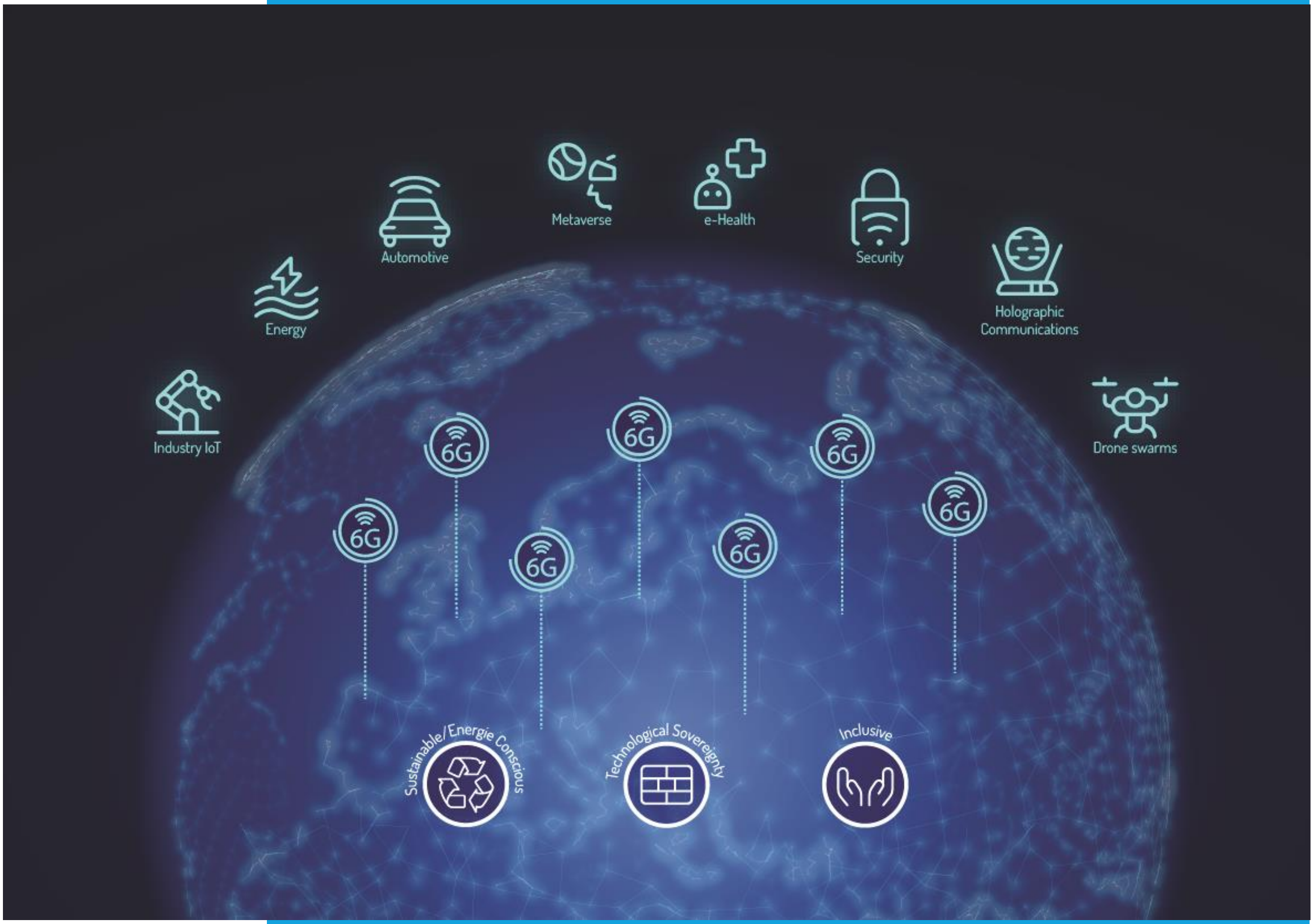
6G-IA Vision Working Group



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WHITE PAPER

EUROPEAN VISION FOR THE 6G NETWORK ECOSYSTEM

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EXECUTIVE SUMMARY

This white paper focuses on the ongoing global efforts to develop and standardise 6G networks, aiming for a commercial launch around 2030. It highlights the importance of creating a unified 6G vision, driven by key stakeholders worldwide, towards a single global consensus. The European perspective, represented by the 6G Smart Networks and Services Industry Association (6G-IA), is emphasized, showcasing Europe's proactive role in 6G Research and Development (R&D) and standardisation, also addressing societal, environmental, economic and market challenges.

We outline the technological advancements anticipated in 6G, such as native artificial intelligence (AI) support, integrated sensing and communications (ISAC), and advanced cybersecurity. We stress the focus on sustainability, both in making 6G systems themselves sustainable and in using 6G to enhance sustainability across various industries, including media, transportation, and healthcare.

Globally, 6G development is driven by key priorities like security, AI, energy efficiency, and ubiquitous coverage. Europe, especially through the Smart Networks and Services Joint Undertaking (SNS-JU) and its R&D projects like the flagship Hexa-X-II project, has been active in aligning its priorities with global standards and contributing to the 6G vision.

Furthermore, we discuss the need for socio-economic considerations in 6G development, including energy efficiency and sustainability goals. We call for integrating sustainability metrics, like Key Value Indicators (KVIs), into the R&D process to ensure that 6G not only meets technical performance targets but also contributes positively to societal, economic and environmental goals. We outline the use cases and key performance indicators (KPIs) for 6G, reflecting the European consolidated Research and Innovation (R&I) perspective. These use cases are based on inputs from various SNS JU projects and are categorized into six families, each with a representative use case and corresponding KPIs. In summary the use case families are: (*i*) Immersive Experience; (*ii*) Collaborative Robots; (*iii*) Physical Awareness; (*iv*) Digital Twins (DTs); (*v*) Fully Connected World; and (*vi*) Trusted Environments.

KPIs are provided for each use case, including data rates, latency, reliability, and positioning accuracy, tailored to the specific needs of each use case family. Furthermore, operational aspects are discussed, with considerations for the efficient operation of 6G networks, including spectrum use, unified interfaces, deployment strategies, and seamless migration from 5G.

The anticipated services of 6G technology from an "outside-in" perspective are also discussed, focusing on services integrated with or enabled by the 6G system and emphasising the need to sustain and build on the innovations of 5G during the transition to 6G. We therefore introduce a "6G-enabled Services Vision" highlighting the importance of interconnected and interoperable smart networks and services and suggest a new ecosystem-level approach to business for sustainable 6G. The key points of our Vision are:

- **Foster transition** from 5G to 6G to sustain and enhance 5G innovations.
- Address **potential shortcomings of 5G** in areas that may have been underdeveloped, e.g., with respect to support of vertical industries.
- **Integrate new service capabilities** with an emphasis on interoperability and service continuity.
- **Propose interconnected and interoperable smart networks** ensuring seamless interconnection and interoperability among network providers beyond just connectivity.

- **Define sustainable 6G ecosystems** prioritising sustainability and encompassing environmental, social, and economic aspects through a new business ecosystem approach.

The R&D of technological enablers for 6G has been underway for some years, building on the features and enhancements of previous generations while also exploring breakthroughs that could revolutionise mobile connectivity in the near future. The most relevant topics related to the upcoming 6G system include advancements in hardware (HW) and radio technology, flexible network topologies, deterministic networking, network softwarisation, and digital twinning, as well as the widespread adoption of AI and ISAC.

The enablers are categorised in a set of concrete areas such as energy efficient technologies, network and service security, deterministic networking, radio and signal processing, new access and flexible topologies, edge-cloud continuum, network softwarisation, network intelligence (NI), optical networks/photonics, DTs, and HW technologies.

We provide an updated vision on the forthcoming 6G architecture, focusing on potential innovations and addressing current 5G limitations. We identify fundamental challenges in 5G that hinder efficient global operations and outline potential architectural innovations for 6G to overcome these challenges. Key areas of focus include interoperability, resource awareness, service-awareness, multi-tenant federation, deeper integration of user equipment (UE), AI/Machine Learning (ML) support, dependable communications, ISAC, seamless integration between terrestrial and non-terrestrial networks (TN and NTN), enhanced security and privacy, network simplification, and sustainability. These innovations are essential for meeting the new objectives and requirements of 6G as defined by the IMT2030 framework. Innovations in the aforementioned areas will be the foundation for 6G architecture, building on the existing 5G system (5GS) but incorporating novel concepts and technologies.

We outline the major differences between 6G (IMT-2030) and 5G (IMT-2020), highlighting significant advancements and new capabilities. IMT-2030 builds on 5G usage scenarios (eMBB, URLLC, and mMTC) and introduces new ones, such as immersive communication, hyper-reliable low-latency communication, and ISAC. The KPIs for 6G are significantly more demanding, with higher data rates, lower latency, and enhanced reliability. 6G, in contrast to 5G, considerably emphasizes sustainability, trustworthiness, and inclusion, aiming to transform technology interactions and support global sustainability goals. The 6G core network will evolve from 5G, integrating AI/ML for enhanced efficiency, security, and real-time resource management. These innovations aim to create a robust, flexible, and sustainable network architecture capable of supporting next-generation applications and services.

To realise 6G by 2030, several key non-technical steps must be addressed, including standardisation, regulation, business strategy, and sustainability.

Standardisation: The International Telecommunication Union (ITU) has named the next generation of mobile technology "IMT-2030" or 6G. By 2025, ITU will outline technical requirements that will guide standardisation bodies like 3GPP in defining what constitutes a 6G-compliant system. 6G will build on 5G foundations but also introduce new concepts such as Ubiquitous Connectivity, AI-driven Communications, and Integrated Sensing. A unified global standard is crucial for a resilient telecommunications ecosystem, supported by contributions from industry groups, associations, and open-source communities.

Regulation: 6G must comply with various regulations to be commercially viable. Key regulations include the Radio Equipment Directive (RED), which covers safety and spectrum use; the Data Act, which addresses data management; the AI Act, which governs AI system use; and the Cybersecurity Act, which establishes security certification frameworks. Compliance with these regulations is essential as 6G becomes deeply integrated into societal infrastructure.

