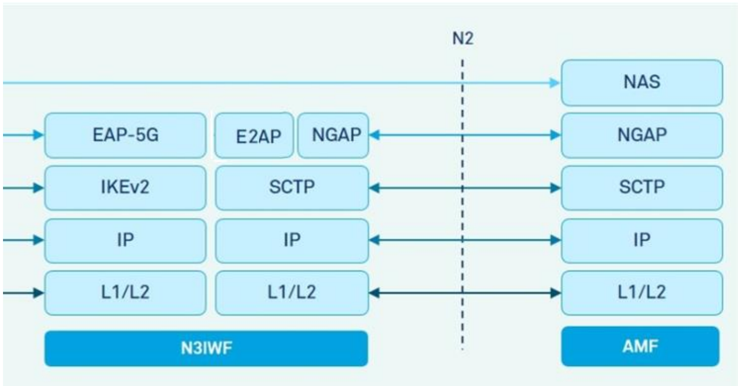



**Figure 5-3 Extended N3IWF protocol stack with E2 capabilities (based on [31])**

Regarding sensing services, 6G-SENSES proposes the creation of a new function and specifically the SeCF that is used to extend AMF functionalities allowing connectivity for external sensors used to complement ISAC services, performing authentication and authorization of sensing devices. This function also handles the sensing information transferred from the CN to the sensing devices as shown in Figure 5-2. Through SeCF sensing devices can be attached to the network either directly (a sensor can connect to the gNB) or indirectly through a trusted UE.

In addition to SeCF, the SAF provides high-level analytic services for sensing services that are exposed through the NEF extending NWDAF functionalities is proposed.

Finally, sensing capabilities of non-3GPP network nodes can be exposed to the RIC through an extended version of a N3IWF supporting the E2 interface or exposed to the CN through the N2 interface. The extended N3IWF protocol stack is illustrated in Figure 5-3.

## 5.3 RIC extensions for RIS and ISAC

RISs are being considered as a technology to enhance network coverage, SE, and energy savings in Beyond 5G (B5G) and 6G networks. Their integration within O-RAN architectures involves considerations of control, management, and deployment.

### 5.3.1 O-RAN Architecture Extensions for RIS

The architectural design and integration of RIS within O-RAN based on multiple sources is presented in Figure 5-4, and described in the following subsections.

The integration of RIS into O-RAN requires modifications to the existing architecture, introducing new control elements and interfaces. RIS configurations can be managed at both Near-RT Non-RT scales. The Near-RT RIC is responsible for controlling RIS settings within a time scale that supports channel adaptation such as RIS per-element configuration or load a precomputed configuration from a codebook. The Non-RT RIC handles optimizations such as RIS logical splitting and offline training of RIS phase shift configurations.

To facilitate RIS management and control, new interfaces are required. The E2+ interface extends the standard E2 interface to include RIS-related SMs such as E2SM-Smart Surface Control (SSC) for near-RT configuration changes and E2SM-Smart Surface Monitoring (SSM) for status reporting. The O1+ interface, based on NETCONF/YAML, provides a mechanism for RIS actuators to communicate with the Non-RT RIC for configuration and monitoring [32]. In some cases, the F1-x interface may be used to coordinate gNB and RIS beamforming. However, for RIS use cases focusing on energy-efficient coverage rather than dynamic beamforming, this interface may not be required [33].

The integration of ISAC with RIS enables additional functionalities. ISAC provides environmental awareness, allowing RIS configurations to adapt based on user distribution and obstacles. For effective implementation, RIS control mechanisms must be synchronized with ISAC data to optimize reflection properties dynamically.

The implementation of ISAC within O-RAN may involve different processing locations. ISAC data can be preprocessed at the O-RU to reduce control overhead. The Near-RT RIC can use ISAC-generated heatmaps to adjust RIS configurations dynamically, while the Non-RT RIC can perform offline optimizations, such as updating RIS phase-shift codebooks.

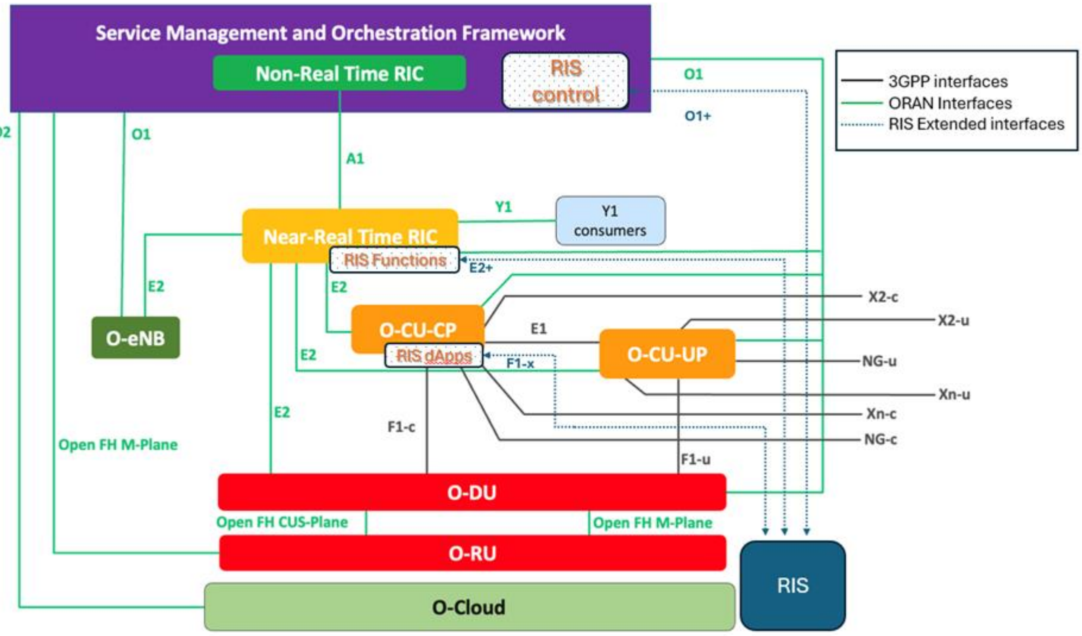



**Figure 5-4 O-RAN extended architecture to serve RIS**

### 5.3.2 Performance Indicators for integration of RIS and ISAC

The integration of RIS into the O-RAN architectures is evaluated based on several performance indicators. SE improvements measure the increase in throughput due to RIS-assisted transmissions. EE gains are assessed by evaluating power savings achieved through optimized RIS deployment. Coverage extension metrics quantify improvements in signal reachability, while control overhead is analyzed to determine the additional signaling required for RIS operations.

Several strategies are proposed for optimizing RIS performance in O-RAN. Dynamic RIS configuration can be implemented using reinforcement learning (RL) techniques to adjust RIS elements in response to changing network conditions. Energy-aware RIS activation ensures that RIS operates selectively when it contributes to network efficiency. Network-aided RIS placement aims to optimize the deployment of RIS elements within an O-RAN framework to maximize benefits while minimizing additional complexity.

### 5.3.3 dApps in O-RAN and their role in sensing

The concept of dApps in O-RAN introduces lightweight, programmable applications that complement xApps and rApps by enabling real-time control at the O-CU and O-DU levels. Unlike xApps and rApps, which primarily focus on higher-layer control loops, dApps allow fine-grained, UP control, extending RIC functionalities to support tasks such as beam management, dynamic spectrum access, and interference mitigation. dApps operate within the O-DUs and O-CU-CP/UP, enabling real-time inference and classification directly at the network edge [34].

For ISAC integration, dApps play a crucial role by extracting and processing sensing data directly from lower-layer physical channels. These applications can access reference signals, IQ samples, and multipath parameters, facilitating real-time environmental awareness. dApps can be used for CSI enhancement, dynamically adjusting network configurations based on detected obstacles, scatterers, and interference patterns. By leveraging this sensing data, dApps improve channel estimation accuracy and reduce pilot overhead, optimizing both SE and energy consumption.

The combination of dApps and ISAC within O-RAN enhances real-time adaptability by enabling localized, distributed intelligence. 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. Accessing sensing information from the gNB requires interaction with lower-layer physical channels, such as reference signals or full IQ samples within the radio frame. dApps can facilitate the extraction of these resources as needed by a sensing application. Another potential application for dApps is environment-assisted CSI estimation. In this case, a dApp can continuously supply environmental sensing data, including obstacle locations, scatter positions, and multipath statistics such as the number of paths and AoA, to the gNB. This additional sensing information enhances CSI estimation accuracy while minimizing pilot overhead.

Finally, dApps can communicate with the RIS via the F1-x interface to support fast data communication in the sub millisecond scale.

### 5.3.4 Challenges and Considerations in RIS Integration

The inclusion of ISAC within O-RAN introduces several challenges that must be addressed for effective deployment. One key challenge is the increased computational burden on the Near-RT RIC due to real-time sensing data processing, requiring enhanced processing capabilities and efficient AI-driven analytics. Another challenge is maintaining low latency for dynamic spectrum sharing and interference management while ensuring seamless coordination between sensing and communication tasks. The security of sensing data also presents a risk, as adversaries could manipulate ISAC-based insights to disrupt network operations.

Furthermore, the standardization of ISAC-related interfaces and data fusion techniques remains an ongoing effort within industry bodies to ensure interoperability across vendors [35].

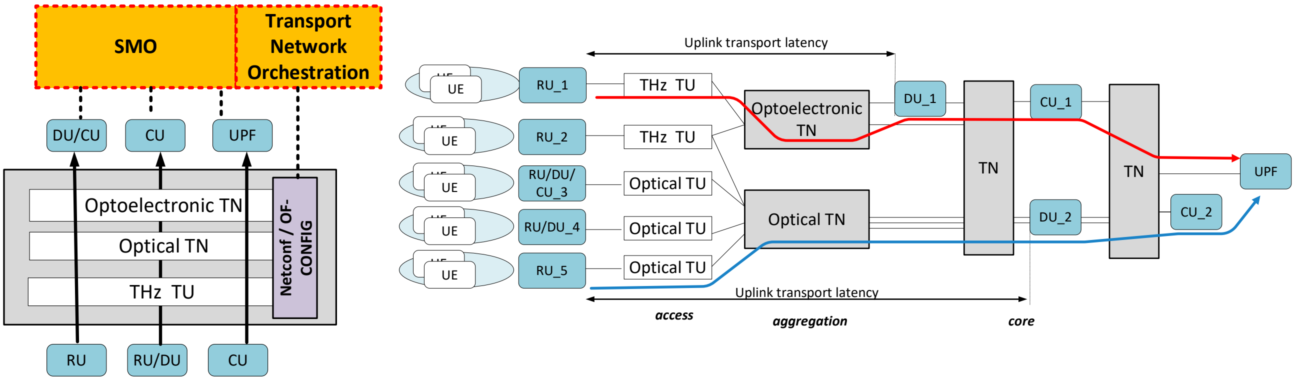
### 5.4 Transport network control for ISAC

This section discusses the transport network control that is required to support ISAC services over the 6G-SENSES infrastructure. It should be noted that 6G-SENSES is not concentrating on the development of novel transport network solutions. However, transporting integrated communication and sensing data over the 6G-SENSES infrastructure imposes specific transport network requirements that demand extensions of existing transport network control and management solutions. The sections below discuss the 6G-SENSES proposed approach with regards to transport network control and management in support of ISAC services.

#### 5.4.1 SDN-controlled transport network

A multi-technology transport network is considered that is operating in a cooperative manner supporting traffic connectivity requirements between RAN NFs (RU-DU, DU-CU) and between RAN NFs and the CN (CU-UPF) as shown in Figure 5-5 a) [36]. The transport network nodes can operate in a complementary and cooperative manner addressing a wide range of transport network connectivity options (i.e. point-to-multi-point and multi-point to multi-point) utilizing optical and opto-electronic switches. Wireless transport network units primarily used for point-to-point connectivity operating in the THz spectrum band are also considered. These technologies support capacities in the range of 1 Gbps up to 100 Gbps and key features such as synchronization.

Low-cost wired (i.e. point-to-point optical) or wireless (mmWave, THz, etc.) transport network units can be installed close to the RUs offering connectivity to the radio transmission points, collecting and aggregating transport traffic from various cell sites to a central location (hub site), where centralized processing is hosted. The overall architecture addresses different disaggregated RAN deployment options and protocols. Optoelectronic and all optical TNs with higher capacity per port and more sophisticated network connectivity capabilities (i.e. mesh connectivity) are used to collect and aggregate traffic from multiple transport network units. This traffic can be further aggregated through the transport CN that is responsible to collect traffic from the aggregation network and forward the corresponding traffic flows deeper into the 6G CN thus fulfilling the requirements of the requested E2E service slices.




a) b)

**Figure 5-5 a) SDN controlled transport network, b) traffic aggregation over multi-technology transport**

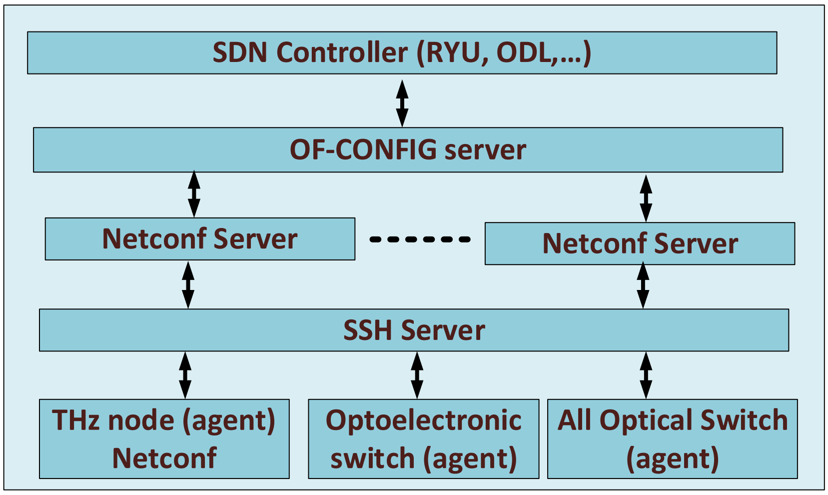



**Figure 5-6 SDN Control of the Integrated Transport Network**

To meet the protocol requirements of the requested service flows, the transport network orchestrator interacts with the SMO (RIC) in order to identify: a) how traffic aggregation and network resource sharing can be performed, and b) where the corresponding services will be terminated. Therefore, through continuous interaction with the RIC, the optoelectronic switches take decisions related to the output ports that the incoming traffic will be forwarded and the scheduling policies that will be applied at the corresponding virtual output queues. For example, as shown in Figure 5-5 (a, b), due to buffering and scheduling latencies introduced by the optoelectronic transport network, the FH connection of *RU_1* will be terminated at *DU_1* to satisfy the corresponding UL transport latency constraints. On the other hand, the all-optical transport network can transparently forward traffic streams without introducing additional delays associated with scheduling policies and buffering and, therefore, enables the transport network orchestrator to direct and terminate connections deeper into the transport network. This results in higher degree of aggregation of the transported traffic flows, thus achieving increased overall resource efficiency.

