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

D2.1 Report on 6G-SENSES use cases, network architecture, KPIs and supported RAN functions

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Executive Summary

6G-SENSES designs and develops a next generation wireless infrastructure aiming to both achieve advanced performance towards the International Mobile Telecommunications (IMT) 2030 vision and Key Performance Indicators (KPIs), outperforming the current network implementations, and to progress research towards fully perceptive networks. To this end, research is focused on integrating Cell-Free (CF) networks, Reconfigurable Intelligent Surface (RIS) infrastructures, as well as Integrated Sensing and Communication (ISAC), using as baseline beyond State-of-the-Art (SotA) Open RAN (O-RAN) and 3GPP specifications for the 5G protocol stack, and developing a network intelligence plane spanning across network segments. The technical enablers of the solution proposed by 6G-SENSES centres around two main axes: (1) Access Network Performance and Sensing, and (2) Network Intelligence.

The focus of this deliverable is to define a set of 6G use cases, including both key 6G service requirements and 6G business concepts that the 6G-SENSES vision, architectural solutions and deployment paradigms will be able to support. These use cases also aim at enabling the validation of the proposed architecture and technologies through intensive testing and demonstration activities that will be carried out in relevant lab and integrated testbed environments.

To this end, initially the 6G trends and vision of the 6G ecosystem are studied. This includes, on the one hand, an informed study of the technical targets of 6G as well as of the envisioned use cases and capabilities to be enabled, and on the other hand the identification of key roles to bring the use cases and capabilities to the market in terms of assets ownership, business processes, provisioning of service to other roles/ entities and the relevant business interfaces. In parallel, the 6G-SENSES system functionalities and capabilities are analysed to identify the value created for the various roles / layers of the on the way to be shaped 6G ecosystem.

The output of these sub-activities is fused to the identification of a concrete set of use cases that will be enabled by 6G-SENSES, along with the KPIs and the requirements that need to be met. Complementarily, considering the growing need to align technology with broader societal values, to address global and local societal challenges and visions, the use cases are analysed in terms of their impact on Key Values (KVs). Specific Key Value Indicators (KVIs) are derived/ defined as absolute or relative, quantitatively (preferably) or qualitatively measures of the impact of technology solution on the identified KVs (under the notion of 6G for Sustainability).

The selected 6G use cases take into consideration both the various service provisioning roles and stakeholders of future 6G ecosystems and the envisioned 6G end-user (vertical or individual) application services. The proposed use cases have been selected to 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. These aspects play a key role with regards to the relevance and novelty of the identified use cases with the project scope and expected outcomes. In brief, the use cases envisioned within 6G-SENSES are the following:

- **Use Case #1: Sensing enabled Services**, which focuses on exploiting sensing information to improve communication services (sensing-aided communication) and on enabling active sensing with Wireless Fidelity (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**, which focuses on storylines exploiting the Cell-Free massive MIMO (CF-mMIMO) and Reconfigurable Intelligent Surfaces (RISs) capabilities

combined with sensing. This use case highlights the work of the project on RIS-assisted CF-mMIMO for coverage and localisation.

- **Use Case #3: Network Digital Twin (DT)**, which 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 energy efficiency (EE) via Artificial Intelligence (AI) / Machine Learning (ML) at Orchestration, Network and User layers.

All these use cases are provided along with a list of requirements and KPIs, which are 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.

1 Introduction

Nowadays, the focus of Information and Communication Technology (ICT) research in academia and industry is towards building the specifications and pre-development of 6G networks. To date, although there is not yet a strictly defined/ standardized set of 6G features, the research community agrees that, in general terms, in the access stratum, 6G will: (1) make use of a combination of new spectral resources, such as upper millimetre wave (mmWave) and terahertz (THz) bands, to improve the peak data rate, and (2) use ultra-massive antenna arrays and flexible cell-free (CF) structures – enabled by the introduction of CF-mMIMO– and/or RIS to enhance spectral efficiency (SE), EE, and to drastically increase the number of parallel connections. At the same time, 6G research focuses on new ways of exploiting radio access systems, such as introducing signal processing capabilities for sensing on systems originally devised for communication, a.k.a. ISAC. In parallel, research efforts focus on augmented monitoring of network infrastructures based on extended collection and processing of (especially) RAN data of different nature. This data aim to feed and enable the envisioned advanced network control and management plane for network optimization and sustainability purposes.

In this landscape, 6G-SENSES proposes the integration of novel 6G RAN technologies such as CF-mMIMO and ISAC, to support the 6G vision that is sustained by the current (and future) architectural framework based on 3GPP and O-RAN. The project considers a multi-technology RAN ecosystem with access technologies that are expected to offer sensing functionalities in the near future. These technologies can be grouped in the macro domains of Wireless-Fidelity (Wi-Fi), mmWave and 5G New Radio (5GNR), which will coexist in an ISAC framework intended to obtain a reliable representation of the surrounding environment. To further strengthen communication and sensing functionalities, 6G-SENSES will leverage RIS and will work on the design, optimization and modelling of those surfaces considering the application scenarios. Sensing information stemming from these technologies will be pushed to the O-RAN framework for network optimization and service provisioning purposes.

Exploiting new spectral resources and RAN technologies will boost the network performance significantly, while the integration of sensing functions into the communication systems envisioned to be an integral part of the 6G and future communication systems, will open-up a plethora of new services and network capabilities. This will also impact – essentially augment – the ecosystem to be formulated around 6G technologies and service provisioning and will enable key 6G use cases in line with the International Mobile Telecommunications (IMT)-2030 vision and envisioned end-user usage scenarios [1],[2],[3].

This document aims to provide an overview of the 6G trends from technical, user and business perspectives, and to identify the ecosystem that 6G-SENSES is targeting by aligning to it in terms of services, technical and commercial requirements as well as societal needs. The methodology to be followed for this purpose, is presented in Figure 1-1.

In particular, initially the 6G trends and vision of the 6G ecosystem are studied. This includes, on the one hand, an informed study of the technical targets of 6G – at a higher level given that at this point there is no available 6G standard – as well as of the envisioned use cases and capabilities to be enabled, and on the other hand the identification of key roles to bring the use cases and capabilities to the market in terms of assets ownership, business processes, provisioning of service to other roles/entities and the relevant business interfaces. The 5G layered service provisioning approach is used as basis. In parallel, 6G-SENSES system functionalities and capabilities are analysed in order to identify the value created for the various roles/layers of the ecosystem.

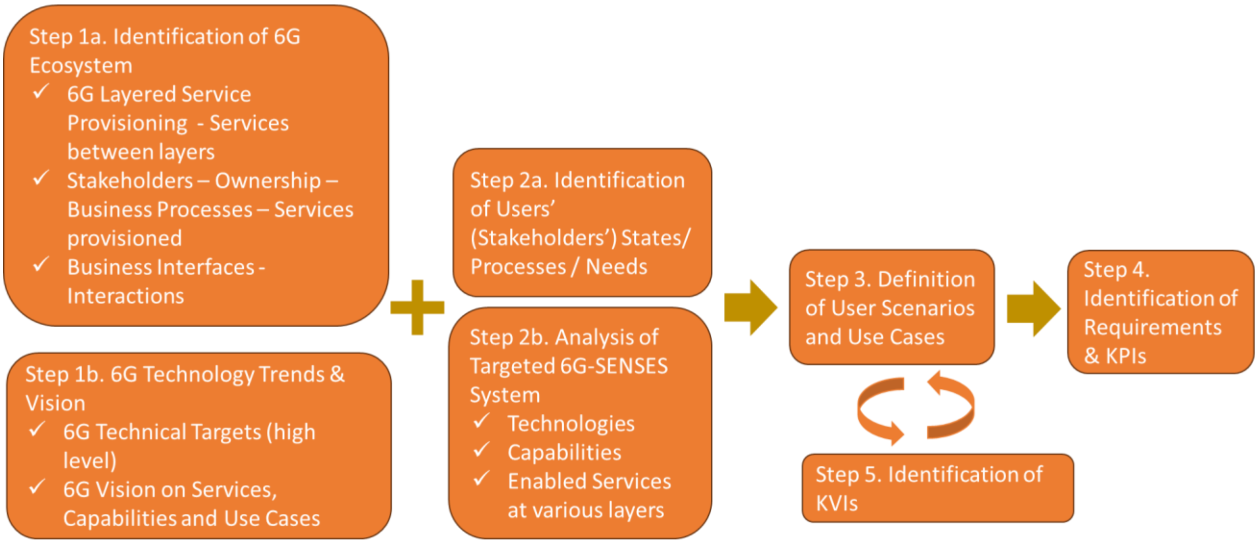

Figure 1-1 Methodology for 6G-SENSES Positioning to 6G Environment: Use Cases, KPIs and KVIs

The output of these sub-activities is fused to the identification of a concrete set of use cases that will be enabled by 6G-SENSES (out of the multitude of scenarios and use cases envisioned for 6G), along with the KPIs and the requirements that need to be met. Complementarily, considering the growing need to align technology with broader societal values, to address global and local societal challenges and visions as outlined by the United Nations (UN) Sustainable Development Goals (SDGs) [5], the European Commission's priorities [6], the European Green Deal [7] and lately with the UN's International Telecommunications Union (ITU) IMT towards 2030 and beyond (IMT-2030) vision [1], the use cases are analysed in terms of impact on KVs. Specific KVIs are derived/ defined as absolute or relative, quantitatively (preferably) or qualitatively measures of the impact of technology solution on the identified KVs (under the notion of 6G for Sustainability).

This work, translated into specifications for the 6G-SENSES solution will be channelled to the implementation activities of the project, and will serve as basis for the validation and evaluation of the project outcomes.

1.1 Organisation of the document

This document elaborates on the system users and the use cases that are addressed by 6G-SENSES, it identifies their user requirements and KPIs, and provides a mapping of the user and system requirements to system specifications and KPIs that need to be met by the 6G-SENSES solution. This document is structured as follows:

Chapter 2 provides an overview of 6G-SENSES vision and objectives along with a brief discussion on the project concepts and technologies.

In Chapter 3 the global vision on 6G services, KPIs and service provisioning aspects is summarised and the 6G-SENSES ecosystem view is positioned in this initially identified landscape. In brief, this chapter identifies the 6G environment, i.e. i) the 6G technical targets as defined by the relevant standardization bodies and communities, and ii) the operations and roles introduced/enabled by foreseen 6G advancements relevant to service provisioning at various infrastructure operation levels and service layers. This chapter also initiates the work on identifying 6G-SENSES impact on KVIs by providing an understanding of the linkage between the technical progress and value creation in versatile domains.

In Chapter 4 these technical and business aspects are taken as the basis for identifying specific use cases for various roles/ stakeholders along with their requirements, KPIs and relevant KVIs where 6G-SENSES advancements are applicable.

In Chapter 5 the user requirements and KPIs are translated into system requirements, a.k.a. system specifications –the terms being interchangeably used in the context of this document – and KPIs that the 6G-SENSES solution needs to fulfil.

Finally, Chapter 6 draws some conclusions and provides a summary of this document.

2 6G-SENSES Concepts and Technologies

6G-SENSES designs and develops a next generation wireless infrastructure aiming to both achieve advanced performance towards the IMT-2030 vision KPIs [1], outperforming the current network implementations, and progress research towards fully perceptive networks [4]. To this end, research is focused on integrating CF networks, RIS infrastructures, as well as ISAC [8], using as baseline beyond SotA O-RAN and 3GPP frameworks, and developing a network intelligence plane spanning across network segments. The technical enablers of the solution span across two main axes: 1) Access Network Performance and Sensing, and 2) Network Intelligence.

2.1 Advancements in Access Network Performance and Sensing

Considering the technologies to be used at the RAN segment, 6G-SENSES relies on the use and integration of several WATs as basis for advancing RAN performance towards the IMT-2030 KPIs, and for the support of sensing. These technologies can be grouped in the macro domains of: Wi-Fi 6/Wi-Fi 7, Sub-6 GHz (non-Wi-Fi standard) and mmWave (60 GHz) as non-3GPP technologies, and 3GPP 5GNR.

These technologies overcome current limitations in terms of bandwidth and signal processing and, on top of them, 6G-SENSES will offer ISAC capabilities at the RAN by means of investigating waveforms and signal processing schemes that exploit the diverse characteristics of these WATs. The target is to allow simultaneous access to the channel by multiple users, as well as support sensing. To this end, research will focus on physical (PHY) and medium access control (MAC) layers to enable ISAC capabilities, especially for those technologies that cannot support sensing natively, as well as the required (6G) network interfaces. The wireless data communication system will also be adapted and optimized for ISAC. At the same time, the application layer for sensing functionalities will be investigated.

Specific advancements are foreseen towards the support of sensing capabilities per WAT. In particular, in Wi-Fi 7 [9], active sensing is being developed at the moment and there are extensions to be incorporated during 6G-SENSES. Additionally, the multi-link operation (MLO) feature in Wi-Fi 7 enables wider sensing bandwidths that were not previously available, a feature that provides better sensing resolution for location, motion detection, etc. Additionally, the usage of active sensing technology will be explored, where some/one of the antennas will be used for transmission, while the remaining antennas are used for simultaneous reception. This enables a “radar-like” sensing operation during regular Wi-Fi communication. All these capabilities will be integrated and managed from a 3GPP- and O-RAN-based infrastructure. To further optimize the performance, 6G-SENSES will focus on porting these sensing enhancements in Wi-Fi 7, towards achieving lower latency (down to sub-msec), higher reliability (by further improving determinism through ultra-high reliability classes), and increased efficiency – by reducing power and over the air control overhead through optimized medium access schemes.

In the context of 6G-SENSES, developments in Sub-6 GHz will focus on adding on top of a Commercial Off-The-Shelf (COTS) platform (based on the SDR Ettus N321), advanced signal processing tools for the PHY layer to support processing in the delay-Doppler domain using Orthogonal Time Frequency and Space (OTFS), towards achieving data communication with sensing methods and localization for fast-moving objects on the same hardware. 6G-SENSES also includes research on mmWave platforms, as the larger bandwidth availability at these frequencies allow for higher throughput and sensing resolution. However, implementing ISAC in such platforms is a challenging task; particularly at mmWave frequencies, where signals are prone to high attenuation and blockage due to the short wavelength and high path loss.

Furthermore, 6G-SENSES focuses on advancing 5G NR performance and capabilities by enabling CF-mMIMO implementation through appropriate modifications at the protocol stack (e.g. the Radio Resource Control (RRC) layer), or at the PHY layer. The OpenAirInterface (OAI) 5GNR implementation will be used as basis. At this point it shall be recalled that we consider the O-RAN and 3GPP frameworks given that the disaggregation, virtualization and network and service management capabilities inherent in O-RAN provide the mechanisms to realize many of the infrastructure control capabilities and also support the optimization strategies, since they allow for tighter coordination between radio elements, which may in turn bring further performance improvements. The disaggregation of network functionalities promoted by O-RAN raises special interest in the development and deployment of CF-mMIMO in real world distributed networks, allowing the split between PHY-layer functionalities across O-DU and O-RU units [10], [11]. Additionally, localization and sensing based on 5G Core Network (5GC) Location Management Function (LMF) will be part of the research carried out in the project.

Finally, 6G-SENSES will enhance the system integration and functionalities of RIS (leveraging on existing concepts [12], [13]), which contributes with yet another strategy for improving the communication, bandwidth and stability. 6G-SENSES will use an RIS infrastructure as one of the enablers for ISAC and CF-mMIMO and will develop methods and algorithms to create RIS-assisted links that will allow to further enhance the availability and sensing performance. This requires an optimization of distributed signal processing and resource allocation schemes tailored for RIS-assisted CF network architecture. 6G-SENSES will also investigate the requirements and deployment options for an O-RAN-compliant sub-millisecond control interface, paying special attention for the support of additional sensing channels that RIS may require. A RIS panel will be leveraged to assess and compare the models with a real-world analysis in a lab environment.

2.2 Network Intelligence and the Edge Segment

AI/ML algorithms have become integral part of signal processing and resource allocation algorithms for complex networks, and are widely considered as key enabler for advance performance and sustainability of 6G networks. Accordingly, 6G-SENSES considers AI-based breakthroughs across the most demanding 6G Radio Resource Management (RRM) areas, such as sustainable data management at the wireless edge, flexible and efficient radio access (coverage) and service provisioning in novel network architectures as well as energy savings. The use of AI/ML solutions will be considered both in the different network segments and across them, and these solutions will be implemented taking into consideration the different WATs. In particular, AI/ML is considered in the following segments/functions/processes:

- Specifically, for Wi-Fi, the adoption of MLO will imply the presence of more links coming from multiple stations with heterogeneous capabilities. In turn, this scenario will bring complex traffic scheduling and resource management problems, which will be tackled applying ML.
- Modeling of mobility information, network traffic characterization and prediction.
- L1/L2 modeling for two specific purposes: traffic steering/offloading and backhauling; in specific, considering cellular/Wi-Fi traffic steering and offloading as well as backhauling in licensed and unlicensed bands using RIS-based CF-mMIMO cases.
- Information caching strategies, both to enhance the behavior of different services and/or as a means to guarantee appropriate sharing and access to the sensing data.

6G-SENSES will consider the application of both supervised and unsupervised ML, reinforcement learning (RL) as well as graph neural networks (NNs). The ML-based algorithms can be easily integrated into the DU or RU, or they could also be run into a virtual environment (Docker, etc.) at either edge or cloud nodes.

Work will provide applicability paradigms and leverage on existing work on AI in O-RAN. In particular, with view to network intelligence, O-RAN is devised as a mean to organize mobile networks thanks to the possibilities for network-wide control protocols [14]. The additional functional blocks that have been introduced, the Near-Real Time RAN Intelligent Controller (Near-RT RIC), the Non-RT RIC, and the Service Management and Orchestration (SMO), enable AI and containerized service orchestration on the network

[15]. In particular, in O-RAN intelligence is considered in many ways ranging from (1) cooperative access network elements (for various optimization targets) to (2) perceptive networks, and (3) enabling network or user Apps on top.

At the first level, the disaggregation of the Central Processing Unit (CPU) into the Near-RT RIC and a set of cooperating O-DUs serves as enabler for intelligent cooperative access networks [11] – with cooperation being considered in many storylines under different terms and optimization goals such as Coordinated Multi-point Joint Transmission (CoMP-JT), distributed-MIMO and CF.

Secondly, the O-RAN next Generation Research Group (nGRG), in Research Streaming (RS) 02 & RS06, is extending the RIC and control-plane intelligence to support 'cross-domain AI optimization' [16], understanding and optimizing the underlying transport and heterogeneous access technologies, to ingest cross-technology sensing, telemetry and control into the evolved 6G RIC, unleashing the xApp/rApp extensibility of this evolved RIC, hosting the 6G Native AI/ML automation and zero-touch optimization, throughout all RAN layers, including 3GPP and Non-3GPP access.

6G-SENSES will tackle the optimum placement and instantiation of AI/ML techniques, considering the stringent requirements imposed by the solutions at the lower layers that were previously introduced. Also, improvements at the connectivity layer will be studied, to ensure that the strict delay needs (real-time) are respected and the information provided by the sensing mechanism is available, in time, at the required nodes. 6G-SENSES will also explore the use of caching strategies to enable an appropriate sharing and access to such information.

The optimum instantiation of these AI/ML solutions would require advanced resource management techniques, not only from the perspective of the communication, but also considering computing capability. As mentioned above, strict delay requirements need to be guaranteed, while these techniques would need to share the computing capability with the corresponding O-RAN Network Function Virtualization (NFV) elements, both at edge and cloud nodes.

It becomes apparent that resource and performance demands will increase significantly not only at application but also at network management layer, and distribution of resources, intelligence, functionalities will be heavily adopted by 6G network paradigms. To this end, the role of the edge segment becomes critical. 6G-SENSES will rely on Multi-access Edge Computing (MEC) structures to exploit cloud computing capabilities at the network edge not only for application provisioning purposes and access network processing but also for sensing and management (AI/ML) plane processing. Especially considering the potential of sensing and management related data capturing, storage and/or processing at MEC, distributed computing for computational offloading and content caching can serve as paradigms to leverage on [17], [18], [19]. Concepts and techniques related to content demand prediction, traffic characterization, mobility information along with big data analytics and AI techniques such as RL or deep learning will be incorporated.

3 Service Provisioning in 6G Networks

3.1 Overview of 6G Services and KPIs

While 5G networks standardisation is still ongoing and 5G Stand Alone (SA) networks are at initial commercial deployment phase around the globe, Research and Innovation activities have started envisioning the new 6G networks era. Although 6G standardisation is planned to commence not before 2025, in EU, North America, China, etc., many are the joint efforts between stakeholders, states and organisations that aspire to set the scene for 6G networks priorities, objectives, and eventually technologies and standards. To this end, one can find a wide number of scientific papers, white papers and position papers aiming to propose targets for high level KPIs, use cases and main technological trends for 6G.

Starting with the 6G-Flagship [20], Next Generation Mobile Networks (NGMN) [2], Smart Networks and Services Joint Undertaking (SNS JU) and the 6G Infrastructure Association (6G-IA) (via a large number of EU funded 6G projects) have been the main channels where European efforts are fused, focusing on the definition of 6G use cases, KPIs and technology trends. The derived 6G vision along with similar efforts from other global organisations (e.g. NextG Alliance, 5G Americas, etc.) have been channelled to the most recent Recommendation ITU-R M.2160-0 [1], which aims to set the global 6G targets and objectives. These efforts are summarised in [21].

As an initial step to the definition of 6G targets, IMT-2030 recognises a short list of so called "usage scenarios", which, essentially, correspond to basic service profiles and network capabilities as a means to separate between different objectives/target domains. The IMT-2030 usage scenarios evolve from and expand on the IMT-2020 5G Service Classes/scenarios (ITU-R Recommendation ITU-R M.2083), namely on: enhanced Mobile BroadBand (eMBB) (3GPP TR 22.863), massive/enhanced Machine Type Communications (m/eMTC) (3GPP TR 22.861) and Ultra-Reliable and Low Latency Communications (URLLC) (3GPP TR 22.862).

In particular, the IMT-2020 eMBB Service Class/ Scenario is extended in the IMT-2030 to an Immersive Communication Usage Scenario, and it is associated with data rate-demanding services beyond video streaming and virtual reality, towards "immersive XR, remote multi-sensory telepresence, and holographic communications" [1].

The IMT-2030 Hyper Reliable and Low-Latency Communication Usage Scenario expands on the URLLC Services of IMT-2020 (associated with emergency and mission critical communication services with stringent reliability, availability and delay requirements). This Usage Scenario includes services with even more stringent latency and reliability requirements, extending the category towards tightly time-synchronized operations in various industrial, corporate, automated environments.

