Seamless Integration of Efficient 6G Wireless Technologies for Communication and Sensing enabling Ecosystems

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Abstract. The vision of 6G foresees telecommunication infrastructures that move from provisioning classical telecommunication and data services to delivering more intelligent, flexible and energy-aware services, opening up and exploiting new sources of information that link physical and digital worlds together. Sensing, localization and network self-organization are key enablers driving this trend. In this context, Research and Development activities focus on enabling sensing and high accuracy localization solutions either exploiting in-bound or out-bound network channels, while network intelligence emerges in various forms, among which as inherent enabler for network optimization, as facilitator of data management and analysis, and as part of service functionalities. These advancements are expected to make room for new roles in 6G ecosystems and novel use cases involving multiple service layer roles. This paper provides insights on preliminary sensing and Artificial Intelligence (AI)-enabled network capabilities to be adopted by 6G networks, as explored by the SNS-JU 6G-SENSES project, and touches upon potential changes in ecosystem formulations in support of forth-coming 6G use cases.

Keywords: 6G, Wireless Sensing, Radio Access Network, O-RAN, ecosystem.

1 Introduction

Nowadays, the focus of Information and Communication Technology (ICT) research academia and industry is towards building the specifications and pre-development of 6G networks. To this end, efforts are driven both bottom-up – from specific technological advancements to their integration in complete network systems – and top-down – from the definition of the networks' capabilities and role of the network in the digital and physical world to the specification of functionalities and technologies. Particularly in the EU, these initiatives are being funded by the European Commission and are mainly driven by the European partnership Smart Networks and Services (SNS) Joint Undertaking (JU) and its private part, the 6G Industry Association (6G-IA) [1].

To date, there is no defined common consensus in the definition of 6G features set, despite broad agreements in terms of generic application scenarios, technology trends, and key performance indicators (KPIs), as 6G standardization is expected to start in 3GPP around 2025 with Release 20 [2]. However, there is already a vast consensus 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 structures – enabled by the introduction of cell-free massive multiple-input multiple output (CF-mMIMO) ([3]-[6])– and/or Reconfigurable Intelligent Surfaces (RIS) ([7]-[8]) to enhance spectral efficiency, energy efficiency, and drastically increase the number of parallel connections. [3]

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. Integrated Sensing and Communication (ISAC) (for instance in [10]-[14]). The integration of sensing functions into the communication systems is envisioned to be an integral part of the 6G and future communication systems, opening up a plethora of new applications and network capabilities. In parallel, research efforts focus on augmented monitoring of network infrastructures based on extended collection and processing of (especially) Radio Access Network (RAN) network 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.

To enable the full potential of the aforementioned technologies in 6G networks, such technologies will be combined with increased intelligence – exploiting Artificial Intelligence/ Machine Learning (AI/ML) – in terms of capturing and processing communication and non-communication data, along with extended distribution of data and processing across multi-edge network infrastructures (for instance in [15]-[18]). To this end, standards incorporating intelligence and enabling distributed network solutions across all segments serve as a basis for these 6G developments, being 3GPP and Open-RAN (O-RAN) the most representative standards for the access stratum segment of cellular networks.

In this landscape, the 6G-SENSES EU-funded research project [19] 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 technologies that are able to offer sensing functionalities. These technologies are Sub-6 GHz, 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. This framework will make use of new physical (PHY) layer technologies to increase the cooperation between technologies and their inherent capabilities to improve the precision/accuracy of the sensing capabilities. To further strengthen communication and sensing functionalities, the project 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 optimization purposes and in order to build up a so-called network (digital) twin.

The paper is organized as follows: Section 2 presents in detail the concepts of 6G-SENSES and the key technical advancements to serve as enablers in support of high performance, perceptive 6G networks. Section 3, discusses the changes that can be incurred in the roles of the 6G provisioning ecosystem along and introduces the 6G use cases that are enabled bridging technology and ecosystem views. Finally, conclusions are drawn.