To integrate the converged transport network with the overall system architecture, a set of Northbound and Southbound Interfaces (NBIs & SBIs) have been developed. These provide the necessary abstraction required for the integration of the network controllers of the various network technologies and the SMO. The overall architecture of the SDN controller developed is shown in Figure 5-6. The SDN controller is able to expose to the orchestrator a set of actions and notifications including: a) its availability for the provisioning of connectivity services, b) details of the internal PHY layer configuration parameters, c) the option to reconfigure the system and change its parameters, and d) termination of connectivity services, etc. The system is also able to expose the actual network topology graph through the NBI of the SDN Controller.

As shown in Figure 5-6, the NETCONF architecture consists of two elements: the server (Agent) and the client (Driver). The server (Agent) is responsible to maintain information on the managed devices and responds to the client-initiated requests. When receiving a request from a NETCONF client, the NETCONF server parses the request, applies the relevant actions to the network node and sends a reply to the client. In the context of 6G-SENSES, the SDN controller will be able to apply the necessary polices and rules supporting connectivity requirements for sensing flows.

### 5.4.2 Transport Network management for sensing streams

6G-SENSES proposes and has experimentally validated an architecture exploiting an optical transport network that interconnects RAN and CN domains, to facilitate joint support of sensing and communication services. Sensing is performed based on the principle of a distributed passive wireless radar, as shown in Figure 5-7. According to this, 6G BSs generate communication signals reflected on “objects” located in the surrounding area, creating IQ echo streams. These IQ echo streams are transmitted in the form of UL FH streams and are redirected to a MEC node for storage and processing. A sensing dApp, deployed at the DU, can analyze the quality of the IQ echo streams at the MEC and decide which IQ streams can be used to support the required sensing. The IQ streams that are not carrying useful information are dropped. The sensing dApp output, including only useful IQ streams, is passed to the network orchestrator that decides the optimal transport network configuration to support both communication and sensing services. To perform this, the orchestrator solves the optical transport network optimization problem considering both communication (i.e. FH, BH) and sensing (IQ echo streams) services. The identified configuration is then executed by the Software Defined Networking (SDN) control of the optical transport network.

The proposed architecture has been experimentally implemented and evaluated using a platform that comprises actual HW for the optical transport network, compute servers and wireless transceivers. The wireless channel (OTA transmission) is emulated through the GNU Radio platform. A detailed description of the experimental results is provided in section 7.3.

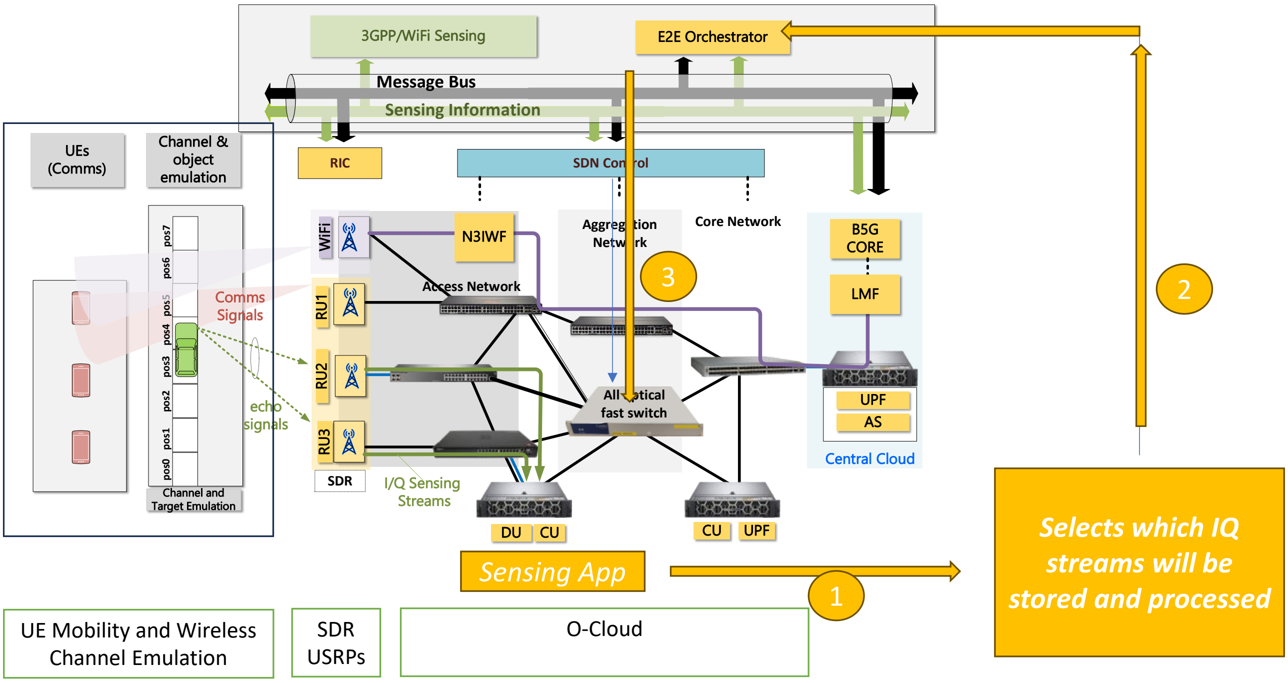



**Figure 5-7 Transport network LCM for sensing streams**

### 5.4.3 QoS related work for the FH part

The Open Fronthaul (O-FH) network is the segment that connects the O-RU and O-DU in the O-RAN architecture. While it provides a novel multi-vendor networking paradigm, it also introduces strict requirements for the transport network that needs to manage this traffic and so poses new challenges. Placing the DU farther away from the RU enables a higher centralization degree, having more RUs being coordinated by a single node. This brings along improved resource management and lower costs in the radio segment, benefiting from the pooling effect. On the other hand, larger distances imply that the FH traffic has to share the underlying network resources with other traffic flows, such as those belonging to the 5G BH or other technologies (i.e. 4G), with heterogeneous performance requirements. In this sense, the realization of ISAC architectures will add more complexity to the network management, which will have to jointly fulfill the existing requirements of communication traffic flows with those required by sensing data.

According to [37], O-RAN defines that the forwarding nodes (i.e. switches, routers) can implement two QoS profiles to accommodate transport network requirements. The first one consists of a flat queue scheme to handle ultra-low latency flows, such as Precision Time Protocol (PTP), and enhanced Common Public Radio Interface (eCPRI). On the other hand, the second profile makes use of a two-layer hierarchy of queues with high, medium and low priority. In this scheme, priority queues support preemption to minimize packet delay variations (PDV) and give preference to critical flows. Specifically, the queue assigned to the FH traffic (i.e. eCPRI) is allowed to interrupt or take priority over other queues.

The specific marking technique (i.e. DSCP, MPLS, etc.) adopted to differentiate traffic flows is left to the network managers. Regardless of the marking solution adopted, O-RAN specifies that latency sensitive and CP traffic should be applied expedited forwarding, as described in IETF RFC 3246. On the other hand, policies have to be applied to avoid starvation of queues with less priority, while ensuring sufficient bandwidth capacity from FH services.

To that end, O-RAN [38] indicates that assured forwarding model, as described in IETF RFC 2597, should be used to provide guaranteed bitrate. In particular, the scheduling schemes should be Weighted Round Robin (WRR), Minimum deficit round robin (MDRR) or weighted fair queue (WFQ) scheduler. In addition, the scheduler needs to have sufficient capacity to avoid losses due to bursts as a consequence of the aggregation of traffic.

As mentioned in section 4.2, sensing information can be obtained either using through CSI or by radar-based solutions. In the former case, sensing information is obtained from existing communication traffic. On the other hand, the radar-based solutions generate additional traffic over the shared infrastructure, whose shape depends on the type of radar (i.e. Sub-6 GHz, mmWave). Thus, it becomes necessary to analyse the sensing traffic and the requirements of the applications/services which will exploit it and adapt the current QoS services accordingly.

# 6 End-to-end Service Delivery

A key role in E2E service delivery in the 6G-SENSES architecture is played by SMO. O-RAN SMO is responsible for managing, automating, and optimizing the RAN. SMO facilitates orchestration and automation by dynamically deploying, scaling, and managing RAN components while supporting zero-touch provisioning. It also provides real-time network monitoring and observability by means of a data lake, collecting KPIs and detecting anomalies to enhance network reliability. By leveraging AI/ML-driven optimization, SMO enhances network efficiency, improves spectrum usage, and boosts EE through intelligent decision-making. Additionally, it interfaces with the RICs and existing Operations Support Systems (OSSs)/Business Support Systems (BSSs) to ensure seamless integration across multi-vendor environments.

In addition, the use of MEC bringing storage, computing, and networking resources closer to the edge of the RAN provides clear benefits in E2E service delivery. In this sense, MEC allows to significantly reduce latency and enable faster data transfers that benefit a variety of user applications particularly in mobile environments, as well as improve RAN performance providing the necessary processing resources to support closed-loop control operations, which are required by the RIC.

Finally, spectrum management strategies are becoming critically important in the context of the 6G-SENSES infrastructure, given the variety of RAN technologies adopted and the potential interference scenarios that may arise under the existing static spectrum co-sharing approach.

## 6.1 Service Management and Orchestration (SMO)

SMO plays a critical role in enabling ISAC by providing centralized intelligence, automation, and real-time data processing ensuring efficient management, coordination, and optimization of ISAC-enabled functionalities including:

1. Centralized Data Collection & Management: SMO acts as the control center for ISAC by collecting CSI, Sounding Reference Signal (SRS), IQ samples, radio wave reflections, Doppler shifts, and other sensing data from gNBs and user terminals in a data lake. Using A1, O1 and O2 interfaces, SMO aggregates and analyzes real-time sensing information, enabling applications such as precise localization, motion detection, and environment mapping.
2. AI/ML-Driven Sensing Optimization: With AI-powered rApps/xApps, SMO can train/apply specific AI models to enhance sensing accuracy, detect patterns in radio signals. In additional, historical sensing data can be used to perform predictive sensing so as to optimize the RAN performance.
3. Close Sensing & Communication optimization loop: SMO/RIC can dynamically manage network resources to balance sensing and communication tasks. For example, it can configure beamforming patterns, time-frequency allocations, and MIMO settings to ensure optimal ISAC performance without compromising communication efficiency.

In addition, Near-RT RIC and rApps could transform the sensing information into a set of actionable policies to achieve the desired objectives. For example, using the positioning information to enforce a handover policy to the best target cell based on the predicated trajectory, migrating the slice to the new cell and allocating the resources while retaining the QoS guarantee during the whole process.

## 6.2 AI/ML for automation

The 6G-SENSES architecture aims to support a native AI/ML RAN management, evolving 3GPP and O-RAN designs to exploit network sensing information in the RAN optimization loop.

Recent works have presented the use of AI/ML techniques for RAN optimization involving network sensing data. On the one hand, these works exploit sensing information to acquire a better perception of the environment, in order take improved decisions for RAN optimization. In addition, some other works also aim to optimize the quality of the sensing information (sensing services) along with communication ones. For instance, in [39] an AI/ML solution is proposed that uses sensing information to provide human-centric services (HCSs). The proposed scheme exploits the distributed information of both UEs and access elements. Following a similar approach but with a different target the authors of [40] proposed an AI/ML scheme for resource allocation in ISAC scenarios that apart from other QoS parameters also considers EMF exposure.

A second category of work jointly considers optimization of sensing and communication services so that traditional QoS communication metrics need to be extended to consider novel sensing requirements. In this sense, Li et al. [41], [42] proposed resource allocation solutions based on Value of Service (VoS) metrics in multi-user ISAC systems exploiting Deep Reinforcement Learning (DRL) [42]. Similarly, in [43] Dong et al. propose new QoS concepts to jointly consider sensing and communication services requirements. Apart from traditional communication metrics, this work also takes into consideration new ones such as detection, localization or tracking; then, a resource allocation solution is presented according to both sensing and communication QoSs. Jin et al. [44] propose a management solution that considers end-to-end inference error of the AI/ML algorithms, so that it can obtain the highest value of sensed data. Besides, some other works address the same problem from a higher perspective, moving from multi-user ISAC scenarios to multi-slice ISAC ones. For instance, [45] addresses RAN slicing over an UAV scenario, where communication and sensing slices are deployed, again exploiting DRL.

The 6G-SENSES architecture is designed to support different AI/ML schemes and application scopes. To that end, the principles outlined by the ITU-R in [46] and the analysis reported in [48], by promoting the collaboration of sensing and AI/ML functionalities, will be followed.

Figure 6-1 illustrates the 6G-SENSES architecture comprising the RAN virtualized NFs, i.e. the DUs and the CUs, the cloud infrastructure hosting the RAN NFs, the 3GPP CN and SMO managing the overall 6G-SENSES infrastructure [49]-[50].

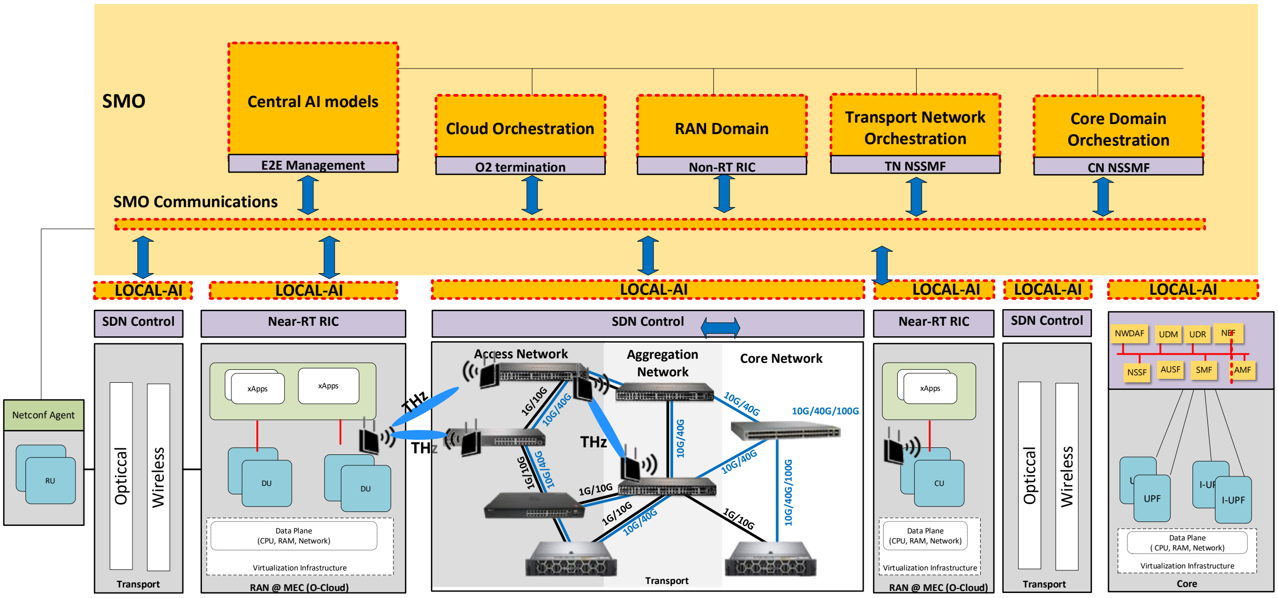



**Figure 6-1 AI-based 6G-SENSES system architecture: multiple heterogeneous network segments are managed by local controllers**

Connectivity between the different components of the architecture is provided through an SDN-controlled multi-technology transport network infrastructure supporting FH i.e. connectivity between the RU and DU, midhaul (F1), i.e. connectivity between the DU and CU and BH services, i.e. connectivity between the CU and the CN. The architecture supports hierarchical control loops managing the RAN segment operating at near real-time (response time in the range 10 ms to 1s) and non-real-time (response time > 1s) time scales. Near real-time decisions are taken by the Near-RT RIC, whereas non-real time decisions are taken by the Non-RT RIC hosted at the SMO.