The IMT-2030 Massive Communication Usage Scenario extends the IMT-2020 mMTC services – previously reflecting the Internet of Things (IoT) services and referring to high device density scenarios – towards a vast variety of machine type services applicable in versatile environments/ use cases such as: smart cities, transportation, health, energy, agriculture.

It shall be noted that the IMT-2030 Usage Scenarios may pose stringent performance requirements over a set of parameters/ KPIs rather than a single one compared to the IMT-2020 service classes.

At the same time, ITU-R IMT-2030 is envisaged to enable new Usage Scenarios arising from capabilities rather than performance. These scenarios are placed between the above-mentioned performance-based ones, and they are the following: Ubiquitous Connectivity, AI, and ISAC.

More specifically, Ubiquitous Connectivity reflects the general objective to enhance connectivity everywhere and encompasses 6G capabilities such as interworking with other systems.

AI and Communication, reflects the objective to incorporate Information Technology (IT) and algorithmic advancements (like distributed computing and AI) in 6G networks for a wide range of services requiring heavy real-time (RT) processing and communications; such as assisted automated driving, medical services, digital twinning, etc.

Last but not least, in IMT-2030, ISAC constitutes a separate Usage Scenario, leveraging on the envisioned use of radio resources jointly for sensing and for communication services. As identified in IMT-2030, these scenarios include “assisted navigation, activity detection and movement tracking, environmental monitoring, and provision of sensing data/information on surroundings for AI, XR and DT applications”.

Considering these Usage Scenarios, IMT-2030 has identified 6G networks capabilities, essentially, high-level target KPIs, which are summarised in Table 3-1.

Table 3-1 IMT 2030 KPIs Overview

IMT-2030 Capability	Definition	Value
Peak data rate	Maximum achievable data rate under ideal conditions per device	50, 100, 200 Gbit/s
User experienced data rate	Achievable data rate that is available ubiquitously across the coverage area to a mobile device.	300 Mbit/s and 500 Mbit/s
Spectrum efficiency	Spectrum efficiency refers to average data throughput per unit of spectrum resource and per cell	1.5 and 3 times greater than that of IMT-2020
Area traffic capacity	Total traffic throughput served per geographic area	30 Mbit/s/m^2 and 50 Mbit/s/m^2
Connection Density	Total number of connected and/or accessible devices per unit area	10^6 – 10^8 devices/km^2
Mobility	Maximum speed, at which a defined QoS can be achieved	500 – 1000 km/h
Latency over the air interface	Contribution by the radio network to the time from when the source sends a packet of a certain size to when the destination receives it	0.1 – 1 ms
Reliability	Capability of transmitting successfully a predefined amount of data within a predetermined time duration with a given probability	1-10^{-5} to 1-10^{-7}
Positioning	Ability to calculate the approximate position of connected devices. Positioning accuracy is defined as the difference between the calculated horizontal/vertical position and the actual horizontal/vertical position of a device	1 – 10 cm
Sensing-related capabilities	Ability to provide functionalities in the radio interface including range/velocity/angle estimation, object detection, localization, imaging, mapping, etc.	These capabilities could be measured in terms of accuracy, resolution, detection rate, false alarm rate, etc.

Complementarily, IMT-2030 sets a number of capabilities as objectives to be met by 6G networks. However, without specific, quantifiable KPIs. These capabilities are: Coverage, Applicable AI-related capabilities, Security and resilience, Sustainability (partially quantifiable but not with certain target by EE) and Interoperability.

On this basis, the work of SNS JU projects is to inherit the ITU-R IMT-2030 vision, use the relevant high-level KPIs as basis and further elaborate on the defined KPIs and nail down how these KPIs can be achieved through a number of KPI components defined at various segments, layers, functions and services of 6G networks. These considered in the context of late activities of 5G-PPP and early activities of SNS-JU, the infrastructure and service KPIs defined by early Phase I SNS projects have been reviewed and consolidated in the whole-set of KPIs included in Table 3-2.

Table 3-2 Early SNS Phase-I KPIs Overview

SNS Phase I Projects KPIs		SNS Phase I Projects KPIs	
Capacity	Peak Data Rate	Compute	Edge computational resource usage
	User Experienced Data Rate		Operation expenditure @edge
	Network Capacity		Delta in network management decision
	Service Bandwidth		Availability
	Area Traffic Capacity		Resource utilization
	Connection Density		Computing resource utilization
Latency	User Plane Latency	Energy	Network EE
	Control Plane Latency		Device EE
	E2E Service Latency		Reduced energy consumption
	New Latency contributi components		VNF Energy consumption reduction
	E2E Application Latency - for Vid processing services	Security	Anomaly detection precision
	Mission critical QoS of services latency related		Security conformance
	Runtime Delay		Tenant data privacy
	Service Setup Delay	Localization	Localization accuracy
	Slice Setup Delay		Direction and orientation accuracy
Packet Loss	Packet Error Rate		Localization related delays
	L2/L3 packet transmission succe rate		Localization (error) integrity
	Packet Loss Rate	Service	Service availability
	Frame Loss		Service reliability
	Signal Packet Loss		Service safety, integrity, maintainability
	CAPEX & OPEX reduction		CAPEX & OPEX reduction

3.2 From 5G to 6G Ecosystems - Roles and Stakeholders

As broadly discussed in the literature [44][23][24], the paradigm shift that comes with 5G network architectural evolution brings the introduction of new processes, activities and operations, thus defining a new layered and segmented Service-Based Architecture (SBA), which is based on various roles. Examples of the technical processes, activities and corresponding roles have been already provided in a number of publications [44][23]. Going beyond the 5G service provisioning approach, the transition from 5G to 6G architectures, together with the inclusion of new network segments, as well as additional streams of information operating in parallel with communication ones (for instance, those arising from the sensing processes), make room for additional roles to be assumed in 6G platforms (from a technical perspective) and in 6G Ecosystems (from a stakeholders' viewpoint). By bringing into the 5G ecosystems 6G-SENSES advancements, we can see that an extended layered service provisioning approach is enabled. A schematic view of the new roles that are brought by 6G-SENSES advancements is shown in Figure 3-2. These new roles are highlighted in orange, unlike the prior 5G ecosystem view [44].

From a technical and functional viewpoint, 6G-SENSES is grounded on the disaggregation of RAN [1] functionalities, along with the development of an intelligent control and management plane exclusively operating on top of the RAN, as well as the inclusion of parallel data streams enabled by RAN sensing (including RIS). As can be seen in Figure 3-2, these features enable various RAN provisioning approaches: (1) RAN as raw infrastructure resources, (2) RAN as virtualized resources, or/ and (3) RAN -captured, -processed -exposed data to Network Operators (NOPs) or (even) service customers. In classical mobile networks, NOPs are essentially the Mobile Network Operators (MNOs).

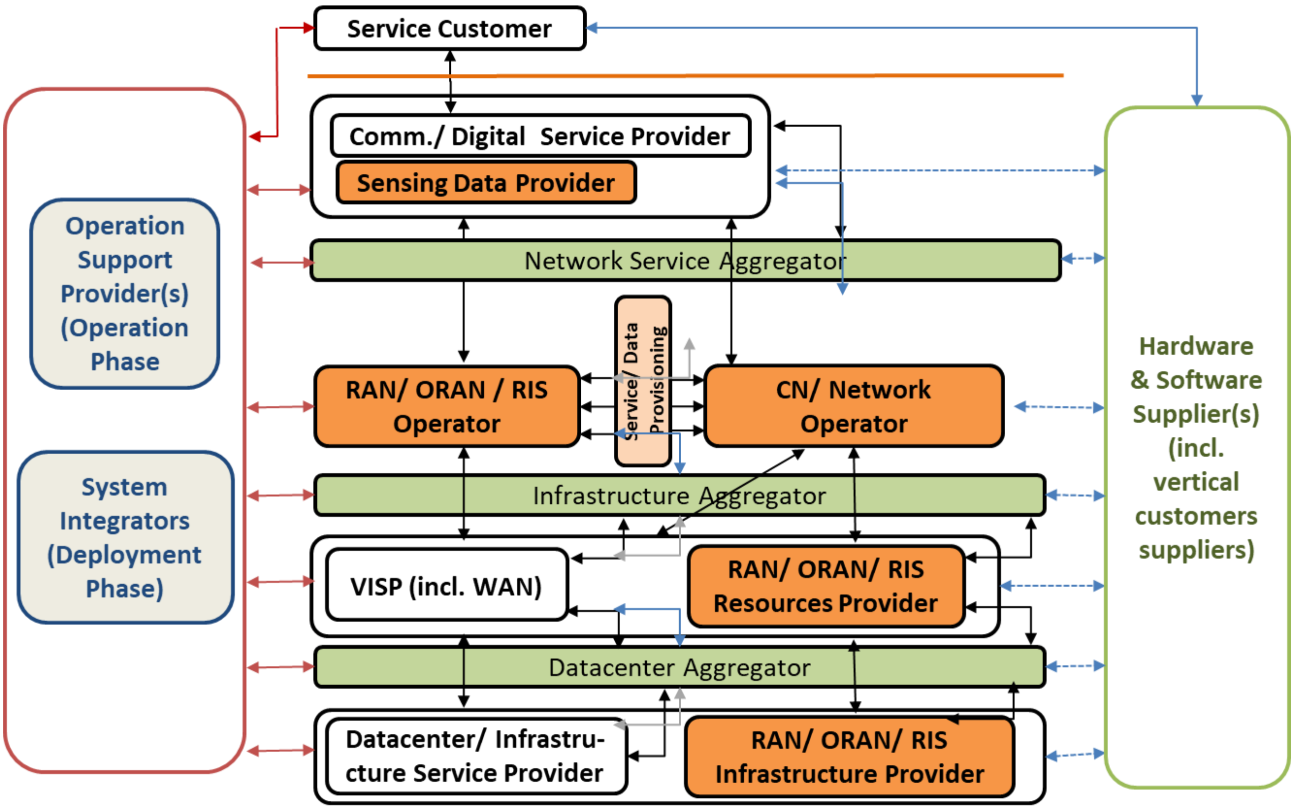

Figure 3-2 Revised Ecosystem view enabled by 6G-SENSES enhancements

[1] The RAN in the context of 6G-SENSES comprises the 3GPP 5G RAN and other WATs considered in the project.

In this context, the technology advancements make room for an extended ecosystem model (cf. orange modules in Figure 3-2) compared to that of 5G described in [23]. In particular, taking as legacy the 5G Ecosystem roles, the Service Provider (SP) is a principal role in the 5G system, which directly interfaces the service customer, and obtains and orchestrates resources from NOPs, Virtualization Infrastructure Service Providers (VISPs) and Datacenter Service Providers (DCSPs) – being here also mentioned as Infrastructure Providers (IPs) collectively. The role of the SP can be distinguished into: i) Communication/Digital Service Provider (CSP), entailing the activities required to offer traditional telecom services, or ii) more refined digital services, such as eMBB and IoT to various Vertical industries. These roles include, among others, the business services provisioning activities towards their interfacing roles, and are technically related to Business Support System (BSS)/Operations Support System (OSS), interfacing the virtual or actual infrastructure resources operated and maintained by the NOP.

If we look at 5G ecosystems service provisioning layers, taking a bottom-up view, the DCSP/IP role performs activities related to offering raw computing resources and/or raw connectivity (transport network) resources. Considering 6G-SENSES, this role can be broadened to include the role of RAN/O-RAN/RIS infrastructure provider – essentially to be undertaken by stakeholders owning the RAN elements (along with edge computing elements) and making them available as raw-resources to NOPs. This can be enabled by providing VISPs or NOPs full access to the control/management plane of the relevant RAN/O-RAN/RIS elements. Illustrative use cases may entail public or commercial buildings with indoor RAN systems deployed and owned by the building owner, municipalities, etc., considering also the trend to foresee and deploy copper and fibre cabling for ICT in the construction of new buildings.

At the next service provisioning layer, the VISP role performs activities related to offering virtualized network or cloud/edge computing resources through Application Programming Interfaces (APIs), and it practically corresponds to the cloud/edge infrastructure provider. Considering 6G advancements, this role can be extended to include the ownership of RAN elements that are made available as access network resources (O-RAN/RIS) to one or multiple NOPs in a shared mode.

At Network Operation service layer, the NOP role implies operating a programmable network infrastructure, spanning from the radio and/or fixed access to the edge, transport and core network (CN), and it is extended to include the operation of virtual resources that might be leased by other DCSP/IPs through appropriate APIs. Considering the 6G-SENSES advancements, the NOP role can be split -both vertically and horizontally- into the RAN/O-RAN/RIS-relevant roles and the CN or (traditional) NOP role. In this case, the RAN/O-RAN/RIS operator role undertakes the operation of the RAN elements, and makes resources and/or additional services (e.g. RIC related services, sensing data) available to third parties. The latter can be either CN or other NOPs, to enhance network provisioning at the same layer, or even SP, to enable applications based on network sensing data.

Finally, the SP role can be broadened to include the provisioning of service over both envisioned streams: the communication stream and the sensing one.

Additional roles can be identified such as the Service Aggregators at various layers, i.e., the Network Service Aggregator, the Infrastructure Aggregator and the Datacenter Aggregator. Entities taking the Service Aggregator role can assume the activities of service provisioning across multiple domains of a specific layer, namely: across multiple NOPs, which might be required, for instance, in the case of multiple private and public network environments, across multiple cloud/edge/RAN providers, across multiple infrastructure providers and so on.

3.3 6G Use Cases Overview

The 6G vision is tightly coupled with the definition of the user cases where 6G will be applicable, or which 6G will enable. To this end, a number of European and international organisations have worked on identifying/

envisioning these use cases and user needs. 6G research activities needs to take this work into consideration towards delivering advancements/innovations that are in line with the European and global goals and envisioned 6G usage scenarios.

From the early stages of 6G conceptualisation, the NGMN Alliance has identified several compelling use cases for 6G technology (each involving several and diverse 6G services from those defined in section 3.1) [2],[3], classified in 4 classes:

- Enhanced Human Communication encompassing use cases designed to enrich human interactions, including immersive experiences, telepresence, and multimodal interactions.
- Enhanced Machine Communication addressing the increasing use of collaborative robotics and autonomous machines, emphasizing the need for environmental sensing and communication between robots and humans.
- Enabling Services covering use cases that demand advanced features such as high-accuracy location tracking, mapping, and environmental or body sensing data.
- Network Evolution focusing on the development of core technologies like AI as a service, EE, and providing ubiquitous coverage. Including generic network use cases (for enabling 6G provisioning stakeholder use cases) such as: Native Trusted AI (AIaaS), Coverage Expansion, Autonomous System for EE.

The 6G Flagship [26][27] had also worked similarly on 6G use cases definition from diverse perspectives (from the early stages of 6G vision definition):

- from the Customer and User experience viewpoint focusing on 4 key user case categories classified in: Communities (scenarios), Customer 6.0 (scenarios), Smart Society (scenarios), I robot (scenarios).
- from Resource Management and business perspective encompassing scenarios for the stakeholders of the 6G provisioning Ecosystem including scenarios for MNO 6.0, OTT, Edge, and Telco broker roles.
- from the value creation and serving UN SDGs purposes viewpoint, considering sustainable 6G developments.

At the same time the 3GPP 22.x series [28] has dedicated a set of technical reports to defining the KPIs and requirements of future (Beyond 5G) services (service components); indicatively for Augmented Reality (AR)/ Extended Reality (XR) services (TR 26.928), Integrated Sensing and Communication (TS 22.137) [29], Presence (TS 22.141), Mobile Metaverse Services (TS 22.156), digital twinning, etc.

At the same time, ITU IMT-2030 in the vision Recommendation [1] has identified 9 user and application trends, (essentially reflecting use case categories of users and provisioning stakeholders), namely: Ubiquitous intelligence, Ubiquitous computing, Immersive multimedia and multi-sensory interactions, DT and virtual world, Smart industrial applications, Digital health and wellbeing, Ubiquitous connectivity, Integration of sensing and communication as well as Sustainability.

Further work on 6G vision, use cases and KPIs has been performed by many national and continental organisations such as: GSMA, 5GMAG, 5G-ACIA, B5GPC, 6G Forum of South Korea, Next G Alliance. The outcome of these works has been presented in the 1st 3GPP Stage 1 Workshop on IMT2030 Use Cases, held on 8-10, May 2024 [30].

In this context, the European vision on 6G Use Cases was initiated by the Hexa-X project [31] and summarized by Smart Networks and Services International and European Cooperation Ecosystem (SNS-ICE)[2] Action and presented in [32], encompassing the following use case categories:

1. **Immersive Experience/Seamless Immersive Reality** including use cases such as: Immersive Enterprise and Industry, Immersive Education, Immersive Gaming, Live and Interactive Immersive Content Creation.

   This use case category includes mixed reality collaboration and immersive telepresence scenarios (based on AR/VR/XR and immersive multi-modal services), enabling seamless RT interaction with both co-located and remote participants, as well as with digital representations of physical or virtual objects within a physical or virtual environment. Use cases of this category may be instantiated in various environments including smart offices, construction sites, education, healthcare, and cultural, social, and personal activities.

2. **Collaborative Robots/Cooperating Mobile Robots**, including Use Cases such as: Autonomous Embodied Agents Within Flexible Manufacturing and Mesh Embodied Intelligence.

   This use case category revolves around the uses of autonomous robots capable of moving, sensing their environment, and performing a variety of tasks in various environments, e.g., industrial manufacturing campuses, construction sites, smart living areas. These robots can communicate with each other, with other machines, and humans to complete versatile tasks – evolving human-machine interaction. Going beyond individual robots use cases, this category considers the performance of works by cooperating robots.

3. **Physical Awareness/Network Assisted 3D Mobility** including use cases such as: Uncovering Illegal Activities on Ground and Sea, Environmental Radio Sensing, Network Physical Data Exposure.

   This use case category considers network units capable to monitor the physical environment, detect objects, analyze data, and relay information to other devices for multiple purposes depending on the tasks and environment in which they are employed. Services provided by networks include network assistance information (trajectories, object locations), network assistance maps (digital 3D map data), network navigation (route recommendations), full operation (remote control of vehicles), context-aware communication (beamforming, path selection, scheduling), etc.

4. **Realtime DTs** including use cases such as: Cloud Continuum, Smart Maintenance, DTs (Building Model), Public Protection and Disaster Relief DT.

   This use case category is based on digital twinning applications and services applied in versatile real-world objects, processes, operations, etc. Digital twining is considered for interaction, control, prediction, test, maintenance, and management of processes and components in various environments such as manufacturing/industrial, smart cities, smart areas, mobile network planning and operation.

5. **Fully Connected World/Ubiquitous and Resilient Networks**, encompassing in a variety of use cases: Earth Monitor/Sustainable Food Production, Autonomous Supply Chain, Virtualization of Device Functionalities, Digital Sobriety and Enhanced Awareness, Resilient Communication for Safety Critical Applications; applicable in various environments/sectors of life such as: food production, health and safety, culture and education, etc.

[2] https://smart-networks.europa.eu/csa-s/#SNS-ICE

6. **Trusted Environments/Human-Centric Networks** category including use cases such as: Wireless In Vehicle Network, Industrial Sensors Network for Safe Production & Manufacturing, Virtual Control Room.

   This category focuses on the human at the centre of a wide range of 6G services where privacy and reliability are key characteristics, in various environments/operations/sectors of life such as: Precision healthcare, Incidents prevention and avoidance in education and institution areas, e.g. kindergartens, schools, homes, day care, workplaces, or hospitals, Public safety services during big events.

In general, 6G generic use cases span various verticals and highlight the transformative potential of 6G technology in different sectors. The usually addressed sectors are: Public Safety, Industrial Automation, Smart Communities, Immersive Experiences, Telepresence and Remote Collaboration under the vision of Sustainable Development of communities and technology.

At the same time [32] considers a number of "Operational Aspects" essentially being capabilities supporting use cases for the 6G provisioning stakeholders. These include: Spectrum Aspects, Seamless Orchestration across compute continuum, Native AI/ML capabilities, Intent-based Management, Unified 6G multi-connectivity solution and Simplified deployment & Management. 6G-SENSES considers this landscape of envisioned 6G use cases and positions the relevant advancements in a set of relevant use cases as elaborated in Chapter 4.

3.4 KVIs Definition: Background and Methodology

Traditionally, ICT development has been primarily driven by performance metrics and market demand. However, there is a growing need to align technology with broader societal values, to address global and local societal challenges and visions as outlined by the UN SDGs [5], The European Commission's priorities [6], the European Green Deal [7] and, lately, with ITU-2030 IMT-2030 vision [1]. In line with these efforts, directives and guidelines, technology innovations are expected not only to meet technical and user requirements, but also to cater for having a positive impact on versatile values (societal, environmental, individual, etc.). Values-driven technology development constitutes a paradigm shift for industries and academia with a high potential for creating a positive impact on society, and it is nowadays the focus of European Research Funding activities (e.g., the SNS programme) as highlighted in [25] [26].

For the purpose of having a common language and understanding of how SNS projects align with value-driven research, the KVs and KVIs as means to align ICT research outcomes with short-, mid- and long-term impact on values have come into play. These terms are discussed in detail in [25]. Hexa-X [33], the 6G Flagship project of the SNS JU program, initiated the concept of including KVs in research. As a follow up, Hexa-X-II [34] envisions an E2E system blueprint for 6G platform with the goals of achieving sustainability, inclusiveness, and trustworthiness; aligning with the concepts of Corporate Social Responsibility (CSR) on sustainability in social, economic and environmental domains. At the same time, EU SNS JU projects – already from Phase I of the programme – have worked on refining, defining and aligning their views on impact, values and KVIs. Indicatively, TARGET-X (https://target-x.eu/), IMAGINE-B5G (https://imagineb5g.eu/), 6G-SANDBOX (https://6g-sandbox.eu/), and 6G-XR (https:/6g-xr.eu) are aiming to identify and validate KVIs verified as relevant to the use cases supported, through demonstration of their importance to end-to-end (E2E) large-scale trials and pilots.

To this end, the Societal Needs and Value Creation (SNVC) subgroup of the Vision and Societal Challenges Work Group (WG) of the 6G Industry Association (6G-IA) was formed with the aim of fusing knowledge and experience from EU SNS JU projects, from external experts (especially representing the social sciences domains) and from the industry, towards providing guidelines for the relevant activities of the project (essentially aligning technology development with values), and towards aligning the relevant activities at EU funded research level. To this end, the SNVC subgroup worked on fusing projects and stakeholders' views and proposing a concrete framework for values-driven next-generation ICT solutions [25]. This framework is further elaborated and developed in the context of Hexa-X-II [21], the 6G-IA SNVC and TMV-KVIs monitoring subgroups.