Spectrum: 6G will need a combination of various frequency ranges to meet the coverage and enhanced capacity requirements and to serve new emerging IMT-2030/6G use cases. It has been estimated that at least 500 MHz of new wide-area spectrum is needed per network, in addition to the re-use of existing spectrum. These new bands, with wide enough bandwidths are needed to meet the foreseen 6G capacity and coverage needs as existing bands would still be needed to provide connectivity and capacity for serving the demands of previous generations' use cases. New frequency bands are being studied within WRC-27 Agenda Item 1.7: 4.4-4.8 GHz, 7.125-8.4 GHz and 14.8-15.35 GHz.

Business Strategy: Europe, home to two of the top three telecom vendors, holds a strong position in the 6G landscape. However, it faces business challenges from dominant non-European streaming and content providers, social networks and platform of hyper-scalers. Opportunities for Europe include leading in industrial applications of 6G and adapting to new business models and regulatory policies that support open networks and AI integration. Robust data management and a holistic approach to network security are vital for maintaining European technological sovereignty and ensuring secure, trustworthy 6G systems.

Sustainability: 6G is set to be a model of sustainability, guided by global and regional goals such as the UN's Sustainable Development Goals and the European Green Deal. This involves assessing environmental, social, and economic impacts, optimizing material use, and reducing waste. The 6G industry must innovate in both technology and business models to ensure that 6G benefits are realised sustainably and equitably, balancing connectivity advancements with environmental considerations.

The 6G industry in Europe must innovate in technology, business models and investment strategies. The focus will be on optimizing the use of resources, reducing environmental impact, and ensuring that the benefits of 6G are realised in a sustainable and equitable manner for society and business.

This whitepaper represents an update of a previous version released in June 2021[1]. It incorporates all the advances at all levels of the 6G technology and presents a more mature vision of both the industry and academy of what 6G will be and what it can enable and mean for the society.

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[1] 'European Vision for the 6G Network Ecosystem', available for download at : https://5g-ppp.eu/wp-content/uploads/2021/06/WhitePaper-6G-Europe.pdf

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1. INTRODUCTION

Research and development activities for 6G networks are at full speed, attempting to develop, test, and validate the technologies that will bring the 6G vision to life by 2030. As standardisation organisations such as 3GPP are also getting ready to initiate their 6G-related activities, recognized experts are converging toward solutions that will deliver the promised performance improvements at a reduced environmental cost. Even though there is not yet a single global 6G vision, key stakeholders have shared their views and priorities regarding technological enablers, targeted performance, use cases, and societal, environmental, and business aspects that should be considered. Through intense discussions in scientific conferences, (pre)standardisation meetings, business networking events, and state/government functions, the 6G stakeholders are slowly converging towards a unified vision of 6G.

This document provides an updated version of the **6G Smart Networks and Services Industry Association (6G-IA)** vision for the 6G smart networks and services [1], as being developed under the Smart Networks and Services Joint Undertaking (SNS JU) [2]. The current document builds upon 6G-IA key strategies for 6G smart networks and services [3].

The 6G-IA represents “The Voice of European Industry and Research” for developing 6G. It addresses all major policy-related aspects, including industry competitiveness, sovereignty, sustainability, innovation, and societal issues. 6G-IA includes more than 360 members representing all the key players of the networking domain today and, additionally, key actors in the IT/cloud, microelectronics, and vertical sectors. It also has a very extensive basis of Academia, Research Centers, and SMEs from all over Europe.

As discussed in the current document, 6G will deliver several cutting-edge technologies. Besides the technical aspects, 6G development efforts target sustainable solutions to address environmental, societal, and business aspects for the networking domain (i.e., “Sustainable 6G”) as well as for a variety of the so-called “vertical” industries (i.e., “6G for sustainability”) such as media, transportation, e-health, industrial IoT, etc.,

This document is organized as follows. Section 1 sets the global scene for 6G and discusses points related to use cases, KPIs and KVIs. It also provides the European perspective in terms of policies and priorities. Section 2 discusses six 6G use case families developed by European Initiatives and presents their targeted KPIs along with the vision to support 6G-enabled services. Section 3 outlines the 6G technological enablers, while Section 4 brings an updated vision of the 6G architectural concepts and potential innovations. Section 5 provides a comprehensive summary of differences between 5G and 6G networks and finally Section 6 discusses future steps and recommendations towards making 6G a reality by 2030, considering standardisation, regulation, business and sustainability aspects.

1.1. 6G GLOBAL ACTIVITIES & THE EUROPEAN CONTRIBUTIONS

6G stakeholders are working towards transforming their vision for future networks and services into reality and preparing for the upcoming discussion and standardisation activities that will shape the final format of 6G. The International Telecommunications Union (ITU) has already aggregated the vision statements from stakeholders and experts around the world and has issued the IMT-2030 Framework [4], which describes the targeted performance, prioritized technologies, and use cases that the global community is working towards.

The European stakeholders have been especially active in the R&D process, and through the SNS JU and its private counterpart 6G-IA, are addressing the most critical challenges and are investigating the most promising technological advancements required for 6G networks. Further developing the globally accepted usage scenarios and aspects of IMT-2030, European stakeholders have elaborated on the work items and topics that are prioritized in EU R&I activities in relation to the IMT-2030 aspects, as shown in Figure 1, while each of these items is elaborated in Section 3.

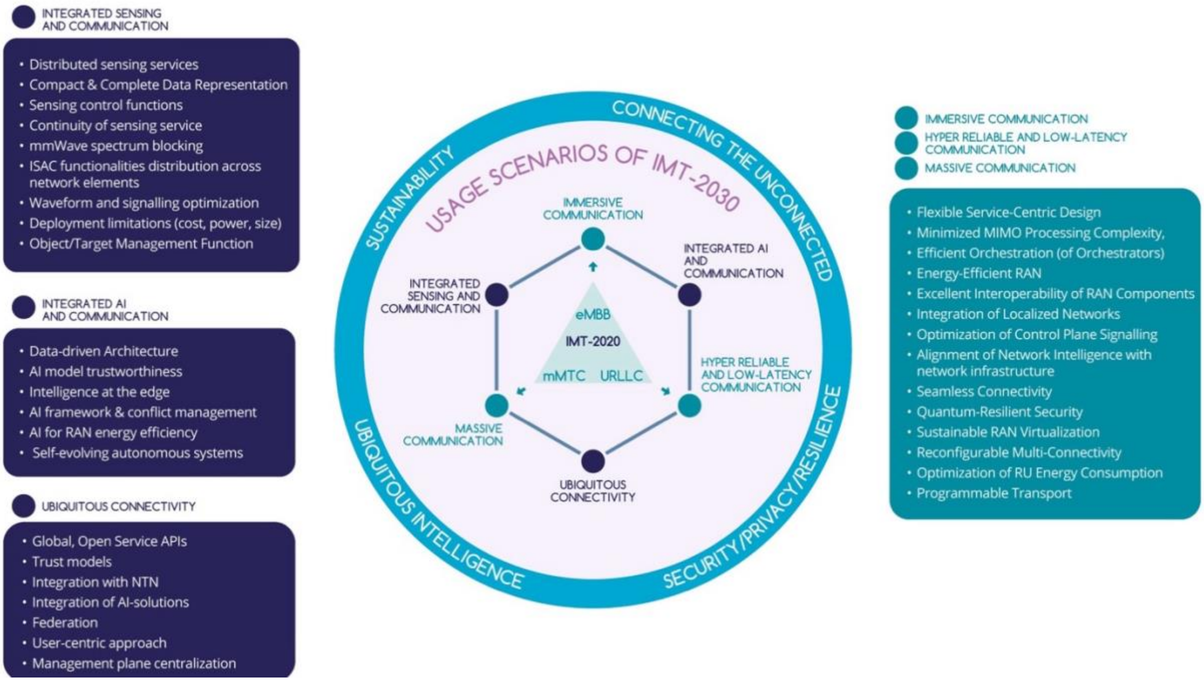

Figure 1: SNS JU / 6G-IA Work Items to meet the IMT-2030 targets

The following sub-sections provide an overview of the R&I landscape and the analysis of the 6G vision of key stakeholders as it was presented via various position papers and vision publications. Targeting a globally accepted 6G standard, it is important to understand the landscape of operations regarding 6G development, and how the European view aligns with or differs from views from other regions.

1.1.1. GLOBAL DRIVERS FOR 6G & TARGETED USE CASES AROUND THE WORLD

As the global R&I race for the development of technologies is underway, stakeholders around the world are sharing their own 6G vision, discussing the challenges and opportunities and aligning their roadmaps according to the timelines of the major global Standards Development Organisations (SDOs), to ensure that their views have a global impact. To align with the various regional priorities and views on 6G, 3GPP SA1 organised a Workshop on May 2024, and invited the leading R&I organisations from major regions of the world to provide contributions regarding their views on use cases and technological enablers that should be prioritized for the development of the 6G standard. That workshop provided the opportunity to investigate the commonalities and differences in the 6G vision of the various regions and to initiate useful discussions in the pursuit of global consensus.

Through the SNS JU, the EU proposed a unified approach during the SA1 workshop, presenting the EU priorities in terms of 6G Use Case families and relevant KPIs. This effort, driven by the SNS ICE[2]

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

Coordination and Support Action (CSA) project and the Hexa-X-II[3] SNS JU Flagship project, brought together the European stakeholders and engaged them into fruitful discussions resulting in a common European contribution towards 3GPP, thus maximising the impact of the European 6G vision.

Based on the presented material, during the 3GPP SA1 workshop, an initial view on the key drivers for 6G was extracted, as presented in the summary of the workshop[4]. According to that, there was an agreement that the key drivers to enable 6G networks and services are:

- Security
- Support of AI
- Immersive Communication
- Sustainability / Energy Efficiency
- Ubiquitous & resilient coverage
- Integrated Sensing & Communications

These six drivers seem to be universally considered as the top priorities for enabling 6G services, and the majority of the workshop attendees indicate that they have active R&I activities on these aspects. However, additional drivers were mentioned, which did not seem to attract a universal acceptance and were more sparsely or sporadically addressed, depending on the different priorities in terms of use cases and socio-economic views. Some of such drivers are *positioning, 'Smart Life' applications, 'Healthcare' applications, North-bound APIs, backward compatibility*. The European vision had a complete match with the six drivers considered as global priorities, while also touching upon some of the secondary ones.