The **Near-RT RIC** enables near real-time control and optimization of services and resources of the DU and CU nodes connected using the E2 interfaces. It hosts one or more xApps that use E2 interface to provide value added services through the collection of near real-time information, e.g., on a UE and/or a cell basis. Based on the available data, the it generates the RAN analytics information that can be exposed to external users via Y1 interface. The **Non-RT RIC** is internal to the SMO used to support intelligent RAN optimization by providing policy-based guidance, ML model management and enrichment information to the Near-RT RIC function. Interaction between the Non-RT RIC and the Near RT RIC is provided through the A1 interface. Non-RT RIC can use data analytics and AI/ML training/inference to determine the RAN optimization actions. Non-RT RIC collects statistics and measurements from the various interfaces it exposes to the underlying physical resources leveraging SMO capabilities. These interfaces include O2 to the O-Cloud infrastructure, O1 to the RAN NFs, Open-FH Management (M)-plane for the RUs, etc. More specifically, configuration and management of RAN NFs, including Fault, Configuration, Accounting, Performance and Security (FCAPS), and their Operation, Administration and Maintenance (OAM) are supported through the O1 and the O-FH Management-plane (M-plane) interfaces that are implemented using the NETCONF protocol.

AI/ML techniques are located at the different controllers to optimize the operation of the integrated infrastructure at different time scales and along all segments, i.e. RAN, CN and transport network. For example, intelligent RAN optimization is supported by the Non-RT RIC through the provisioning of policy-based guidance, ML model management and enrichment information offered to the Near-RT RIC function. Intelligent radio resource management (RRM) can be also performed within a non-real-time interval (i.e., greater than 1 second). The Non-RT RIC can determine the RAN optimization actions through data analytics and AI/ML training/inference leveraging SMO services. These services include data collection and provisioning of the O-RAN nodes through O1 and O2 interfaces. Non-RT RIC can provide AI/ML capabilities through rApps. Similarly, near-real-time control and optimization of RAN elements and resources is provided through the Near-Real-Time RIC adopting also AI/ML techniques. These are achieved through high granularity data collection and other actions supported by the E2 interface. Overall, the Near-RT RIC functionalities are supported through xApps.

The overall intelligence management processes are shown in Figure 6-2. As can be observed, in addition to RAN NFs information, the Intelligence Management can also aggregate data from the CN, the application functions which, in turn, provide BS and UE data, and the transport network. The collected data can be either regular monitoring information or enriched statistics that can then be utilized for ML model training and inference. Data, ML training and inference can be hosted at different locations depending on the available physical resources and the specifications of the services. The trained ML model is stored in an ML repository, which can be then selected for inference. The output of the inference can be used by a control function (i.e., Non/near RT RIC, SDN controller, CN controller) to provide the "AI/ML assisted Solution" optimizing the performance of a specific network segment.

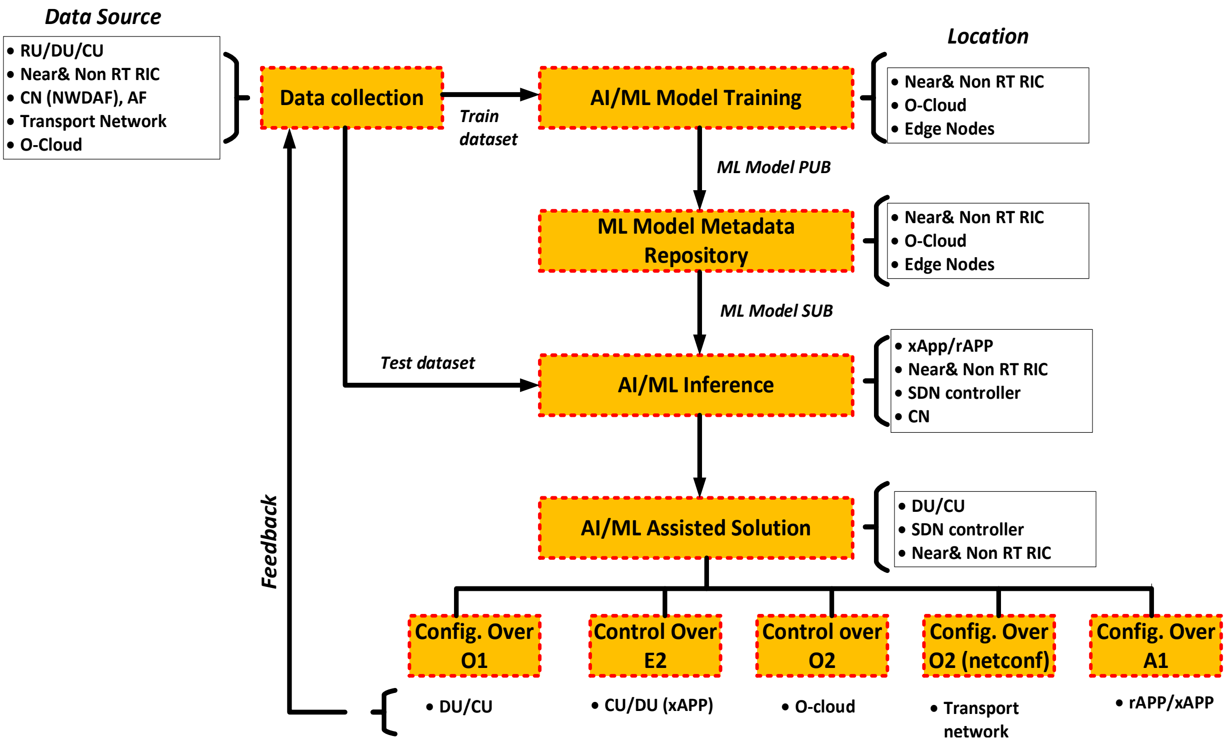



**Figure 6-2 Intelligence Management: Supported AI/ML workflows and caching locations for data, ML inference and training metadata**

The relevant actions (i.e., network configurations, management policies, scheduling and routing decisions, etc.) are applied to the targeted entity using appropriate interfaces (i.e., O1, O2, E2, A1). The ultimate goal of the intelligence management system is to support a wide variety of application scenarios, so that the AI/ML models can be exploited by the xApps/rApps to optimize the operation of the 6G-SENSES building blocks.

According to the location of the ML training and inference, the time scale where decisions need to be taken, data availability and computational complexity, multiple ML deployment options can be considered [52]:

- Option 1: Offline training and inference. In this case the ML workflow is used to support non-real time decisions (with response time >1s) exploiting perception information for network reconfiguration. Therefore, ML training and inference can be hosted in the SMO and/or in the domain specific orchestrators (i.e., Non-RT RIC for RAN, transport network orchestrator, CN orchestrator, etc.) as shown in the top layer of Figure 6-1. As an example, after data collection is carried out at the SMO training and inference can be implemented as rApps at the non-RT RIC. After inference, the rApp reconfigures the disaggregated BSs components (RU/DU/CU) through the O1 interface. This way, changes in the RAN configuration would happen as a response to events in network statistics or changes in the overall scenario. The rApp would get acquainted of such changes by either sensing information or a combination of sensing and legacy control information.
- Option 2: Offline training and online inference. In this deployment, option ML training is performed at the SMO whereas inference is typically running close to the edge. Due to the large volume of training dataset, the SMO needs to be supported by significant computational resources. This configuration is suitable for distributed RAN optimization varying environments exploiting previous global perception information. For instance, training can be implemented as an rApp, while inference as an xApp, located in the non and near RT RICs, respectively. In this sense, xApp decisions would be triggered by real-time information provided by either DU/CU, exploiting the knowledge of the model trained with more general sensing information.

- Option 3: Online training and online inference where both ML training and inference are performed at the edge using limited (local) information, mitigating privacy risks. In this case, a possible deployment is the implementation of the whole AI/ML functionality (i.e. training and inference) as an xApp. As in the previous case, actions would be triggered by real-time information (i.e. notifications), while decisions would be based only on local data.
- Option 4: Distributed training and online inference. This approach, also known as Federated Learning (FL), combines the benefits of Option 2 and 3 as it allows multiple AI/ML entities to train an ML model collaboratively, whereas inference is performed at the edge. Instead of gathering training data into a central server, FL keeps the training data decentralized to mitigate privacy risks. AI/ML models are trained locally in distributed entities, and the local models are aggregated allowing distributed RAN optimization with locally cached data. For instance, data collection and training would take place in both the rApps in a non-real time manner (i.e. statistics, etc.), and in the xApps. Then, inference would be performed only by the xApp at the near-RT RIC. It would allow exploiting both previous and current information for real-time network management. In this case, management decisions would be triggered by either sensing information collected by the xApp, or by the combination of sensing and legacy control information.

### 6.3 Multi-Access Edge Computing

MEC [51] focuses on enhancing mobile networks by bringing storage, computing, and networking resources closer to the edge of the RAN. This architecture places commodity servers at the edge of the network, allowing them to handle tasks such as application execution and data processing. By positioning these resources closer to end-users, MEC significantly reduces latency and enables faster data transfers, as information no longer needs to travel to a centralized cloud for processing. This proximity improves RAN performances as it provides the necessary processing resources to support closed-loop control operations required by the RIC as shown in Figure 6-3, including:

1. Applications running at time scales of 1s or more usually executed at the SMO, known as rApps.
2. Applications running at time scales of 10ms to 1s executed at the Near-Real-Time, or Near-RT, RIC known as xApps.
3. Applications running at time scales of 1ms to 10ms, known as dApps, used to implement fine-grained data-driven management and control in real-time at the O-CU-CP/UP and O-DUs[2].

For example, an xApp hosted at MEC "can *automate the network monitoring process and provide real-time insights into the performance of the OpenRAN network. It can detect network anomalies, identify performance bottlenecks, and provide network operators with real-time alerts and notifications. xApp can be also used to optimise the energy efficiency of the network the energy consumption patterns of different network elements and identifying opportunities for energy savings*"[3]. Similarly, a dApp can be used in real time to process IQ sensing streams and make estimates for the position of a target.

MEC servers can be also used to host end-user applications providing real time data and reducing latency for video streaming, gaming, and IoT services, while also alleviating the load on CN infrastructure.

[2] https://moniem-tech.com/2024/10/06/what-are-dapps-in-oran-architecture/

[3] https://accelleran.com/xapp-rapp-2/2/

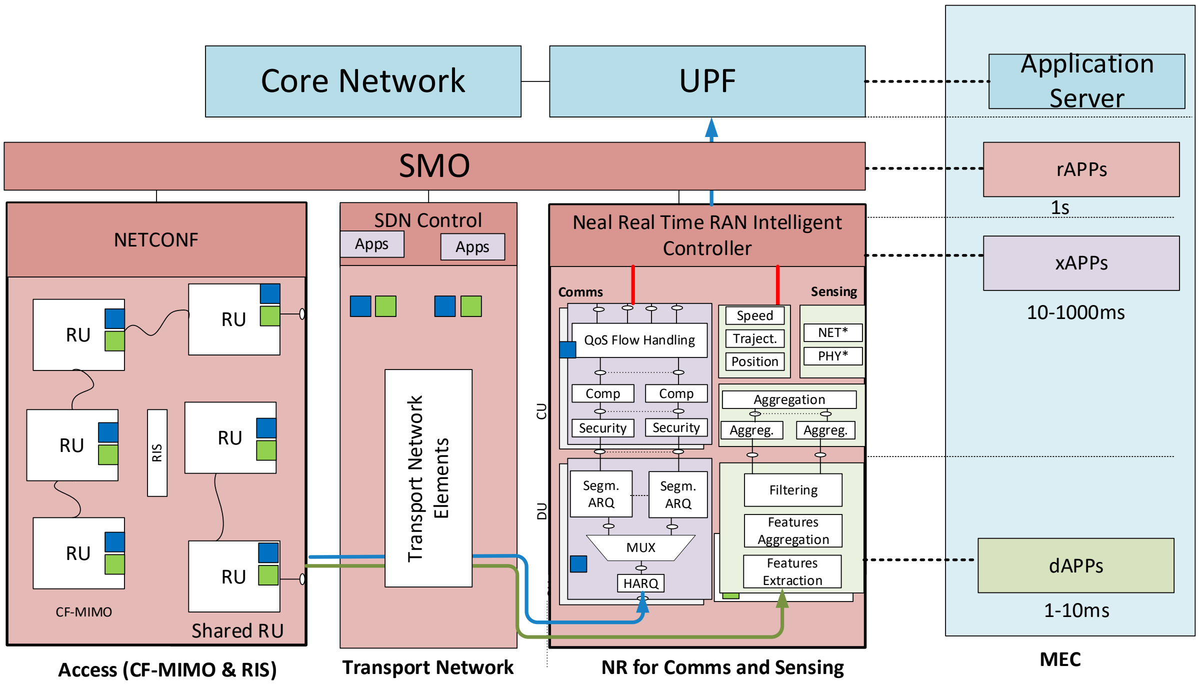



**Figure 6-3 MEC supporting different services in 6G-SENSES**

Mobility plays a crucial role in addressing the challenges of caching within wireless networks, especially in dynamic environments where users are constantly on the move. An effective caching strategy should go beyond simply storing frequently accessed data closer to the user, it must also anticipate user mobility and proactively relocate cached data to different edge nodes based on predictive models on the movement of the user. By doing so, the system can ensure that relevant data remains accessible as users transition between different cells or network areas.

This proactive approach can significantly enhance Mobile Edge Caching strategies by ensuring seamless session continuity, even during user handovers between different network cells. As a result, users experience lower E2E latency and improved service quality; this is particularly beneficial for latency-sensitive applications such as video streaming, gaming, or real-time communication. Predictive caching mechanisms not only optimize resource allocation but also reduce the likelihood of interruptions, making mobile services more reliable and responsive in dynamic network environments.

Specifically, for sensing applications, proactive Mobile Edge Caching strategies (Figure 6-4) will be used to solve the sensing service continuity problem.