At this point it shall be noted that efforts on KVs/KVIs definition discriminate between two notions of impact on values: "a direct impact" where technologies are studied in terms of required resources, environmental footprint (in various aspects), etc., (known as Sustainable ICT or Sustainable 6G); and an "indirect impact", where the usage of technology on other sectors is studied (often referred to as ICT for Sustainability or 6G for Sustainability) [33]. Both notions are investigated in the context of SNS JU projects, at various stages of R&D activities.

The proposed KVs/KVIs definition and monitoring framework (by SNVC) comprises a flow of steps to be followed in various iterations along with the Technology Readiness Level (TRLs) and Society Readiness Levels (SRLs), of the technological solution and the use case acceptance/deployment status). 6G-SENSES will inherit and align with the proposed framework and will work on nailing down the set of KVs, KVIs and validation methods applicable to the project advancements, work and vision.

An overview of the stepwise methodology of SNS to define KVs and KVIs is illustrated in Figure 3-3.

In particular, the steps are:

Step 1- Definition of scenario and use cases; where the global scenario and the separate use cases addressed by the technological solution are defined.

This document fulfils these steps (in the following chapters), by elaborating on the 6G-SENSES scenarios and use cases.

Step 2- Elicitation of KVs as criteria and as outcome that are affected -in any way- by the instantiation and the proliferation of the use case. This step provides a linkage between the KVs, both as criteria and outcomes, to the vision and objectives of R&D activities.

KVs as criteria could include a range of values, often framed at a high level within Environmental Sustainability, Economical Sustainability and Societal Sustainability [35], following relevant directions from UN SDGs adopted by policy or funding agencies of international, EU, national or community level. These KVs however need to be nailed down to the scope of the ICT/6G project and the ICT industry. The sources used for KVs definition are primarily the mandate of R&D program and the R&D project description of work and various groups of stakeholders.

These sources for KVs definition are also used in the context of 6G-SENSES. This step is also fulfilled in this document at this low TRL/SRL stage, by elicitating on KVs as criteria and outcome and KVIs on a per use case basis in Chapter 4.

Step 3 - Analysis of outcome on value domains. This step includes a more thorough analysis of the impact on value domains and the derivation of KVIs as absolute or relative, quantitatively (preferably) or qualitatively measures of the impact of technology solution on the identified KVs (under the notion of 6G for Sustainability). Essentially, for each of the KVs identified as relevant for a specific use case, certain use-case specific KVIs should be formulated.

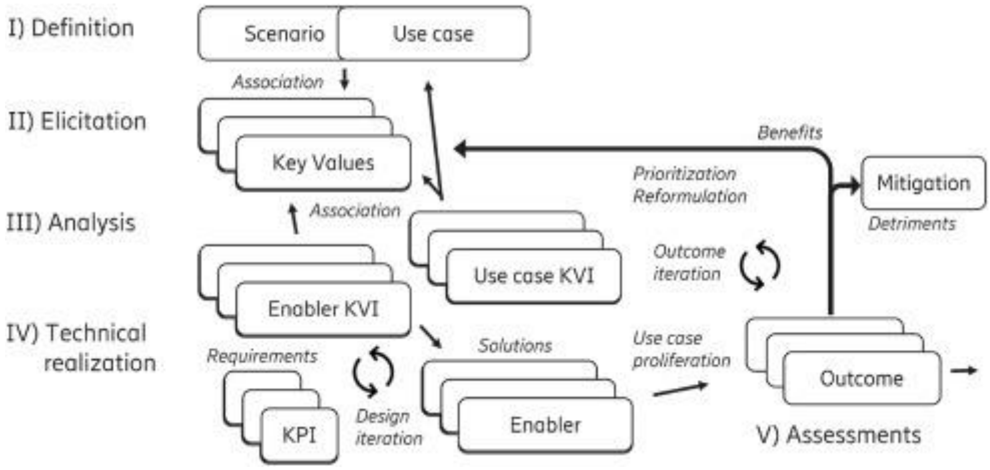

Figure 3-3 SNS KVIs definition methodology [25]

The impact can be beneficial or adverse, direct or indirect, at various timeframes and for various use case proliferation stages. Appropriately selected use case KVIs can be either utilized to demonstrate or validate that a developed technology usage is in the direction mandated by the international/EU/local, etc., policies on values.

This step is performed iteratively throughout the technology development and deployment/project lifecycle and at more mature stages it includes a more speculated view on the KVI as outcome and more valid estimations of use case proliferation/ foreseen acceptance at various time scales.

This step is also fulfilled in this document at this low TRL/SRL stage, by elicitating on KVIs on a per KV and use case basis in the following chapter. According to the methodology, this work will be refined along the project lifecycle, and the updates will be reported in the context of the Impact Assessment activities of the project (in Work Package 6 – WP6).

Step 4 - Technical realization, involving identification and specification of enablers (i.e. ICT solutions). This step is closely associated with the technical realisation (under the notion of Sustainable 6G solutions), and design iterations towards meeting the KPIs as a pre-condition for achieving the target KVIs (under both the notion of 6G for Sustainability and Sustainable 6G). In the context of 6G-SENSES, this step will be implemented by using the KPIs and KVIs definitions – of this document – to co-steer the implementation WPs of the project.

Step 5 – Assessment. This step includes the activities to be followed subsequently to monitor and evaluate KVIs following various methodologies depending on the TRL, SRL and use case proliferation stage. This step will be fulfilled as part of the 6G-SENSES project Impact Assessment activities.

4 6G-SENSES Use Cases, Requirements, KPIs and KVIs

Considering the above-mentioned transformation of the ecosystem (see section 3.2), both **6G vertical use cases** and a wide range of **service provisioning use cases** can be enabled.

It shall be noted that, given the fact that 6G research is at its initial phases, vertical use cases are envisioned as the ultimate goal, in deployments where 6G-SENSES developments are incorporated in fully-fledged/full-stack 6G networks (mainly mapped to the IMT-2030 Usage Scenarios). Instead, service provisioning use cases are more applicable, addressing sets of capabilities provided by 6G-SENSES enabling or facilitating service/ network providers' activities (mainly mapped to IMT-2030 New Capabilities). Considering the stage of 6G research, in the context of this deliverable, 6G-SENSES use cases are described from the service provisioning viewpoint (thus with technical details), while the long-term services-related use cases are simply mentioned on top.

To this end, **service provisioning use cases** are in the focus of 6G-SENSES (in line with the IMT-2030 new usage scenarios [1]), paying special attention to ISAC, as well as AI and Communication. These 6G use cases, requirements and KPIs represent the starting point for technology design and subsequent implementation of 6G-SENSES technologies.

For the former category of use cases, i.e., **vertical use cases**, in particular, the expected data rates, coverage availability and network reliability values are the key enablers for applications relying on Immersive and possibly HRLLC communication [44], [36] – in line with IMT-2030 and envisioned end-user usage scenarios [37], [44], [2]. Digital twinning of areas of interest and/or avatar-based visiting of areas of interest (e.g. archaeological/ monument site, museum, industrial/ office facilities) is a (non-restrictive) category of use cases envisioned in the context of 6G-SENSES.

This chapter provides detailed descriptions of the targeted 6G-SENSES use cases. The information pertaining to each of the use cases is structured as follows:

- Affected/Involved Roles of the Stakeholders.
- Main Objective.
- Description of the services required by the affected roles, along with their interactions/activities where applicable, their key operational and performance requirements.
- The current status and limitations faced in today's solutions.
- The way these use cases are addressed by the 6G-SENSES framework and innovations, including a brief description of the proposed technical solution.
- An indication of where this use case will be developed and tested, considering the available 6G-SENSES testing facilities.

4.1 6G-SENSES Use Cases Overview

Service provisioning use cases are in the focus of 6G-SENSES (in line with the IMT-2030 new usage scenarios [1]. From a technical perspective, in the **use case category of ISAC** we envision RAN sensing used as a means to obtain information on environmental conditions, density of people or machines (e.g. robots), speed of mobility of objects residing in the coverage of an access node, etc. To this end, the edge segment plays a key role in capturing and intelligently processing the sensing information streams that are parallel to the data communication ones. From the ecosystem roles viewpoint, sensing information is captured and/or processed by the RAN/O-RAN/RIS operator role and is communicated to the NOP under specific terms and conditions. The NOP can use this information to adjust the radio network in different ways, such as coverage optimization, efficient resource provisioning, or mitigation of network unavailability events within the area.

Similar information can be communicated by the RAN/O-RAN/RIS operator to SP. In this sub-case, the SP can exploit this information for multiple purposes, depending on the nature of the facility, on the supported applications and the requirements of the service customer. For instance, in the case of a monument site, this information could trigger a decision on the entrance rate of visitors considering the exhibit's healthcare, or in the case of an Industry 5.0 or office environment this information could trigger a decision on manufacturing pace/ activities/ machinery mobility, etc. In both cases, the RAN/O-RAN/RIS operator plays an active role in communication and application service provisioning.

In the **use case category AI and Communication**, we envision an AI layer that can be dynamically distributed across edge and core computing resources, for network and for application purposes. To this end, when considering AI processing as an integral part of the resources (of various segments and layers) management plane, AI processing belongs to the corresponding service provisioning layer, i.e. to SAs, or/and the VISP or/ and the NOP and or the SP, depending on the data to be captured and the specific capabilities to be enabled. The storylines falling in this category of use cases are several, e.g., resource efficient networking for NOP, cost-efficient provisioning of virtualized resources, intelligent aggregation of resources from multiple underlying layer stakeholders. What should be highlighted at this point is the advancement of the role of Infrastructure Providers from (semi-static) provisioning of computing re-sources to application services, to provisioning of computing resources for AI processing to the stakeholders of upper service provisioning layers. In such use cases the DCSP/IP can provision edge resources to NOP or VISP for 6G network AI processing.

In summary, it becomes evident that 6G advancements will enable future networks to go beyond meeting end-user requirements and beyond supporting innovative user applications. Indeed, it will enable the inclusion of even more stakeholders in service creation, in service provisioning and (also) in service consumption.

4.2 Use Cases & Requirements Template

For the purpose of following the same approach when presenting the information about use cases and requirements, each requirement has been specified according to the template shown in Table 4-3.

Table 4-3 Template for Requirements Definition in the context of use ases

<Req. ID>	<Requirement Title>
Priority	*Essential/Optional*
Description	*The 'Description' field contains the specification of the requirement (description of the purpose and goals to be fulfilled).*
KPIs/Parameters to be measured **Or/And** **Success Criteria**	*The 'KPIs/Parameters to be measured' field contains:* *for measurable requirements, the definition of the parameters to measure the satisfaction of this requirement; and the associated target values against one will base his/her evaluation.* *for immeasurable requirements, the qualitative criteria (or designed/deployed functionalities) to indicate the satisfaction of this requirement; and information related to the way these can be verified and evaluated.*
Network Segment / Component/ Layer	*The "Network Segment / Component / Layer / Role" contains information related to the part of the deployment and is mainly relevant for the System Requirements/ Specifications.*

<Req. ID>: This field provides a unique code to exclusively identify each individual requirement and facilitate tracking of its fulfilment in the next steps of the project. This field has the following generic format: P/VU/S-TYPE-RQT#. In this format, the following sub-fields are identified:

- P/VU/S indicates whether this is Service Provisioning, a Vertical/User requirement or System requirement/specification.
- TYPE indicates the type of the requirements and may take the following values:
  - FUNC & PERF – Functional or Performance requirement.
  - NFUNC – Non-functional requirement, e.g. related to security/privacy, extensibility, maintainability, interoperability, architecture, etc. requirement.
- RQT# is an incremental number uniquely identifying the requirement.

4.3 Use Case #1: Sensing enabled Services – Storyline #1: Exploiting sensing information to improve communication services (sensing-aided communication)

4.3.1 Key Technical ground of the Use Case

The integration of sensing functions into wireless communication systems is envisioned to be an integral part of 6G and future communication systems [38]. ISAC allows NOPs to optimize communication configuration and parameters based on the sensed information, e.g. location of the receiver, presence of obstacles, Doppler, or even tracking of the receiver(s) trajectory. This provides information necessary for the optimization of beamforming, handovers, bandwidth allocation or assisted PHY layer security. Sensing information can be also used for prediction of communication channel quality. Sensing enables detecting obstacles that have a detrimental impact on the communication links. Thus, based on the obstacle detection it is possible to avoid connectivity disruptions not only in user connectivity to base stations (BSs) but also in device-to-device connectivity. In those cases where disruption cannot be avoided, an AI/ML based caching mechanism should come into play to reduce the disruption of the service to the minimum achievable.

ISAC systems are designed nowadays to fulfil four main types of use cases [34]: Firstly, they enable high-accuracy localization and tracking, allowing precise identification and monitoring of objects or UEs. Secondly, they facilitate simultaneous imaging, mapping, and localization, enabling the creation of detailed maps while accurately determining the location of the system. Thirdly, they enhance human senses through augmented reality, providing users with additional information or sensory input. Lastly, the ISAC systems are capable of recognizing and interpreting gestures and activities, allowing for intuitive interaction and understanding of human actions.

From the ecosystem roles viewpoint, sensing information is captured and/or processed by the RAN/O-RAN/RIS operator role and is communicated to the NOP under specific terms and conditions. The NOP can use this information to adjust the radio network in different ways, such as coverage optimization, efficient resource provisioning, or mitigation of network unavailability events within the area. Similar information can be communicated by the RAN/O-RAN/RIS operator to SP. In this sub-case, the SP can exploit this information for multiple purposes, depending on the nature of the facility, on the supported applications and the requirements of the service customer. For instance, in the case of a monument site, this information could trigger a decision on the entrance rate of visitors considering the exhibits healthcare, or in the case of an Industry 5.0 or office environment this information could trigger a decision on manufacturing pace/ activities/machinery mobility, etc. In both cases, the RAN/O-RAN/RIS operator plays an active role in communication and application service provisioning.

Table 4-4 provides additional information about **Use Case #1** following the structure described at the beginning of the chapter.

Table 4-4 Use Case #1 – Storyline #1: Exploiting sensing information to improve communication services

Use Case #1 – Sc #1: Exploiting sensing information to improve communication services (sensing-aided communication)
Roles - Stakeholders: RAN/O-RAN/RIS operator (capture/process sensing information), NOP (takes decisions based on the information), Service Provider.
Objective: The main objective of the proposed use case is to enhance RAN performance and EE and to optimize PHY-layer algorithms leveraging on sensing assisted data communication methods. This use case experimentally measures and assess the performance and energy improvement in different deployments considering different user spatio-temporal connectivity and traffic patterns. Considering the 6G capabilities landscape, this use case focuses on the development and applicability of (IMT-2030) new capabilities “Ubiquitous Connectivity” and “ISAC” especially considering Immersive Communication services, and details on the NGMN Enabling Service and Network Evolution categories. Considering the SNS ICE use case categories, the concepts to be implemented in this use case is directly applicable to the following service categories: the “Immersive Experience/ Seamless Immersive Reality” along with “Physical Awareness” service components in various environments (e.g., smart office, historical monument). Complementarily, considering the 5G Automotive Association (5GAA) vision, the concepts to be implemented in this use case can be applicable to Vehicle-to-Everything (V2X) environments.
Description: ***Current status, Problem statement - limitations of today’s situation.*** Nowadays, MNOs are essentially the dominant stakeholders operating mobile networks serving large numbers of devices. 5G solutions usually aim at exploiting 5G network information captured by gNBs or UEs and processed by networks planning applications, towards optimising network deployment following time-consuming planning- configuration – replanning- reconfiguration cycles. In micro-planning cases where link quality is significant, radio network solutions automatically optimising link quality and performance are focusing on exploiting closed-loop beamforming to focus the antenna beams towards communicating devices (user devices, vehicles, etc.). Also, in this case, this incurs significant planning overhead as it is not fully automated. Moreover, the communication channel quality can be affected by obstacles, i.e., objects blocking or reflecting the propagation of the communication signal; cases which need to be detected to avoid steering beams towards blocked directions. Further considering existing technical challenges, beamforming is used based on exhaustive or hierarchical beam search to optimize the communication services. Beam prediction is leveraged to lessen the measurement overhead and latency, primarily based on supervised learning using neural networks. However, these face scalability issues due to the complexity of training and deployment. Therefore, solutions for beam prediction exploiting another type of sensor have been proposed, such as radar, camera or combination of camera and GPS, which can lead to improved performance but at the cost of increasing the complexity and the cost of the deployment. In both cases it becomes apparent that automated sensing of the environment (in terms of traffic demand, or physical structures) is crucial in optimising network performance towards delivering high quality services. From a third perspective, device positioning services (required both for network optimisation and for service provisioning) are already available in traditional wireless communication systems. However, the accuracy is limited by the location, availability of Line-of-Sight (LoS) and number of APs. Compared with deploying APs, deploying RIS is more flexible and the cost is lower, but still the integration needs to be performed to reap the higher spatial resolution and positioning accuracy. The combination of ISAC and RIS can offer a solution to this problem.

6G-SENSES Concept

Considering the 6G vision, a multitude of basic and advanced services will be delivered to verticals or individuals as end users in versatile environments. A precondition – and, at the same time, an enabling capability for this – is the provisioning of Ubiquitous coverage with the required service performance. At the same time, the advent of RIS and ISAC introduce new capabilities for achieving this goal, while enabling new roles of the 6G ecosystem. This use case revolves around the development of ISAC capabilities in multi-WAT radio units (RUs), extended to RIS, with the purpose of delivering a solution for network coverage and performance optimisation based on environment sensing.

More specifically, we consider the case of a 6G ecosystem as detailed in Chapter **3**. Multiple RAN Resource providers/ RAN Operators undertake the role of deploying RAN elements (of various technologies) - including RIS- that enable ISAC. The sensing data/information captured by RAN resource providing elements/roles is either processed and used for RAN self-optimisation (e.g. via closed loop beamforming, RIS configuration for communication enhancement) or sent to a RAN Operator or NOP for deciding on the network reconfiguration to optimise performance based on environment and traffic assumptions.

In more technical terms, 6G-SENSES leverages the work on ISAC to demonstrate – in an E2E small-scale proof-of-concept (PoC) prototype –ISAC performance in a form of an operated RU, DU, and CU/UPF pools with a RT control fabric providing sub-millisecond control loop over each network component. This solution will benefit from the availability of sensing information stemming from other non-3GPP technologies, such as Wi-Fi, and mmWave. This use case will deliver 6G communication links and sensing of the RAN environment and simultaneous access to the channel by multiple users.

Optionally, this use case can involve RIS panels, in a way that a LoS link can be established to provide the sensing service for the Non-Line-of-Sight (NLoS) areas and an extra LoS reflected link can be provided by the RIS to sense the target from a different angle, thus the sensing performance of the RIS-assisted networks can be significantly improved. Wireless communication will be optimized given the availability of sensing information stemming from a multi- WAT RAN. This sensing information is extracted from static and mobile environments and the information will be harnessed for the optimization of beamforming, allocation of resources and even for prediction purposes.

RIS-assisted sensing

RIS panels can be integrated with devices able to perform sensing data to enhance the overall performance of communication and sensing systems [40] [41] [42]. The integration involves leveraging the capabilities of RIS can lead to both the optimization of wireless communication links and the improvement of sensing capabilities simultaneously. One aspect of integration is utilizing RIS to enhance the quality of communication channels in ISAC systems. The intelligent tuning of the electromagnetic properties of the RIS panels can improve signal quality, increase coverage, and mitigate interference. This leads to improved reliability and higher data rates in the communication link between sensors, devices, or networks involved in ISAC applications.

Additionally, RIS can 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 can be particularly useful in storylines where the quality of sensing signals is compromised due to obstacles, interference, or noise. RIS can optimize the sensing environment by redirecting or focusing signals to enhance target detection, imaging, and tracking. The integration of RIS with ISAC data involves a collaborative approach where the RIS, communication devices, and sensing systems work in conjunction to achieve optimal performance. The RIS dynamically adapts its properties based on the communication and sensing requirements, ensuring that both aspects are optimized simultaneously, with certain challenges discussed in [76] and [77].

Note:

*Besides ensuring ubiquitous coverage, complementarily, the environment sensing data provided to service providers/ verticals, can potentially enable Immersive Communication and Collaborative Robots service elements for relevant applications. It shall be noted that considering the applicability of the solution in fast environment changing conditions, it appears that the solution is aligned with various V2X use cases envisioned by 5GAA [30]. The following paragraphs explain such applicability of the proposed **6G-SENSES** solution, which however will not be part of the project demonstrations.*

UAV-enhanced RIS-assisted V2X ArchitectureV2X

Augmenting the envisioned Use Case with the vertical service perspective; *with the development of IoT technologies and their wide application in urban traffic, the next-generation V2X communication network should support high-capacity, ultra-reliable, and low-latency massive information exchange to provide unprecedentedly diverse user experiences. The recently proposed 6G use case at 3GPP will pave the way for realizing this vision. The RISs, a critical 6G technology, are expected to make a big difference in V2X communications when used with unmanned aerial vehicles (UAVs), allowing for highly increased communication capacity and reduced latency. Experimental studies [79] have also been conducted to verify the performance of OTFS in realistic environments.*

The figures below show the V2X application scenario aligned with the 3GPP 6G ISAC Use Case scenario, an urban traffic section with many buildings and overpasses. RISs are deployed at certain intervals on the surface of buildings next to the road. When the traffic section generates congestion or other abnormal emergencies, we deploy several rotary-wing UAVs at certain intervals over the section. The traffic section is divided into multiple cells as shown in the figures below. Each cell has an RIS, a hovering UAV, and multiple intelligent connected vehicles (ICVs). The UAV can communicate with all ICVs located in the cell when unobstructed. Each ICV has a GPS device that allows to obtain RT location, speed, and direction information.