A study on the technological enablers that the attendees prioritize can be found in [5]. Based on the key findings, enabling technologies were identified as crucial or strategic for the development and advancement of 6G networks. The study further compares them with the final recommendations included in the ITU IMT-2030 document. A broad coverage of several of these key enablers/drivers is observed among the global stakeholders, indicating the expectation that many technologies are required to deliver on the global vision of 6G and enable the targeted use cases. With regards to the prioritization of these technologies on a global scale, a large group of enablers is shared among most stakeholders, namely:

- AI related enablers
- Cloud Native Network and RAN-Core Convergence
- mmWave and THz Radio
- Communications and Sensing co-design (a.k.a., ISAC)
- Spectrum Migration
- Integrated Satellite hybrid infrastructures (aka NTN)
- New Antenna Technologies (e.g., Reconfigurable Intelligent Surfaces (RIS))
- Trustworthiness / Multilateral trust architecture

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[3] https://hexa-x-ii.eu/

[4] https://www.3gpp.org/ftp/workshop/2024-05-08_3GPP_Stage1_IMT2030_UC_WS/Docs/SWS-240025.zip

The common global belief is that these enablers are the key to the development of 6G networks. This showcases the importance of these technologies and explains the interest of the global research community on these topics. Another testament of the global consensus around these enabling technologies is the fact that the ITU recommendations document directly references most of them, as the key enablers taken into account for IMT-2030 (except for spectrum migration, which is implicitly addressed, as it is handled by the World Radiocommunication Conference). The specific Use Cases that seem to be prioritized by major global stakeholders are presented in Table 1 below.

Table 1: 6G USE CASES IN FOCUS IN VARIOUS REGIONS OF THE WORLD [5]

6G Use Cases	Networld Europe SRIA 2022	5G Americas / Next G Alliance	Huawei (China)	B5G Consortium (Japan)	TSDSI (India)	MediaTek (Taiwan)	Survey Paper	ITU IMT-2030
Holographic Communications	✓	✓	✓	✓	✓	✓	✓	✓
Cyber-Physical Systems, DT, Manufacturing	✓	✓	✓	✓	✓	✓	✓	✓
Multi-Sensory extended Reality (XR), Gaming/Entertainment	✓	✓	✓	✓	✓	✓	✓	✓
Tactile/Haptic Communications	✓	✓	✓	✓	✓	✓		✓
Medical/Health Vertical, Telesurgery	✓	✓	✓	✓	✓	✓	✓	
Cooperative Operation among a Group of Service Robots / drones	✓	✓	✓	✓	✓		✓	✓
Imaging and Sensing	✓	✓	✓	✓	✓			✓
Transportation Vertical (automotive, logistics, aerial, marine, etc.)	✓	✓	✓	✓	✓		✓	
Space-Terrestrial integrated network	✓	✓		✓	✓		✓	✓
Intelligent Operation Network	✓		✓		✓		✓	✓
Critical Infra, Government/National Security	✓	✓		✓				
First Responder/Emergency Services		✓		✓	✓			
Smart Buildings			✓	✓	✓			
Agriculture / Smart Farming				✓	✓			

1.1.2. GLOBAL TARGETS FOR 6G KEY PERFORMANCE INDICATORS (KPIS)

When discussing the global 6G vision it is important to investigate the respective performance targets that each global region has set, to have an estimation of how well aligned (or not) are the expectation for the new standard. Through a process of discussion and exchanging views on several aspects, the international community has agreed on a set of commonly acceptable targets which are reflected in [4]. Besides the global consensus, it is also interesting to be aware of the starting position of each stakeholder, and the deviation of their initial vision compared to the finally adopted targets. Such comparison is available in [5] and illustrates that even though the various stakeholders come from different backgrounds with potentially different visions of what 6G networks should accomplish, their requirements in terms of performance appear to be well aligned. Even though minor differences can be detected for certain KPIs, the overall "big picture" points towards an aligned view for these main KPIs. Some differences can be detected between the regional targets and the adopted values from ITU, which seems to have opted for a more conservative approach regarding certain KPIs such as peak data rate, user data rate, and positioning accuracy.

Regarding peak data rates, most stakeholders seem to agree that a value of up to 1 Tbps should be targeted, while only one stakeholder adopted a more modest target of 200 Gbps. The ITU has adopted the smaller value for the IMT-2030 recommendations. Regarding average user data rates there were ambitious stakeholders targeting up to 10 Gbps or even 100 Gbps, and more modest ones targeting 1 Gbps. The ITU recommendations have opted for an even lower value of up to 500 Mbps. On the other hand, a good alignment on density, reliability, and user-plane latency could be found. All global stakeholders seem to agree that a 10 million devices/km^2 target is suitable for 6G. The ITU stills considers what the appropriate value should be. In terms of reliability, expressed in targeted Block Error Rate (BLER), there is also an alignment as all stakeholders propose values between 10^{-7} – 10^{-9}. In this case, the ITU adopts a more modest target again, considering the 10^{-7} target as the best-case scenario. Almost all stakeholders share similar targets for user-plane latency where values between 0.1-1 ms seem to be commonly desirable, and also the ITU recommendation targets the same values.

Finally, it is interesting to note that even though it is commonly agreed that energy efficiency is one of the primary goals of 6G, several different definitions and approaches can be detected among the global stakeholders. A significant number of global stakeholders attempt to approach this KPI in terms of expected improvement with regard to improvement over the energy efficiency of 5G, e.g., targeting values of 100x compared to 5G as the most appropriate. However different values are also mentioned, while some stakeholders don't provide any specific value for this KPI. In a similar approach, ITU has not provided a specific target value for energy efficiency in the IMT 2030 recommendations.

Network improvements in terms of KPIs usually come with a cost (complexity of equipment, additional spectrum needed, increased energy consumption etc.). This is why it is essential not only to set ambitious targets for every generation of networks but also to have a clear reasoning if the targeted use cases need these improvements.

1.1.3. SOCIETAL & SUSTAINABILITY ASPECTS

Besides the technical aspects, envisioned use cases and performance targets, it is imperative to examine socio-economic factors as well when taking the initial steps for the development of a new technology or service. The 6G-IA and the SNS JU have long ago set the stage to discuss societal, policy and business aspects of the future networks and services, and how they affect the broader community. Dedicated working groups (WGs) have been set up from the SNS JU and the 6G-IA to specifically discuss these issues and to ensure parallel evolution along with the technological advancements.

Especially when it comes to societal challenges and aspects to be considered, energy efficiency has probably received the most attention, as it includes multi-faceted aspects which stand to greatly affect the design and operation of the entire network. When discussing sustainability, it is important to distinguish between "**Sustainable 6G**", i.e., making the 6G system itself sustainable, and "**6G for Sustainability**", i.e., ensuring 6G contributes to the sustainability of other sectors. This encompasses all three pillars of sustainability, namely ***environmental, social***, and ***economic***, emphasizing network aspects such as trustworthiness, privacy, and digital inclusion.

The UN's Agenda 2030 provides a comprehensive global framework for sustainability, recognised by the European and US ICT industries. These industries are committed to aligning their efforts with the 17 Sustainable Development Goals (SDGs), which aim to create a connected world. For 6G R&D and standards, the primary goal is to minimise CO_2 emissions and improve resource efficiency. This involves reducing energy and material use, ensuring efficient spectrum utilization, and employing intelligent spectrum use methods. The industry must optimise every phase of the HW lifecycle, from design and production to end of life, ensuring sustainable use of AI, cloud services, devices, and frequency bands. Promoting the transition to renewable energy sources is also a critical objective. Additionally, there is a strong emphasis on transitioning towards a circular economy by designing products that support reduction, reuse, recycling, and recovery of materials. This approach is guided by the 9R framework (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover) [6].

6G holds significant potential to transform society by supporting new use cases in various industries and increasing levels of digitalization. This transformation can reduce negative footprints by enabling remote work and learning, thus decreasing commuting and transport emissions. Previous studies of 4G and 5G network rollouts have demonstrated positive economic growth effects from wireless connectivity. This suggests that 6G can contribute to “green growth” and decouple economic activity from negative sustainability impacts. By enhancing productivity, innovation, and efficiency, 6G can create new business models and market segments, while also improving public services such as healthcare, education, safety, and environmental protection.

Ensuring that these developments align with sustainability goals requires clear guidelines and processes for the 6G R&D community. This includes adopting frameworks like KVIs [7] to complement traditional KPIs. KVIs focus on values-driven development and assess sustainability impacts through dedicated metrics. Policy makers can use these metrics to push development towards specific sustainability targets. It is crucial to develop effective measurement criteria for KVIs and to integrate them into the technology development process to mitigate any potential negative impacts.

1.2. EUROPEAN PERSPECTIVE ON 6G

The SNS JU targets a reinforced European leadership in the development and deployment of next generation network technologies, connected devices and services, while accelerating European digital industry and the digitalization of the Public Administrations. It aims at positioning Europe as a lead market and positively impacting citizen’s quality of life, by supporting key SDGs while boosting the European data economy and contributing to ensure European sovereignty in these critical supply chains.

At the heart of the SNS JU lies a dual ambition: fortify European capacities in 6G technologies, laying the groundwork for future digital services up to 2030, while concurrently nurture lead markets for 5G infrastructure and services across Europe.

Europe’s objective is clear: leading the design and standardisation of 6G technologies, with a holistic industrial approach that focuses on connectivity but also tackles important enabling technologies in networks such as AI, edge/cloud integration and future HW architectures for 6G. The overarching aim is to steer Europe’s technological vision into the 6G standardisation process, positioning Europe as a key player in shaping the future of telecommunications. The SNS JU has been designed to be fully aligned with the European policy priorities and address a strong European position on critical infrastructure supply chains (e.g., connectivity, cloud, data economy components and devices). Moreover, the evolving geopolitical environment has highlighted, even more than in the past, that network and service infrastructures are critical infrastructures and hence require to develop cybersecure infrastructures and to secure European sovereignty for supply chains in critical technologies and systems [8].

On 21 February 2024, the European Commission adopted the White Paper “How to master Europe's digital infrastructure needs?”, which details its vision for the Connected Collaborative Computing Networks “3C Network”. This vision calls for reinforced actions on the Telco Cloud in view of securing a better European position in the cloud and edge cloud domain, whilst progressing in other domains of the value chain like microelectronics. The Pillar 1 of the White Paper foresees the need to establish a coordinated approach to the development of integrated connectivity and computing infrastructures, making sure that today’s connectivity providers become tomorrow’s providers of collaborative connectivity and computing, capable of orchestrating the different computing elements that this ecosystem requires. To do so it is necessary to continue developing a synergetic ecosystem between actors and to make the most of existing funding programmes.