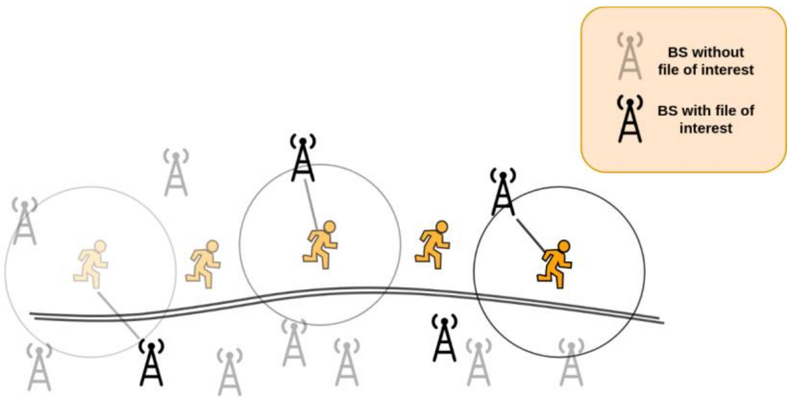



**Figure 6-4 Mobile Edge Caching application in execution**

# 7 Preliminary Architecture Evaluation

This chapter presents initial activities carried out towards the evaluation of various elements of the 6G-SENSES architecture and some initial results produced in this context. A more detailed evaluation framework and relevant results will be reported in deliverable **D2.3** "6G-SENSES architecture evaluation and benchmarking".

## 7.1 Multi-WAT interfacing

We consider a multi-RAT environment that integrates both 5G RAN and non-3GPP connectivity, as illustrated in Figure 4-5. The setup consists of a single 5G gNB and a Wi-Fi AP, enabling multi-RAT positioning. The UE is equipped with both 5G and Wi-Fi modules, allowing it to collect signal measurements from both technologies. The set of access nodes is defined as $B=\{b_{5G}, b_{WiFi}\}$, where $b_{5G}$ represents the gNB and $b_{WiFi}$ the Wi-Fi AP. To obtain real-time signal data, an xApp periodically sends measurement requests to the near RT-RIC to retrieve signal strength indicators from both networks. These measurements are then used for fingerprint-based positioning.

Fingerprint positioning is based on collecting signal characteristics at different locations and then match them with real-time data to estimate the location of the device. This is executed in a two-step process: 1) an offline phase that includes the creation of fingerprint database, and 2) an online phase where the real-time positioning takes place. During the offline phase, a predefined physical location (where the positioning will take place) is depicted as a grid with multiple reference points (RPs), where each RP acts as a ground truth location to train the system. The set of RPs is denoted as $RP=\{rp_1, rp_2, ...\}$ with each RP, $rp_i$, having known coordinates $(x_i,y_i)$. At every $rp_i$, the xApp collects signal measurements from both the 5G gNB and the Wi-Fi AP (SNR, RSSP, RSSI, etc.) at fixed time intervals. Then, the signal measurements, along with the corresponding $rp_i$, form a record $F_{p,r,i}=\{p_i, SM_{gNB}, SM_{WiFi}\}$ that is stored in a fingerprint database (radio-map).

The online phase follows once the fingerprint database is ready, where based on actual real-time signal measurements generated from the UE, the estimation of its location takes place. The UE captures its signal parameters (5G/Wi-Fi) in a location that is unaware of, and sends them to the location where the positioning algorithm is executed (fingerprint database). These metrics are then compared with the radio-map measurements) and, finally, the system makes an estimation for the position of the device based on the closest fingerprint match. If multiple locations are similar, weighted averaging or interpolation is used to refine accuracy.

For the execution of the fingerprint positioning algorithm, we begin by dividing a predefined space into multiple grid points (as shown in Figure 7-1). This space covers 4 meters in length and 3 meters in width, and it is divided into 12 RPs, with equal distances between them. In our setup, the Wi-Fi AP and the gNB – based on OpenAirInterface (OAI) – are positioned at opposite ends of the grid. The UE used in this experiment was a Quectel device along with a Commercial Off-The-Shelf (COTS) UE that connects to the non-3GPP network.

To build the radio-map (or offline database), we collect multiple signal measurements from each RP, from both the Wi-Fi and 5G networks. Specifically, the 5G signal metrics captured by the Quectel UE are forwarded to the RIC via the E2 interface. For the Wi-Fi part, the COTS UE is used collocated with the Quectel device, as the latter lacks a Wi-Fi Network Interface Card (NIC). The AP records the received signal strength from the connected device, and these metrics are exposed to the RIC. This procedure can be carried out using one of the three approaches discussed in Section 4.2.1.2.

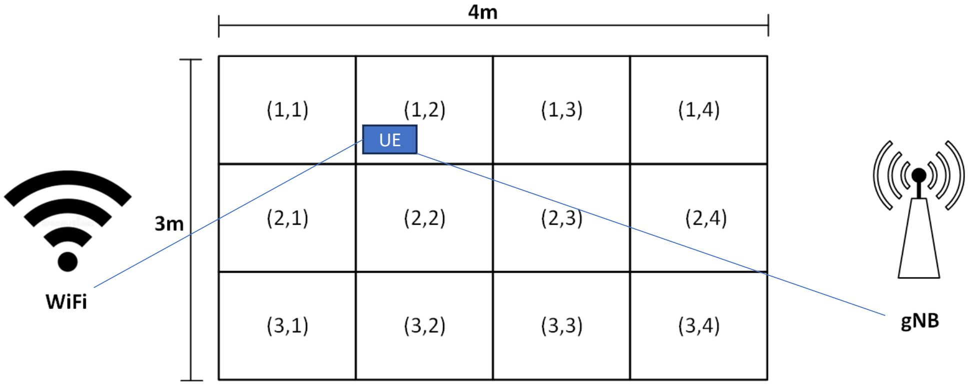



**Figure 7-1 Fingerprint localization**

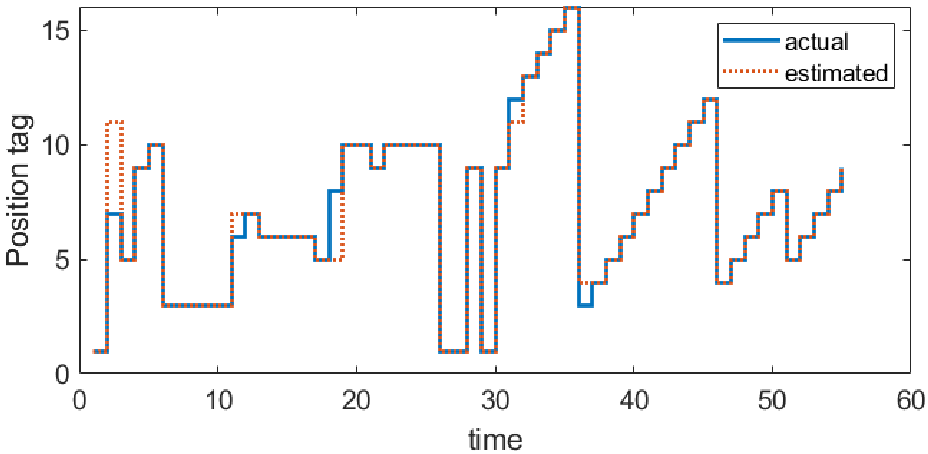



**Figure 7-2 Actual and xApp based estimated trajectories for a UE**

For the Wi-Fi part, the AP (model) captures the received signal strength of the connected device and the metrics are then exposed to the RIC. This procedure has been implemented exposing Wi-Fi measurements to the RIC through an E2 agent built on top of the N3IWF protocol stack. Once the signal measurements from both ANs have reached RIC, they are stored in the in-memory creating an RF map with multi-technology RAN measurements. The RF map is then used to train a Support Vector Machine (SVM) classification ML model. The training ML models is ported in an xApp that uses as input real time RF measurements which are then mapped into position IDs.

The corresponding results for a moving UE are provided in Figure 7-2, where the actual and the estimated positions utilizing Wi-Fi and gNB CSI measurements are illustrated.

### 7.2 ISAC lab implementation and evaluation

6G-SENSES proposes a 6G architecture that interconnects a multi-technology RAN able to offer sensing functionalities (3GPP and non-3GPP) with CN domains through an advanced transport network, to facilitate joint support of sensing and communication services.

Sensing is performed based on the principle of a distributed passive wireless radar considering a monostatic sensing scheme, as presented for the Sub-6 and mmWave WATs in sections 4.1.2 and 4.1.3. Extension of the ISAC platforms to support bistatic sensing are considered for the remaining of the duration of the project, and they could potentially play a role in 6G-SENSES PoC#1.

In the first place, the multi-technology RUs will generate communication signals reflected on “objects” located in the surrounding area, creating IQ echo streams. A sample of the IQ echo streams – depending of the signals of interest per WAT – are transmitted in the form of UL FH streams to the O-DU (in the case of the O-RUs) and as a collection of metrics from the WATs to the Near-RT RIC from non-3GPP WATs, either periodically or after pre-defined trigger events. The sensing app (xApp) output can be passed to the network orchestrator that decides the optimal network resource configuration to support both communication and sensing services.

Currently, the standard defines guidelines to monitor the Key Performance Measurements (E2SM KPM) provided to the xApps [16]. However, these are limited upper-layer metrics to optimize scheduling policies or RAN slicing [9]. We propose enhancements with a novel SM that enables the E2 interface to transmit sensing-specific measurements or signals, broadening the utility model of the service.

The WATs will be equipped with SDN-based control interfaces that will be exposed to an SDN controller residing in the SMO/MANO layer. It will permit the reconfiguration of the communication and sensing capabilities of the multi-WAT RUs at a large time scale according to the scenario characteristics. Sensing-assisted management will be implemented as xApps, located at the near-RT RIC, able to fine-tune the operation of the gNBs in a more time strict manner. These applications will leverage the gathered sensing information, along with legacy network data, to optimize the usage of radio resources by the O-RUs.

### 7.3 ISAC based transport network optimization

This section experimentally validates an architecture exploiting an optical transport network interconnecting RAN and CN domains, to facilitate joint support of sensing and communication services in accordance with the 6G-SENSES vision

The system architecture considered in this study (Figure 7-3) exploits an optoelectronic transport network interconnecting the RAN with the CN functions located at the MEC. The hierarchical structure of the proposed architecture offers RAN connectivity and collects and aggregates transport network and sensing traffic streams from the BSs, while it transports these to the servers (shown in green). Both the RAN and aggregation transport network segments are implemented through multi-vendor SDN-controlled optoelectronic switches with different capabilities (port no, capacity per port & latency). The access network is equipped with low energy consuming switching nodes with limited number of input ports and relatively small capacity (1/10GbE/port). The aggregation transport network comprises high-end optoelectronic and all-optical fast switches with higher capacity and density (10G/40G/100GbE/ports), offering much higher energy efficiency. All-optical fast switches are a key enabler that facilitates transparent routing of IQ sensing flows to the MEC servers needed to achieve acceptable transport delays. For the RAN segment, a SDR platform (based on USRP B210 and N310) transmitting 5G NR OFDM modulated signals is used (Figure 7-3-②) to support the functionality of RUs. For the compute domain, edge servers attached to the access switches and central cloud servers connected to the aggregation/core switches are adopted. These servers are used to host containerized RAN elements (i.e. DU/ CU) and sensing functions (storage of IQ echoes and processing). The sensing app implements a passive OFDM-based radar [54] that uses as input, signals reflected on objects in the surrounding area, when connectivity between BSs and UEs is established. The sensing app evaluates the quality of the reflected signals captured per BS and, if these are above a specific Signal-to-Noise-Ratio (SNR) threshold, they are used to estimate the position of the corresponding object. These results are then communicated to the E2E orchestrator that calculates the optimal resource allocation policy needed to accommodate both communication and sensing services. This is achieved by identifying the appropriate capacity for the paths implementing “RU-DU-CU” and “RU-Sensing” function connectivity, executed by the SDN transport network controller. Finally, for the wireless channel, a dedicated virtual machine has been deployed hosting the open-source GNU Radio platform, emulating channel impairments and objects in the surrounding area using the “Noise Source” and “Static Target Simulator” blocks, respectively [55]. Sensing

Information exchange between different system building blocks is based on ZeroMQ messaging platform [56].

To evaluate the performance of the proposed architectural approach and technical implementation an optimization framework has been designed and deployed in the testbed of Figure 7-3. This framework tries to minimize the number of network links used by identifying the optimal routing and network capacity allocation policies under communication (fronthaul, backhaul) and sensing flow (IQ echo streams) traffic requests. This problem is solved considering the following parameters and constraints:

(*1) The characteristics of* the optical transport network and compute servers including number of nodes, connectivity graph, and capacity.

(*2) The characteristics of* the RAN and mobile core segments including deployment option for the mobile communication (location of RU, DU, CU, UPF elements) and its operational parameters (spectrum allocation, numerology).

(3) *The received signal strength* of the echoes captured by the various BSs. This last parameter is quite important, as received signals with low SNR cannot be exploited by the sensing app in the estimation of the object location. To reduce unnecessary overheads, the model considers as input sensing streams captured by BSs with SNRs exceeding a predefined SNR threshold ($\mathrm{SNR_{th}}$). $\mathrm{SNR_{th}}$ depends on several parameters such as transmission conditions, the environment where the system is installed, the location of the RUs, etc., and can be experimentally precomputed. A typical numerical example is shown in the left column of Figure 7-3-③, illustrating the spectrograms of the received IQ streams at BS2 and BS3 when their distance from the object is 200 and 400 m, respectively. From the same figure we observe (right column) that for objects closely located to a BS (case of BS2) the received SNR is high and, therefore, the object can be detected with high accuracy. However, as the object-BS distance increases, the received SNR is reduced, reducing also the track detection accuracy. The object detection accuracy can be further improved combining estimations from multiple BSs [57].

(4) *The capacity requirements* for the sensing and communication traffic flow. For the sensing flows, these requirements increase with the number of BSs involved in the sensing process collecting and transmitting IQ echo streams. A typical set of measurements for IQ streams collected for 10MHz bandwidth allocation in the wireless segment (OFDM modulated) is shown in Figure 7-3-④. This set of measurements shows the throughput of the IQ streams forwarded by "BS3", "BS3-BS2" and "BS3-BS2-BS1" to the edge server #1. For the fronthaul and backhaul requirements (due to space limitations) the reader is referred to [8] providing a detailed discussion.

(5) *Delay requirements for the sensing streams.* To handle this, sensing flows are transparently transported to the sensing servers through the all-optical transport network switch, acting as an IQ sensing switch, eliminating transmission delays introduced by optoelectronic devices. The use of the all-optical switch is a key enable that allows to maintain the overall transport delay acceptable.