2 6G-SENSES Concepts

6G-SENSES designs and develops a next generation wireless infrastructure aiming to achieve advanced performance towards the IMT 2030 vision KPIs [20]-outperforming the current network implementations and, at the same time, to progress research towards fully perceptive networks. To this end, research is focused on integrating Cell-Free networks, RIS infrastructures as well as ISAC function mapping and network placement, using as baseline beyond state-of-the-art 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 radio access segment, 6G-SENSES relies on the use and integration of several Radio Access Technologies (RATs) as basis for advancing access network performance towards the IMT-2030 KPIs, and for the support of sensing. Namely, these technologies are: Wi-Fi 8-9, Sub-6 GHz Software Defined Radio (SDR)-based implementations, mmWave at 60 GHz and 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 RATs. 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 PHY and media access control (MAC) layers to enable ISAC capabilities especially for those technologies that cannot support sensing natively, as well as the necessary 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 RAT. In particular, in Wi-Fi 7 [21] 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 beyond Wi-Fi 7, in Wi-Fi 8-9 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) Sub-6 GHz platform (based on software defined radio NI Ettus N321 [22]), 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 HW. The Ettus N321 framework offers signal processing functions for this bandwidth and intelligent functions for accelerated signal processing to achieve quasi real-time performance. These radios support instantaneous bandwidth of 160 MHz and have the possibility for synchronization using 10 MHz/1 PPS signals as well as synchronization using White Rabbit (WR) – offering sub-nanosecond precision synchronization, which is particularly suitable if high precision sensing is required.

6G-SENSES also includes research on mmWave platforms, as the larger bandwidth availability at theses frequencies allow for higher throughput and sensing resolution. However, integrating sensing and communication is a challenging task, in particular, at mmWave frequencies, where signals are prone to high attenuation and blockage due to the short wavelength and high path loss. In the context of 6G-SENSES, mmWave is used based on Xilinx RFSoC devices that comprise Field Programmable Gate Array (FPGA) logic and ARM processors, as well as Analog-to-Digital (A/D) and Digital-to-Analog (D/A) converters with sampling rates in the GHz range. Almost all signal processing, including D/A and A/D conversion, is thus performed in one chip. The devices are extremely high-performance and therefore well suited for implementing very fast and complex signal processing in parallel. In one RFSoC chip, 8 antennas, including full signal processing with a sampling rate up to 6 GHz, can be implemented. Special consideration will be taken to reduce the element-to-element mutual coupling for the antennas to integrate both communication and sensing operations. With this compact and scalable solution, the construction of massive MIMO systems with a large number of antennas (>100) and high bandwidth is possible.

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 framework 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 to 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 ([23], [24]). Additionally, localization and sensing based on 5G Core Network (5GC) Location Management Function (LMF) will be part of the research.

Finally, 6G-SENSES will enhance the system integration and functionalities of RIS (leveraging on existing concepts [7], [8]), 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 Cell-Free 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 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 will be implemented taking into consideration the different RATs. 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, his 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 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 [35].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 [36]. 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 [24] – with cooperation being considered in many scenarios 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’ [25], 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 ([16], [17], [26]). Concepts and techniques related to content demand prediction, traffic characterization, mobility information along with big data analytics and AI techniques such as reinforcement learning or deep learning will be incorporated.

3 A view of 6G-SENSES on Ecosystems and Use Cases

3.1 From 5G to 6G Service Provisioning Roles

As broadly discussed in literature (e.g. [28], [29], [30]), the paradigm shift that came 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 (summarized in [28], [29]). 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), makes 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 (highlighted in orange), when compared to the prior 5G ecosystem view is shown in Fig. 1.

From a technical and functional viewpoint, 6G-SENSES is grounded on the disaggregation of RAN functionalities, along with the development of an intelligent control and management plane exclusively operating on top of the RAN and the inclusion of parallel data streams enabled by RAN (including RIS) sensing. As can be seen in Fig, 1, 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 or (even) service customers.

In this context, the technology advancements make room for an extended ecosystem model (cf. orange modules in Fig. 1) compared to that of 5G described in [29]. 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 Network Operators (NOPs), Virtualization Infrastructure Service Providers (VISPs) and Datacenter Service Providers (DCSPs) (in this paper being 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 enhance Mobile Broadband (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.