Within this broader context, the SNS Strategic Research and Innovation Agenda (SRIA) and corresponding work programmes address the technological and business realisation underpinning the 6G vision, targeting massive digitisation of societal and business processes through intelligent connectivity across the human, physical and digital world. As SNS JU is currently halfway through its full implementation (in its 2nd phase) the focus of 6G R&I is to complement system-oriented R&I, enabling technologies with dedicated prototyping and experimentation whilst also considering longer-term disruptive technologies. At the same time, SNS work programmes will continue to consider all key European policy objectives and strategic orientations of the Horizon Europe (green and digital transition, a more resilient, competitive, inclusive, and democratic Europe), as well as the 5G deployment experience and progress of the 6G landscape.

The recent ITU framework and usage scenarios have largely been inspired and contributed by EU R&I and are hence very much in line with the SNS R&I work. The SNS JU vision includes notably:

- Moving beyond a simple increase in speed or performance of connectivity platforms, and beyond 5G capabilities bringing unique new service capabilities with wider economic implications. This requires capabilities for new classes of services and applications as defined e.g., in Hexa-X-II, aligned with sustainability targets and a human-centric approach. Applying them to the level of 6G development, there is consensus to equally address how the 6G E2E system will be sustainable (“Sustainable 6G”) and how it will contribute to the sustainability of other sectors (“6G for Sustainability”) through enabling use-cases with a positive footprint. This naturally encompasses all three pillars of sustainability (environmental, social, and economical) and will eventually lead to 6G services, like the “Internet of Senses”, realising a fusion between the communication and sensing environment, massively scalable immersive environments, like XR/VR, massive twinning, and holographic type communication.
- The integration of future connectivity and service platforms into larger globally applicable infrastructures, including their fully automated (AI support) management whilst preserving European competitiveness and sovereignty. The implementation of networks will increasingly take place across heterogeneous domains and with open technologies (e.g., open-source solutions for telco cloud), and the challenge will be to keep a strong EU influence whilst ensuring service delivery and control from an E2E perspective.
- Strong synergies and collaboration for defining the technological roadmap and for the extension of European effort across the overall value chain, from microelectronics to service platforms. This includes synergies between the actions of the SNS JU and national or regional initiatives and policies based on information received by the participating states or the States Representatives Group (SRG) as well as synergies with other Union programmes.
- The further development of trust, security and communication privacy-enhancing technologies, processes and architectures as required for massively heterogeneous, virtualised and SW platforms of the future, and their associated enablers.
- The participation of new actors from and beyond the verticals. Contributions from industry, Research and Technology Organisations (RTOs), Universities and Small and Medium enterprises (SMEs) actors in the connectivity, IoT and cloud/IT domains are expected to be complemented by appropriate participation of the microelectronics and photonics industries, in view of their potential impacts in the standardisation process.
- A reliable and extensible experimental framework towards minimising R&I risk and validating core technologies and use-cases.

- A unified consensus framework promoting a European approach towards 6G that takes into consideration national specificities (e.g., current infrastructures, economic power, societal needs), facilitating international cooperation and placing Europe on par with other regions developing bold 6G initiatives. International cooperation remains a very important and strategic target of the SNS Work Programmes, in order to achieve global standardisation and develop inter-regional synergies.
- Leveraging standardisation stages, including a consensus of 6G KPIs and KVIs that will frame future developments. 3GPP has by now defined its 6G standardisation roadmap, in parallel to the ITU work. Therefore, considering the influence of the running SNS JU projects on the selection of the study items, the focus is targeting to further test/validate early Standards and Systems and provide further input to future standardisation phases & releases. SNS will further focus on (1) the validation of the KPIs where a consensus has been established; (2) the further definition of the specific European KPIs that are not yet reflected in international consensus; (3) progress on the KVIs definition towards their operational usage. The integration of concepts and technologies originating from the Cloud/IT/Microelectronics environments to support massive device (IoT) connectivity and ultra-reliable communications and services on top of enhanced mobile broadband services will be continued. The target is to address a comprehensive value/supply chain materialised by an IoT device-connectivity-service platform.
- The stimulation of strategic alliances, with vertical (industrial) sectors to build and offer powerful and persuasive Business to Business (B2B) and Business to Consumer (B2C) propositions. This should leverage upon general, local, regional, or even global smart interconnected public and private networks and services. A strategic goal of the SNS JU is to empower many vertical domains with capabilities beyond what is currently possible with 5G networks. Participation and contribution of these actors to SNS programme is considered important, both to drive the requirements and to validate the technologies and their versatility in specific business contexts.

The SNS JU is at the forefront of the European 6G journey towards a hyperconnected future, as demonstrated by the current portfolio of projects and activities, with significant achievements and tangible results, as clearly reflected in the SNS JU KPIs [9]. The SNS programme in its two-pillar mission addresses all key societal and political challenges and creates business opportunities to secure European leadership in the smart networks domain, taking into account the 5G experience and further boosting the deployment of a solid 5G infrastructure. Europe's commitment to 6G technologies is a testimony of SNS vision, innovation, and resilience; at the same time SNS JU achievements and future targets are signalling Europe's readiness to shape the future of technology and connectivity in a way that is aligned with our core values.

2. WHAT IS 6G?

2.1. 6G USE CASES AND KPIS

Defining use cases is an important step in the development of any new mobile network technology. Use cases describe the kind of functionality that needs to be provided. Use cases are also used to derive new functional requirements and a sound justification for the targeted performance requirements.

The use cases described in this document are based on the European consolidated R&I view on 6G use cases presented during the 3GPP SA1 workshop on 6G use cases (Rotterdam, May 2024)[5]. These use cases are in turn based on the Hexa-X-II use cases [10] with input from various SNS projects and national 6G initiatives in European member states. The resulting set of use cases is displayed in Figure 2. The use cases are clustered in 6 use case families. Each use case family includes a number of detailed use cases. The use case best representing the key aspects of each family has been selected as the representative use case and is indicated first in the list of use cases for each family in Figure 2. Use cases' overview descriptions are summarised in section 2.1.1.

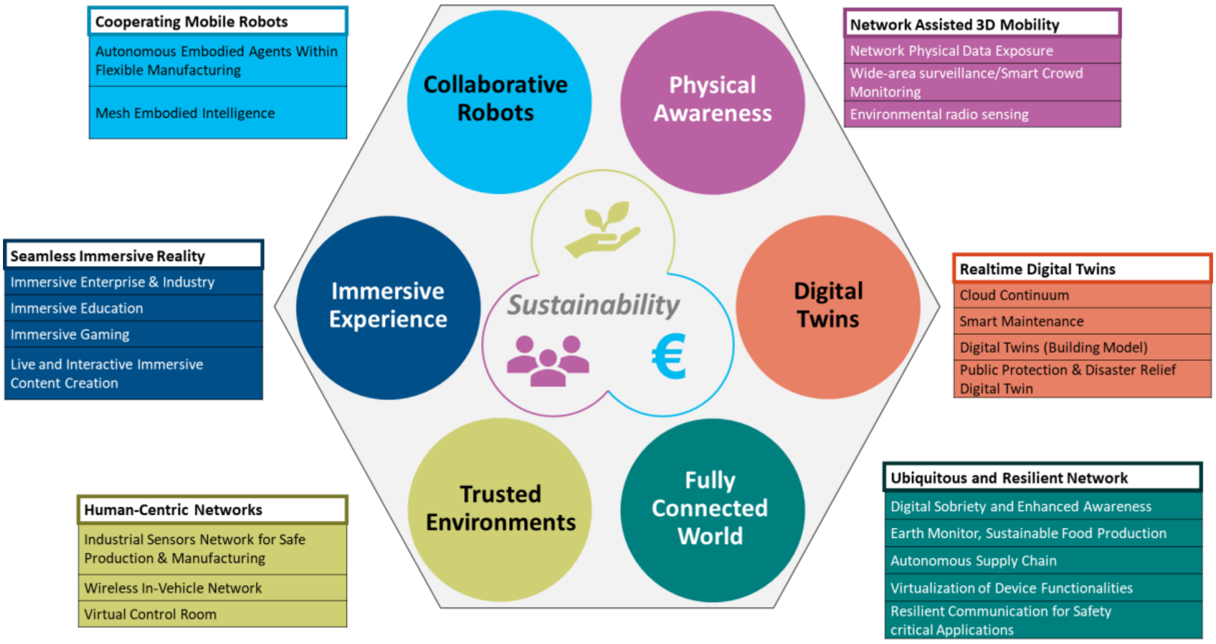

Figure 2: European consolidated R&I view on 6G use cases. Use case families (circles) with the representative use case mentioned first in the list of use cases in the respective family.

For each of the representative use cases, use case-specific KPIs are provided. These KPIs emphasise what E2E performance is needed to make the use case possible. The KPIs are summarised in section 2.1.2.

Not all requirements for 6G can be represented through end-user use cases. There are also requirements from an operational perspective. Subsection 2.13 provides a specific section on such operational aspects.

2.1.1. USE CASE FAMILIES

2.1.1.1. IMMERSIVE EXPERIENCE

This use case family is based on XR technologies. The immersion is built through the combination of immersive and sensorial technologies (e.g., 3D visual perception, spatial audio, haptics) and the synchronisation of data streams so that multiple participants have simultaneous, consistent, and collaborative experiences.

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[5] https://www.3gpp.org/ftp/workshop/2024-05-08_3GPP_Stage1_IMT2030_UC_WS/Docs/SWS-240018.zip

The representative use case for this family is *Seamless Immersive Reality* (*SIR*). Two example scenarios are (*i*) **Immersive collaboration meeting/classroom/event**, describing the possibility of displaying a particular content in an AR/VR/MR environment while interacting with remote and co-located participants; and (*ii*) **Immersive Experiences "on the go"**, where information from the real world is incorporated and used to provide a better user experience (e.g., sight-seeing landmarks) but also can be shared with others (e.g., joint virtual city tour).

To achieve this superior Quality of Experience (QoE) and seamless service continuity, data rates are required beyond what 5G typically delivers, plus strict E2E latency and reliability guarantees. Additionally, new 6G capabilities such as sensing, positioning, and AI/ML are key technology enablers for *SIR*.

Finally, privacy and security requirements are important for the proper functioning of these immersive experience use cases, as vast amounts of data will be transported. Technical, administrative and legislative means are required to protect privacy in a hierarchical and heterogeneous 6G system, i.e. across wide area networks, public and private local networks, as well as subnetworks.