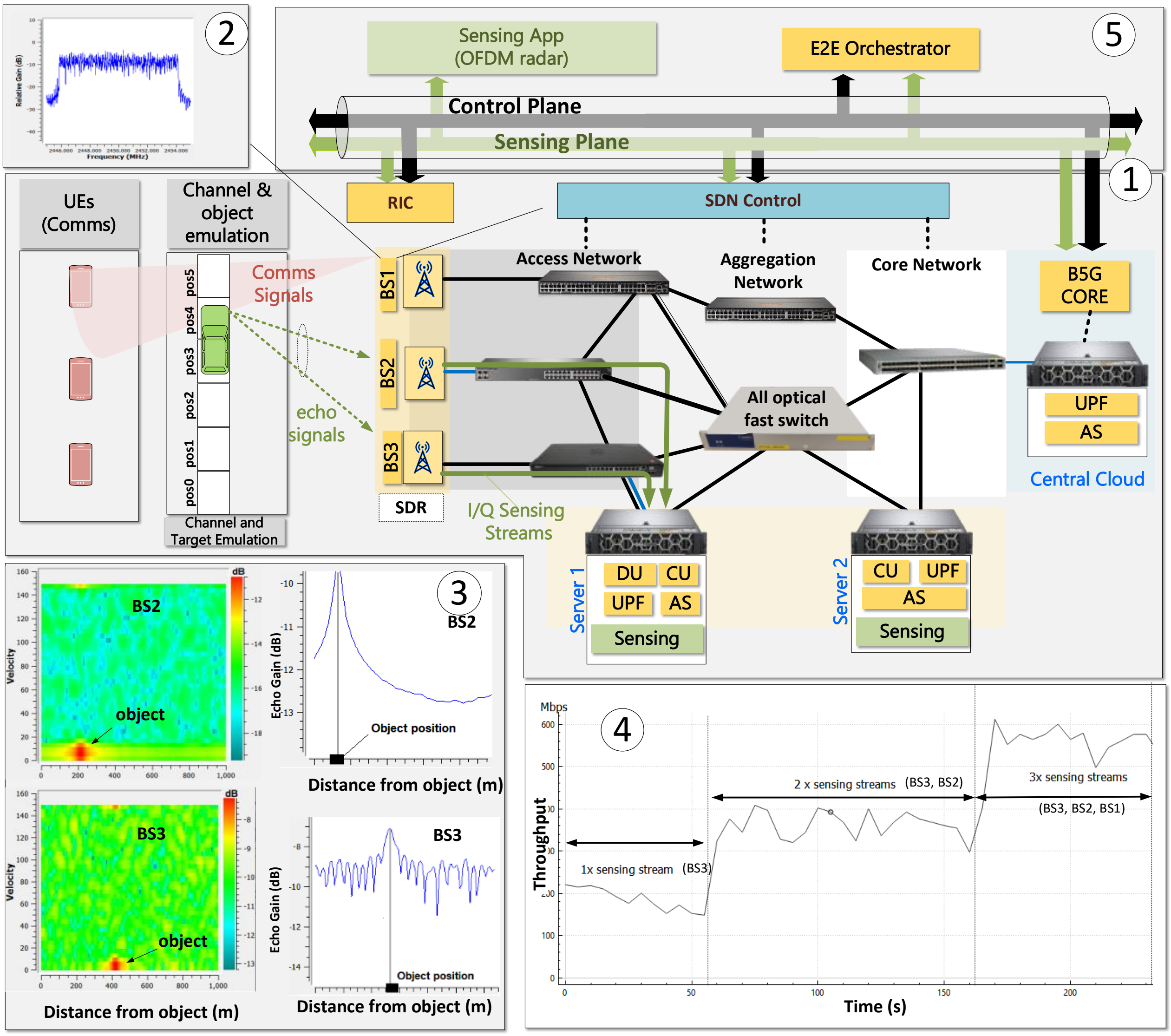



**Figure 7-3 ① Optical Transport network supporting ISAC ② Transmitted 5G-NR compliant OFDM signal ③ (left) Object detection using the echoes at BS2 and BS3. (right) Echoes used for the estimation of the object from BS2 and BS3, ④ Echo streams from various BSs directed to server 1. ⑤ Sensing information exchange between the sensing app and network orchestrator**

The proposed scheme is evaluated for the topology of Figure 7-3-① considering an object located at different positions. We evaluate three different management policies:

a) "single" echo approach, where IQ signals captured by the BS with the strongest SNR are transmitted to the sensing app,

b) "optimal" dynamic approach considering echoes with SNR exceeding a specific threshold, and

c) "all-active" approach using echoes from all BSs. IQ streams for communication services coexist with sensing streams.

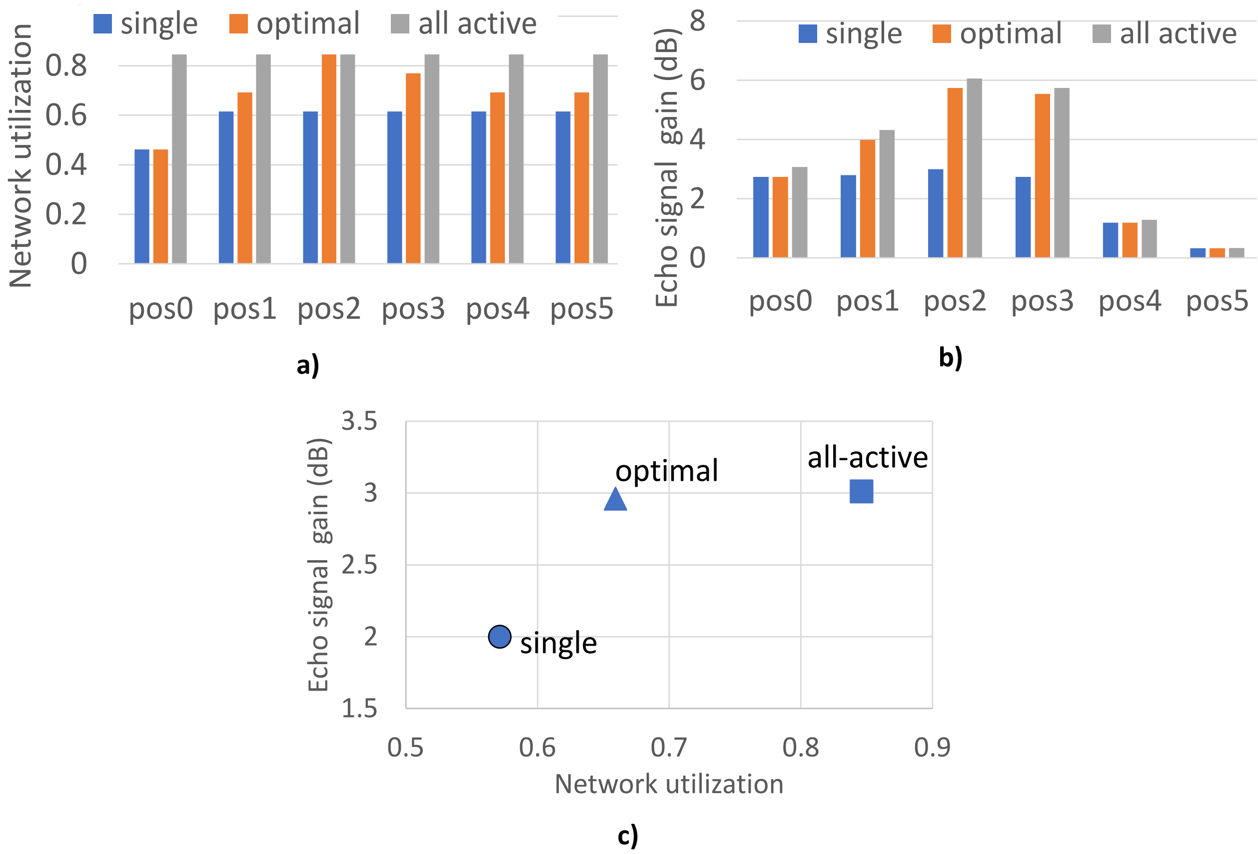



**Figure 7-4 (a) Network utilization vs object position for different ISAC optimization policies b) Sensing accuracy (measured through echo signal margin) vs object positions. (c) Echo signals strength vs network utilization**

Figure 7-4 a) and b) compare the transport network utilization (ratio of links used vs total available links) and received echo SNR, respectively, for different object positions and ISAC optimization policies. In the “optimal” approach, the selected echoes are dynamically routed to the sensing server. Optimal routing paths are calculated by the E2E orchestrator and executed by the transport network SDN controller. The “optimal” approach has higher network requirements compared to the “single” echo (~15%) and it is 30% more efficient than the static “all-active” approach. As shown in Figure 7-4 c), illustrating the sensing accuracy of all schemes, the “optimal” scheme receives echoes of similar SNR with the “all-active” approach, while requiring 50% less network resources.

### 7.4 Wi-Fi-60 GHz sensing experimental validation

To evaluate the capabilities of a Wi-Fi 60 GHz sensing solution, a numerical simulation is conducted. Using the WLAN software tool in MATLAB, the wideband mmWave sensing scenario is simulated by extending the legacy IEEE 802.11ay E2E PHY layer protocol. An Imaging Wi-Fi radar framework for multiple human monostatic sensing is built with a modified IEEE 802.11ay protocol (integrating OFDM and legacy EDMG CEF waveforms). As shown in Figure 7-5, the indoor two-human monostatic sensing channel is implemented with ray tracing, adopting the IEEE TGay Q-D channel model and the human Boulic model.

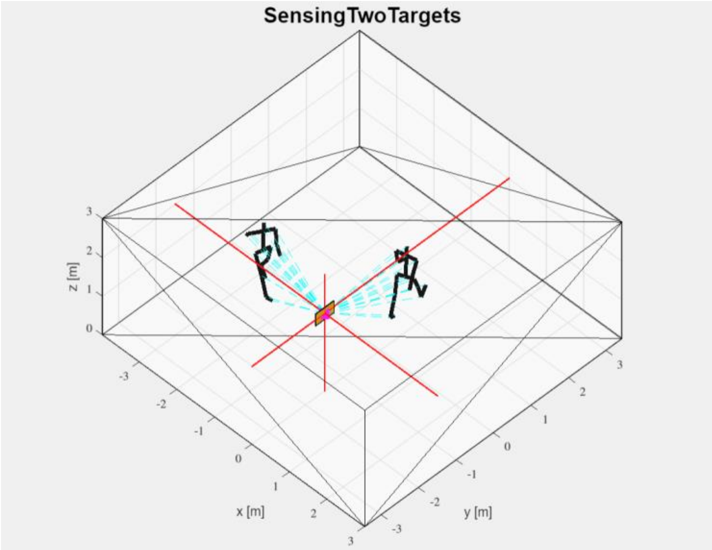



**Figure 7-5 The indoor two human monostatic sensing channel with ray tracing**

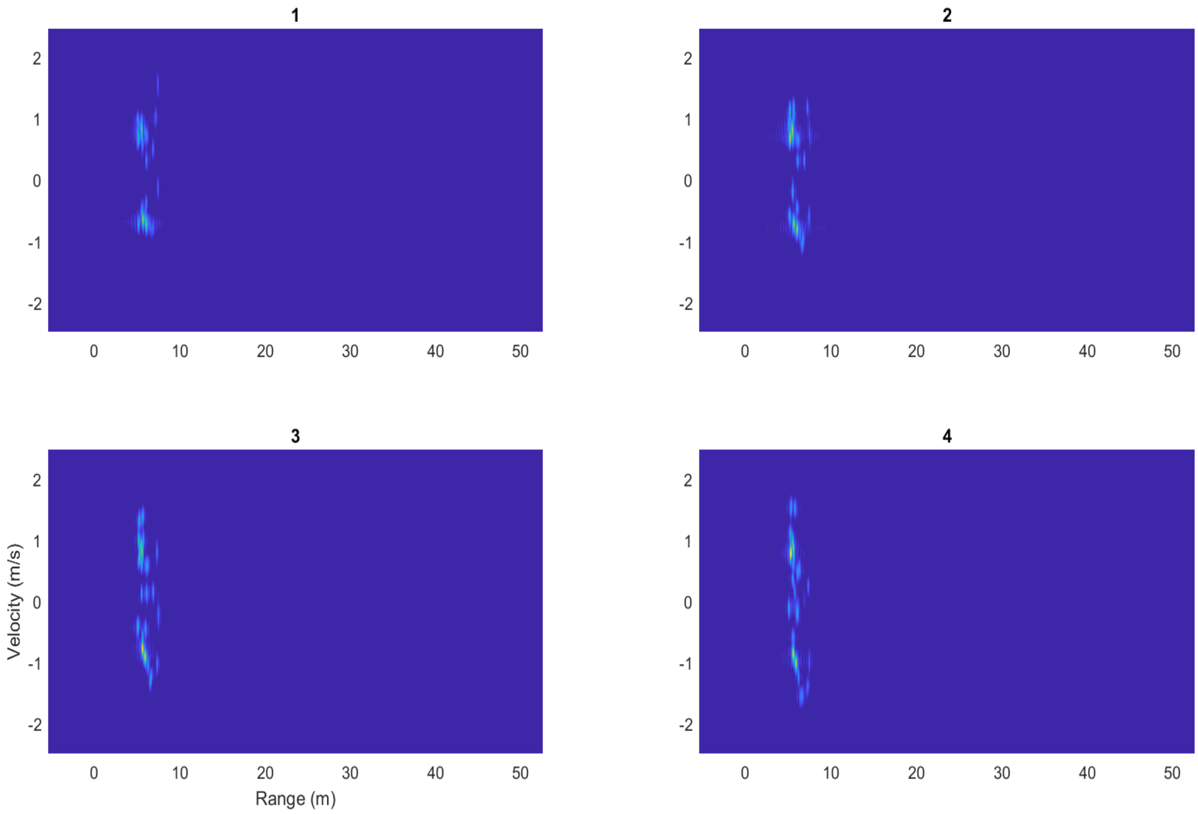



**Figure 7-6 2D Range-Doppler Map of the Wi-Fi two Human sensing at SNR=20 dB**

At the receiver side, the channel state information is estimated based on the legacy DEMG-CEF sequences. Thus, the classic radar sensing processing procedure is further performed on the acquired channel state information. Herein, the SNR value within the mmWave Wi-Fi radar framework is configured as 20 dB. Figure 7-6 shows that the positive and negative peaks within the 2D Range-Doppler Map correspond to the two human walking velocities. The imaging results of the mmWave Wi-Fi radar closely match the simulated indoor two-human walking scenario, where one person walks toward and away from the PC with a concurrent Wi-Fi transceiver at 1.1 meters per second.

### 7.5 CF-mMIMO evaluation studies

This section studies the tradeoffs between the different multiple access techniques when they are applied to the CF network architecture taking FH constraints into account.

Existing work highlights the potential of Rate-Splitting Multiple Access (RSMA) for future mobile networks and this is summarized by two tutorial and survey papers [63], [64] providing a comprehensive overview of RSMA including comparisons with Orthogonal Multiple Access (OMA), Non-Orthogonal Multiple Access (NOMA) and Spatial Division Multiple Access (SDMA). In addition, a recent overview of next generation multiple access technologies is provided in [65].

The combination of RS and cloud RAN is studied in [66]. Statistical CSI at the transmitter is considered and the problem of stochastic coordinated beamforming for ergodic sum rate maximization is proposed and solved. A gain of up to 27% of RS compared to TIN and NOMA is reported. The combination of RS at the AP to improve the achievable data rates of the wireless connection is performed in [67] for specific beamformers and in terms of sum rate. In [68] max-min power control for RS in cell-free MIMO is performed. Robustness against pilot contamination is reported. Finally, asynchronous CF-mMIMO with RS and its robustness against hardware impairments are reported in [69]. In [70], joint fronthaul load balancing and compute resource allocation is performed.