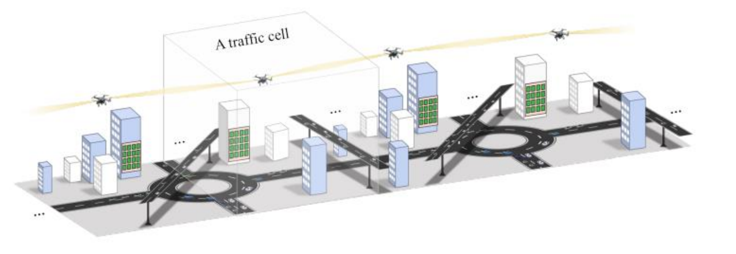

Figure 4-4 V2X application case

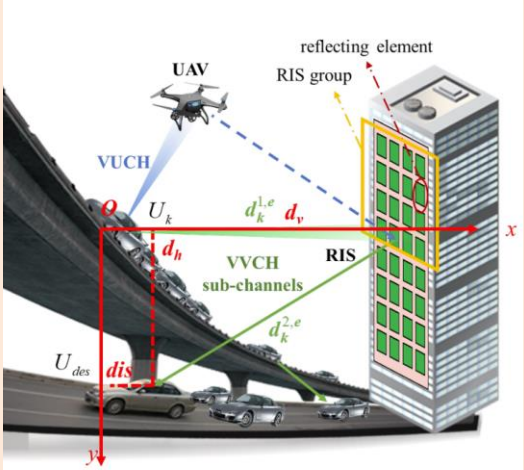

Figure 4-5 Details inside a traffic cell

Service Definition: RAN/RIS Provider provisioning (a) sensing data as a service to NOP, – for NOP to initiate network optimisation etc. (on-demand or automatically – self-consumption by RAN Operator of sensing data as a service for network self-optimisation). RAN/ NOP Operator provisioning sensing data to SPs – for SPs to enable specific vertical services to end-users. SPs to provide applications/ services with Physical Awareness along with Collaborative Robots/Cooperating Mobile Robots service components in various static or fast changing radio environments.
6G-SENSES Technical Solution/ Innovation – as Enabler: This use case will be enabled based on the following principles/ innovations to be delivered by 6G-SENSES: • Provision of ISAC functionality to the APUs, i.e. ISAC transmitter APUs, and transmitted signals used for sensing (OFDM-based, OTFS, etc.). • Multi-sensing approach leveraging Wi-Fi, non-Wi-Fi (Sub-6), mmWave, and 5G NR. • Use of ISAC for network load prediction and optimal network resource assignment. • ISAC-assisted beam search and beam tracking. • Explore the usage in Wi-Fi of active sensing technology, where one of the antennas is used for transmit while the remaining antennas are used for simultaneous receive. • AI/ML algorithms for higher positioning accuracy in challenging NLoS conditions. • Cross-layer approach to improve the edge caching mechanism by mixing different kinds of features (network traffic characterization, mobility information, etc.). • Evaluation on how ISAC can be exploited for improving the operation and deployment of RIS. It shall be noted that considering ISAC, there are various levels at which the integration of sensing and communication functions can occur, ranging from loosely coupled to fully integrated. This integration can involve shared spectrum, shared HW, and shared signal processing and protocol stacks. Additionally, cross-module and cross-layer information sharing can occur, with each function benefiting the other. This poses a variety of requirements that can vary depending on this level of integration. The project will analyse different options before taking a decision on the final implementation.
Relevance to 6G-SENSES PoC: PoC#1

4.3.2 Requirements and KPIs

To enable the aforementioned use cases solution proposed by 6G-SENSES we shall consider various technical, performance and operational requirements and KPIs posed by the various roles/stakeholders of the 6G ecosystem. Knowledge about these requirements and KPIs would help taking early design decisions and detail the solution architecture at next stages, to assess the limitations of the practical implementation of the use case, and to identify potential modules of performance requirements that could inform the design of core capabilities (or 'service clusters') that could reside in the 'center' of an ISAC architecture.

Potential **KPIs from a demand/end user value** perspective are:

- Range resolution (level of detail sensed at distance) – (to meet application demand).
- Location accuracy – (to meet application demand).
- Orientation accuracy.
- Angular resolution.
- Motion rate accuracy.

- Maximum link range (unambiguous range).
- Coverage area.
- Value added apps integrating ISAC capabilities.
- Service availability.
- Update rate.
- Maximal sensing service latency.

Potential KPIs from the NOP perspective offering ISAC capabilities:

- Cost – CAPital EXpenditures (CAPEX) / OPerational EXpenditures (OPEX) of the solution – as low as possible.
- Robustness of service to meet application demand.

Table 4-5 Requirement #1 – Capturing object positioning and motion information with required accuracy

P/VU -FUNC-#1	Capturing positioning and motion information with required accuracy
Priority	Essential / Optional
Description	Network nodes need to be able to perform radar-like measurements using the radio interface, to detect unconnected objects, which is delivered by ISAC functionality. In conjunction with this capability, precise device positioning is required. For both these capabilities, it is expected that networks will only be able to deliver part of the required precision and coverage. A sensor fusion functionality would therefore be needed, where networks collect data from multiple sources, e.g., onboard camera and GPS, and fuse it with the network measurements to create an enhanced dataset that is shared with the device and other devices. Sensing accuracy refers to the degree of deviation between the true results and the sensing results at a certain confidence level, which can be characterized by the sensing error, e.g., root mean square error. The smaller the sensing error, the higher the sensing accuracy. Sensing accuracy includes distance accuracy, velocity accuracy, angle accuracy, etc.
Success Criteria / KPIs	**Success Criteria:** Verification of the capability of the solution to capture positioning and motion information with required/adjustable accuracy. KPIs relevant to positioning: • Positioning Latency – lower than 10 ms to comply with E2E service latency of <1 – 10 ms. (in line with **KPI-O.2.2-2**). • Positioning Availability – depending on type of services. (**KPI-O.2.2-3**). • Control loop for mini-slot (200 µs) for large number of cells (**KPI-0.2.2-4**). **KPIs:** The required accuracy depends on achievable beamwidth at given distance and depends on application. Additional KPIs are: • Range resolution (level of detail sensed at distance) – (to meet application demand). • Location accuracy – (to meet application demand). • Orientation accuracy. • Angular resolution. • Motion rate accuracy.
Network Segment / Component/ Layer	RAN Network; ISAC capabilities.

Table 4-6 Requirement #2 – Service Area

P/VU -PERF-#2	Service Area
Priority	Optional
Description	There exists an intrinsic difference between wireless sensing and communication in terms of coverage requirement. Current cellular networks that are deliberately planned mainly for communication coverage can hardly achieve seamless sensing coverage. Optimally, it shall be possible to obtain sensing information from the whole communication coverage area.
Success Criteria / KPIs	**Success Criteria:** Verification of the capability of the solution to jointly provide communication and sensing over a specific area – even via different RAN technologies. **KPIs:** The required service area depends on application/environment where a use case is deployed. • Maximum link range (performance vs distance from RAN nodes) • Coverage area for Communication (surface in sqm vs performance) • Coverage area for sensing (metric % of communication coverage area or link range for communication)
Network Segment / Component/ Layer	RAN Network; ISAC capabilities.

Table 4-7 Requirement #3 – Sensing Latency components

P/VU -PERF-#3	Sensing Latency components
Priority	Essential
Description	Network nodes need to be able to perform radar-like measurements using the radio interface, to detect unconnected objects, which is delivered by ISAC functionality. In conjunction with this capability, precise device positioning is required. For both these capabilities, it is expected that networks will only be able to deliver part of the required precision and coverage. A sensor fusion functionality would therefore be needed, where networks collect data from multiple sources, e.g. onboard camera and GPS, and fuse it with the network measurements to create an enhanced dataset that is shared with the device and other devices. This requirement is related to scalability. The sensing update rate is the inverse of the time interval between two adjacent sensing results. Sensing latency is used to quantitatively describe the RT requirements of a sensing service, such as the maximum latency from the generation of a sensing service request to the feedback of the sensing result. The sensing service latency [29] is the time elapsed between an event occurring or sensing triggered by the sensing system and the availability of sensing results on the sensing system.
Success Criteria / KPIs	**KPIs:** The required sensing latency components depend on application/environment where a use case is deployed: • Sensing Latency • Sensing update rate • Sensing service latency
Network Segment / Component/ Layer	RAN / From RAN to Core; sensing capabilities

Table 4-8 Requirement #4 – Mobility

P/VU -PERF-#4	Mobility
Priority	Optional
Description	Sensing shall be able to detect fast moving objects and provide indications on fast changing radio environment. The mobility targets may differ depending on the environment of the network deployment
Success Criteria / KPIs	**KPIs:** • Max Mobility Range (100 km/h (city environment) – 300 Km/h (railway environment)
Network Segment / Component/ Layer	Sensing capabilities

Table 4-9 Requirement #5 – Cost Efficiency

P -PERF-#5	Cost Efficiency
Priority	Essential
Description	The solution shall be cost efficient in terms of CAPEX/OPEX for the RAN Operator/ and or NOP Operator to adopt.
Success Criteria	**Success Criteria:** • Low CAPEX/OPEX solution (to be verified via relevant techno-economic studies)
Network Segment / Component/ Layer	Complete solution for this use case.

4.4 Use Case #1: Sensing enabled Services - Storyline #2: Enabling Active Sensing with Wi-Fi system and Wi-Fi sensing standardization design

4.4.1 Key Technical ground of the Use Case:

Wi-Fi active sensing technology represents a significant leap forward in the realm of wireless communication, offering a multifaceted approach to RT data analysis and environmental interaction. By utilizing one antenna to transmit signals and the remaining antennas to receive, this technology enables a device to engage in duplex communication, effectively 'listening' while it 'speaks.' This dual capability is the cornerstone of a Proof-of-Concept (PoC) that aims to demonstrate the practicality and efficiency of active sensing in a Wi-Fi context.

Table 4-14 Use Case #1 - Storyline #2: Enabling Active Sensing with Wi-Fi system and Wi-Fi sensing standardization design.

Use Case #1 -Sc #2: Enabling Active Sensing with Wi-Fi system and Wi-Fi sensing standardization design
Roles - Stakeholders: Service Providers (sensing data provider)
Objective: The primary objective is to integrate active sensing technology within Wi-Fi systems enhancing both communication and sensing capabilities by using one antenna for transmission and one antenna for simultaneous reception (enables a "radar-like" sensing operation during regular Wi-Fi communication). Considering the 6G capabilities landscape, this use case aims to contribute to the development of technologies with applicability on (IMT 2030) new capability "ISAC", especially enabling Immersive

Communication and partially HRLLC usage scenarios. This use case details on the NGMN Enabling Service and Network Evolution categories.

Considering the SNS ICE use case categories, the concepts to be implemented in this use case will be directly applicable to various service categories e.g. the "Immersive Experience/ Seamless Immersive Reality" along with "Physical Awareness" service components in various environments – where environment sensing will be needed.

Description:

Current status, Problem statement - limitations of today's situation.

The current SoTA primarily utilizes passive Wi-Fi signals for sensing, but the active approach proposed here is a novel concept that has yet to be fully explored. By integrating active sensing, we can expect to see a new wave of innovation in ISAC, leading to more immersive AR/VR/XR experiences and a transformative impact on user interaction with laptops and other smart devices. This proposal not only aligns with the current trajectory of technological advancement but also charts a course for future innovations that will enrich our interaction with the digital world. An additional significant impact of active sensing lies in motion presence detection. This capability plays a crucial role in managing network resources and optimizing the EE of the network based on sensing information. By intelligently detecting the human presence, the system can optimize the energy and resources of the network based on this information.

6G-SENSES Concept

Considering the 6G vision, a multitude of basic and advanced services will be delivered to verticals or individuals as end users in versatile environments. Key enabler for the support of "Immersive Experience/ Seamless Immersive Reality" along with "Collaborative Robots/ Cooperating Mobile Robots" services is the incorporation of sensing capabilities.

More specifically, we consider the case of a 6G ecosystem as detailed in Chapter 3. Multiple RAN Resource providers/RAN Operators undertake the role of deploying RAN elements (of various technologies) - including Wi-Fi- that enable ISAC. The sensing data/information captured by RAN (Wi-Fi) resource providing elements/roles is either processed and for network optimisation (see **Storyline #1**) or sent to provided as a service to service providers/ verticals, to enable Immersive Communication and Collaborative Robots service elements for relevant applications.

In more technical terms, considering the afore mentioned technical limitations of current solutions, the algorithms developed for this purpose are designed to refine the process of delay and Doppler estimation, which are critical parameters in determining the relative motion and distance of objects in the vicinity of the sensor. These advancements pave the way for a host of applications, particularly in the burgeoning fields of AR, VR, and XR. The implications for these technologies are profound, as they rely heavily on seamless and intuitive interaction with virtual environments.

Furthermore, active Wi-Fi sensing has the potential to revolutionize power management and network resources. By intelligently detecting the absence of human presence, for example, the system can transition into a low-power state, thereby conserving battery life and extending the usability of the device.

This proposal has the potential to revolutionize how we interact with Wi-Fi networks, making them not only data conduits but also valuable sensors for understanding human behavior and environmental dynamics. The expected outcomes are the following:

- A comprehensive evaluation of Wi-Fi-based activity sensing techniques.
- Clear requirements and standardization guidelines for incorporating activity sensing into Wi-Fi protocols.
- Innovative applications leveraging Wi-Fi intrinsic ability to sense the surrounding environment.

• Develop active sensing ability that works simultaneously with regular communications.
Service Definition: RAN/ NOP Operator provisioning sensing data to SPs – for SPs to enable specific vertical services to end-users. SPs to provide applications/services with Immersive Experience/Seamless Immersive Reality along with Collaborative Robots/Cooperating Mobile Robots service components in various environments.
6G-SENSES Technical Solution/ Innovation: This use case will be enabled by the following innovations to be delivered by 6G-SENSES: • Enable active sensing with Wi-Fi system.
Relevance to 6G-SENSES PoC: PoC#1

4.4.2 Requirements and KPIs

Table 4-10 Requirement #6 – Sensing Capabilities

P -FUNC-#6	Service Area
Priority	Essential
Description	The following capabilities shall be supported for enabling user services: • **Motion Presence Detection:** technology can ascertain the presence of individuals, enhancing security and automation systems. • **Gesture Recognition/Hand Tracking:** systems can interpret hand movements and consider these as precise input commands, allowing for more natural and intuitive user interfaces.
Success Criteria / KPIs	**Success Criteria:** • Detect presence of individuals with high reliability levels • Recognise gestures/perform hand tracking
Network Segment / Component/ Layer	Wi-Fi Sensing Capabilities

Table 4-11 Requirement #7 – Accuracy of Sensing

P -FUNC-#7	Service Area
Priority	Essential
Description	Sensing strategies shall comply with the following accuracy-related requirements: • Full duplex operation on active sensing with self-interference mitigation enables detection of human movement within a distance smaller than 2 m from the sensor. • Hand Motion Doppler detection at smaller distance of 50 cm.
Success Criteria / KPIs	**KPIs:** • Precision/accuracy of the developed sensing strategies (in line with KPI-O.2.2-1) • Positioning Latency (in line with KPI-O.2.2-2) • Positioning Availability (in line with KPI-O.2.2-3)
Network Segment / Component/ Layer	RAN Network; Sensing Capabilities

Table 4-12 Requirement #8 – Susceptibility to background motion around the sensing device

P -FUNC-#8	Susceptibility to background motion around the sensing device
Priority	Essential
Description	The system shall be capable of distinguishing between two objects/targets with similar RCS values but different velocity by analyzing their distinct Doppler shifts, and detect both targets/objects (e.g., 2 people, one walking towards the radar, the other moving away). Isolate static clutter spectrum from moving objects to enhance detection.
Success Criteria / KPIs	**KPIs:** • Precision/accuracy of the developed sensing strategies. (in line with KPI-O.2.2-1)
Network Segment / Component/ Layer	Wi-Fi Sensing Capabilities.

Table 4-13 Requirement #9 – Cost Efficiency

P -NFUNC-#9	Cost Efficiency
Priority	Essential
Description	The solution shall be cost efficient in terms of TCO (CAPEX/OPEX) for the RAN Operator and/or NOP Operator to adopt.
Success Criteria / KPIs	**Success Criteria:** • Low TCO solution (to be verified via relevant techno-economic studies)
Network Segment / Component/ Layer	Wi-Fi Sensing Capabilities.

4.4.3 Use Case KVIs

6G-SENSES focuses on devising an ISAC architecture that enables not only the achievement of 6G KPIs, but also efficient network options by making use of new capabilities toward enabling 6G use cases and addressing global values. To this end, 6G-SENSES allocates effort in the identification of the impact of its advancements in terms of impacted KVs and KVIs, when the enabled use cases are proliferated. For this purpose, following the KVIs definition framework explained in Section 3.4, we foresee a 6G environment with a widespread deployment of the aforementioned 6G-SENSES innovations, and with the aforementioned use cases massively proliferated in the future.

In particular, in widespread deployments of multiple overlaying RUs (BSs and antennas) the environment effects need to be considered especially regarding the cumulative Electromagnetic field (EMF) radiation from multiple sources. So far, EMF compliance limits are addressed at equipment level, failing to take into consideration the cumulative effect from many sources over the same area, although EMF regulations and EC directives consider cumulative limits. For this purpose, sensing can be utilized to help with deployment by providing sensing-assistance in antenna systems of a mobile radio systems, allowing a dynamic adaption and shaping of antenna beam characteristics jointly optimizing the communication performance towards UEs and keeping at the same time safety margins set by EMF regulations around the antenna site. This directly results also in lower energy consumption at the radio segment. In this context, the proliferation of such capabilities (reflecting 6G-SENSES **Use Case #1** – **Storyline #1**) can significantly contribute to the general KVs as criterion of “Environmental Sustainability”. This can be interpreted as a project outcome KV achieving a deployment with “Low EMF”, and “Low Energy Consumption”, with respective KVIs being: **KVI #1** – “Optimisation of EMF for given coverage”, and **KVI #2** –“Optimisation of Energy Footprint for given services”.

Considering the **Storyline #2** of this use case, we foresee a future 6G environment with a widespread deployment of the aforementioned 6G-SENSES innovations, and with user/vertical cases falling in the category of Immersive Experience and Physical Awareness. Indicatively we consider Immersive Education-related and Culture-related Services or Immersive services enabling the remote participation in events enabled by the proliferation and adoption of the sensing capabilities of **Use Case #1** – **Storyline #2**. This could be, e.g., a teacher remotely teaching a class, showing a student how to answer a question, showing a virtual board, using gestures to express scientific concepts – which are then viewed immersively by the students. It could also be a cultural event where artists move around and their movement and gestures are immersively perceived by an audience at remote locations. In the latter case other types of events – such as sports events - can be considered. Considering the UN SDGs, through the massive proliferation of these enabled services the high level KVs (as criteria) that are addressed could be: Quality Education, Reduced Inequalities, Quality of Living and Inclusion and Sustainable cities and communities, the list being non-restrictive. These KVs are nailed down to KVs as outcome and KVIs in Table 4-14.

Table 4-14 KVs and KVIs addressed by Use Case #1

Use Case/ Storyline	KV as Criterion	KV as Outcome	KVIs
Use Case #1 Storyline #1	Environmental Sustainability	**Stakeholder**: Providers & Users **Effect on**: State of Being **KV1**: Low EMF. **KV2**: Lower Energy Consumption	**KVI 1**: Optimisation of EMF for given coverage. **KVI 1**: Optimisation of Energy Footprint for given services
Use Case #1 Storyline #2	Quality Education & Reduced Inequalities	**Stakeholder**: Users **Effect on**: Activities **KV1**: Remote/Live Participation in education. **KV2**: Economically efficient participation in education and cultural products	**KVI 1/KVI 2**: Increase in # of educational/cultural products available as immersive services. **KVI 3**: Increase in areas (population/coverage) having access to these products
Use Case #1 Storyline #2	Quality of Living & Inclusion; sustainable cities and communities	**Stakeholder**: Users **Effect on**: Activities **KV1**: Remote/Live Participation in various events (enabled by Immersive services support)	**KVI 1**: Increase in # events available as immersive services **KVI 2**: Increase in areas (population/coverage) having access to these events

4.5 Use Case #2: Ubiquitous Connectivity & Immersive Services

4.5.1 Key Technical ground of the Use Case:

CF-mMIMO systems can provide seamless and high-quality connectivity for users, not disrupted by network congestion, poor coverage at cell edges, or interference [43]. This is particularly important for enabling highly demanding services requiring low latency and high data rates such as immersive experience applications, AR, VR, immersive gaming/education, and RT collaborative experiences. CF-mMIMO systems provide more uniform performance across the network, including at cell edges, and improve the user experience by leveraging the additional macro-diversity and the coherent user-centric transmission, where several APs in the network cooperate to serve users jointly. The CF-mMIMO system can leverage the complementary coverage and capabilities of the sub-6 GHz and mmWave WATs in the RU pool to ensure seamless mobility for users. The sub-6 GHz WAT can provide wide-area coverage and robust connectivity, while the mmWave RAT can deliver high bandwidth for immersive applications in localized hotspots. Improved performance, increased capacity, and enhanced EE can be provided by incorporating RIS into the CF-mMIMO system, thus making the system more suitable for a wide range of applications and storylines.

6G-SENSES leverages the existing work related to CF-mMIMO and provides a 6G CF-mMIMO PHY prototype and extend it to support RT control loop. The algorithms related to this implementation will be deployed on top of representative RT SDR HW components to demonstrate the feasibility of the concept (as PoC#2) as well as achieving high network performance. All relevant aspects of an operational CF-mMIMO network will be demonstrated, including tight timing synchronization, distributed signal processing for channel estimation and beamforming and fronthaul/backhaul data plane traffic exchange.

Table 4-15 Use Case #2: Ubiquitous Connectivity and Immersive Services

Use Case #2: Ubiquitous Connectivity and Immersive Services
Roles - Stakeholders: Service Providers (CSP, DSP, NSaaS Provider), NOP, RAN providers.
Objective: The main objective of the proposed use case is to deliver a 6G CF-mMIMO PHY prototype and extend it to support RT control loop. The algorithms related to this implementation will be deployed on top of representative RT SDR HW components to demonstrate the feasibility of the concept as well as achieving high network performance. All relevant aspects of an operational CF-mMIMO network will be demonstrated, including tight timing synchronization, distributed signal processing for channel estimation and beamforming and fronthaul/backhaul data plane traffic exchange. In addition, RIS panels can be leveraged jointly with the CF-mMIMO system to further achieve 6G ubiquitous high-capacity communication coverage. Considering the 6G capabilities landscape, this Use Case aims to contribute to the development of technologies with applicability on (IMT-2030) new capability "Ubiquitous Connectivity", and it reflects the requirements to be met by the infrastructure and virtualisation layer in order to support Immersive Communications Usage Scenarios. This use case details on the NGMN Enabling Service and Network Evolution categories. Considering the SNS ICE use case categories, the concepts to be implemented in this use case will be directly applicable to the following service categories: the "Immersive Experience/ Seamless Immersive Reality" along with "Collaborative Robots/Cooperating Mobile Robots" service components in various environments – where ubiquitous connectivity for a great number of services will be needed.
Description: ***Current status, Problem statement - limitations of today's situation.*** CF-mMIMO is currently in the focus of 6G research due to the promising capacity and link performance capabilities, in view of delivering high capacity/high reliability immersive services. Experimental work related to CF-mMIMO is carried out in many SNS JU research projects (e.g. MARSAL ([19], https://www.marsalproject.eu/). The main challenges associated to such technology are listed below, with some in the context of deployments of CF-mMIMO in large outdoor service areas. • Synchronization (Phase coherence). In the coherent transmission mode, the APs coherently precode and broadcast the identical data symbol to every user and function as a distinct antenna array. However, that requires phase synchronization among APs, which is challenging when APs are managed under different CPUs owing to the difficulty in synchronizing the transmission channel. • Mobility. The impact of a large Doppler on the wireless channel. Effective estimation and evaluation of CF-mMIMO systems in mobile situations are rendered more challenging owing to the fluctuations in the mobile users' velocity in RT. • Given the large number of deployed APs, selecting the optimal APs (dynamic AP cluster per user) for handover can be challenging.