2.1.1.2. COLLABORATIVE ROBOTS (COBOTS)

This family includes several use cases for intelligent, collaborative, and mobile robots with the ability to move, sense their environment, perform a task, and cooperate with humans or with other robots to achieve a set goal. Application domains include home robots, robots for facility management, robots in daycare or hospitals, as well as robots in flexible manufacturing.

The representative use case for this family is *Cooperating Mobile Robots*. As the name suggests, it revolves around robots being able to move and cooperate safely, enabling them to perform tasks beyond their individual capabilities, and perceive their environment beyond their local sensing capabilities. Furthermore, it focuses primarily on local *ad hoc* connectivity embedded in private networks, and the challenges imposed by the mobility aspects. A few example scenarios are (*i*) **cooperative carrying with robots**, where robots work together to transport an object that exceeds the carrying capacity of a single robot; (*ii*) '**Lot size one' production** where the flexibility and adaptability of cobots enable products to be created individually and uniquely, rather than in batches; and (*iii*) **autonomous farming,** referring to the use of self-driving, smart machines that work collaboratively in agricultural operations.

Related to requirements and KPIs, local *ad hoc* connectivity and extremely reliable and low latency communications are key for the correct functioning of the system, (e.g., E2E latency < 0.8 ms; Service-level reliability = 99.999-99.99999%; Mobility < 20 km/h). Additionally, Integrated sensing capabilities within the 6G network and devices can potentially enhance the perception of the robot of its environment. The introduction of AI/ML traffic types and AI/ML execution in edge nodes can further enhance robot coordination. Finally, positioning accuracy is also mandatory for tasks such as environment mapping, robot navigation, or localisation.

2.1.1.3. PHYSICAL AWARENESS

This family refers to use cases where sensing and positioning are used together with communication and NI to enable for instance physical scene analysis, tracking, context awareness, trajectory prediction, navigational support, and collision avoidance. The network sensing can be enhanced by embedded sensors and derivative information delivered by network nodes and surrounding devices. Example scenarios refer to cars, automated guided vehicles, and drones as well as pedestrians and bikes.

The representative use case for this family is *Network Assisted 3D Mobility*. Here, networks measure the physical environment in traffic scenarios and analyse to detect and capture information on objects (e.g., size, speed, trajectories, positioning). From this large data set, information is extracted and relayed to vehicles subject to the vehicle's capabilities. Thereby, the network can support vehicles with different levels of autonomy and modes of operation, and also enable smart transport in urban areas. Example scenarios described comprise: (*i*) **Autonomous drone transport**, whereupon carrying goods in urban areas, drones can be updated in real-time on the fastest and more energy-efficient traffic routes; (*ii*) **Smart intersections**, where vehicles are informed about the conditions at an intersection to advert collisions; and (*iii*) **Assisted vehicles**, where the benefits of autonomous driving are expanded into the ecosystem, benefiting from the contextual data resulting through the fusion of the wide-area sensor information provided by the network, vehicle on-board sensors and/or even sensors embedded in the transport infrastructure.

As this use case family aims at preventing undesired outcomes such as collisions, the system is required to be highly reliable, both in communication aspects (Reliability, Coverage, Service availability = 99.99%) and data quality/accuracy (Positioning, Sensing, AI/ML). Additionally, the availability of reliable compute capabilities offered by the network, and privacy and security requirements are also essential to this use case.

2.1.1.4. DIGITAL TWINS

This family collects a set of use cases where digital equivalents of the real world are created and displayed for interaction, control, maintenance, as well as process and component management. DTs can be part of managing manufacturing plants, construction sites, city infrastructure, or communication networks with or without real-time needs. Also, specific use cases around distributing the SW between operators and network locations are included.

The representative use case for this family is *Realtime DTs*. As the name suggests, along with the creation of an accurate digital representation of a given object/process/person, this use case expands the potential offered by these representations by benefiting from the real-time aspect, which allows extending the DT also towards the direct control of ongoing physical processes. An example scenario is: (*i*) **control over a chemical process** in real-time in a production plant; (*ii*) **control and monitoring of machines, robots, and vehicles** in the same production facility for 24/7 usage and maintenance needs; and (*iii*) **testing or simulation of a specific configuration** to avoid any hazardous situations.

To achieve a *Realtime DT*, AI/ML, positioning, and sensing capabilities are required to deliver a seamless user interaction. Moreover, network and device interoperability are key to the success of the working ecosystem. For the latter, using open interfaces and relying on strong system integrators are essential. Finally, other specific requirements that the *Realtime DT use case brings* are 3D coverage, compute capabilities, and privacy/trustworthiness of the network.

2.1.1.5. FULLY CONNECTED WORLD

This family unites use cases demonstrating the need for ubiquitous network access and service coverage across the whole population. Ubiquitous access will be enabled both through terrestrial networks (TN) and NTN and amended by infrastructure-less network extensions to wide-area network deployments.

The representative use case for this family is *Ubiquitous and Resilient Networks.* This use case focuses on delivering Mobile Broadband connectivity to every human on Earth, leaving no "white zones". Three main scenarios can be mentioned: (*i*) **Connectivity at remote locations**, providing a user in a mountainous area with a wide range of options (e.g., remote health consultations, voting, or emergency calls if being lost in the mountains); (*ii*) **Improved connectivity in developing countries**, where a small-scale farmer can apply the benefits of connectivity to the crops (e.g., precision farming); and (*iii*) **Connectivity during natural disasters and emergencies**, which builds on the role NTN can play in case of a terrestrial natural disaster (e.g., earthquake, fire, flood) for emergency services and disaster relief.

Ubiquitous and Resilient Networks has a big impact on social (e.g., digital inclusion, education, disaster relief), economic (e.g., deployment cost, new business opportunities), and environmental (e.g., earth monitoring, less invasive deployment) issues, but also increases network resilience significantly. Therefore, the biggest challenge lies in delivering a tight and reliable integration of different networks from the initial phases of 6G.

Coverage is an important KPI for ubiquitous networks (up to 1—15 km cell radius for TNs, 99.9% human environment coverage with NTN included). Affordability is important to ensure a widespread adoption.

2.1.1.6. TRUSTED ENVIRONMENTS

This family encompasses use cases with high reliability and privacy requirements as key characteristics. The *Trusted Environments* use cases build primarily on a combination of AI, sensing, and computing capabilities to create spatial and situation awareness to enable context-driven interventions.

The representative use case for this family is *Human-centric services.* This use case describes three scenarios that put humans at the centre of a wide range of 6G services: (*i*) **Precision healthcare**, which delivers personalized diagnosis and treatment; (*ii*) **Safe environments**, based on spatial- and situation awareness to prevent accidents or trigger changes in the environment (e.g., ramps deployment); and (*iii*) **Public safety services during big events**, aimed at predicting disorder and delivering solutions to aid the people in moments of need.

Delivering these services imposes very high privacy requirements and consequently the mechanisms to ensure the data is held secure and the system is trustworthy (e.g., anonymization, advanced information coding, additive homomorphic technology). For the latter, availability and reliability also play a key role when dealing with health and well-being situations. Both the new technical requirements/capabilities and the considerations emerging from the use case (secure by design) are topics for which 6G can provide an answer.

Besides, AI/ML and sensing capabilities, being fundamental in delivering these services Reliability (99.9-99.999%), and connection density (1-10 devices/m^2) are some of the most pressing KPIs.

2.1.2. KPI SUMMARY

This section summarises in Table 2 the relevant KPIs that have been identified for the different representative use cases within the use case families.

Table 2: KPIs to consider for 6G representative use cases

	Seamless Immersive Reality	Cooperating Mobile Robots	Network Assisted 3D Mobility	Realtime DTs	Ubiquitous and Resilient Networks	Human-Centric Networks
User experience data rate [Mb/s]	< 250	< 10	< 100	< 100	DL: 0.1 - 25 Mbps | UL: 2 Mbps	-
Mobility [km/h]	Pedestrian, up-to vehicular speeds	<20	<300	<100	<120	Pedestrian, slow vehicular
E2E latency [ms]	< 10 ms for split rendering | < 50 ms for voice | < 150 ms for collaboration	< 0.8	1-20	< 1	10-100	< 250 ms for AGV and care robots | < 1000 ms for initiating an intervention
Reliability [%]	99.9 - 99.999 %	99.999-99.99999 %	99.99 %	99.999 - 99.99999 %	99.9 - 99.999 %	99.99 - 99.999 %
Connection density [devices/m^2]	-	< 0.1-1	0.01 d/m^2 0.01 d/m^3)	1-10 d/m^3	0.1	1-10 indoor | <0.001 outdoor
Area Traffic Capacity [Mb/s/m^2]	< 250 Mbps/m2 for Indoor, per floor | <20 Mbps/m2 for wide area/outdoor	-	-	-	-	-
Service Availability	-	-	99.99 %	-	98.5 %	-
Coverage	-	-	99.9 %	99.99 %	Up to 10-15 kms range (cell radius) | 99.9% area coverage with integrated networks	-
Positioning Accuracy [m]	<= 0.1, horizontal & vertical	< 0.1 fine, <1 coarse | 99.9% availability	1 (3D) precision with 99.9% reliability within 99.9% of service space (0.1)	<= 0.1	< 10 | 99% of availability	< 10 location accuracy | <0.3 - <1 positioning accuracy | <0.1 relative positioning accuracy
Sensing-Related Capabilities	YES / Required	YES / Required	YES / Required	YES / Required	NO	YES / Required
AI/ML-Related Capabilities	YES / Required	YES / Required	YES / Required	YES / Required	NO	YES / Required

2.1.3. Operational aspects

Figure 3: Operational aspects to consider for 6G.

As outlined in section 2.1.1 and section 2.1.2, the use cases that 6G should deliver places requirements on the system design. However, separately from these demands there are aspects related to the operation of networks, important from cost and network ecosystem perspectives, that should be considered in the design. These operational aspects are in a sense independent from the services that the network offers but need to be harmonized with the purpose of providing services to end users. Figure 3 provides a summary of the main areas.

Spectrum aspects

To efficiently use both available spectrum resources and potentially new bands for 6G, 6G should be deployable in 5G bands through Multi-Radio Access Technology (RAT) Spectrum Sharing (MRSS). This also ensures robust connectivity through low and mid band coverage.