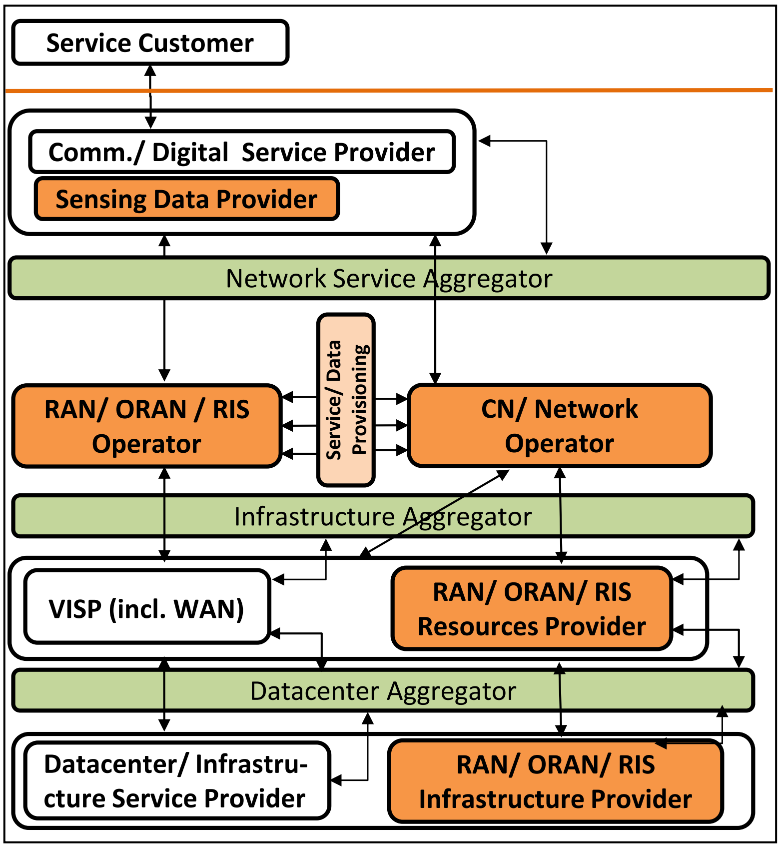

Fig. 1. Revised Ecosystem view enabled by 6G-SENSES enhancements

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 radio access 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 fiber 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 radio access 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 radio access elements, and makes resources and/or additional services (e.g. RIC related services, sensing data, etc.) 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 (SA) at various layers, i.e. the Network Service Aggregator, the Infrastructure Aggregator and the Datacenter Aggregator. Entities taking the SA 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.

3.2 6G-SENSES - enabled Use Cases

Considering the transformation of the ecosystem, both 6G vertical use cases and a wide range of service provisioning use cases can be enabled. In particular, the expected data rates, coverage availability and latency values are the key enablers for applications relying on Immersive and Massive communication ([31], [32]) – in line with IMT-2030 and envisioned end-user usage scenarios ([20], [33], [34]). Digital twinning of areas of interest and/or avatar-based visiting of areas of interest (e.g. archaeological/ monument site, museum, industrial/ office facilities etc.) is a use case within the aforementioned categories -to be supported in the context of 6G-SENSES.

Beyond that, service provisioning use cases are in the focus of 6G-SENSES (in line with the IMT-2030 new usage scenarios [20]), paying special attention to ISAC, as well as AI and Communication.

In brief, from a technical perspective in the category *Integrated Sensing and Communication - 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 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.

In the 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 scenarios 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, etc. What should be highlighted at this point is the advancement of the role of Infrastructure Providers from (semi-static) provisioning of computing resources 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 Conclusions

This paper provided an overview of the main technologies and concepts considered in 6G networks towards augmenting the provisioning of classical telecommunication services to new service paradigms, by exploiting sensing and network intelligence. The discussion is based on the advancements envisioned in the EU funded project 6G-SENSES.

These advancements are expected to make room for new roles in 6G ecosystems and novel use cases involving multiple service layers roles. Using the 5G ecosystem view as basis and considering 6G-SENSES advancements, we have identified extensions in the layered service provisioning approach. The cornerstone of these extensions is the evolved capabilities of the RAN, enabling 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 or (even) service customers. The new usage scenarios of IMT-2030 i.e. ISAC and AI and Communication, will be among the main use case categories to be supported by the envisioned technical and ecosystem extensions.

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