- Coordination of the beamforming vectors among the distant APs can be challenging and may introduce latency.

6G-SENSES Concept

Considering the 6G vision, a multitude of basic and advanced services will be delivered to verticals or individuals as end users in versatile environments. Especially for the support of Immersive Services Usage scenarios, a precondition – and at the same time an enabling capability for this is the provisioning of Ubiquitous coverage with the required service performance. At the same time, the advent of CF-mMIMO and RIS introduce new capabilities for achieving this goal, while enabling new roles of the 6G ecosystem. This use case revolves around the development of CF-mMIMO capabilities (also RIS-assisted), with the purpose of delivering a solution for augmented network coverage with high channel quality.

More specifically, we consider the case of a 6G ecosystem as detailed in Chapter 3. Multiple RAN Operators undertake the role of deploying RAN elements and provide these to a CN/Network OP. These elements feature CF-mMIMO capabilities (being also RIS-assisted) enabling high-capacity network deployments, and connectivity for massive number of devices.

In more technical terms, the CF-mMIMO system consists of many distributed APs, with multiple APs serving one user (which is known as user-centric). It has been shown that a distributed CF-mMIMO system performs better than a centralized system under certain conditions. In recent years, the CF-mMIMO systems have been evaluated for data rate, outage probability, and EE. Topics such as pilot contamination, scalability, and system integration have also been studied theoretically.

The major challenge in the practical implementation of CF-mMIMO systems is the overhead in terms of signaling and coordination for pre- and de-coding of the transmitting and receive data, the data itself, and the required control signals for synchronization or scheduling. The scheduling and UE to AP assignment is a difficult combinatorial problem which could be solved by machine learning, e.g., by graph neural networks [80] Different splits of the transceiver chains are available and the so-called functional split can be selected and optimized. Different options to perform rate splitting in the CF-mMIMO can lower the demand on the front-haul links [81]. Depending on which calculations and functions are running on the APUs and on the virtual RANs, the corresponding interfaces and signaling via the fronthaul connections must be defined. Depending on the architecture of the physical network (fronthaul network) between the APs and the (one or more) Central Units (or CPUs) and, depending on the functional split, an efficient signaling of the data (user plane) and the control signals (control plane) must be found.

Consider a multi-WAT deployment case where some of the nodes (Sub-6, mmWave) feature CF-mMIMO capabilities. The APs and UE CF-mMIMO PHY layer are able to establish a data plane and expose interfaces to be monitored and controlled. A RAN RT control fabric will enable the RT control of the 6G PHY prototype, e.g. instructing each AP to be active or passive when serving a user.

Service Definition:

RAN/RIS Provider provisioning RAN elements.

NOP Operator provisioning network connectivity to various SPs/ Verticals.

SPs to provide applications/services with Immersive Experience/Seamless Immersive Reality along with Collaborative Robots/Cooperating Mobile Robots service components in various radio environments – especially requiring high channel quality and connectivity for a massive number of devices.

6G-SENSES Technical Solution/ Innovation:

This use case will be enabled by the following innovations to be delivered by 6G-SENSES:

- Seamless mobility for users leveraging the complementary coverage and capabilities of the sub-6 GHz and mmWave WATs.

• Dynamic adaptation of the user's connection to the most suitable RAT based on factors such as user location, network conditions, and application requirements. • Dynamic user-centric cluster formation and pilot assignment leveraging sensing data. • Joint precoding at the access points (APs) and optimization of the RISs for improved coverage and improved signal quality.
Relevance to 6G-SENSES PoC: PoC#2

4.5.2 Requirements and KPIs

Despite the considerable gains in SE offered by massive MIMO in general and, more particularly, by CF-mMIMO, there are concerns regarding the implementation costs and EE of multi-antenna systems [44]. Indeed, it has been demonstrated that significantly increasing the number of antennas is not the best solution to enhance the EE of future networks. This is due to the fact that the total energy consumption rises linearly with the number of RF chains needed by the active components, while data rates exhibit logarithmic growth.

Table 4-16 Requirement #11 – Capacity

P -PERF-#10	Capacity
Priority	Essential
Description	It is needed to provide per user outage capacity which significantly lower outage probability. By the user-centric design and assignment of multiple APs to one user, the reliability (outage probability) is improved by one order of magnitude with the same transmission rate per user.
Success Criteria / KPIs	**KPI:** Ubiquitous connectivity with high reliability (factor 10 times) compared to the base line network-centric design is demonstrated in a small-scale scenario.
Network Segment / Component/ Layer	Performance demonstrated on small-scale cf-mMIMO PHY/MAC Network Layer.

Table 4-17 Requirement #12 – Cost Efficiency

P -NFUNC-#11	Cost Efficiency
Priority	Essential
Description	The solution shall be cost efficient in terms of TCO (CAPEX/OPEX) for the RAN Operator/ and or NOP Operator to adopt.
Success Criteria / KPIs	**Success Criteria:** • Low TCO solution (to be verified via relevant techno-economic studies); Up to 7x OPEX reduction for CF-mMIMO; Up to 3x RIS-assisted CF-mMIMO.
Network Segment / Component/ Layer	RAN segment; CF-mMIMO; RIS assisted CF-mMIMO

4.5.3 Use Case KVIs

As already mentioned, 6G-SENSES allocates effort in the identification of the impact of its advancements in terms of impacted KVs and KVIs, when the enabled use cases are proliferated. Following the KVIs definition framework explained in Section 3.4, we foresee a 6G environment with a widespread deployment of the aforementioned 6G-SENSES innovations, and with the aforementioned use cases massively proliferated in the future. In particular, considering widespread deployment of resource efficient, interference free, high-capacity CF-mMIMO deployments supported by the relevant **Use Case #2** 6G-SENSES advancements will enable the effective provisioning and proliferation of immersive and collaborative services. The reflected 6G-SENSES capabilities actually contribute to the support and delivery of the services envisioned in Storyline #2 of **Use Case #1**. In particular, we foresee a future 6G environment with a widespread deployment of the CF-mMIMO and RIS along with ISAC innovations of 6G-SENSES, and with user/vertical cases falling in the category of Immersive Experience and Collaborative entities. Indicatively, we consider Immersive Education-related and Culture-related Services or Immersive services enabling the remote participation in events enabled by the proliferation and adoption of the capabilities of **Use Case #2**. This could be e.g. a teacher remotely teaching a class, a cultural event where artists move around and their movement and gestures are immersively perceived by an audience at remote locations, and these end users are co-located at the same area (even house), enabled by a high capacity density CF-mMIMO deployments. Complementarily, by enabling immersive services, entities (not only humans but also devices, e.g., collaborative devices/robots) that operate in remote locations, can be fully aware of the status/position/activities/etc. of other peer entities in another location; taking decisions on actions based on this information etc. In this case, services of collaborative robots can be enabled, which are usually envisioned in sustainable/ smart cities and communities' context – promoting sustainability through efficient manufacturing processes, through minimisation of human presence (minimising human effort and energy for commuting, etc.).

Considering the UN SDGs, through the massive proliferation of these enabled services the high level KVs (as criteria) that are addressed could be: Quality Education, Reduced Inequalities, Quality of Living and Inclusion and Sustainable cities and communities, the list being non-restrictive. These KVs are nailed down to KVs as outcome and KVIs in Table 4-18.

Table 4-18 KVs and KVIs addressed by Use Case #2

Use Case	KV as Criterion	KV as Outcome	KVIs
Use Case #2	Quality Education & Reduced Inequalities	**Stakeholder**: Users **Effect on**: Activities **KV1**: Remote/Live Participation in education. **KV2**: Economically efficient participation in education and cultural products	**KVI 1/KVI 2**: Increase in # of educational/cultural products available as immersive services **KVI 3**: Increase in areas (population/coverage) having access to these products
Use Case #2	Quality of Living & Inclusion	**Stakeholder**: Users **Effect on**: Activities **KV1**: Remote/Live Participation in various events (enabled by Immersive services support).	**KVI 1**: Increase in # events available as immersive services. **KVI 2**: Increase in areas (population/coverage) having access to these events.
Use Case #2	Sustainable cities and communities	**Stakeholder**: Industries **Effect on**: Activities **KV1**: Enablement of Industry 5.0 (enabled by Immersive services support) – Effective Manufacturing. **KV2**: Resource efficient Manufacturing	**KVI 1**: Increase in # processes enabled by immersive services. **KVI 2**: Energy savings enabled via introducing Collaborative services in manufacturing.

4.6 Use Case #3: Network DT - Storyline #1- Network Optimisation and Storyline #2- EE

4.6.1 Key Technical ground of the Use Case

O-RAN is going to play a vital role in the design and implementation of 6G networks and beyond. ORAN based xApps/rApps residing on top of network infrastructure helps in improving the network performance, reliability and also in network planning for the NOPs. xApps/rApps receives telemetry from multiple nodes which can be within the same wireless network or from different network or even different wireless domain. The data can be processed to steer the traffic, improve the EE as well as increase the SE for NOPs and save on CAPEX and OPEX.

SE and energy saving need to be balanced properly in a network and RIC residing on top is in perfect position to cater this through optimized smart decisions considering inputs from multiple APs and multiple domains.

The RIC handles various metrics from multiple RAN nodes and process it to optimize the network configuration, performance, increase SE and increase the reliability of cell edge users. Different telemetry formats need to be handled to support various O-RAN nodes vendors and data is propagated to the supported xApp/rApp and processed to produce decisions/outputs, which helps in better performance of network for NOPs.

Table 4-19 Use Case #3 - Storyline #1: Network DT - Network Optimization

Use Case #3 – Sc #1: Network DT network optimization
Roles - Stakeholders: RAN/O-RAN Resources Provider, RAN/O-RAN/CN Operator (NOPs), Sensing Data Provider, SPs.
Objective: Optimise network deployment in real or semi-real time based on environment sensing information. Based on RAN sensing capabilities, the RAN domain stakeholders undertake the role of capturing environment information and transferring it to core network stakeholders and service providers aiming at optimising network performance and coverage to match the user demand and/ or to provide specific vertical services to end-users. Considering the 6G capabilities landscape, this use case focuses on the development and applicability of (IMT-2030) new capabilities “Ubiquitous Connectivity”, “AI and Communication” and “ISAC”, and details on the NGMN Enabling Service and Network Evolution categories. It also works towards the “Connecting the unconnected” overarching aspect. Considering the SNS ICE use case categories, this use case aims to further work on the concepts of the “Realtime DTs” category considering the mobile network planning and operation as a “vertical industry” adopting twinning of their infrastructure, and the “Fully Connected World” category (in terms of addressing the Ubiquitous and Resilient Network capabilities). Furthermore, this use case can be extended to the vertical service provisioning layer with applications/services with Immersive Experience/ Seamless Immersive Reality along with Collaborative Robots/Cooperating Mobile Robots service components in the environment of a smart office or historical monument.
Description: ***Current status, Problem statement - limitations of today’s situation*** Nowadays, networks are designed based on initial information/estimation about the environment and the traffic demand. Based on these, network elements are placed so to optimize the network performance and deployment efficiency. However, the surrounding environment and traffic demand may change after the network deployment is ready, in ways that are not foreseen at initial network planning phases, e.g., due to an incident or the evolution of services to be provided. In legacy network deployments this is

performed via manual network reconfiguration, or by the deployment of additional network elements, being not instantaneous and requiring from hours to days timedays. The vision of "Ubiquitous coverage" (in terms of place and time) implies that 6G networks should continuously monitor the environment and optimize their configuration to optimise network performance for all service provisioning stakeholders.

Moreover, a wide set of vertical services envisioned for 6G require knowledge of the environment. This can be captured by tailored sensors detecting, e.g., movement/obstacle/carbon/air/ noise, etc., at application level or by the implementation of ISAC as inherent network capabilities. 6G vision is steered towards ISAC and AI capabilities as means to enable 6G services. Such types of services, as indicated in Chapter **3**, include Immersive Communication and/or Collaborative Robots service elements.

From a vertical service perspective, digital twining involves creating a virtual representation of a physical system. The virtual entity is synchronized in real-time with its physical counterpart, allowing for monitoring, analysis and optimization throughout the physical system lifecycle. In contrast, Massive IoT refers to the large-scale deployment of interconnected IoT devices collecting and exchanging vast amounts of data from a multitude of sensors and systems. Nowadays, this plethora of IoT devices enables comprehensive monitoring, automation, and data-driven decision-making across various industries. This data-driven approach improves decision-making, lifecycle management, and customer experiences by offering detailed insights and remote monitoring capabilities. Latest efforts focus on combining IoT data with DTs to support sustainability and energy management by identifying and implementing energy-saving measures, ultimately driving efficiency and innovation in various industries.

An exemplary storyline of such vertical use case is the deployment of various sensors in a historical monument, providing temperature, humidity, air quality, motion detection, and movement information, which are used to simulate potential issues, provide predictive maintenance schedules, and ensure the optimal preservation of historical artefacts and architecture. However, sensor-based sensing requires the deployment of a massive number of sensors along with radio network coverage for communication.

6G-SENSES Concept

Considering the 6G vision, a multitude of basic and advanced services will be delivered to Verticals or individuals as end users in versatile environments. A precondition and, at the same time, an enabling capability for this is the provisioning of Ubiquitous coverage with the required service performance. Simultaneously, the advent of O-RAN and ISAC introduce new capabilities for achieving this goal, while enabling new roles of the 6G ecosystem. This use case revolves around the joint exploitation and development of O-RAN and ISAC capabilities – coupled with AI and digital twinning functionalities – with the purpose of delivering a solution for network coverage and performance optimisation based on environment sensing.

More specifically, we consider the case of a 6G ecosystem as detailed in Chapter 3. Multiple RAN Resource providers/RAN Operators undertake the role of deploying RAN elements (of various technologies) that enable ISAC. At the same time, the O-RAN Operator maintains the network configuration data and fuses it to a relevant xApp that shapes the network DT. The sensing data/ information captured by RAN resource providing roles is sent to the O-RAN Operator who fuses this information in relevant xApp. The latter suggests changes to the network configuration with the aim to optimise network performance based on environment and traffic assumptions.

Based on the xApps/rApps, the O-RAN Operator can undertake the task to:

- Self-serve network optimization.
- Provide optimal network configuration suggestions to the NOPs.
- Help NOPs in better network architecture planning. NOPs based on suggestions can decide whether to accept the suggestion, to delay it, or even to reject the suggestion.

- Provide sensing data and enable Immersive Communication and Collaborative Robots service elements for applications to service providers/ verticals.

Augmenting the envisioned Use Case with the vertical service perspective**,** we consider the sensing data captured by the O-RAN segment being provided to the Service provisioning layer under specific terms and conditions; in order to further enable a number of Vertical services (the Vertical being both the site owner and/or the site visitors). Indicatively, such data can be exploited by digital twinning applications similarly with the aforementioned IoT/sensor captured data (especially in crowd/ human activity sensitive sites/environments), so as to optimize comfort, EE, and efforts to ensure the optimal preservation of the site (e.g. historical artefacts and architecture). These data, and enabled services, can also improve crowd management, event planning, and overall site visitor experiences along with site infrastructure management services (e.g. smart lightning and heat energy savings).

Service Definition:

O-RAN Resources Provider provisioning: a) sensing data as a service, and/or b) network related information based on network digital twinning to CN Operator/ NOP, – for CN Operator to request O-RAN resources/network configuration, etc. (on-demand or automatically – self-consumption by O-RAN Operator of sensing data as a service and network digital twinning results for network self-optimisation)

O-RAN Resources Provider/O-RAN Operator provisioning of: a) sensing data as a service, and/or b) network related information based on network digital twinning to CN Operator/ NOP – for the CN Operator/NOP to enhance CN functions deployment.

O-RAN/NOP Operator provisioning sensing data to SPs – for SPs to enable specific vertical services to end-users.

SPs to provide applications/services with Immersive Experience/Seamless Immersive Reality along with Collaborative Robots/Cooperating Mobile Robots service components in the environment of a smart office or historical monument. (Ubiquitous coverage based on ISAC and network twinning will enable these services).

6G-SENSES Technical Solution/ Innovation:

This use case will be enabled by the following innovations to be delivered by **6G-SENSES**:

- Sensing information will be captured from multiple WATs both 3GPP/O-RAN nodes as well as non-3GPP nodes like Wi-Fi in different network deployment environments and topologies. The ingestion of sensing information is based on availability and capability of different nodes.
- The received telemetry/ sensing information from various sources (multiple APs/RUs/SDRs and multiple WATs) will be injected into the O-RAN RIC. In a multi-vendor, multi WAT environment, RIC should be capable of handling telemetry in different formats over the E2 interface.
- As next step, multiple xApps/rApps consider the telemetry from multiple SDRs including cross technology sources (based on availability and capability), and evaluate the data in different scenarios/ storylines and in both offline and online modes to produce a meaningful outcome (e.g. a network reconfiguration suggestion to optimise coverage/performance based on the network digital twinning capability). The processing of the information can incorporate also AI/ML algorithms and the output channelled to the network control plane.

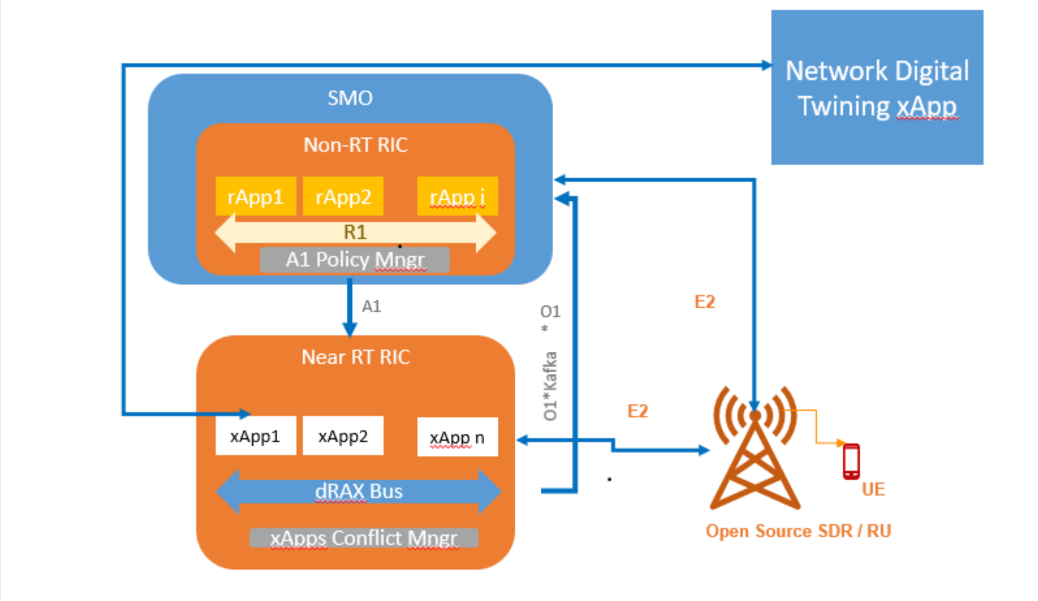

Figure 4-6 Network DT in O-RAN

Relevance to 6G-SENSES PoC: PoC#3

Table 4-20 Use Case #3.2: Network DT – Storyline #2: Energy Saving

Use Case #3.2: Network DT Energy Saving
Roles - Stakeholders: RAN/O-RAN Resources Provider, RAN/O-RAN/CN Operator (NOPs)
Objective: Optimize the EE of the network based on sensing information in different network deployment environments and topologies. Based on RAN sensing capabilities, the RAN domain stakeholders undertake the role of capturing radio-environment information and transferring them to network operating stakeholders aiming at optimising EE while maintaining the necessary network performance and coverage levels. Considering the 6G capabilities landscape, this use case focuses on the development and applicability of (IMT 2030) new capabilities "AI and Communication" and "ISAC", and directly addresses the overarching aspect of "Sustainability". Considering the SNS ICE use case categories, this use case aims to further work on the concepts of the "Realtime DTs" category considering the mobile network planning and operation as a "vertical industry" adopting twinning of their infrastructure, and the "Fully Connected World" category (in terms of addressing the Ubiquitous and Resilient Network capabilities).
Description: ***Current status, Problem statement - limitations of today's situation.*** Currently, networks are designed based on initial information/estimation about the environment and the traffic demand and network elements are placed so to optimize the network performance and deployment efficiency at peak times (or for specific performance and availability levels), based on these assumptions. However, the surrounding environment and traffic demand undergo significant changes over short or longer periods, in ways that are foreseen or not, e.g., due to normal demand periodicity, an incident, the evolution of services to be provided.

In legacy network deployments, apparently EE is (only) considered in network planning and deployment, for given the maximum service levels to be provided, rendering the network structures energy inefficient for long periods of low demand.

The vision of "Sustainability" as an overarching aspect of 6G networks implies that 6G networks should continuously monitor the environment and optimize network configuration based on both performance and EE criteria.

6G-SENSES Concept

Considering the 6G vision, delivering sustainable 6G deployments is a core goal. At the same time, the advent of O-RAN and ISAC introduce new capabilities for achieving this goal. This use case revolves around the exploitation and development of O-RAN and ISAC capabilities – coupled with AI and digital twinning functionalities, with the purpose of delivering a solution for network EE optimisation based on environment sensing.

More specifically, we consider the case of a 6G ecosystem as detailed in Chapter 3. Multiple RAN Resource providers/ RAN Operators undertake the role of deploying RAN elements (of various technologies) that enable ISAC. At the same time the O-RAN Operator maintains the network configuration data and fuses it to a relevant xApp that shapes the network DT. The sensing data/ information captured by RAN resource providing roles is sent to the O-RAN Operator who fuses this information in relevant xApp. The latter suggests changes to the network configuration with the aim to optimise network efficiency while maintaining the required performance levels.

Based on the xApps/rApps, the O-RAN Operator can undertake the task to:

- Self-serve network energy optimization.
- Provide optimal network configuration suggestions to the NOPs (for EE CN operation).
- NOPs based on suggestions can decide whether to accept the suggestion, to delay it, or even to reject the suggestion.

Service Definition:

O-RAN Operator or O-RAN Resources Provider provisioning (a) sensing data as a service and/or (b) network related information based on network digital twinning to O-RAN Operator or/ and NOP, – for O-RAN Operator or NOP to perform network (re)configuration optimising EE (on-demand or automatically – for self-consumption by O-RAN Operator of sensing data as a service and network digital twinning results for O-RAN self-optimisation).