Unified interface aspects

To establish a viable 6G ecosystem, key external interfaces are needed: between devices (e.g., in industrial and commercial settings), towards communication/cloud/application service providers (through APIs), and towards the network manager (through intents).

Network of network aspects

To enable cost-efficient device support, it is preferred to have one standard for multiple requirements and accesses, which could be delivered on a few different chipsets. This is relevant, e.g., for NTN and IoT capable devices, which can be supported by the same standard as eMBB.

Deployment aspects

Solutions to make deployment and management of networks simpler and more cost-efficient are important to support a continued expansion of network services into underserved areas.

Migration and mobility aspects

The introduction of 6G should not disrupt the 5G ecosystem, and therefore it is important to ensure a smooth migration in terms of gradual introduction of 6G devices through MRSS and continued support of 5G devices, with full mobility between systems.

Feature parity aspects

To support greenfield deployments of 6G, e.g., in currently underserved areas, it is important to support vital services from start in 6G, notably voice, along with key 5G services such as IoT.

Novel services aspects

To spur a growth in the telco ecosystem into the 6G era, it is key to provide new exposure opportunities of services, such as differentiated connectivity, AI, compute, and localization, utilizing the network assets.

Considering these aspects in the design of 6G will significantly strengthen the business outlook of telco networks in the 6G era.

2.1.4. SUSTAINABILITY

Complementary to the use case families, the European vision is to lead the transformation of global connectivity through 6G technology, making sustainability inherent in future communication systems. In a world facing unprecedented challenges—climate change, economic disparities, political instability, and an ageing population—we envision 6G as a pivotal technology that connects the unconnected as well as drives holistic sustainability across environmental, societal, and economic dimensions.

To champion this vision, we must holistically address the sustainability challenges for both 6G technology (“Sustainable 6G”) and vertical solutions and applications integrating 6G technology (“6G for sustainability”). This approach can ensure that 6G technology is sustainable in its design and operation, and is endorsed as a catalyst for sustainability in every industry it touches. We must aim to integrate sustainability into the very fabric of 6G, from the materials and processes used in its deployment to the diverse use cases it supports in real-world scenarios.

By addressing sustainability at every stage—E2E and across the full lifecycle of assets—6G shall redefine how communication technologies contribute to society. The challenge is to identify the critical intersections between sustainability needs and technological innovation and develop solutions that meet these needs and set new benchmarks for responsible, sustainable growth. Through collaborative R&I and practical application, Europe shall evolve into a hub for exchanging ideas, pioneering new concepts, and validating sustainability impacts. Insights, processes and methodologies on how to attain sustainable 6G systems, as well as on how to support sustainability targets in the sectors, must be consolidated into regulations, guidelines, best practices, and standards that will shape the future of communication systems. This approach has the potential to ensuring an environmentally responsible, a socially equitable, and an economically viable 6G.

2.2. TOWARDS 6G SMART NETWORKS AND SERVICES

This section considers the external environment and viewpoints, such as customer needs, market trends, and competitive landscape for 6G smart networks and services, and focuses on the anticipated services of 6G, “on-top-off” and integrated with the 6G system, as well as services directly or indirectly interworking with the 6G system. We call these services “6G-enabled”. The boundaries between these services and the scope of a 6G system are defined through standardisation activities. We recognise that the future 6G system could take the form of various models, allowing for multiple types of deployable 6G systems.

First, perspectives and directions for the transition to 6G are presented, emphasizing the need to sustain and enhance 5G innovations throughout this process. This is corroborated by a set of KPIs, striving to preserve specific properties of 6G-enabled services. Building on this, a comprehensive "6G-enabled” services vision is introduced, followed by a discussion on: i) the essential requirements for advancing the telecommunications industry via interconnected and interoperable smart networks and services; and ii) the importance of adopting a new ecosystem-level approach to business for a sustainable 6G smart networks and services future.

2.2.1. AFFIRMING TRANSITION: SUSTAINING 5G INNOVATIONS INTO THE NEXT ERA

5G is the first mobile telecommunication system generation that holistically considers the seamless delivery of data, services, and applications across all components of the network, from the originating device or application to the receiving device or application. 5G features greater service customisation, paving the way to supporting so-called vertical industries. From the point of view of the telecoms industry, the consideration of vertical industries was a groundbreaking step, with the consequence of delving into the intricacies of many utterly new and diverse sectors, with expectations, cultures and time scales very different from the mobile broadband and telephony service subscribers to whom the industry provided services so far. In this context, 5G pushed existing boundaries and prepared the ground for a revolution in the telecoms sector. While the support for different radio modes and core network slicing plus the accompanying transition towards virtualisation are technological innovations, the emergence of and support for Non-Public Networks (NPNs) and private spectrum licenses shook up the entire business ecosystems and required changes in regulation. NPNs can take the form of local area NPNs, which provide a private, secure network within a specific location, offering complete control and customisation potentially without reliance on any public network service, logical NPNs across public networks, which provide essentially the same capabilities across multiple locations, using public networks to extend their geographic reach without compromising security and control, and a combination of the above.

As with any new beginning, supporting vertical sectors in telecoms is challenging. It was unrealistic to expect a new system to immediately satisfy all potential use cases, each with unique service expectations. However, it quickly became clear that understanding these diverse requirements would require more than just new technological solutions and provisions. New industry associations were created, such as the 5G Automotive Association (5GAA) and the 5G Alliance for Connected Industries and Automation (5G-ACIA), with the goal to better aligning potential offerings with existing expectations across various domains, such as automotive and manufacturing. While this successful work continues, the rollout of 5G has been faster than any previous mobile generation, though this speed was limited to areas already prepared for deployment. The adoption and standardisation of new technological features, such as slicing and NPN, have followed a more prudent approach. Even now, with discussions and visions for 6G already underway, the implementation of relevant 5G SA (stand-alone) features is still lagging behind initial expectations.

We are convinced that the new opportunities enabled by 5G are heading to the right direction and simply need further development. Therefore, we suggest that the transition from 5G to 6G should primarily be an ***affirming transition***, meaning that it should sustain and build upon the successful innovations of 5G through extensions, enhancements or modifications, where necessary. While we certainly aim to preserve the valuable contributions of the community and industry, leveraging the existing framework to deliver new types of services to emerging customer segments, it is important to clarify that this approach does not necessarily characterise our overall perspective on 6G as merely "evolutionary".To frame and formalize such an affirming transition to the next generation, in 6G, in addition to the KPIs listed in Section 2.1.2, it would be crucial to consider more general KPIs, e.g., the **overall service completion time**, **successful service throughput ("service goodput")**, **storage and compute resource availability** and **service continuity**. Such KPIs, which are currently either inadequately addressed or entirely missing, would provide a justifiable extension of the existing 5G functionality (as previously discussed). Moreover, these KPIs would effectively connect 5G to the 6G discourse by more precisely defining the 6G features described above.

2.2.2. 6G ENABLED SERVICES VISION

This section presents an overarching vision on 6G enabled services, with a focus on user services and features going beyond connectivity. The section also recognises the need for wholesale services among and across communication and network services providers to enable this vision on *6G enabled services and Interoperable Smart Networks Services*. An attempt has been made to develop an illustration to picture this vision.

First, and as the main area of services facing the end-customer, we recognise the "6G enabled User Services and Features". The 6G enabled Communications Service Provider (CSP) or Network Service Provider (NSP) directly or indirectly owns and manages available resources such as spectrum, physical communication medium (e.g., fibre), and HW (e.g., compute and storage). From these and corresponding assets, such as wireless and fixed network elements, compute devices, and controllable eSIM/SIM assets, the 6G enabled CSP can offer connectivity and potentially beyond connectivity services with various features. At the basic level, this may include ISAC, compute execution, and storage (e.g., cashing) services. Advancing from this basic level, we anticipate potential further service elements, such as application enablers, in-network embedded compute and storage (with optimised performance, compared with non-embedded variants), and packaged services solutions based on elements of the above into a network enabled edge compute service solution. This also includes specialized connectivity that can be offered on-demand, that can extend across network operator domains.

Complementary service enablers are also introduced and shown in Figure 4, such as DT, AR/VR, ML/AI, and security enablers. We anticipate these being available in two fundamentally different forms. Either as globally standardised enablers, generally available (potentially universally), or as ad-hoc enablers by specific operator offerings, where special integrator or application developer solutions can build from these enablers into targeted applications services. The generally available and (globally) standardised enablers can be part of higher level, standardised universal application services. Here, the IMS enabled telecom voice and SMS service is a basic example. This vision points to a new and anticipated significant innovation opportunity landscape of both universal application (enabler) services as well as targeted application (enabler) services.

Central to these services is the Logical Network as a Service (LNaaS) concept. Building from APN based services in 4G and DNN based services in 5G these service concepts and offering will be further evolved with the 6G user services and features going beyond today's enterprise VPN services offered by CSPs. These logical network offerings will deliver user services and features according to specific enterprise customer (vertical) needs, with support of any kind of connectivity to/from any relevant end-point (device, UE, such as IoT device), also to/from 3rd party and/or partner end-points, and including any relevant set of beyond connectivity features and capabilities as already indicated above.