However, there does not exist a solid understanding of the tradeoffs between the different multiple access techniques when they are applied to the cell-free network architecture taking fronthaul constraints into account. The two studies [71], [73] deal with the optimisation of cell-free massive MIMO (CF-mMIMO) systems, with the first study focusing on user assignment and the second study on rate splitting. The first study proposes an unsupervised ML approach with a hierarchical permutation-equivariant (HPE) graph neural network (GNN) to solve the assignment problem between access points (APs) and users. The study addresses the challenges of mmWave CF-mMIMO, such as the high path loss, the limited output power of the amplifiers, and the combinatorial nature of the assignment problem, and uses the Augmented Lagrangian Method (ALM) for training the GNN. The second study investigates the combination of Rate Splitting Multiple Access (RSMA) with CF networks, where RS is applied on the central processing unit (CPU) to optimise the fronthaul rate constraints. It shows that the proposed adaptive RS method outperforms baseline as well as current multiple access schemes and highlights the benefits of jointly optimising fronthaul and wireless access schemes.

While we have described the novel RS approach in [3], we focus here on the scalability of the AP-UE assignment from a system-level perspective. Given the hardware and channel properties, optimizing mmWave CF-mMIMO is primarily an assignment problem between AP and users. Sophisticated precoding techniques, such as ZF and MMSE, are neither feasible (due to the immature hardware) nor indispensable (the spectral efficiency is not as crucial as in lower frequencies given a very large bandwidth).

Instead, conjugate precoding is more feasible with simple hardware, realizes high antenna gain given many antennas, and reduces interference significantly because multi-user channels become asymptotically orthogonal as the number of antennas increases [74]. Moreover, transmit power control is not necessary because the optimal transmit power is always the maximum available power given the high path loss for typical objectives.

In the literature, a mixed-integer programming problem for CF fronthaul resource allocation is considered in [70]. AP and pilots are assigned in a rule-based, distributed way in [75]. An alternative selection method is proposed for AP-user assignment in [76]. The block-sparsity norm is applied to optimize AP-user assignment and power control simultaneously in [77]. The pilot assignment problem is considered based on serving set in [78].

It can be concluded from the above that the assignment problem in CF optimization is difficult to solve due to its non-differentiability. The existing algorithms are either heuristic or do not scale well. Therefore, in [73] we propose a model-based ML approach to optimize the assignment between AP and users using a customized GNN. Compared to existing works, the proposed solution is unsupervised (i.e., it does not need correct labels) and model based. We propose a customized HPE [79] GNN, i.e., any permutation of AP and users leads to the same permutation of the solution. Moreover, data traffic in the fronthaul between AP (i.e., message passing between nodes of the GNN) is reduced significantly compared to the canonical GNN. We relax the original combinatorial problem to a continuous one, design a penalty inspired by information entropy to enforce discreteness, and apply the ALM for training. Beyond the AP-user assignment problem, this work is an early contribution to unsupervised ML for general scalable combinatorial optimization problems.

For illustration, we consider a small-scale and a large-scale scenario in Figure 7-7.

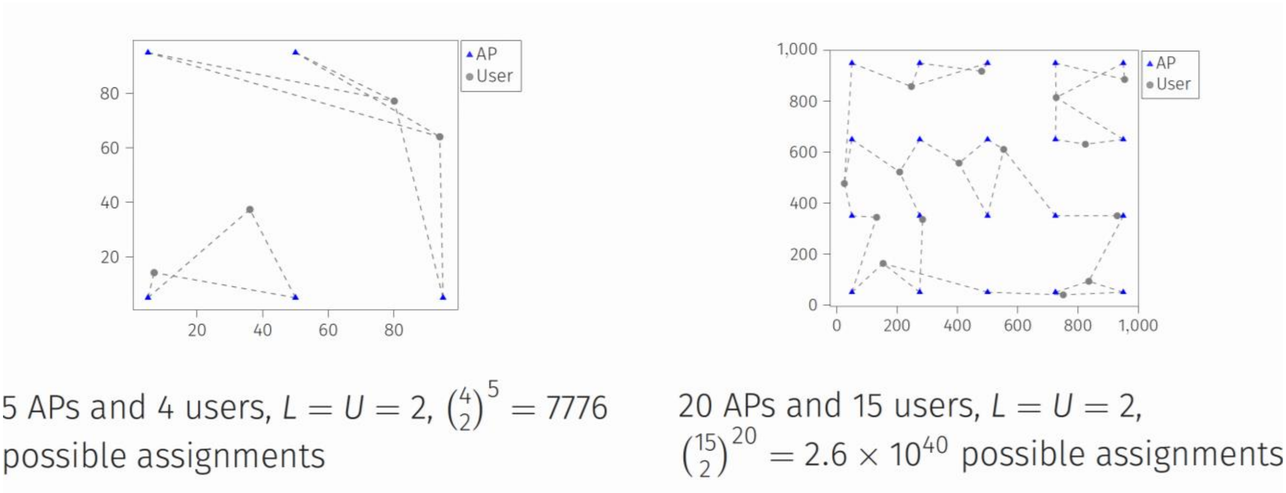



**Figure 7-7 Visualization of AP-user assignment in two scenarios.**

Table 7-1 represents a comparison of sum spectral efficiency obtained with the proposed method, an upper bound (found via exhaustive search), the average performance of 100 random assignments, and two heuristic baseline algorithms: the GSD algorithm [80] and the mu-mechanism [81].

When performing an exhaustive search, we evaluate all possible assignments while considering the binary, the upper and lower quota constraints. This results in 7776 and 2.6 $10^{40}$ assignments in the small and large network scenarios, respectively. The proposed method achieves a performance very close to the upper bound in the small network scenario, whereas the upper bound cannot be calculated in the large network scenario due to limited memory and time.

In both scenarios, the proposed method outperforms the random assignment and two baseline algorithms because the two baseline algorithms are heuristic and therefore suboptimal. Note that algorithms with proven optimality, such as branch-and-bound, do not scale well to large problems. Therefore, they are not chosen as baselines. Additionally, the proposed method provides a solution within a few milliseconds with reduced data traffic in fronthaul and without a centralized processing unit, indicating potential for real-time application. Furthermore, we apply the model trained for the large scenario to the small scenario. It achieves a sum spectral efficiency of 1.03 bit/s/Hz, which is roughly in line with baselines GSD and mu-mechanism, indicating the potential of generalizability of the proposed solution.

**Table 7-1 Achieved sum spectral efficiencies (bit/Hz/s) of proposed method and baselines**

| | Small scenario | Large scenario |
|---|---|---|
| Proposed | 1.14 | 3.67 |
| Upper bound | 1.15 | Not available |
| Random | 0.60 | 0.51 |
| GSD | 1.06 | 3.34 |
| $\mu_R$ | 1.07 | 3.36 |

### 7.6 Improved MAC scheduling

As an illustrative and preliminary example of how the use of AI/ML can be integrated within the proposed 6G-SENSES architecture that was introduced earlier in this document, we include herewith an example of an xApp, which leverages DRL to dynamically tune the operation of a MAC scheduler that allocates PRBs to users based on their specific QoS requirement, link quality and the type of traffic.

The proposed MAC scheduler, so-called Drift-Plus-Penalty (DPP), which was originally introduced in [82], is based on control theory. DPP uses a set of parameters to tune its operation, which seeks jointly keep delay and throughput requirements, while minimizing the allocated resources.

Figure 7-13 shows throughput yielded by the scheduler over time with different static configurations. In particular, we fix the parameter, $V$, which strengthens the reduction of allocated resources (resource efficiency), $\omega_Q$, which focuses on the delay, and $\omega_G$, whose main goal is to ensure the throughput requirement is met. The scenario comprises a number of UEs sending XR traffic, in particular, Virtual Reality (VR) and Cloud Gaming (CG). The dashed lines correspond to the throughput target for each traffic type, and the shaded areas correspond to situations where the channel conditions were worsened. In the different situations, the labelled circles (A, B and C) correspond to regions where the performance of the scheduled might be more clearly affected by the particular scheduler configuration. As can be observed the scheduler behavior is highly impacted by the parameters which should be tackles according to the specific scenario characteristics.

To optimize the scheduler behavior over time, according to the specific scenario characteristics, DRL could be applied following the architecture shown in Figure 7-14. The DRL agent is implemented as an xApp which tweaks the scheduler configuration be changing its weights. The implementation would correspond to option 3 from Section 6.2. This way, the DRL agent would get acquainted of the environment through both sensing and control information, and decisions would be sent through the E2 interface. Then, the learning would be performed by measuring the impact of the decisions over the system performance.

### 7.7 6G CF Multi-Function Reconfigurable Metasurfaces Communications evaluation

The integration of DT technology with CF reconfigurable metasurfaces (CFRM) presents a transformative approach to addressing the stringent demands of 6G wireless communication networks. CF-mMIMO and CFRM offer an energy- and hardware-efficient solution but introduce significant challenges in data management, resource allocation, and network optimization. DT serves as a virtualized framework that enables real-time simulation, analysis, and optimization of CFRM systems, enhancing network performance.

A DT-enabled CFRM communications framework is proposed with three primary contributions. First, a general DT-enabled CFRM architecture is developed, incorporating an interactive DT system that continuously updates network parameters. This approach enables the intelligent deployment of RIS/ reconfigurable holographic surfaces (RHS) elements, improving coverage and capacity while optimizing hybrid beamforming and resource orchestration for real-time adaptive network management. Second, the application of DT in CFRM use cases is explored. The framework enhances RIS/RHS deployment optimization through DT-based simulations that determine optimal placement strategies for reconfigurable metasurfaces. Hybrid beamforming optimization is achieved through AI-powered beamforming techniques that reduce interference and maximize spectral efficiency. Additionally, DT is employed to allocate network, storage, and computing resources efficiently, enabling intelligent resource orchestration. Third, performance evaluation through simulations demonstrates that DT-based modeling significantly improves energy efficiency, optimizes beamforming, and enhances overall network performance.

The proposed DT-enabled CFRM framework integrates three layers: the PHY layer, which comprises CF-mMIMO, RIS/RHS elements, and APs for network deployment; the DT layer, which simulates network conditions using AI models and real-time feedback; and the application layer, which implements optimized deployment, scheduling, and AI-driven decision-making. We propose a DT-enabled CFRM communications architecture, with the following contributions:

- We present a general design architecture of DT-enabled CFRM communications, followed by key principles and features.
- The potential use cases of DT in CFRM communications as 6G key enablers are illustrated, including intelligent sites deployment, robust adaptive beamforming, model and resource orchestration.
- Open challenges and future research directions towards the design of RHS/RISs, robustness and explainability of application models in DT-enabled CFRM communications are presented.

Figure 7-8 provides a comprehensive overview of the system components and their interactions, illustrating how DT technology supports real-time adaptation and intelligent management.

Several case studies highlight the benefits of DT-enabled CFRM communications. One case study focuses on intelligent site deployment optimization, addressing the challenge of real-time adaptive deployment in CFRM networks. DT creates virtual replicas of the network, allowing for the prediction of optimal placement strategies for RIS/RHS elements. The results indicate that DT-enabled deployment reduces power consumption and enhances signal coverage. Figure 7-9 demonstrates the impact of site deployment optimization and how AI-powered DT simulations improve coverage and efficiency.

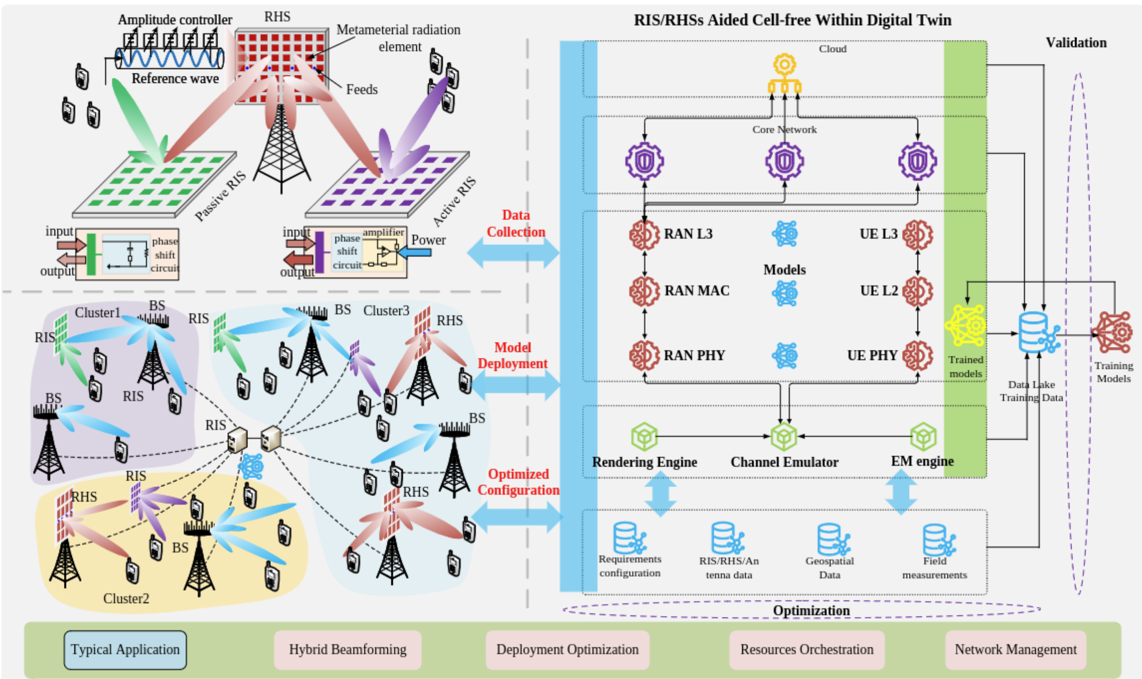



**Figure 7-8 The architecture of DT enabled 6G RHS wireless communications**

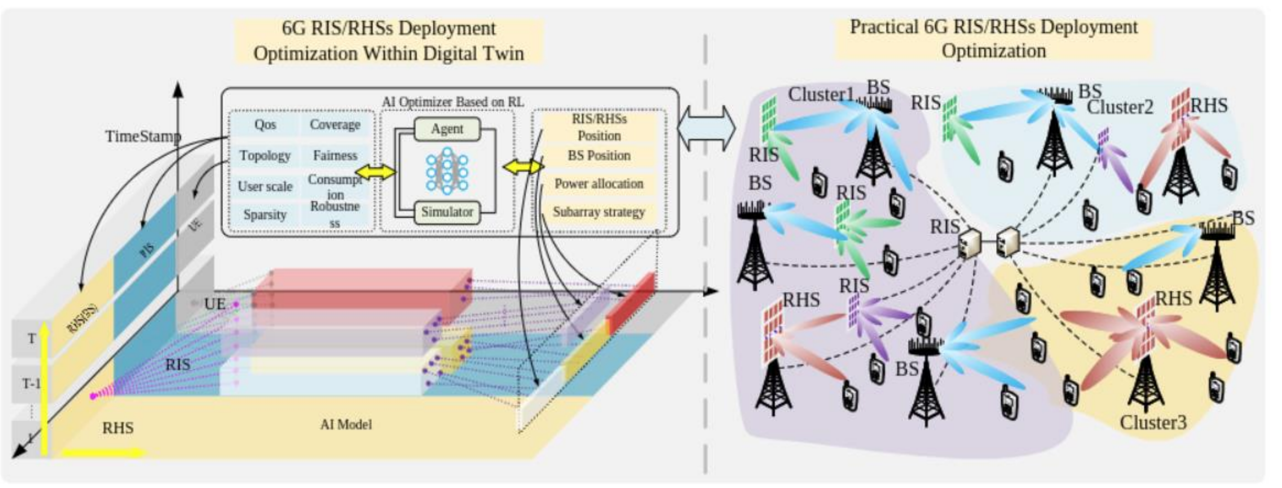


**Figure 7-9 The architecture of RHS/RIS deployment optimization based on dynamic DT and AI optimizer**

Another case study explores DT-enabled multi-agent RL for hybrid beamforming. Hybrid beamforming requires dynamic AI-driven optimization to enhance network performance. By integrating DT with multi-agent RL, beam management and traffic steering are improved, resulting in enhanced beamforming efficiency and signal quality. The RL-based beamforming process, shown Figure 7-10, illustrates how different agents optimize the formation and adaptation of beams in various environmental conditions.