O-RAN Resources Provider/ O-RAN Operator provisioning of (a) sensing data as a service and/or (b) network related information based on network digital twinning to NOP – for the CN Operator/NOP to enhance CN functions deployment towards optimising EE of the CN.

6G-SENSES Technical Solution/ Innovation:

This use case will be enabled by the following innovations to be delivered by 6G-SENSES:

- Sensing information from multiple APs/SDRs and multiple WATs (based on availability) will be injected into the O-RAN RIC over the E2 interface. Based on various KPIs like network load, UE mobility, time of day, etc., the xApps/rApps will decide to optimize the network setting.
- In the example depicted in Figure 4-7 and Figure 4-8, multiple SDR are present providing the network coverage to a specific area. The SDRs will transfer the sensing information towards the RIC over the E2 interface. Based on the received sensing information, the xApp/rApp will provide suggestions on the network topology. Any changes required in the network topology will be communicated towards the SDRs over the E2 interface.

- The energy saving procedure will be highly dependent on the SDR capability to handle the communication of KPIs and messages over the E2 interface, as well as run time configurability of the SDRs. If the decision is made to switch off an SDR, the UEs served by that SDR should be moved to other SDRs and based on an algorithm, the power of others SDRs will be recalculated and changed accordingly.
- Based on input, xApps/rApps will be able to suggest optimal network topology at any time of day towards improving network EE.

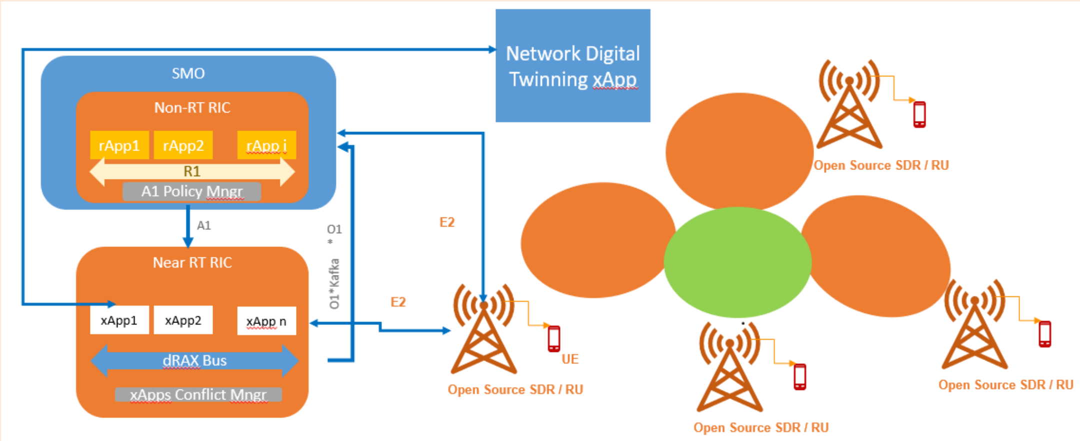

Figure 4-7 Energy efficient network operation via addition of an SDR/RU

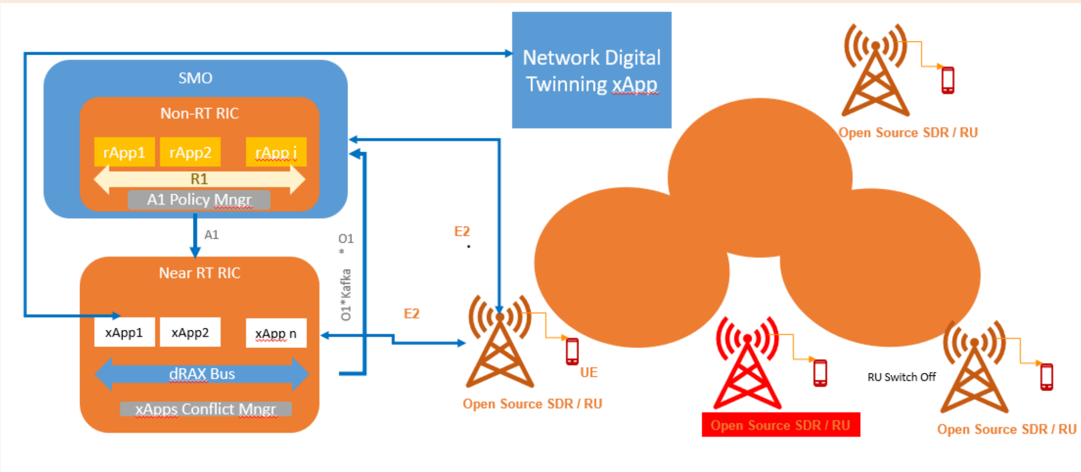

Figure 4-8 Energy efficient network operation via change in SDR/RUs configuration

Relevance to 6G-SENSES PoC: PoC#3

4.6.2 Requirements and KPIs

Considering the envisioned **Use Case #3**, a list of requirements posed from the SP stakeholder are identified. These are listed in the tables below.

Table 4-21 Requirement #13 – Network Coverage Availability

P -PERF-#12	Network Coverage Availability
Priority	Essential
Description	Network coverage availability needs to be optimized to address the 6G services requirements. The network availability levels depend highly on the service demand and service requirements

	and fluctuate in short and long time periods, thus to optimize network deployment, network planning and network coverage shall be quickly adjustable to respond to requested services availability requirements.
Success Criteria / KPIs	Network planning/ network coverage is adjusted based on network/environment sensing data.
Network Segment / Component/ Layer	RAN / From RAN to Core.

Table 4-22 Requirement #14 – RAN EE Optimisation

P -PERF-#13	RAN Energy Efficiency
Priority	Essential
Description	RAN energy efficiency needs to be optimized to address the 6G sustainability goals. The RAN energy consumption levels depend highly on the service demand and fluctuate in short and long time periods. Therefore, to optimize network energy efficiency, RAN network planning and deployment shall be quickly adjustable to respond to service requests, while preserving low energy consumption levels in low demand periods.
Success Criteria / KPIs	RAN planning/ RAN network deployment is optimized in terms of energy efficiency based on network/environment sensing data.
Network Segment / Component/ Layer	RAN Segment.

Table 4-23 Requirement #15 – CN EE Optimisation

P -PERF-#14	CN Energy Efficiency
Priority	Essential
Description	CN EE needs to be optimized to address the 6G sustainability goals. The CN energy consumption levels can be highly influenced on the service demand – especially for MEC related network functions- and fluctuate in short and long time periods. Therefore, to optimize network EE, CN (functions) planning and deployment shall be adjustable to respond to service requests, while preserving low energy consumption levels in low demand periods.
Success Criteria / KPIs	CN (functions) deployment is optimized in terms of EE based on network/environment sensing data.
Network Segment / Component/ Layer	From RAN to Core Segment

Table 4-24 Requirement #16 – Cost Efficiency

P -NFUNC-#15	Cost Efficiency
Priority	Essential
Description	The solution shall be cost efficient in terms of TCO (CAPEX/OPEX) for the RAN Operator and/or NOP Operator to adopt.
Success Criteria / KPIs	Success Criteria: • Low TCO solution (to be verified via relevant techno-economic studies) – Up to 2x OPEX reduction for O-RAN system integration.
Network Segment / Component/ Layer	RAN / From RAN to Core / 3GPP Network function 3GPP and Orchestration Layer

4.6.3 Use Case KVIs

As already mentioned, 6G-SENSES allocates effort in the identification of the impact of its advancements in on KVs and KVIs, when the enabled use cases are proliferated. Following the KVIs definition framework explained in Section 3.4, we foresee a widespread 6G deployment of **Use Case #3** related innovations, and the relevant use cases massively proliferated in the future. In particular, network digital-twinning as explained in **Use Case #3** impacts network coverage availability and optimises resources allocation thus achieving coverage of lower cost and required resources compared to legacy static nodes operation. With this, we can foresee an impact of **Use Case #3** proliferation on "Economic Sustainability" of deployments, and on bridging the digital gap thus reducing inequalities in terms of access to digital services. From another perspective, digital-twinning as explained in **Use Case #3** optimises network EE, thus addressing the global goal of "Environmental Sustainability". These "KVs as criteria" are nailed down to "KVs as outcome" and KVIs in Table 4-25.

Table 4-25 KVs and KVIs addressed by Use Case #3

Use Case / Storyline	KV as Criterion	KV as Outcome	KVIs
Use Case #3 / Storyline #1	Economic Sustainability	**Stakeholder**: Providers & Users **Effect on**: State of Being **KV1**: Economically efficient solution. **KV2**: Economically efficient service provisioning to end users	**KVI 1**: Reduction of TCO for service provisioning
Use Case #3 / Storyline #1 & **Storyline #2**	Reduced Inequalities	**Stakeholder**: Users **Effect on**: Activities **KV1**: Connecting the unconnected thus fostering inclusion of remote populations in digital services	**KVI 1**: Increase in coverage footprint
Use Case #3 / Storyline #2	Environmental Sustainability	**Stakeholder**: Providers & Users **Effect on**: State of Being **KV1**: Lower Energy Consumption. **KV2**: Lower Energy Resources utilisation	**KVI 1**: Optimisation of Energy Footprint for given services

4.7 Mapping of 6G-SENSES Use Cases to IMT-2030 and SNS JU vision

In the afore-mentioned sections, a mapping onto the IMT-2030 usage scenarios and 6G networks' new capabilities has been performed, as summarised in Figure 4-9, illustrating the relevance of 6G-SENSES work on the 6G vision.

Similarly, 6G-SENSES use cases – defined/described at network service provisioning level – are mapped onto vertical uses cases defined by SNS ICE as the vision of SNS JU delivered to ETSI. This mapping essentially projects the enablement of vertical use cases via the proliferation of 6G-SENSES advancements given a full-stack 6G network deployments. This mapping is summarised in Figure 4-10, illustrating the relevance of 6G-SENSES work on the SNS-JU vision (by SNS-ICE).

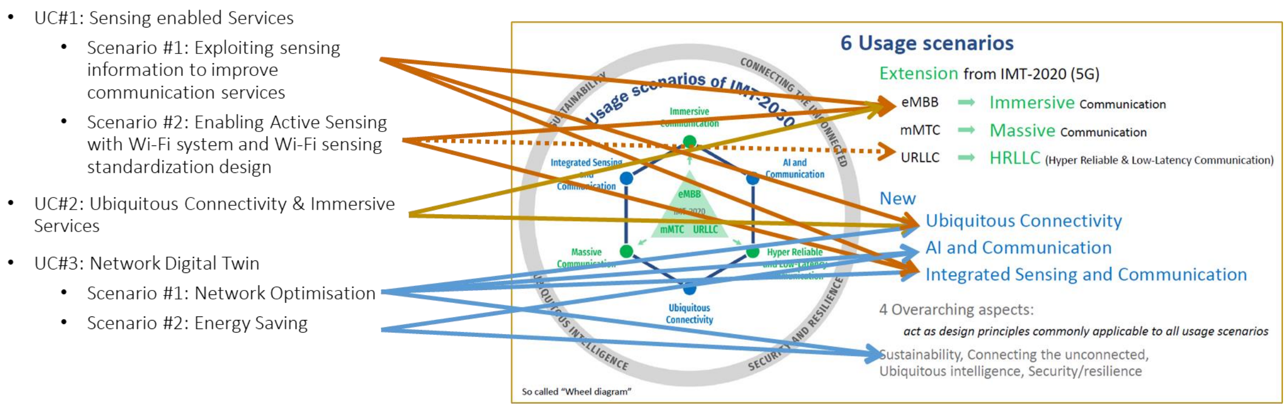

Figure 4-9 Mapping of 6G-SENSES use cases on IMT-2030 vision

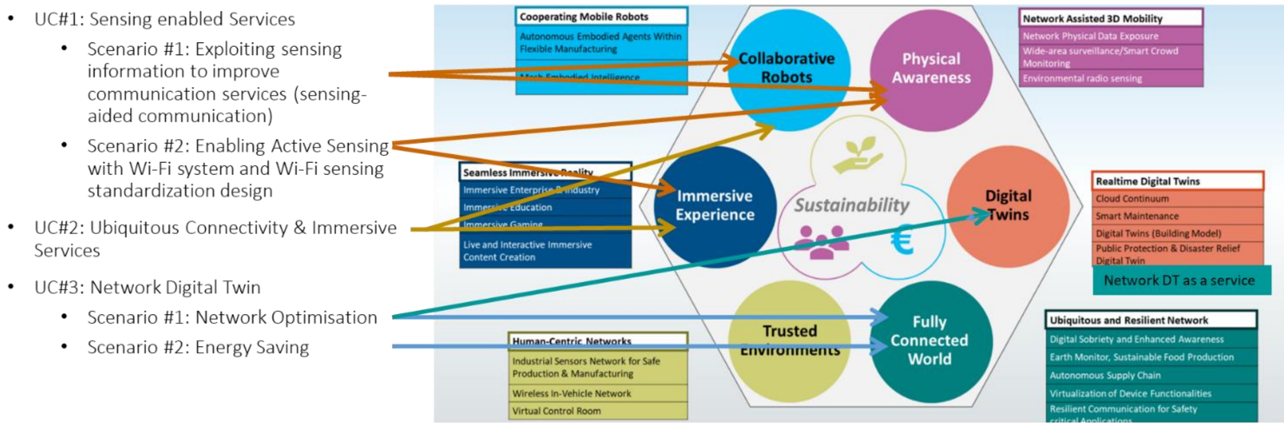

Figure 4-10 Mapping of 6G-SENSES use cases on SNS-ICE 6G vision

5 6G-SENSES System Requirements

An initial list of system requirements – to be directly translated into specifications for the 6G-SENSES solution – is defined in this chapter and will be channelled to the implementation activities of the project. That is achieved on the one hand, identifying the key innovations and main domains of research of 6G-SENSES, and on the other hand defining the set of use cases addressed by the project solutions, and the relevant user (User/ Vertical/ Provider) requirements.

5.1 E2E System Performance Requirements

Summarising and combining the User, Vertical and Provider requirements deriving from the use cases, the following E2E system performance requirements are identified.

Table 5-26 Requirement #17 – Maximum Data rates

P/U/V -PERF-#16	User Maximum Data rate
Priority	Essential / Optional
Description	The solution components shall meet the maximum user data rate requirements of the envisioned 6G services, in line with IMT-2030 capabilities definition (max 250 Mb/s [32]).
Success Criteria / KPIs	KPIs: • >50% improvement in throughput with the 6G-SENSES solution as compared to the 5G network (KPIs-O.3.4-3).
Network Segment / Component/ Layer	End-to-End

Table 5-27 Requirement #18 – Latency

P/U/V -PERF-#17	Latency
Priority	Essential / Optional
Description	The solution components shall meet the latency requirements of the envisioned 6G services, in line with IMT-2030 capabilities definition (< 1 ms based on [32]).
Success Criteria / KPIs	KPIs: • E2E latency reduction towards the 0.1 – 1 ms target (KPI-O.3.4-1).
Network Segment / Component/ Layer	End-to-End

Table 5-28 Requirement #19 – Site Coverage

P/U/V -PERF-#18	Site Coverage
Priority	Essential / Optional
Description	6G-SENSES shall improve site coverage characteristics compared to existing solutions.
Success Criteria / KPIs	KPIs: • >20% improvement in coverage as compared to the 5G network (KPI-O.3.4-2).
Network Segment / Component/ Layer	RAN

Table 5-29 Requirement #20 – EE

P -PERF-19	EE
Priority	Essential / Optional
Description	The solution shall be energy efficient – i.e. have optimised energy footprint while meeting user performance and coverage requirements – addressing the sustainability overarching aspect of IMT-2030 vision.
Success Criteria / KPIs	KPIs: • >15% enhanced resource usage efficiency while supporting use cases with extreme performance requirements (**KPIs-O.3.4-4**).
Network Segment / Component/ Layer	RAN segment; Wi-Fi Sensing; Orchestration Layers

Table 5-30 Requirement #21 – Connection Density

P/U/V -PERF-#20	Connection Density
Priority	Essential / Optional
Description	The solution components shall meet the connection density requirements of the envisioned 6G deployments, in line with IMT-2030 capabilities definition (target ranging between 10^6-10^8 devices/km^2).
Success Criteria / KPIs	KPIs: • Intelligent connectivity density: >20% connection density compared with existing systems based on non-intelligent connectivity (**KPIs-O.3.4-5**).
Network Segment / Component/ Layer	End-to-End

5.2 O-RAN / RAN System Requirements

The adoption of novel technologies such as ISAC and CF-mMIMO in 6G networks poses numerous new requirements in the RAN. Some of them have been already addressed or are currently being studied by 3GPP work groups.

For instance, one of the topics in the ongoing Release 19 is the enhancement of proximity services with Multi-hop support for UE-to-Network and UE-to-UE Relays or Multi-path transmission via different UE-to-Network Relays. This is one of the requirements introduced by CF-mMIMO, along with accurate time synchronization (e.g., bounded delay-jitter) between the UE and the gNB (also addressed by 3GPP specifications).

Regarding higher positioning accuracy, the recently concluded Release 18 offered expanded positioning, while dedicated 5G positioning reference signals had been already introduced since Release 16, i.e. Positioning Reference Signal (PRS) – in the downlink; and the Sounding Reference Signal (SRS) in the uplink.

ISAC also introduces new requirements for a RAN processing pipeline dedicated to sensing along with the capability to distribute sensing functions across multiple RAN entities (RU, DU or gNBs) for coordinated processing and control. The sensing information can be computed based on the I/Q samples, further processed by a sensing module to finally optimize the RAN (e.g., enhance MAC scheduling) through control actions. This could be further enhanced by means of an O-RAN service model and its associated RAN function within the E2 node to bring such data to the level of xApps, allowing the realization of custom ISAC processing far from the PHY layer, where free CPU resources are normally scarce.

The 3GPP RAN requirements by 6G-SENSES technologies are summarized in Table 5-31. Note that this table is more about reporting a number of key required features. In 6G-SENSES we primarily focus on the requirement for a specialized sensing model RAN function.

Table 5-31 Requirement #22 – 3GPP RAN Enhanced Capabilities

S- FUNC- #21	3GPP RAN requirements
Priority	Essential / Optional
Description	The adoption of novel technologies such as ISAC and CFmMIMO in 6G networks pose numerous new requirements in the RAN, such as: • Proximity services. • Time synchronization between UE and gNB. • Positioning signals. • Sensing function in the RAN pipeline at the PHY layer (at the level of channel estimation). • O-RAN RAN function for sensing. • Sensing-aware MAC scheduler design. • Coordinated interference management.
Success Criteria / KPIs	Success Criteria: • Resource consumption of sensing module in terms of CPU. • Accuracy of the sensing information. • User Performance improvement with sensing information. • Performance Stability in the presence of wrong sensing information or inference.
Network Segment / Component/ Layer	RAN

Table 5-32 Requirement #23 – O-RAN RICs Sensing Capabilities

S- FUNC- #22	O-RAN RICs for ISAC
Priority	Essential / Optional
Description	To deliver the sensing related functionalities of ISAC, it is necessary to have 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.
Success Criteria / KPIs	Success Criteria: • Capability to ingest sensing data from multiple sources in O-RAN RICs. • Capability to process the sensing data in O-RAN RIC.
Network Segment / Component/ Layer	RAN

Table 5-33 Requirement #24 – O-RAN RICs Interfaces

S- FUNC- #23	O-RAN Interfaces
Priority	Essential / Optional
Description	To deliver the sensing related functionalities of ISAC, it is necessary to analyse and prove the function mapping and network placement of the CF-mMIMO / ISAC RIS assisted technology with the 3GPP and O-RAN functional splits and specification.

Success Criteria / KPIs	Success Criteria: • Validation of integrated coordination of O-DUs through means of near RT and RT RIC (in line with KPI-O1.3-1). • Inclusion of definition of O-RAN interfaces to support CF mMIMO and ISAC RIS assisted devices in the architecture design (in line with KPI-O1.3-2).
Network Segment / Component/ Layer	RAN

Table 5-34 Requirement #25 – Accuracy of Sensing Data for RIC sApps/rApps

S- FUNC- #24	Sensing Data for RIC xApps/rApps
Priority	Essential / Optional
Description	Various types of sensing data are required as input to the RIC xApps/rApps, such as (the list being currently non-exhaustive): • User Location. • User Mobility. • Received signal strength information. • Resource allocation information. • APs load and power details. The quality of network reconfiguration suggestions of the RIC xApps/rApps depends highly on the existence and the accuracy levels and the quality (error probability) of the sensing data. Telemetry from multiple APs and cross domain data from Wi-Fi are important input to the RIC.
Success Criteria / KPIs	The required accuracy depends on the RAN technology specifications (e.g. whether it is RU/ SDR/ Wi-Fi) and on decisions related to the frequency rate. At first stage the success criteria is the capability of capturing and processing the relevant sensing data by the RIC. Accuracy and precision targets depend highly on the applied scenario. In terms of metrics the following KPIs need to be considered: • Precision of the developed sensing algorithm for detecting potential users (in line with **KPI-O.1.2-1**).
Network Segment / Component/ Layer	RAN / From RAN to Core / 3GPP Network function 3GPP and Orchestration Layer

Table 5-35 Requirement #26 – Sensing Frequency and Sensing Latency for RIC sApps/rApps

P- FUNC- #25	Sensing Latency
Priority	Essential / Optional
Description	The quality of network reconfiguration suggestions of the RIC xApps/rApps depends highly on the existence and the accuracy levels and the quality (error probability) of the sensing data. These levels are highly influenced by the sensing frequency (number of samples per unit of time) and the sensing latency (the time to start sensing, the time to process sensing data).
Success Criteria / KPIs	The required accuracy depends on the RAN technology specifications (e.g. whether it is RU/ SDR/ Wi-Fi).

	The required sensing frequency depends on the technology specifications, on the specific application scenario of the solution (e.g., whether it refers to immediate, short-term or long-term network (re)-configuration), and on the amount of data to be processed per unit of time/processing capability/storage capacity, etc. At a first stage the success criteria is the capability of capturing and processing the relevant sensing data by the RIC at variable sensing frequencies. The sensing latency will be measured from the time that sensing data is captured until the time that the RIC xApp/rApp suggestion is generated.
Network Segment / Component/ Layer	RAN / From RAN to Core / 3GPP Network function 3GPP and Orchestration Layer

5.3 Wi-Fi System Requirements

The primary objective of this part of the work in the project is to integrate active sensing technology within Wi-Fi systems enhancing both communication and sensing capabilities by using one antenna for transmission and others for simultaneous reception (enables a "radar-like" sensing operation during regular Wi-Fi communication). Table 5-36 presents the Wi-Fi sensing requirements in the context of 6G-SENSES.