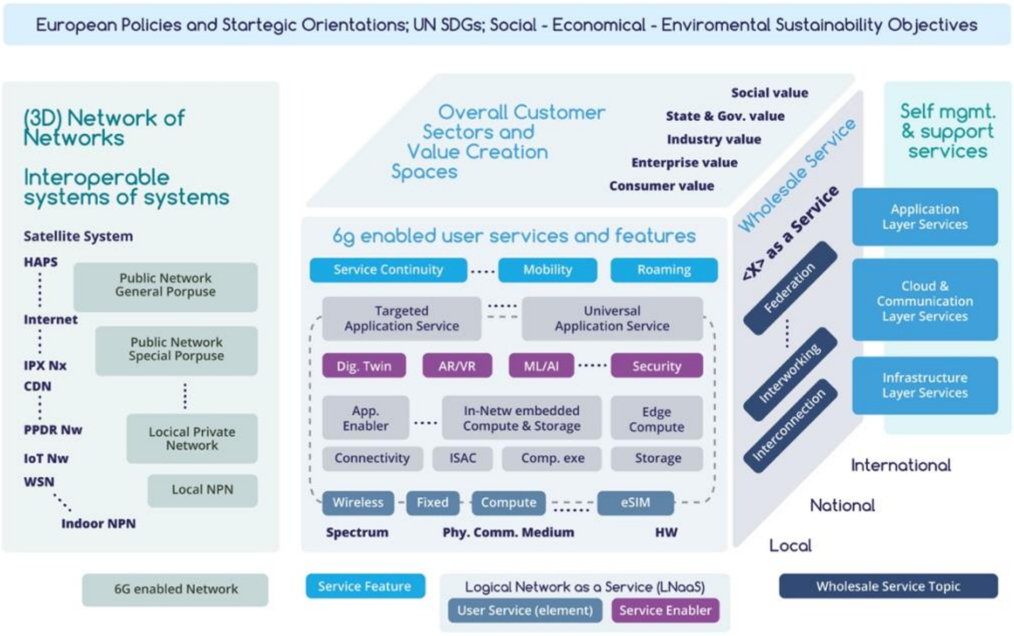

Figure 4: A Vision for 6G enabled Services and Interoperable Smart Networks (6G SNS)

To the left side of Figure 4 a variety of example 6G enabled networks are shown, along with what is often positioned as 3D network of networks. To realise a vision of network of networks in a geographically localised (indoor as well as outdoor), in high altitude (i.e., High Altitude Platform Stations - HAPS), and in space (satellite), we rely on interconnected and interoperable networks or systems of systems, each having an operator or administrative boundary, and with specific address spaces, managed according to regulation and operator policies. Example categories of 6G enabled networks are Local NPN, Logical Private Network, Public Network for Special purpose (e.g. PPDR network), or Public network for General purpose. Example types of network or system are Wireless Sensor Network (WSN), IoT network, Content Delivery Network (CDN), the IP eXchange (IPX) specified by GSMA for mobile roaming and interconnection, and not the least, the Internet.

The vision and illustration for 6G enabled Services and Interoperable Smart Networks also show overarching European Policies and Strategic Orientations, as those derived from the UN SDGs, which again drive Sustainability Objectives (including all three pillars; Social, Economic, and Environmental). Moreover, this shows that value is generated for and across several customer sectors and value creation spaces. The main categories or spaces of value creation are: Consumer, Enterprise, Industry, State, and Government, as well as the broader space of Societal in general, either directly (e.g., via government-oriented value offerings) or indirectly as synergy effects of the other value creating spaces.

To realise this 6G vision there is fundamentally a need to have standardised, interconnected, and interoperable networks, ensuring that services and enablers can interoperate and work across and among the network operator administrative domains. This is illustrated in the right side of Figure 4, where the wholesale services are considered. These services and business relationships can range from a geographically local focus to a national or regional scope, to the full global and universal services scope. These are services offered by one CSP/NSP to another CSP/NSP, often in peer-to-peer more or less symmetric relationships, or by NSP roles in a hub or transit role, such as IPX operators, or Internet eXchange Point (IXP) network operator. The 6G enabled end-customer facing CSP/NSP can also come in a variety of forms, such as Internet Service Provider (ISP), Mobile Network Operator (MNO), Fixed or wireless broadband network operator, or Virtual NSPs/MNOs. The following section elaborates on these services, while also considering challenges, risks, and opportunities for the corresponding variety of service providers.

The last area to address in this section is the “Self-management and support Services”. Advanced services for the customer itself to manage their services is key. This area is in particular important for enterprise customers. We recognise here the different layers of services, from infrastructure (such as transport connections, and data centre or cloud resources) that is more stable while still being manageable, the layer of connectivity and communication services, related enablers, and platform support, to the application layer. These services for enterprise customers, including peer CSPs/NSPs, might be delivered by different service providers dedicated for specific service portfolios, and the abilities for aligning service operations across multiple stakeholders need particular attention.

2.2.3. 6G ENABLED INTEROPERABLE SMART NETWORKS AND SERVICES

The use case families introduced above put high expectations on what 6G can deliver. The above section and illustration introduce 6G enabled User Services and Features that should deliver the anticipated services, and the service features needed by the variety of use cases with the expected KPIs. The vision and ambition are clearly that the services can relate to end-points and devices beyond the coverage offered directly by the “on-net” or “home” CSP. While some of these ambitions were already introduced by 5G, the 6G ambitions go even further with a broader spectrum of services and service features, and there is a need to ensure a consistent and globally standardised service offerings, service handling, and service feature performance across smart network operator administrative domains.

The essence of this is illustrated in Figure 5, which recognises the main categories or sectors (and implicitly, the numerous verticals or more specific sectors covered by 5G and the coming 6G). Each have numerous requirements, and these requirements are partially overlapping and can be conceived as a continuum, as highlighted by the right side. All sectors or vertical can relate to criticality and urgency, and even for consumers, we need to recognise consumer critical services. However, not all applications are equally critical at all times, and all of these sectors may have applications that at a given moment is not critical, and latency requirements are very elastic. So, there is a range of criticality and urgency, from non-critical to highly critical for all sectors. This translates to a need of a variety of connectivity properties, where for instance the latency property may hugely vary and still meet the desired customer SLA.

We can observe that network resources (considering also beyond connectivity resources) are shared across multiple sectors and verticals while the performance must comply with the respective SLAs. Smartness across multiple dimensions is needed to ensure resources are used efficiently to reduce cost and to deliver on the energy efficiency ambitions, and ultimately on the sustainability ambitions. This goes not only for connectivity resources and services but also for the compute, storage, and the application and application enablers, and how all these resources, service elements, and service offerings are aligned in terms of desired performance and resilience, to delivery any XasS.

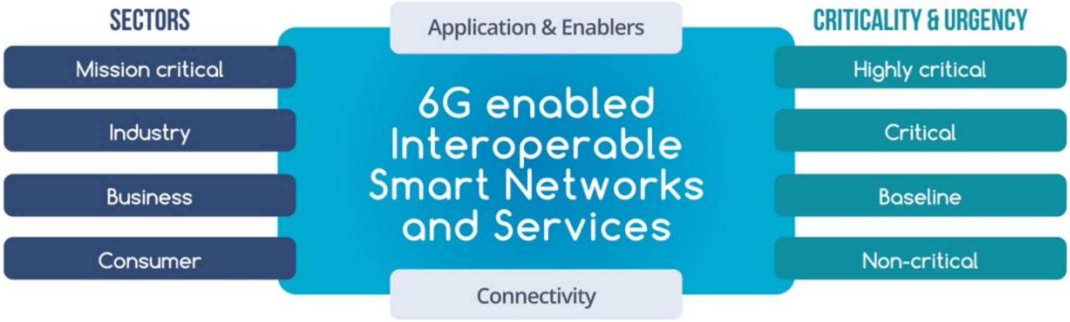

Figure 5: Requirements and service features to be harmonized across interoperable smart networks and services

The 6G services vision points not only to beyond connectivity services and features complementary to today's connectivity, broadband, and Internet access services, but also to a rich set of service offerings. UEs, devices such as IoT devices, and their service end-points or even sets of end-points and UEs, connected either in a general public network context and/or in the context of specific LNaaS instances can move freely and roam across network operators and CSPs boundaries. This should be enabled by the support of specialized connectivity services offered on-demand to/from any end-point across public and private networks [11]. This will be fundamental to enable and support the anticipated variety of foreseeable applications and application enablers, enriching the current and future use cases. Some of the needed service provider-to-service provider services and interconnection capabilities are presented in [12][13].

In the Introduction above the whitepaper by the European Commission "How to master Europe's digital infrastructure needs?" was introduced. The challenges, opportunities, and directions introduced in this section are addressing the ambitions of the whitepaper, and the vision of the so-called Connected Collaborative Computing Networks "3C Network". Such a future of 6G enabled interoperable smart networks and services and the capabilities envisaged raises questions also related to the feasibility of today's net neutrality regulation. These challenges and opportunities are discussed in [11], including suggestions for evolving the net neutrality regulations, as well as new service concepts related to even universally available specialized connectivity.

An important approach for effective development of service concepts and features is to establish means and support for exploration, testing, experimentation, and validation enabled by large-scale trials and pilots. This calls for evolving and scaling up todays SNS JU experimental platforms into experimental platforms with a stronger emphasis on interoperable smart networks and services across European service providers and stakeholder. This approach should target a stronger and more effective approach for a European multi-stakeholder ecosystem platform. To provide an example, the PPDR sector represents an important user and customer community in need for such a platform and will benefit greatly from a stronger European experimental capability.

2.2.4 TOWARDS A NEW ECOSYSTEM LEVEL APPROACH TO BUSINESS MODEL INNOVATION

The use case families and use case descriptions introduced in Chapter 2.1 above include an initial stakeholder and business model analysis. The complexities of the use cases in terms of the involved stakeholders, the business actors and the various business roles are evident. This was already studied with 5G [14] and continues with deeper understand as the 6G use cases are analysed. As introduced in Chapter 1.1.3 a key driver for European 6G research and development is **sustainability**, aiming at developing sustainable 6G solutions that at the same time can address sustainability challenges in the wider business, industry, and societal context. The approach developed for use case definition and analysis take sustainability considerations directly into account and includes analysis of the obstacles and uncertainties in achieving environmental, social, and economic sustainability for 6G and for 6G-supported solutions [15].

In this context, and along with 5G enabled use cases, an **ecosystem level approach to 5G and 6G business modelling** is advised and developed [16]. This is an approach that considers all potential configurations of how an ecosystem can be formed, i.e., complementary to the given enterprise in focus, considerations of potential business models that will be adopted by other adjacent players and the resulting network effects. The inherent ecosystem dynamics induce an iterative process for enterprises to continuously adjust and optimise their initially formulated business models, following the interactions with other ecosystem actors. With sustainability in mind, business models should prioritise long-term values over short-term interests and gains and combine these with the definition of extended values that consider societal and environmental sustainability targets along with economic outcomes [16].

There can be different characteristics for ecosystems around different 6G deployments to deliver use cases through resource combinations. Examples include a port and a factory which have different stakeholders and use cases. Stakeholders in 6G ecosystem can include operators, vendors, application providers, regulators, and end users among others, and can vary depending on the use case and location. Stronger ecosystem awareness and enablement is needed to deliver environmentally and socially sustainable 6G solutions which are economically feasible for the stakeholders allowing business for the involved stakeholders. At the same time, business model evolution and innovation system thinking are needed towards incorporating sustainability and circular economy principles at the ecosystem level to maximize environmental, social and economic benefits while minimizing negative impacts. Leveraging circular economy principles helps retain and recover value from resources and extend lifetime through such important considerations as reusing, repairing, repurposing or recycling leading to new 6G business models.