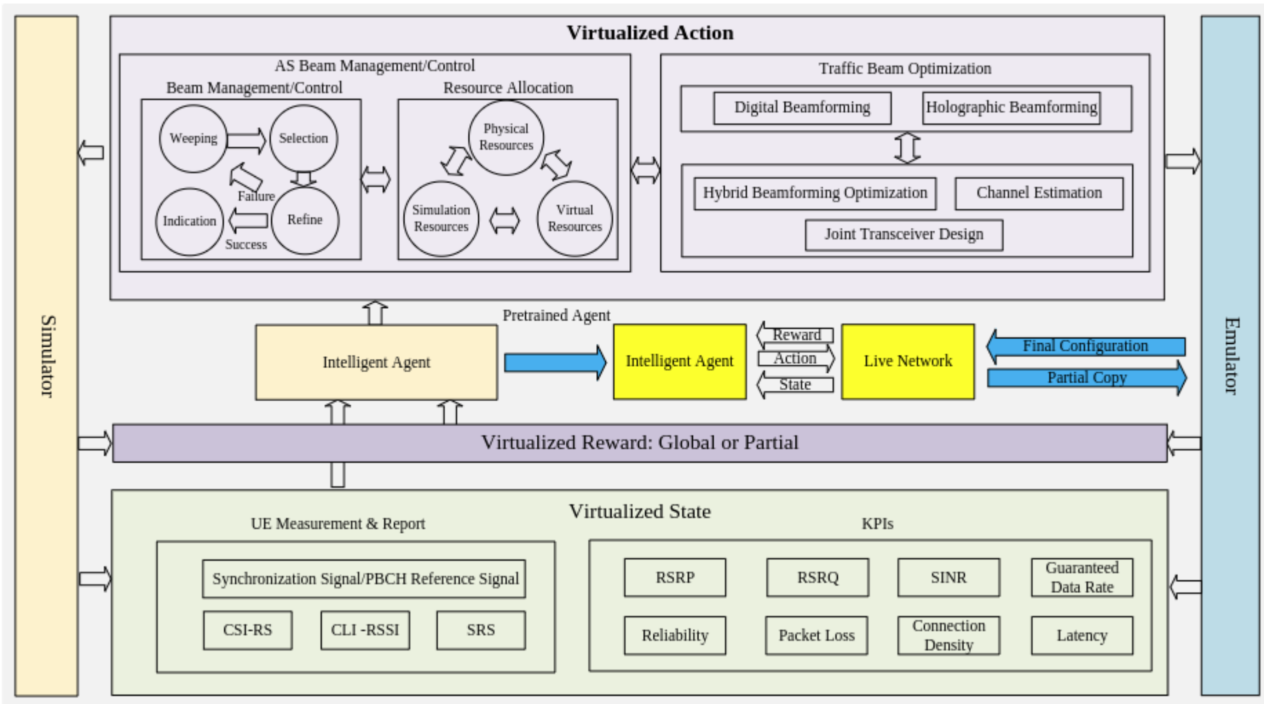


**Figure 7-10 The architecture of DT enabled multi-agent RL for hybrid beamforming optimization**

A third case study examines intelligent models and resource orchestration within the CFRM framework. Orchestrating large-scale heterogeneous resources such as data, storage, and computing power remains a challenge. DT-powered AI models dynamically allocate resources based on network demand, reducing latency and improving overall efficiency. Figure 7-11 provides an overview of intelligent function orchestration within DT-based CFRM, demonstrating how AI models interact with various network components to optimize performance.

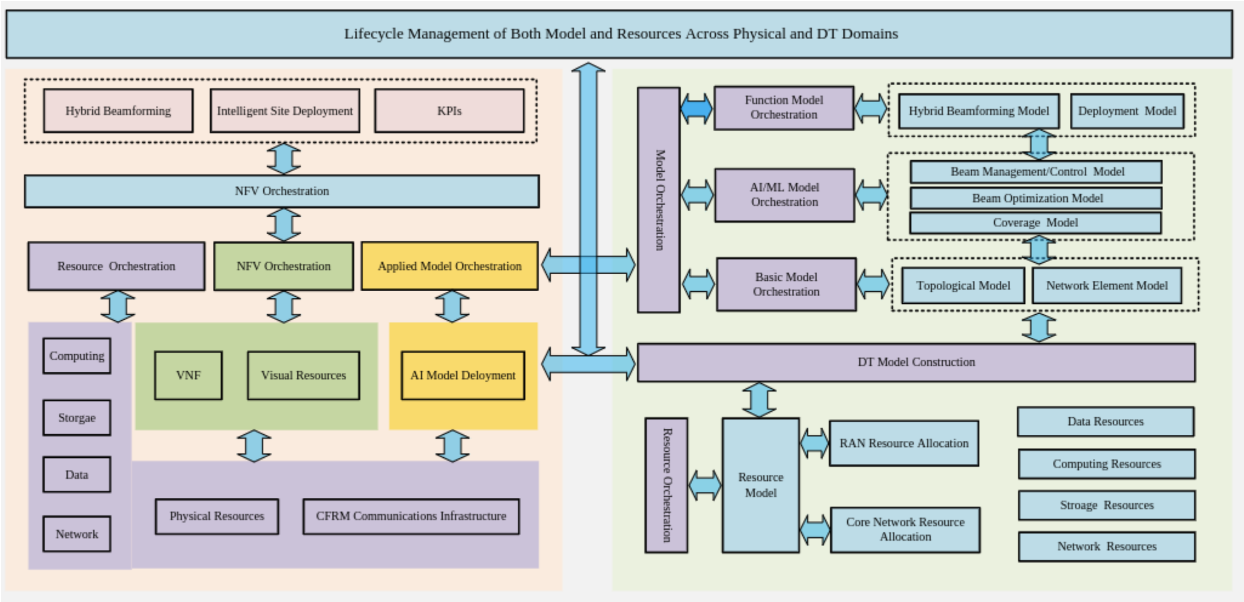



**Figure 7-11 LCM across physical and DT domains**

The evaluation of EE performance in active RIS-assisted CF architectures uses RL to optimize transmission strategies. Key findings indicate that larger RIS subarrays enhance energy efficiency up to an optimal point. There is a trade-off between RIS size, transmission power, and efficiency, with optimal efficiency achieved using a 64-element RIS and 10 dBm transmission power. However, efficiency declines at higher transmission power levels due to increased energy consumption. DT-based channel modeling, combined with ray tracing and RL agents, effectively trains AI models and optimizes network energy consumption. Figure 7-12 illustrates the relationship between energy efficiency performance and RIS subarray size in DT-enabled CFRM, showing how different configurations impact overall efficiency.

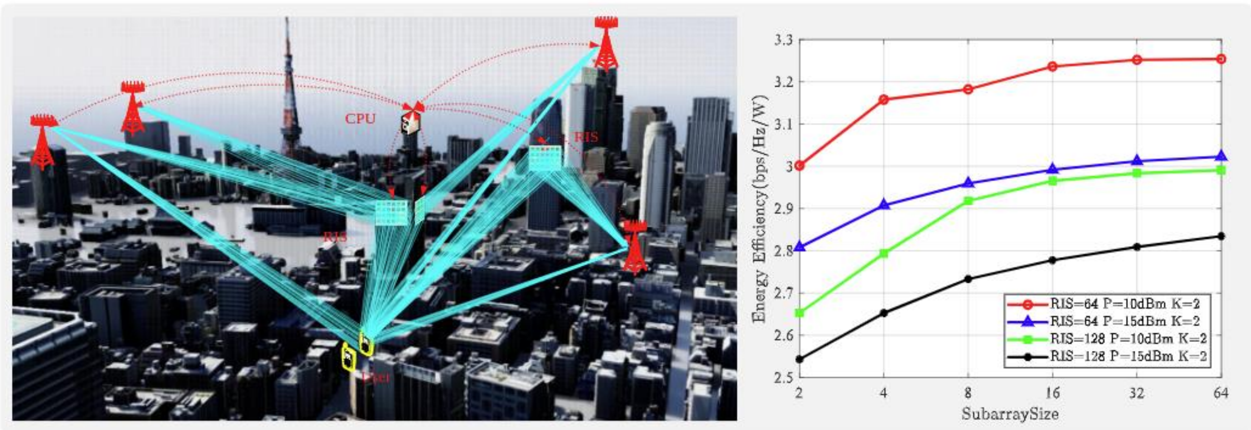



**Figure 7-12 The system average capacity of RL via different RISs subarray size within CF architecture**

Such study provides a comprehensive overview of DT-enabled CFRM communications, demonstrating its ability to optimize site deployment, hybrid beamforming, and resource orchestration. Simulation results validate the effectiveness of DT-based modeling in achieving energy-efficient 6G networks.

Despite its advantages, DT-enabled CFRM faces several challenges. The design and channel estimation of RHS/RIS require advanced structural designs and AI-powered estimation techniques to improve performance and reliability. Ensuring the robustness of AI models is crucial, particularly in adaptive hybrid beamforming and resource allocation. Furthermore, LCM for DT networks requires the development of automated AI-based orchestration techniques to optimize network operations. Addressing these challenges will be critical for achieving a fully optimized, AI-driven, and energy-efficient 6G communication framework. Future research should focus on improving AI robustness, channel estimation, and LCM within DT-integrated CFRM architectures. The integration of DT technology offers significant potential for advancing 6G networks, ensuring adaptive and intelligent communication systems that meet evolving demands efficiently.

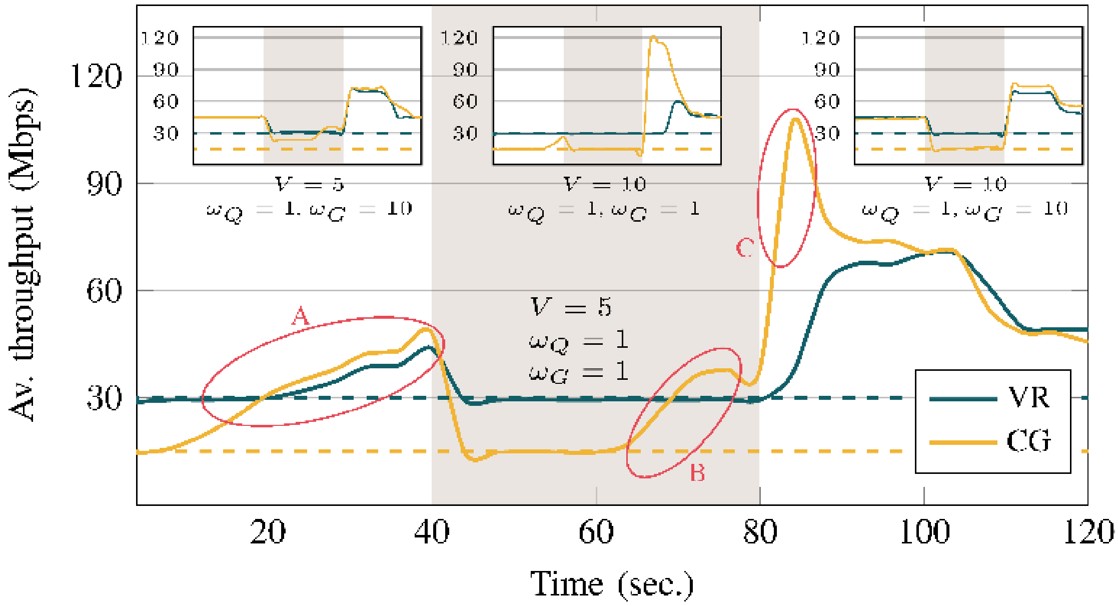



**Figure 7-13 DPP MAC scheduler behaviour upon different configurations**

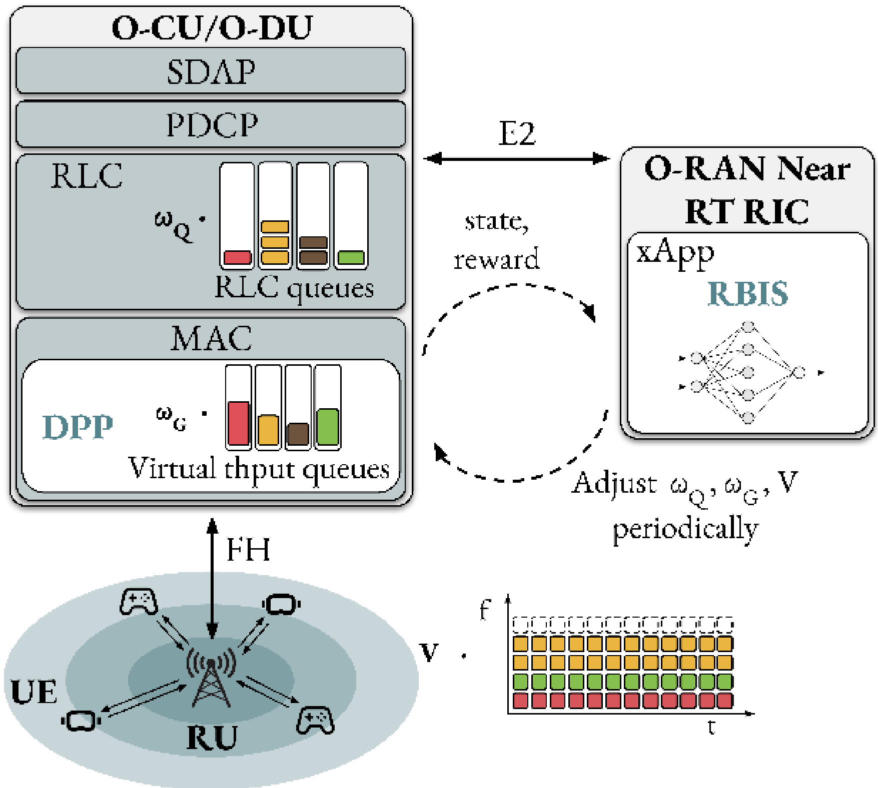



**Figure 7-14 Architecture of sensing and AI/ML supported MAC scheduler**

# 8 Conclusions

This document provides and overview of the 6G-SENSES architecture offering integrated communication and sensing capabilities. It discusses both the high-level functional architecture as well as the multi-layer system architecture proposed as well as the technologies adopted and developed by the project and presents preliminary architecture evaluation activities and some initial evaluation results.