Table 5-36 Requirement #27 – Wi-Fi Sensing

S- FUNC- #26	Wi-Fi Sensing
Priority	Essential / Optional
Description	Enable active sensing technology based on Wi-Fi, where one of the antennas is used for transmitting while the remaining antennas are used for simultaneous receive. PoC enabling active sensing using a Wi-Fi device, based on one transmitter and receiver antenna with duplex transmission. Algorithms will be proposed to enable delay and Doppler estimation based on active sensing. The use case scenarios of this application will be mainly active recognition, gesture recognition/hand tracking, human presence detection and breathing rate.
Success Criteria / KPIs	**KPIs:** **Accuracy of the sensing strategies (detection range) (KPI-O.2.4-1)** Active Sensing: 1. Full duplex operation on active sensing with self-interference mitigation enables detection of human movement within 2 m from the sensor. 2. Hand Motion Doppler detection at < 50 cm. Passive Sensing: 1. Detection of human movement within 4 m from the sensor (human walking/crossing the line between the Wi-Fi devices). **Susceptibility to background motion around the sensing device (KPI-O.2.4-2)** 1. The capability of the system to differentiate between two moving targets will be measured as part of this KPI. Two objects/targets with similar RCS values but different velocity will be considered by analyzing their distinct Doppler shifts to detect and discriminate both targets/objects (e.g., two people, one walking towards the radar, the other moving away). 2. Isolate static clutter spectrum from moving objects to enhance detection.
Network Segment / Component/ Layer	Component and PHY Layer: component -- active Wi-Fi sensing device; PHY layer – algorithm to enable active sensing

5.4 mmWave/THz Wireless System Requirements

mmWave and THz communication systems require large antenna arrays and use narrow directive beams to ensure sufficient receive signal power. However, selecting the optimal beams for these large antenna arrays incurs a significant beam training overhead, making it challenging to support applications involving high mobility.

To boost the network capacity and align with exponentially growing traffic demand, we consider a wide deployment of APs at a CF network. It will result in high network densification in dense urban area (e.g., campus, airports, stadiums), where inter-AP distances could be less than 100 meters.

There may be micro cellular deployments that require relying on FR2, non-3GPP carrier frequencies such as 60 GHz, and sub-THz frequencies. These may be key to sense the environment in, for example industrial environments. Macro-cellular deployments would require Sub-6 bands only as they may serve the purpose of sensing in outdoor scenarios.

5.4.1 Frontend chipset

Custom designed frontend integrated circuits (ICs) are essential, especially at the mmWave frequencies, to achieve low-voltage operation and high EE. In a typical design, the transistors are biased to attain their peak f_T, however at the cost of increased collector current and dc power consumption. The high f_T offered by IHP's Silicon-Germanium (SiGe) technology is preferred for the frontend chipset here to bias the transistors with lower collector current while maintaining a high effective f_T with sufficient power gain at the 60 GHz band. New circuit design approaches are investigated to operate with the lower supply voltage. In addition, design efforts are focused on enabling Continuous Wave (CW) / Frequency-Modulated Continuous Wave (FMCW) radar operation along with low- to medium-speed communication without any HW modification through the use of new building blocks.

Table 5-37 Requirement #28 – mmWave/THz Front End Chipset Characteristics

S8 FUNC- #27	Front End Chipset
Priority	Essential
Description	The frontend chipset developed in this study aims operation with lower supply voltage and dc power, improving the frontend EE. The lower supply voltage requirement (related to **KPI-O.2.3-3**) enables operation with batteries which is essential for portable applications. For such applications, the dc power consumptions are also crucial. Therefore, the frontend ICs developed here aim significantly reduced dc power requirement (related to **KPI-O.2.3-2**) as well. The implication on the circuit designer is that new building block topologies and design techniques compliant with the stricter dc voltage/power budget must be sought after. Furthermore, the high EE facilitates the scaling in the MIMO case which is essential for high angular resolution (related to **KPI-O.2.3-4**). In this direction, the chipset shall be designed in a scalable way such that multiple of them can be cascaded along the Local Oscillator (LO) signal propagation. The radar/communication functionality of the chipset in MIMO configuration will enable detection/communication with the active users and avoid the non-active users (related to **KPI-O.2.3-1**).
Success Criteria / KPIs	• Decrease in the required supply voltage by the frontend ICs. • Improvement in the frontend EE. • CW/FMCW radar and low/medium-speed communication functionality. • **KPI-O.2.3-1**: Reduced EMF human exposure. • **KPI-O.2.3-2**: Lower dc power consumption compared to SoA SiGe frontend chipsets (for high efficiency).

	• **KPI-O.2.3-2**: Lower dc voltage required compared to SoA SiGe frontend chipsets (for battery operability). • **KPI-O.2.3-4**: Angular resolution of 10 degrees (35 cm of separation resolvable assuming 2 m target range) and range resolution of 10 cm in sensing using the developed frontend.
Network Segment / Component/ Layer	RAN (antenna, front-end components)

5.4.2 Antenna in-package solution

mmWave spectrum is favorable for its large relative bandwidth enabling future data-intensive and low-latency applications. However, these advantages are attained on the cost of the distinct propagation characteristics of the mmWaves, especially the higher path loss. For some special frequency bands, this loss is further increased by the oxygen absorption in the atmosphere. One example is the 60 GHz unlicensed band. The higher loss makes this band favorable for short-range indoor communication. However, it imposes special constraints on the antenna systems to either use the high-gain beams or imply a diversity combination to maintain the required SNR for the link. Due to the higher transmission loss of the mmWaves in the guided media, antennae are preferred to be integrated into the package instead of the cable-connector system.

Table 5-38 Requirement #29 – mmWave/THz Antenna Characteristics

S- FUNC- #28	Antenna in-package
Priority	Essential / Optional
Description	Antenna arrays have been a popular choice to enhance the gain with the freedom of beam-steering through a beamformer mechanism, resulting in phased arrays. Phased array provides capacity enhancement in communication systems and lateral accuracy in the radar frontends (relevant **KPI-O.2.3-4**). Furthermore, they enhance performance of the radio systems by reducing the radiating power requirement (relevant **KPI-O.2.3-2**) and minimizing human exposure to electromagnetic energy (relevant **KPI-O.2.3-1**). Apart from phased arrays, the antenna arrays are also useable for MIMO functions, both in communication and radars, where the SNR is compensated by exploiting multiple channels in a multipath environment without increasing the radiation power (relevant **KPI-O.2.3-2**). However, the antenna array designs are complicated compared to the single-element designs. The close packaging of the antenna elements causes mutual coupling between the elements which can result in an active reflection coefficient for the individual element resulting in scan blindness in radar. The straightforward way to reduce the mutual coupling is to increase the interelement spacing which in return creates the grating lobes which is an aliasing in the beam pattern due to under-sampling of the signal in space. Grating lobes can introduce false targets in the radar operation. Similarly, gain fluctuation in the space appears due to the frequency-dependent beamwidth of the individual elements which is again challenging for wideband radar waveforms. It creates target blindness for wide beam angles due to lower gain and hence reduced returns. Nevertheless, gain fluctuations are manageable by digital pre-distortion. This work addresses the antenna in-package (AiP) development by balancing the trade-off between the above-mentioned challenges with the help of modern enabling technologies to optimize the front-end for ISAC purposes. Starting with the basic planar radiating patch at 61 GHz this study explores the opportunities of array packing in a smarter way to reduce the size as well as maintain sufficient isolation between the elements. Electromagnetic bandgap and defective ground structure technologies have shown the potential to suppress surface waves. The goal of this research is the selection, optimization, and application of suitable technology for enhancing the interelement coupling within the array. The optimal placement of the elements will be studied to attain

	the low grating lobes. The designed antenna system will be interfaced with the partner-provided radar and communication chipsets. Bondwire connections have been a promising technology providing chip-to-antenna connections. Bondwire imposes a significant challenge at mmWave operation due to its inductive nature, nevertheless, it is useable with application-specific matching network design. This study also includes the development of low-loss bondwire interconnects suitable for AiP solutions at 61 GHz.
Success Criteria / KPIs	• Inter-element mutual coupling mitigation. • Low loss integration of the antenna array into communication and radar chipsets. • EE and radar lateral resolution improvement. • **KPI-O.2.3-1**: Reduced EMF human exposure. • **KPI-O.2.3-4**: Angular resolution of 10 degrees (35 cm of separation resolvable assuming 2 m target range) and range resolution of 10 cm in sensing using the developed frontend.
Network Segment / Component/ Layer	RAN

5.5 CF-mMIMO System Requirements

In 6G mobile communications, when all cells cooperate, the concept of cells fades and eventually evolves toward CF-mMIMO. The initial idea of a CF system is the distribution of a large number of antennas in a particular area, where all the antennas can potentially serve all the users [67]. In such original concept of CF, all the APUs forward all signals to a central processing unit which processes the data from and to all users.

In 6G-SENSES we consider a user-centric architecture for CF-mMIMO, where each user connects to a number of APUs required to obtain the service. The APUs serving a user form a cooperation cluster for that particular user. In this scenario the main challenge is to achieve the benefits of CF operation in a practical way, with computational complexity and fronthaul requirements that are scalable to enable massively large networks with many mobile devices. The corresponding relevant KPIs are summarized in Table 5-39.

Table 5-39 Requirement #30 – Resource Efficiency of CF-mMIMO

S- FUNC- #29	Resource Efficient CF-mMIMO
Priority	Essential / Optional
Description	Compared to the classical network-centric architecture, where each user is served by the closest BS in typical small-cell systems, the CF user-centric architecture should improve spectral and energy efficiencies. Furthermore, coverage probability is improved. The constraints are formulated in terms of maximum number of users served by RU and fronthaul data rate.
Success Criteria / KPIs	• SE: 5x improvement in 95%-likely per-user throughput over small-cell systems (under uncorrelated shadow fading conditions) • 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). • Coverage probability: 5x coverage probability improvements for 95% of users achieving a certain rate • User-centric clustering: number of APs serving each user device is flexible, but there is an upper quota determined by the number of antennas at RU. • Fronthaul signaling load: The amount of signaling data transmitted between O-RUs and the O-DU/O-CU depends on the functional split.

Table 5-40 Requirement #31 – Performance of CF-mMIMO

S- FUNC- #30	Cell-Free Massive MIMO
Priority	Essential / Optional
Description	To accommodate the abundant IoT applications, 6G must offer excellent support for the MTC scenarios. Therefore, we will investigate grant-free random access (GFRA) with orthogonal preambles in CF-mMIMO, promising to enable enormous connectivity. In particular, we will consider the potential capture effect, which refers to the successful decoding under preamble collision, occurring when the received signal-to-interference-plus-noise ratio (SINR) surpasses a predefined threshold. Using a stochastic geometry approach, we will develop an analytical framework for GFRA with the capture effect. Subsequently, the approximated analytical expressions of the received SINR and the access success probability are derived for the typical GFRA transmission structure. Leveraging these theoretical expressions, we will formulate an optimisation problem to determine the most suitable preamble length that maximises the effective throughput.
Success Criteria / KPIs	• KPI: A significant EE increase (Mbit/y) by a factor of >2. - • KPI2: A cost reduction of GaN components by a factor of >50. • KPI3: The improvement of the failure probability by several orders of magnitude (>3) with simultaneously reduced latency. • It will improve the algorithm efficiency in the CF-mMIMO Network in the above KPIs and reduce OPEX by 5X.
Network Segment / Component/ Layer	RAN

5.6 Synchronization Requirements

To reach the desired level of coverage and performance expected in 6G, it is of paramount importance that the APs are in-synch with each other and share the same time reference with all surrounding RAN elements. Timing accuracy is needed to support technologies like: 1) Time Division Duplex (TDD), where both the uplink and downlink are on the same frequency, and 2) beamforming, which allows beams to be directed to multiple users and IoT devices.

TDD uses one dedicated frequency band for both the downlink and the uplink. As each direction must transmit during specific time slots, the synchronized timing in frequency and in phase between the user equipment and the radio is critical to ensure that the downlink and the uplink are not interfering with each other. The deployment of many more APs can also cause big timing issues. If they are not on the same time reference, they could interfere with each other and impact RF performance.

For CF-mMIMO (also in the past with CoMP, uplink of Carrier Aggregation in TDD), precise network-based positioning/location, etc.) much of the S-Plane SotA is insufficient as the RUs need to be coherent (therefore phase synchronized, not just ToD). Indeed, this is not limited to just CF-mMIMO and CoMP, but also for the demands of precise positioning, dense interference-prone TDD operation and ISAC. In short, 6G will demand a better S-Plane. Previous research has yielded the new high accuracy profile for IEEE 1588-2019 (based on White Rabbit to synchronize nodes with sub-ns accuracy) [47] and beyond [48].

In a TDD system the downlink channel is estimated by the pilots sent on the uplink assuming reciprocity between the uplink and downlink channels, thus significantly reducing the overhead associated with channel estimation. However, transmit and receive RF chains are not identical, so the uplink and downlink channels including the RF chains are not reciprocal in practice. Although there can be both amplitude and phase mismatches, the latter is more relevant as it impacts achieving coherent reception at the UE of the signals transmitted by the different APs serving it. As shown in [49][50], phase mismatches larger than 15° can significantly affect the performance of a CF-mMIMO system. Therefore, over-the-air (OTA) phase calibration or phase synchronization between antennas within the same AP and between different distributed APs are crucial techniques for implementing a scalable CF-mMIMO. Self-calibration OTA techniques [51], such as the recently proposed BeamSync [52], which do not require the transmission of signals between UEs and APs, are more desirable from a practical point of view and are the ones we will consider in 6G-SENSES. After calibration, the phase differences between antennas of the same AP remain unchanged for long periods (on the order of minutes), whereas the phase differences between antennas of different APs should be recalibrated much more frequently (on the order of hundreds of ms, depending on the mobility of UEs).

Table 5-41 Requirement #32 – Synchronization requirements

S- FUNC- #31	Synchronization
Priority	Essential / Optional
Description	Phase synchronization is a critical challenge in CF-mMIMO systems. In CF-mMIMO networks, multiple APs cooperate to serve users simultaneously, but the lack of a common clock reference can lead to phase misalignment between APs, as well as between the antennas of each AP. This phase misalignment can significantly degrade system performance by causing destructive interference and reducing the benefits of coherent transmission. The CF-mMIMO platform must, therefore, incorporate distributed algorithms for the phase synchronization of the different antennas of each AP (intra-AP reciprocity calibration), as well as between the different APs serving a given user (inter-AP reciprocity calibration). Phase synchronization algorithms such as Beam-Sync [52] (inter-AP calibration) and Argos [53] (intra-AP calibration) will be implemented in a distributed manner. The drift of the local oscillator (LO) phases determines how often the calibration process must be performed. The reciprocity calibration process will be implemented and evaluated on a Universal Software Radio Peripheral (USRP)-based platform. The implementation of these phase calibration algorithms will maximize the potential gains in SE and coverage that CF-mMIMO promises.
Success Criteria / KPIs	• The phase difference between the APs needs to be tightly controlled. Phase synchronization errors should be kept below 5 degrees between different APs and below 1 degree between antennas of the same AP for coherent combining at the UEs (without LO phase drift). More stringent phase calibration requirements are expected for sensing purposes. • A significant increase in SNR by a factor of 2 (more than 3 dB) for more than 50% of the CF-mMIMO users in comparison to uncalibrated systems. This will translate into an improvement of on average zero outage capacities. • The frequency offsets between the APs should be minimized. Frequency offsets should be less than 100 Hz to ensure proper coherent combining • Timing Synchronization: In addition to phase and frequency, the timing synchronization between APs is also critical. Timing offsets should be less than 100 ns to enable effective coherent combining in indoor scenarios. We assume time synchronization provided by White Rabbit or any other high-accuracy time-synchronization system.
Network Segment / Component/ Layer	RAN segment

5.7 RIS-assisted Wireless Systems

One potential approach to reach a spectrally and energy-efficient system while keeping HW costs to a minimum is by embracing the concept of passive MIMO, specifically in the form of RIS. These comprise numerous small elements (unit cells) that can reflect incoming signals in a controllable manner. An RIS can be deployed in a flexible manner to address coverage gaps or to enhance capacity in areas where it is required.

RISs are believed to require only minimal operational power and can be integrated in CF-mMIMO systems and systems relying on ISAC functionalities to further achieve 6G ubiquitous high-capacity communication coverage and improved EE. This is why, recently, the combination of CF mMIMO and ISAC schemes with RIS have attracted widespread attention and research in the industry to achieve the vision of 6G.

In fact, the purpose of the RIS technology is not to supplant or compete with CF-mMIMO but to complement it. Similarly, RIS capability of manipulating the propagation of EM waves and engineer virtual LoS conditions has been also recently leveraged to create additional signal propagation paths for the purposes of RF localization, sensing, and ISAC.

Table 5-42 Requirement #33 – RIS-assisted systems

S- FUNC- #32	RIS-assisted systems
Priority	Essential / Optional
Description	The performance gains of the RIS-assisted network architecture are compared to the same baseline architecture without RIS. For single links, the SNR gain is measured. For multiple user networks, e.g., the MIMO interference channel, the throughput and reduced interference are evaluated. Further KPIs comprise coverage probability, EE and sensing accuracy.
Success Criteria / KPIs	• 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. • RIS-enabled throughput: > 10% in rate due to the assistance of RIS. • Performance of traditional communication systems with poor direct path conditions has a 30% -40% improvement with RIS [54]. • RIS-reduced interference: Reductions up to 20 dB in interference-to-noise ratio levels in RIS-assisted MIMO-ICs. • RIS-improved coverage: coverage to blocked users or users in blind spots. • RIS-optimized EE: average max-min EE >50% for optimized RIS designs with static power consumption < 1 dBm. • RIS-optimized sensing accuracy: 3dB MSE reduction in azimuth and elevation angles with RIS-assisted ISAC systems. • Additional throughput improvements > 10% with more flexible beyond-diagonal RIS (BD-RIS) architectures.
Network Segment / Component/ Layer	RAN segment

5.8 Sensing-related Requirements

The integration of sensing and communication functionalities within the same wireless system requires to revisit traditional systems considering the requirements from both domains. This integration will provide enhanced capabilities such as high-precision positioning, environment reconstruction, imaging and recognition. These capabilities not only open the possibility of new services but also help to improve the performance and efficiency of communications by being able to adapt and optimize radio resources in a changing environment [34]. What is even more challenging to meet the expected 6G demands is to employ network-level ISAC by jointly designing the signal processing and resource allocation over the entire network [39].

Table 5-43 Requirement #34 – ISAC: Sensing Mode

S- FUNC- #33	Sensing Mode
Priority	Essential / Optional
Description	From an architectural point of view, there exist four standard sensing modes: 1) **Monostatic sensing**: A TX and RX are co-located at the same device and share a common clock and knowledge about the transmitted signal, 2) **Bistatic sensing**: A TX and RX are located on separate devices and they may or may not share a common clock and full knowledge of the transmitted signal. Therefore, the positioning of a UE relies on bistatic sensing to and from multiple BSs, 3) **Multistatic sensing**: A system comprising at least 2 transmitters (and 1 receiver) and/or at least 2 receivers (and 1 transmitter) separated in space, without a common clock, and 4) **Passive sensing**: The transmitted signal is provided by an external system (for example radio broadcast tower), while there is a sensing receiver, which has limited knowledge regarding the transmitted signal (for example only carrier frequency and bandwidth). From a functional point of view, there exist two modes that may be combined with any of the abovementioned architectural modes: 1) **Radar-like sensing**, where the radio signal is processed to extract distances, angles, or Doppler shifts, to detect the presence and state (position, velocity) of objects/targets and track them over time. Radar-like sensing thus starts with detection/channel parameter estimation, followed by data association and by tracking. When objects are static, the process is called mapping, whereas when objects are moving, the process is called tracking. 2) **Non-radar-like sensing**, as any other type of sensing, including pollution monitoring, weather monitoring, detection and tracking based directly on the received waveform or features extracted from the received waveform. These features can be applied to ML for classification or regression.
Success Criteria / KPIs	Requirements and KPIs differ depending on the sensing mode to be used, e.g. in a **monostatic sensing** scheme, reception of the signal should be simultaneous to transmission to be able to measure the reflecting and scattering waves, thus functioning as an in-band full duplex (IBFD) transceiver.
Network Segment / Component/ Layer	RAN node, either full gNB/Wi-Fi node, or the O-RU

Table 5-44 Requirement #35 – ISAC: Interference mitigation

S- FUNC- #34	Interference mitigation
Priority	Essential / Optional
Description	Typical interference for radar and communication systems, e.g., clutter and multiuser interference (MUI), will occur in ISAC systems. Second, the amalgamation nature of ISAC systems causes unprecedented interference. This includes the self-interference (SI) due to the simultaneous transmission and reception of communication and sensing signals (typical in monostatic schemes), and the inherent mutual interference (MI) between sensing and communication. Third, the network-level integration introduces additional crosstalk between different nodes in ISAC systems [39].

Success Criteria / KPIs	• Achieve isolation ≥30 dB for narrowband and wideband operation
Network Segment / Component/ Layer	RAN node, either full gNB/Wi-Fi node, or the O-RU

5.8.1 RIS-assisted sensing

RIS can be integrated with ISAC data to enhance the overall performance of communication and sensing systems. The integration involves leveraging the capabilities of RIS to optimize wireless communication links and improve sensing capabilities simultaneously. One aspect of integration is utilizing RIS to enhance the quality of communication channels in ISAC systems.

By intelligently manipulating the reflection and refraction of electromagnetic waves, RIS can improve signal quality, increase coverage, and mitigate interference. This leads to improved reliability and higher data rates in the communication link between sensors, devices, or networks involved in ISAC applications. Additionally, RIS can 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 can be particularly useful in scenarios where the quality of sensing signals is compromised due to obstacles, interference, or noise. RIS can optimize the sensing environment by redirecting or focusing signals to enhance target detection, imaging, and tracking. The integration of RIS with ISAC data involves a collaborative approach where the RIS, communication devices, and sensing systems work in conjunction to achieve optimal performance. The RIS dynamically adapts its properties based on the communication and sensing requirements, ensuring that both aspects are optimized simultaneously.

Table 5-45 Requirement #37 – RIS-assisted Sensing

S- FUNC- #35	**RIS-assisted Sensing**
Priority	Essential / Optional
Description	The substantial power consumption attributed to the active components within the fully connected RIS architecture significantly hinders the efficiency and sustainability of DT-enabled MEC networks. To tackle this challenge, we present an innovative sub-connected architecture for active RIS within the DT integrated MEC framework of an IoT networks, capitalising on edge intelligence to enhance URLLC services. The primary aim of our research is to improve uplink data transmission from IoT URLLC user nodes (UNs) to a BS with the aid of an active RIS, even under an imperfect channel state information (CSI). We have formulated the total E2E latency minimisation problem, which is solved using an efficient Alternating Optimisation (AO) algorithm. The algorithm breaks down the proposed non-convex problem into five subproblems: beamforming design, sensing, caching and offloading policy optimisation, joint communication and computation optimisation, and joint active RIS phase shift and amplification factor vector optimisation. We will thoroughly analyse the convergence properties of the proposed AO algorithm, benchmarking its performance against the established Heuristic algorithm.
Success Criteria / KPIs	• EE and SE improvements in RIS-assisted systems. • Average and outage capacities, zero-outage rates. • Resilience improvement by RIS. • It will improve the EE in the RIS network in the above KPIs and reduce OPEX by 2X compared with non-RIS networks.
Network Segment / Component/ Layer	RAN

5.8.2 Sensing Service Model requirements

Sensing is becoming critical for the next generation of cellular networks. Using radio waves, environmental ambient can be inexpensively sensed and mapped using its I/Q samples and different antennas.

However, due to its latency and bandwidth requirements (e.g., a 5 MHz cell configured with a slot of 1 ms and 15 kHz, will generate 25 Resource Blocks x 12 subcarriers x 14 symbols x 4 bytes per I/Q sample x 1000 ms = 16.8 Mbytes/sec data) sensing has been excluded from O-RAN focus. Therefore, nowadays Service Models (SMs) for KPI, RAN Control (RC) and Cell Configuration and Control (CCC) exist, while no SM has been standardised for gathering data directly from the PHY layer. Additionally, O-RAN near RT-RIC latency constraints (i.e., 10 ms to 1 second control loop), are not suitable for handling such use cases.

Developing a SM will usher the possibility to start writing sensing related algorithms within the xApps, avoiding the burden of embedding algorithms directly into the HW and enhancing its portability on the road to 6G. Moreover, the SM will be validated using FlexRIC, which supports multi-language capabilities. This will bridge the gap between algorithm writers and implementers, as the former tend to write their algorithms in a high-level language (e.g., Python) while the latter need to implement them in a low-level language (e.g., C). This SM will pave the way towards 6G facilitating a wider adoption of sensing algorithms.

Table 5-46 Requirement #38 – Sensing Service Model

S- FUNC- #36	Sensing Service Model
Priority	Essential / Optional
Description	The major contribution of this task is to develop a 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 amount of listening antennas, as they are essential for the sensing algorithms.
Success Criteria / KPIs	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. **KPIs:** • **Latency**: < 10 ms stipulated by O-RAN • **Bandwidth**: in the order of MB/s. • **Antennas**: > 2 Antennas.
Network Segment / Component/ Layer	O-RAN framework, RICs.

5.9 Advanced Spectrum Management Techniques

5G technology has revolutionized wireless communications, offering significantly enhanced data rates and low latency. However, the deployment of 5G faces significant challenges related to spectrum management. The increasing demand for spectrum resources and limited spectrum availability necessitates innovative solutions. Integrated sensing and communication technology offers a promising solution for spectrum management in 5G. Leveraging the sensing capabilities of 5G cellular networks enables intelligent spectrum sharing and resource management. This integration enables efficient utilization of spectrum resources, leading to improved network performance and reduced interference.

The integration of sensing and communication in 5G provides several advantages. Firstly, it allows for real-time monitoring of spectrum usage, enabling dynamic spectrum allocation and interference mitigation. Secondly, it allows spectrum sharing between users, such as licensed and unlicensed spectrum bands. This flexibility enhances spectrum utilization and enables the coexistence of different services. Moreover, integrated sensing and communication technology offers opportunities for developing new applications. It can enable applications such as cognitive radio networks, spectrum sensing-based intrusion detection, and spectrum-aware routing. These applications can potentially revolutionize various industries and improve the quality of life.

Table 5-47 Requirement #39 – ISAC-based Spectrum Management

S- FUNC- #37	ISAC-based Spectrum Management
Priority	Essential / Optional
Description	Spectrum sensing and sharing provide a rapid migration pathway toward 6G by enabling the coexistence of the forthcoming 6G RAN with 4G LTE, 5GNR and IEEE 802 based systems, that share the same spectrum. Due to significant differences in the above-mentioned air interfaces, several enablers are required to facilitate spectrum sensing and sharing. This study explores the coexistence features and investigates their impacts on network performance. For static and dynamic spectrum sensing and sharing scenarios, we assess the impacts of different spectrum-sharing ratios, user ratios, MIMO configurations, mixed numerology profiles and traffic patterns on the user throughput and network capacities of spectrum sensing and sharing networks, compared with the LTE-only and 5GNR-only networks with exclusive spectrum access. The key results show that spectrum sensing and sharing leads to a marginal capacity gain over an LTE-only network and achieves considerably lower capacity than the 5GNR-only network. Also, the results show that mixed numerology profiles between the LTE and 5GNR lead to capacity losses due to inter-numerology interference. In addition, user and spectrum sharing ratios between LTE and 5G-NR critically impact performance. Reduced spectrum per device as the number of 5G devices increases, higher signalling overhead, and higher scheduling complexity are other limiting factors for spectrum sensing and sharing networks. The results show limited capacity benefits and reinforce spectrum sensing and sharing between LTE and 5G-NR as an evolutionary path to accommodate 5G users in the same LTE spectrum while migrating to the fully-fledged 5G networks. Other features such as carrier aggregation, overlay of small cells, and higher order MIMO would need to be incorporated into the network to increase capacity significantly.
Success Criteria / KPIs	• KPI: SE: >10% SE compared with a 5G system. • KPI: A significant EE increase (Mbit/y) by a factor of >2. • It will improve the algorithmic efficiency in active sensing in the above KPIs and reduce OPEX by 3X.
Network Segment / Component/ Layer	It will enable the use of spectrum in areas, where several systems are competing for the same spectrum. A central data base might be necessary to among the shared access.

5.10 Orchestration-related Requirements

This section focuses on how the 6G-SENSES architecture would address the strict requirements, mostly those related to delay and reliability, posed by the use of the sensing information. Sensing information would need to be shared among different entities, traversing the underlying transport networks, where various techniques and algorithms should be used to appropriately address such flows, without hindering the performance of other services. This would guarantee that the corresponding network measurements are handled

On the other hand, computing resources should be appropriately allocated, to handle the decision-taking tasks, again with the main objective of respecting their stringent delay requirements. Such tasks would be instanced together with other services and applications, and they would not only need to fulfil their own needs, but also not to harm the others.

One of the techniques that would be particularly relevant are the caching mechanisms that would certainly play a key role to ensure that the sensing information is handled according to its particular requirements.

Table 5-48 Requirement #40 – Orchestration: Level of centralization requirements

S- FUNC- #38	Level of centralization
Priority	Essential / Optional
Description	The location of RAN disaggregated entities (i.e. DU/CU) have a strong impact on the radio access network performance. On the one hand, the fronthaul network communicating the RUs and DUs must fulfil strict requirements in terms of both throughput and delay, which would be more easily satisfied locating DUs closer to RUs. On the other hand, in scenarios with a large number of APs, such as the ones envisaged for CF-mMIMO, the co-location of DUs would enable a tighter cooperation between them and between their managed RUs and it would be necessary to attach a large number of RUs to each DU. Thus, it becomes necessary to find placement schemes able to pool together as many DUs as possible subjected to the limitation imposed to the underlying fronthaul network. An Intelligent Plane, able to manage the interaction between DU and RU, in the O-RAN-based architecture would be needed. This would enable an appropriate placement of the corresponding entities, as well as the optimum instantiation of the corresponding computing tasks.
Success Criteria / KPIs	This requirement partially tackles Objective **1.3, KPI O1.3-1**. It is also related to Objective 3.3, **KPI-O.3.3-1** and **KPI-O.3.3-2**. The target is the maximization of the centralization of DU entities in as few as possible points of presence. It will be measured by means of suitable metrics that consider the number of locations used between the total number of them, as well as the number of RUs attached per DUs.
Network Segment / Component/ Layer	Network segments: the centralization impacts the fronthaul network and RAN segment of the optimized network. In addition, it may have an impact on the backhaul network of other services sharing the same physical infrastructure.

Table 5-49 Requirement #41 – Orchestration: Computation resources management requirements

S- FUNC- #39	Computation resource management
Priority	Essential / Optional
Description	Sensing information will be exploited to take decisions to optimize the network performance or to yield better QoS levels to the end-users. The techniques and algorithms that will be used for such decision processes might require significant computing resources, which are provided by nodes that are additionally shared by other functionalities. In this sense, it becomes of utmost relevance to efficiently distribute computing loads and to perform an optimal computing resource management, and ensure that decisions are available within the required time limits. 6G-SENSES will explore load balancing solutions, as well as load scheduling mechanisms, in distributed computing systems.

	This would also impact the mechanisms that will be used to perform advanced caching solutions.
Success Criteria / KPIs	This requirement is related to **KPI-O.3.1-1** of Objective 3.1. It also partially tackles Objective 2.7, and its **KPI-O.2.7-1** as well as Objective 3.2 and **KPI-O.3.2.-1**. The focus would be on the delay in completing computing tasks (for instance, taking a decision) from the moment it was triggered. Additionally, we will also look at load balancing, and how the computing load is fairly distributed between the available nodes. From the perspective of the caching solutions, we will look at how the proposed solutions can be exploited to guarantee the corresponding delay requirements are met.
Network Segment / Component/ Layer	Network layer: management of computation tasks is related to the intelligent plane. In addition, it will also affect the performance of RIC nodes.

Table 5-50 Requirement #42 – AI/ML: QoS Techniques for the transport network

S- FUNC- #40	Transport Network QoS Techniques
Priority	Essential / Optional
Description	6G-SENSES architecture considers the separation of network functions between CU, DU and RU. The connectivity between these entities (as well as with the RIC) will likely involve going through intermediate nodes (switches and routers). In order to guarantee that the strict delay requirements (in particular for certain traffic flows, such as sensing) are met, different QoS-aware techniques need to be integrated in such intermediate nodes, to prioritize the appropriate traffic flows. Some techniques that will be explored include: (delay-aware) scheduling and Active Queue Management.
Success Criteria / KPIs	The current requirement partially tackles objective 3.2 and **KPI-O3.2.1**, as it aims to optimize the underlying transport network. We will particularly focus on delay-related performance indicators. In the case of sensing information, we will explore the Age-of-Information (AoI) metric, and how the proposed solutions can help to meet the needs of the services that might rely on such information. - Delay of sensing-related flows. - AoI for sensing-related information.
Network Segment / Component/ Layer	Fronthaul network. Intermediate nodes connecting the DU with the RUs, or the RIC with the corresponding nodes.

Table 5-51 Requirement #43 – AI/ML: Non-sensing traffic flow management

S- FUNC- #41	Non-sensing traffic flow management
Priority	Essential / Optional
Description	The prioritization of different traffic flows and, in particular, those related to sensing information should not severely harm other services and traffic flows. This can be tackled by considering the delay as a constraint instead of as an objective to be minimized. In any case, there might be circumstances where admission control solutions might need to be used so that the remaining flows perceive an appropriate QoS level. 6G-SENSES will tackle this by fostering a smart management of the fronthaul network and its corresponding nodes, from the corresponding intelligent plane.

Success Criteria / KPIs	This requirement relates to objective 3.2, and **KPI-O3.2.1**, as it tackles the optimization of the transport network and the impact of sensing data may have over other traffic flows. The focus will be on studying the performance perceived by flows that are not necessarily prioritized in the fronthaul network, paying special attention to DNH-related metrics. We will explore, for instance, the percentage of discarded flows, or how the resources are distributed between them (Fairness-related metrics). We will also study the performance of such flows: relative delay increase, etc.
Network Segment / Component/ Layer	Fronthaul network. Intermediate nodes connecting the DU with the RUs, or the RIC with the corresponding nodes.

5.11 Architecture and Other Requirements

In addition to the system specific requirements deriving from the use case definition, there is a number of generic requirements that address the general system architecture. These requirements are listed below, and will be considered in the activities of the 6G-SENSES system architecture definition.

Table 5-52: Requirement #44 – Scalability of interfaces / infrastructure

S- FUNC- #42	Scalability of interfaces / infrastructure
Priority	Essential / Optional
Description	The network elements shall be easily scalable to deal with large scale deployments.
Success Criteria / KPIs	Scalability shall be ensured by design for all network elements. Efficiency of scalability will be assessed as part of relevant architecture evaluation studies.
Network Segment / Component/ Layer	All interfaces and elements

Table 5-53: Requirement #45 – Interoperability

S- FUNC- #43	Interoperability
Priority	Essential / Optional
Description	Interoperability between network elements with B5G/ 6G network interfaces shall be ensured.
Success Criteria / KPIs	Interoperability shall be ensured by design for all network elements. Interoperability shall be validated by E2E system testing and demonstration.
Network Segment / Component/ Layer	All interfaces and elements at each layer.

Table 5-54: Requirement #46 – Harmonization of sensing data (by Multi-WAT sources)

S- FUNC- #44	Harmonization of sensing data (by Multi-WAT sources)
Priority	Essential / Optional
Description	Capturing and processing of sensing data by different WAT sources shall be harmonised in order to ensure same/similar service availability over the coverage area of a multi-WAT RAN environment.
Success Criteria / KPIs	Harmonization of sensing data shall be ensured by design across (especially RAN) network elements.

	Service availability in a multi-WAT RAN environment shall be validated by E2E system testing and demonstration.
Network Segment / Component/ Layer	RAN segment, sensing technologies

Table 5-55: Requirement #47 – Sensing data management practices

S- FUNC- #45	Sensing data management practices
Priority	Essential / Optional
Description	Effective sensing data management practices shall be followed, adhering to general data management principles.
Success Criteria / KPIs	Sensing data management practices to be followed shall be ensured by design across network segments and layers. Sensing data management practices shall be validated by E2E system testing and demonstration.
Network Segment / Component/ Layer	RAN sensing technologies; Data Management plane

Table 5-56: Requirement #48 – E2E System Efficiency / Sustainability

S- PERF- #46	E2E System Efficiency / Sustainability
Priority	Essential / Optional
Description	The 6G-SENSES system shall be efficient in terms of performance and sustainable in terms of resource utilisation and cost.
Success Criteria / KPIs	E2E System efficiency, in terms of performance and energy etc. shall be ensured by design for all network elements, and also shall be optimised during system operation (i.e. the system shall have functionalities dealing with performance and EE optimisation jointly). Performance and EE will be assessed for multiple operational scenarios by relevant system architecture efficiency studies. System sustainability will be also assessed via relevant impact assessment study.
Network Segment / Component/ Layer	E2E system

Table 5-57: Requirement #49 – Cost Efficiency of E2E Solution

S- PERF- #47	Cost Efficiency of E2E Solution
Priority	Essential / Optional
Description	Each network element and the E2E solution shall provide a cost-efficient solution for a given performance/ functionality implementation.
Success Criteria / KPIs	Cost efficiency shall be ensured by design for all network elements. Cost efficiency will be assessed by relevant technoeconomic studies.
Network Segment / Component/ Layer	E2E system

6 Summary - Conclusions

6G-SENSES designs and develops a next generation wireless infrastructure aiming to achieve advanced performance towards the IMT- 2030 vision and KPIs, outperforming the current network implementations and to progress research towards fully perceptive networks. To this end, research is focused on integrating CF networks, RIS infrastructures, as well as ISAC, using as baseline beyond SotA O-RAN and 3GPP specifications for the 5G protocol stack, and developing a sensing and a network intelligence plane spanning across network segments. The technical enablers of the proposed 6G-SENSES solutions centre around two main axes: 1) Access Network Performance and Sensing, and 2) Network Intelligence.

This deliverable outlines a set of 6G use cases that are addressed by the 6G-SENSES vision, concepts and technology advancements. To this end, a concrete methodology is followed comprising 5 main steps. Initially (Step 1), the 6G trends, the vision of the 6G ecosystem along with the main stakeholders and their roles, and the technical targets of 6G along with the envisioned 6G services (enabling use cases) are studied. In parallel (Step 2), the proposed 6G-SENSES system advancements are thoroughly analysed to identify the capabilities, performance, services that they can enable the creation of value for the various roles/layers of the ecosystem. In Step 3, this information is fused to the identification of a concrete set of use cases that will be enabled by 6G-SENSES, along with the KPIs and the requirements that need to be met (Step 4).

Considering the 6G ecosystem (building on the 5G Ecosystem), both vertical 6G use cases and a variety of service provisioning scenarios are envisioned. Since 6G research is still in its early stages, vertical use cases are seen as the long-term objective, ultimately supported in fully-developed 6G networks (aligned with IMT-2030 usage scenarios). Instead, service provisioning use cases are more applicable, addressing sets of capabilities provided by 6G-SENSES enabling or facilitating service/network providers' activities (mainly mapped to IMT-2030 New Capabilities). In this context, 6G-SENSES use cases are primarily described from the service provisioning viewpoint, while a longer-term, vertical-service use cases are simply mentioned.

To this end, service provisioning use cases are the primary focus of 6G-SENSES, particularly with regards to ISAC, as well as AI and communication. For vertical use cases, considering the data rates, coverage, and network reliability levels that are targeted by 6G-SENSES innovations, Immersive applications and HRLLC communication – based use cases (aligned with IMT-2030) are in focus of the project.

In brief, the use cases envisioned within 6G-SENSES are the following:

- **Use Case #1**: **Sensing enabled Services**, focusing on exploiting sensing information to improve communication services (sensing-aided communication), and on enabling active sensing with Wi-Fi system. This Use Case highlights the work of the project on Sensing and in particular on Multi-WAT sensing & integration in 6G RAN. From the vertical perspective the proposed capabilities can enable numerous Immersive Services, while being applicable in future use cases.
- **Use Case #2**: **Ubiquitous Connectivity & Immersive Services**, focusing on storylines exploiting the cell-free mMIMO and RIS capabilities combined with sensing. This Use Case highlights the work of the project on RIS assisted CF-mMIMO for coverage & localisation. From the vertical perspective the proposed capabilities can enable numerous Immersive Services, while high reliability/availability services are also in focus.
- **Use Case #3**: **Network DT**, focusing 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 & User layers. From the vertical perspective the proposed capabilities can enable numerous Immersive Services, while vertical level digital twinning is considered – essentially

highlighting that digital twinning can be a service for various network and service provisioning layers.

The selected 6G use cases are described in terms of value and capabilities offered both for the various service provisioning roles and stakeholders of future 6G ecosystems and for the envisioned 6G end-user (vertical or individual) application services (at later stages of 6G deployment). In addition, the description of the use cases includes aspects of their technical realisation (linkage to the 6G-SENSES technologies and innovations proposed), along with the requirements and KPIs. The latter are subsequently translated into system level requirements (a.k.a. system/ technical specifications) and KPIs that the 6G-SENSES architecture and technology developments need to meet.

Finally, recognizing the importance of aligning technology with societal values and addressing global challenges, the use cases are evaluated for their impact on KVs. Specific KVIs are defined to quantitatively or qualitatively measure the impact of these technologies on identified KVs, with a focus on sustainability. This work will be further channelled to the Project Impact Assessment work in 6G-SENSES WP6.

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8 Acronyms

Acronym	Description
5GAA	5G Automotive Association
5GC	5G Core Network
5GNR	5G New Radio
6G-IA	6G Infrastructure Association
A/D	Analogue-to-Digital
AiP	Antenna in Package
AO	Alternating Optimization
AoI	Age-of-Information
AP	Access Point
API	Application Programming Interface
BS	Base Station
BSS	Business Support System
CAPEX	CAPital EXpenditures
CCC	Cell Configuration and Control
CF	Cell-Free
CF-mMIMO	Cell-Free massive MIMO
CoMP-JT	Coordinated Multi-point Joint Transmission
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
CSI	Channel State Information
CSP	Communication Service Provider
CSR	Corporate Social Responsibility
CW	Continuous Wave
D/A	Digital-to-Analogue
DoW	Description of Work
DCSP	DataCenter Service Provider
DT	Digital Twin
E2E	End-to-End
EA	Ethics Advisor
EC	European Commission
eMBB	enhanced Mobile BroadBand
EMF	Electromagnetic field
FMCW	Frequency-Modulated Continuous Wave
GA	Grant Agreement
GDPR	General Data Protection Regulation
GFRA	Grant-Free Random Access
ICV	Intelligent Connected Vehicle
IBFD	In-Band Full Duplex
IC	Integrated Circuit

ICT	Information and Communication Technology
IMT	International Mobile Telecommunications
ISAC	Integrated Sensing and Communication
IT	Information Technology
ITU	International Telecommunications Union
KPI	Key Performance Indicator
KV	Key Value
KVI	Key Value Indicator
LMF	Location Management Function
LO	Local Oscillator
LoS	Line-of-Sight
m/eMTC	massive/enhanced Machine Type Communications
MAC	Medium Access Control
MEC	Multi-access Edge Computing
MGA	Model Grant Agreement
MIMO	Multiple-Input Multiple-Output
MLO	Multi-Link Operation
mMIMO	Massive MIMO
MNO	Mobile Network Operator
MUI	MultiUser Interference
nGRG	O-RAN next Generation Research Group
NFV	Network Function Virtualization
NGMN	Next Generation Mobile Networks
NLoS	Non-Line-of-Sight
NN	Neural Network
NOP	Network Operator
NSaaS	Network Security as a Service
OAI	OpenAirInterface
OPEX	OPerational EXpenditures
OSS	Operations Support System
OTA	Over-The-Air
OTFS	Orthogonal Time Frequency Space
QM	Quality Manager
PHY	Physical layer
PoC	Proof-of-Concept
PRS	Positioning Reference Signal
RAN	Radio Access Network
RC	RAN Control
RIS	Reconfigurable Intelligent Surface
RL	Reinforcement Learning
RRM	Radio Resource Management
RU	Radio Unit

SA	Stand Alone
SBA	Service-Based Architecture
SDG	Sustainable Development Goal
SDR	Software Defined Radio
SE	Spectral Efficiency
SiGe	Silicon-Germanium
SINR	Signal-to-Interference-plus-Noise Ratio
SM	Service Model
SMO	Service Management and Orchestration
SNS JU	Smart Networks and Services Joint Undertaking
SNVC	Societal Needs and Value Creation
SRL	Society Readiness Level
SRS	Sounding Reference Signal
THz	Terahertz
TL	Task Leader
TM	Technical Manager
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicles
UN	United Nations
URLLC	Ultra-Reliable and Low-Latency Communications
USRP	Universal Software Radio Peripheral
V2X	Vehicle-to-Everything
VISP	Virtualization Infrastructure Service Provider
WAT	Wireless Access Technology
WG	Work Group
Wi-Fi	Wireless-Fidelity
WP	Work Package