The proposed architecture is inspired by the 3G PPP and Open Radio Access Network (O-RAN) standards and adopts a disaggregated network approach that separates RAN and CN functions offering increased flexibility and scalability**.**

The RAN user plane comprises multi- RATs, including 3GPP (5G NR) and non-3GPP (Wi-Fi, mmWave, Sub-6 GHz) technologies supporting ISAC capabilities, which enable networks to use existing signals available for communication purposes to sense objects and the surrounding environment. It leverages RIS to enhance network efficiency, sensing accuracy, and energy optimization, as well as CF-MIMO technology to improve coverage, spectral efficiency, and latency while reducing energy consumption and dynamically optimizing resources.

To support sensing capabilities, 6G-SENSES exploits 5G NR-based sensing using radio wave reflections, Doppler shifts, and beamforming for precise object detection and tracking, Wi-Fi-based sensing using monostatic active sensing (single device as transmitter & receiver) and passive sensing to detect movement, activity, and gestures, Sub-6 GHz Sensing utilizing Software-Defined Radios (SDRs) for high-resolution environmental sensing and mmWave sensing to supports high-frequency radar-like sensing with fine-grained spatial resolution.

The document also describes the 6G-SENSES control plane, giving emphasis on the extension required with respect to the capabilities of existing CN functions to support ISAC services and incorporates Near-Real-Time (Near-RT) and Non-Real-Time (Non-RT) RAN Intelligent Controllers (RICs) to dynamically adjust network behavior. Taking into consideration the 6G-SENSES multi-RAN/multi-technology environment several innovations for the control of the RAN, the transport network and the CN functions are proposed. These include: new functions supporting sensing services and enhancement of existing ones for localization in the CN, extension of the N3IWF with a new E2 interface to allow exposure of sensing capabilities from non-3GPP network nodes to the RIC, extensions in the RIC controller to enable ingestion and processing of sensing measurements from 3GPP and non-3GPP networks and development of new SDN-based control policies to facilitate the support of sensing services through the transport network.

The document also discusses the role that the 6G-SENSES SMO has in the end-to-end (E2E) service delivery over the 6G-SENSES infrastructure. More specifically, O-RAN SMO is responsible for managing, automating, and optimizing the RAN. SMO facilitates orchestration and automation by dynamically deploying, scaling, and managing RAN components while supporting zero-touch provisioning. It also provides real-time network monitoring and observability by means of a data lake, collecting key performance indicators (KPIs) and detecting anomalies to enhance network reliability. By leveraging AI/ML-driven optimization, SMO enhances network efficiency, improves spectrum usage, and boosts energy efficiency through intelligent decision-making. Additionally, it interfaces with RAN Intelligent Controllers (RICs) and existing OSS/BSS systems to ensure seamless integration across multi-vendor environments. In addition, the use of Multi-Access Edge Computing (MEC) bringing storage, computing, and networking resources closer to the edge of the RAN provides clear benefits in E2E service delivery. This is due to that MEC allows to significantly reduce latency and enable faster data transfers that benefit a variety of user applications particularly in mobile environments as well as improve RAN performance providing the necessary processing resources to support closed-loop control operations required by the RIC.

Finally, preliminary studies have started being performed with the target to validate the feasibility of the proposed architecture. However, the final evaluation and benchmarking is planned to be reported as part of deliverable **D2.3** “6G-SENSES architecture evaluation and benchmarking”.

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# 10 Acronyms

| Acronym | Description |
|---|---|
| 2D | Two-Dimensional |
| 3GPP | 3rd Generation Partnership Project |
| 5GC | 5G Core Network |
| 5GNR | 5G New Radio |
| 6G-IA | 6G Infrastructure Association |
| A/D | Analog-to-Digital |
| ABEP | Average Bit Error Probability |
| ADMM | Alternating Direction Method of Multipliers |
| AI | Artificial Intelligence |
| AiP | Antenna in Package |
| AMF | Access and Mobility Management Function |
| AO | Alternating Optimization |
| AoA | Angle of Arrival |
| AoI | Age-of-Information |
| AP | Access Point |
| API | Application Programming Interface |
| BB | Baseband |
| BER | Bit Error Rate |
| BH | Backhaul |
| BPSK | Binary Phase-Shift Keying |
| BI | *Barkhausen Institut* (6G-SENSES Beneficiary) |
| BR | BubbleRAN (6G-SENSES Beneficiary) |
| BS | Base Station |
| BSS | Business Support System |
| CAPEX | CAPital EXpenditures |
| CCC | Cell Configuration and Control |
| CCWD | Communication-Centric Waveform Design |
| CDF | Cumulative Density Function |
| CEF | Channel Estimation Field |
| CF | Cell-Free |
| CFAR | Constant False Alarm Rate |
| CFO | Carrier Frequency Offset |
| CF-mMIMO | Cell-Free massive MIMO |
| CFRM | Cell-Free reconfigurable metasurfaces |
| CIR | Channel Impulse Response |

| | |
|---|---|
| CN | Core Network |
| CoMP-JT | Coordinated Multi-point Joint Transmission |
| COTS | Commercial Off-The-Shelf |
| CPO | Carrier Phase Offset |
| CPU | Central Processing Unit |
| CRB | Cramér-Rao Bound |
| CSI | Channel State Information |
| CU | Central Unit |
| CSP | Communication Service Provider |
| CW | Continuous Wave |
| D/A | Digital-to-Analog |
| DBaaS | DataBase as a Service |
| DMRS | Demodulation Reference Signal |
| DoW | Description of Work |
| DCSP | DataCenter Service Provider |
| DNN | Deep Neural Network |
| DoA | Direction of Arrival |
| DoW | Description of Work |
| DPP | Drift-Plus-Penalty |
| DRL | Deep Reinforcement Learning |
| DT | Digital Twin |
| DU | Distributed Unit |
| DZT | Discrete Zak Transform |
| e2e | End-to-End |
| E2AP | E2 Application Protocol |
| EA | Ethics Advisor |
| EC | European Commission |
| eCPRI | enhanced Common Public Radio Interface |
| EDMG | Enhanced directional multi-gigabit |
| EE | Energy Efficiency |
| eMBB | enhanced Mobile BroadBand |
| EMF | Electromagnetic field |
| ESPRIT | Estimation of signal parameters via rotational invariant techniques |
| EVM | Error Vector Magnitude |
| FBL | Finite Blocklength |
| FCAPS | Fault, Configuration, Accounting, Performance and Security |
| FDSOI | Fully Depleted Silicon on Insulator |
| FFT | Fast Fourier Transform |

| | |
|---|---|
| **FH** | Fronthaul |
| **FMCW** | Frequency-Modulated Continuous Wave |
| **FoV** | Field of View |
| **FSS** | Fixed Satellite Service |
| **GA** | Grant Agreement |
| **GPSDO** | GPS Disciplined Oscillator |
| **HW** | Hardware |
| **IASA** | Institute of Accelerating Systems and Applications (6G-SENSES Beneficiary) |
| **IBFD** | In-Band Full Duplex |
| **IC** | Integrated Circuit |
| **ICT** | Information and Communication Technology |
| **IFFT** | Inverse Fast Fourier Transform |
| **IHP** | *IHP – Leibniz Institut für innovative Mikroelektronik* (6G-SENSES Beneficiary) |
| **IMT** | International Mobile Telecommunications |
| **INT** | *Intel Deutschland GmbH* (6G-SENSES Beneficiary) |
| **IoE** | Internet of Everything |
| **IoT** | Internet of Things |
| **IQ** | In-Phase and Quadrature |
| **ISAC** | Integrated Sensing and Communication |
| **ISFT** | Inverse Symplectic Fourier Transform |
| **ISM** | Industrial, Scientific and Medical |
| **IT** | Information Technology |
| **ITU** | International Telecommunications Union |
| **JWOD** | Joint Waveform Optimization and Design |
| **KPI** | Key Performance Indicator |
| **KV** | Key Value |
| **KVI** | Key Value Indicator |
| **LCM** | Lifecycle Management |
| **LMF** | Location Management Function |
| **LMMSE** | Linear Minimum Mean-Square Error |
| **LO** | Local Oscillator |
| **LoS** | Line-of-Sight |
| **LTF** | Long Training Field |
| **LTS** | Long Training Sequence |
| **m/eMTC** | massive/enhanced Machine Type Communications |
| **MAC** | Medium Access Control |
| **MDRR** | Minimum Deficit Round Robin |
| **MEC** | Multi-access Edge Computing |

| | |
|---|---|
| MGA | Model Grant Agreement |
| MIMO | Multiple-Input Multiple-Output |
| ML | Machine Learning |
| MLO | Multi-Link Operation |
| mMIMO | Massive MIMO |
| mMTC | massive Machine Type Communications |
| MNO | Mobile Network Operator |
| MP | Message Passing |
| MRT | Maximum-Ratio Combining |
| MUI | MultiUser Interference |
| MX | Multi-x (i.e. multi-vendor, multi-version, multi-node, multi-distribution, multi-runtime, multi-cloud, and multi-instance) |
| MUSIC | MUltiple SIgnal Classification |
| N3IWF | Non-3GPP Interworking Function |
| NEF | Network Exposure Function |
| NFV | Network Function Virtualization |
| NGAP | Next Generation Access Protocol |
| NGAS | Next Generation Access Stratum |
| nGRG | O-RAN next Generation Research Group |
| NLoS | Non-Line-of-Sight |
| NIC | Network Interface Card |
| NN | Neural Network |
| Non-RT RIC | Non-Real Time Radio Intelligent Controller |
| NOP | Network Operator |
| NR | New Radio |
| NRF | Network Repository Function |
| NSaaS | Network Security as a Service |
| NTU | Nottingham Trent University |
| NWDAF | Network Data Analytics Function |
| OAI | OpenAirInterface |
| OAM | Operation, Administration and Maintenance |
| OCXO | Oven Controlled Crystal Oscillator |
| OIBS | Offset-Based Block Selection |
| OIM | Offset Index Modulation |
| OMA | Orthogonal Multiple Access |
| OPEX | OPerational EXpenditures |
| OS | Operating System |
| OSS | Operations Support System |

| | |
|---|---|
| OTA | Over-The-Air |
| OTFS | Orthogonal Time Frequency Space |
| QM | Quality Manager |
| PBCH | Physical Broadcast Channel (PBCH) |
| PCA | Principal Component Analysis |
| PCB | Printed Circuit Board |
| PCT | Printed Circuit Technology |
| PDSCH | Physical Downlink Shared Channel |
| PDV | Packet Delay Variation |
| PHY | Physical |
| PoC | Proof-of-Concept |
| PRS | Positioning Reference Signal |
| PTP | Precision Time Protocol |
| PUPE | Per-User Probability of Error |
| PUSCH | Physical Uplink Shared Channel |
| RAN | Radio Access Network |
| RB | Resource Block |
| RC | RAN Control |
| RF | Radio Frequency |
| RHS | Reconfigurable Holographic Surface |
| RIS | Reconfigurable Intelligent Surface |
| RIC | Radio Intelligent Controller |
| RL | Reinforcement Learning |
| RP | Reference Point |
| RRM | Radio Resource Management |
| RSMA | Rate-Splitting Multiple Access |
| RTT | Round Trip Time |
| RU | Radio Unit |
| SA | Stand Alone |
| SAF | Sensing Analytics Function |
| SBA | Service-Based Architecture |
| SCTP | Stream Control Transport Protocol |
| SCWD | Sensing-Centric Waveform Design |
| SDC | Software-Defined Communications |
| SDG | Sustainable Development Goal |
| SDK | Software Development Kit |
| SDMA | Spatial Division Multiple Access |
| SDN | Software Defined Networking |

| | |
|---|---|
| **SDR** | Software Defined Radio |
| **SE** | Spectral Efficiency |
| **SeCF** | Sensing Control Function |
| **SFFT** | Symplectic Fast Fourier Transform |
| **SFO** | Sampling Frequency Offset |
| **SiGe** | Silicon-Germanium |
| **SINR** | Signal-to-Interference-plus-Noise Ratio |
| **SM** | Service Model |
| **SMO** | Service Management and Orchestration |
| **SNR** | Signal-to-Noise-Ratio |
| **SNS JU** | Smart Networks and Services Joint Undertaking |
| **SOF** | Start Of Frame |
| **SRL** | Society Readiness Level |
| **SRS** | Sounding Reference Signal |
| **SS** | Synchronization Signal |
| **SSC** | Smart Surface Control |
| **SSM** | Smart Surface Monitoring |
| **STAR-RIS** | Simultaneously Transmitting and Reflecting RIS |
| **STFT** | Short-Time Fourier Transform |
| **STO** | Sampling Time Offset |
| **STS** | Short Training Sequence |
| **SVM** | Support Vector Machine |
| **SW** | Software |
| **TDD** | Time Division Duplex |
| **TDoA** | Time Difference of Arrival |
| **TDM** | Time-Division Multiplexing |
| **TDMA** | Time Division Multiple Access |
| **THz** | Terahertz |
| **TL** | Task Leader |
| **TM** | Technical Manager |
| **TRL** | Technology Readiness Level |
| **TSDB** | TimeScale DataBase |
| **TUBS** | *Technische Universität Braunschweig* (6G-SENSES Beneficiary) |
| **Tx** | Transmission |
| **UAV** | Unmanned Aerial Vehicles |
| **UC** | University of Cantabria (6G-SENSES Beneficiary) |
| **UE** | User Equipment |
| **UHD** | USRP Hardware Driver |

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|---|---|
| **ULA** | Uniform Linear Array |
| **UN** | United Nations |
| **UPF** | User Plane Function |
| **URA** | Unsourced Random Access |
| **URLLC** | Ultra-Reliable and Low-Latency Communications |
| **USRP** | Universal Software Radio Peripheral |
| **UWB** | Ultra-Wideband |
| **V2X** | Vehicle-to-Everything |
| **VISP** | Virtualization Infrastructure Service Provider |
| **VOS** | Value of Service |
| **WAT** | Wireless Access Technology |
| **WG** | Work Group |
| **Wi-Fi** | Wireless-Fidelity |
| **WFQ** | Weighted Fair Queue |
| **WLAN** | Wireless Local Area Network |
| **WP** | Work Package |
| **WR** | White Rabbit |
| **WRR** | Weighted Round Robin |