Considering the richness of 6G enabled services and topologies of interoperable smart networks (and their administrative actors), there is a need to develop business model blueprints that provides advice on likely beneficial business model structures and their business relationship interaction patterns. These structures and blueprints must consider both the horizontal dimension and the vertical dimension, as well as the geographical dimension, from local and per country sub-regions, to intercontinental and global perspectives and even multi-country regions. Today, and for many years, there are two key international business models for the backbone of communications networks. The Internet with IP peering and IP transit is one, and the other is the IPX model developed and maintained by GSMA. The further analysis and evolution of these and adjacent business models will be a central topic to the enhancement of 6G enabled interoperable smart networks and services.

Central to any business model is anyway the end-user and end customer perspectives and how value is created. There are many dimensions to this, and the service user and usage dimensions will be key to understand. The service concepts and the means of end-user – application interaction and correspondingly application – network interaction are crucial to develop. These must include and reflect the relevant sustainability aspect central to the service usage and service level performance and must allow for proper alignment of expectations amongst these roles, where the created value indeed has multiple dimensions.

3. TECHNOLOGICAL ENABLERS

The R&D of technological enablers for 6G have been ongoing for several years, building on the features and enhancements of previous generations as well as exploring technological breakthroughs that may revolutionize mobile connectivity in the coming years. As shown in Figure 6, this section outlines the most relevant topics associated with the forthcoming 6G system, spanning from further development of technologies related to HW and radio technology, flexible network topologies, deterministic networking, network softwarisation and digital twinning, as well as pervasive adoption of AI and ISAC. Furthermore, to improve resilience and to achieve the UN SDGs[6], it will be essential to ensure security and trustworthiness as well as address energy efficiency and low-power operation of the networks.

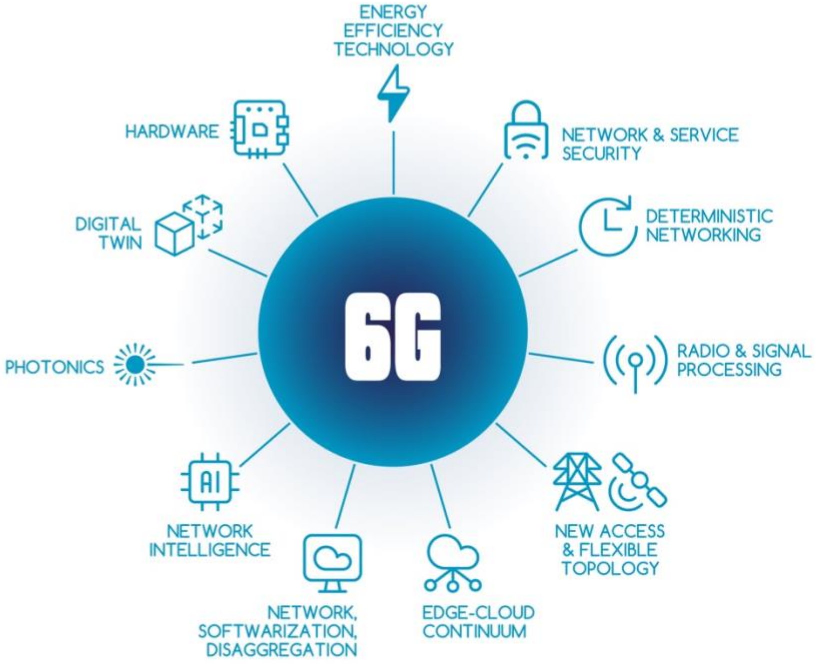

Figure 6: 6G technology enablers

3.1. ENERGY EFFICIENCY TECHNOLOGY

Network energy efficiency: It is expected that the data traffic will continue to grow in the coming years, along with the introduction of novel services such as sensing or AI, which can increase the power consumption. To cope with the rising environmental threats, increasing energy costs, and the

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[6] United Nation Sustainable Development Goals: https://sdgs.un.org/goals.

continued data growth it is imperative to enhance the network energy saving solutions in particular to offset the potential rebound effect. However, by simply adding energy efficient 6G systems to the existing deployments will not reduce the energy consumption, as long as the legacy systems are operational. Already in 5GSs, several new sustainability-aware network operation techniques have been studied, e.g., exposure of energy related metrics internally or externally to authorized 3rd party as well as and AI/ML techniques for predictive network management and advanced edge methods [17][18][19]. To minimise the network energy consumption, it is important to streamline network procedures and enable efficient sleep modes of the network modules. By incorporating smart scheduling and predictive offloading between cells it is possible to redirect traffic from one cell to nearby cells and shut down cells with low traffic.

Energy harvesting: For IoT devices, limited battery capacity limits the device lifetime or necessitates recurrent battery replacements increasing the cost of operation. Through energy harvesting (EH), energy from diverse ambient sources [20] (such as solar, thermal, kinetic and radio frequency energy) is captured and stored so to make systems more resilient and cost-effective. In addition to harvesting the energy, it is equally important to efficiently store the energy [21] as well as be able to combine energy from multiple diverse energy inputs with varying characteristics and inconsistencies [22]. Furthermore, wireless power transfer (WPT) may support widespread deployment and operation of ultra-low power and ultra-low cost IoT devices by providing controllable and predictable energy supply, in particular RF based WPT may provide energy over relatively long distances, charging multiple devices simultaneously even in non-line-of-sight conditions [23][24]. At the network side, the 6G base stations would need to be designed and configured with efficient dedicated protocols to support the WPT [25] which may only be viable in dense deployment. However, dedicated WPT nodes, usually referred to as power beacons [24] may also be viable in certain scenarios.

3.2. NETWORK AND SERVICE SECURITY

Cybersecurity and privacy remain key requirements for 6G. Indeed, implementing robust cybersecurity has been challenging in the past and recent trends have even further increased the cybersecurity risks. In fact, as society turns to a data-driven economy, pervasive approaches are required for handling and protecting data and privacy, including data supply chains, traceable provenance and well-defined and machine-readable privacy guarantees. For instance, more and more commercial services in private or public spaces leverage on camera-based applications, in which the balance between privacy and accuracy needs to be carefully considered [27]. Furthermore, cyber-threats are continuously increasing e.g., from nation-state adversaries employing cyberwarfare, rogue actors that are marketing or hiding zero-day vulnerabilities, and the increased threat surfaces from the generally increased reliance on ICT for decentralized economies and workforces. To address this, it is important to allow so called zero-trust architectures, which rely on the paradigm “never trust always verify” and thus allow exclusion of compromised nodes at run-time. This necessitates dynamic risk assessment with continuous trust evaluation of the system in an intelligent manner throughout its lifetime. Furthermore, to respond to emergent threats, cybersecurity must be agile and allow in-field upgrades during operations. For example, with the advent of quantum computers, the existing ICT systems will need to rapidly switch to post-quantum cryptography.

Furthermore, considering the growing complexity of network services and applications, along with the challenges and costs associated with the current operational and maintenance management methods in 4G and 5G networks, it is essential to ensure a seamless and dynamic orchestration, e.g., by leveraging AI/ML to ensure responsible and trustworthy operation, including fairness, privacy, robustness and explainability. In this direction a promising trajectory for 6G development appears to be Intent-Based Networking (IBN) [28] with AI assistance, towards LLM-centric intent life-cycle management (e.g., intent decomposition), enabling the management and configuration of network services using natural language. An overarching Trust Assessment Framework (TAF) will be needed to attain the required level of trustworthiness of the service orchestrator that can associate the intents with the required trust level as well as providing run-time estimation of the actual trust levels of services with built-in trustworthiness metrics. Furthermore, secure, auditable data sharing is crucial for robust orchestration, with technologies such as blockchain, homomorphic encryption, or differential privacy, ensuring integrity and privacy across inter-domain deployments, further supported by privacy-enhancing access control mechanisms. In addition, new capabilities such as ISAC in 6G networks would also require specialised security and privacy mechanisms.

3.3. DETERMINISTIC NETWORKING

To support the stringent requirements of certain time-critical applications, e.g., XR or collaborative robots, 6G should offer a high degree of deterministic performance, with predictable bounded latency, minimal time jitter and high reliability. IEEE 802 has originally developed the Time-Sensitive Networking (TSN) standard for wired communications [29][30] aiming to improve efficiency through predictability and offering a deterministic approach instead of a statistical one [26], which has recently been adopted for Wi-Fi [31] and 3GPP since release 16 [32].

Another approach to improve determinism and dependability of networks is by applying redundancy methods, e.g., based on IEEE 802.1CB, also known as Frame Replication and Elimination for Reliability (FRER). FRER has been applied to wired networks, but for heterogeneous (wired and wireless) networks still many open points are to be addressed [33][34], solving which one would be able to provide tangible benefits especially for autonomous mobile robots scenarios in the broad Industry 4.0 vertical sector.

Although 3GPP Release 16 introduced the TSN bridge adapter, which allows the network to appear like a TSN domain thus enabling integration into other TSN domain, this would require an E2E coordination, typically addressed by a Centralized Network Controller (CNC). However, the information that can be shared from the TSN adapter to the CNC is currently limited as there is no standardised interface which results in sub-optimal optimizations.

Finally, to obtain an overarching communication system made of heterogeneous subnetworks, i.e., mixing wired and wireless, cellular, Wi-Fi and other access technologies, a new architectural concept is to be introduced, which can manage E2E solutions in such complex scenarios. To tame such a complex problem, advances to the control and user planes, that can simultaneously manage several networks based on diverse standards, are to be devised, as proposed by some recent works [35][36][37].

3.4. RADIO AND SIGNAL PROCESSING

The 6G network is expected to deliver evolved and new capabilities and services while also improving the cost optimization and energy performance. With the continued development of the radio interface, several new technological enablers have emerged, e.g., massive multiple-input, multiple-output (MIMO) and distribute MIMO, to increase the performance, MRSS to leverage on existing 5G infrastructure deployments, RIS to enhance local coverage, improved waveforms modulation and coding schemes and multiple access techniques to improve the performance at higher frequencies as well as ISAC to enable new “beyond communication services”.

Massive and Ultra-massive MIMO: Modern MIMO technologies, including distributed MIMO (D-MIMO), massive MIMO (mMIMO), and multi-user MIMO (MU-MIMO) transmissions, are recognised as critical for the deployment of 6G [38][39], which allow devices equipped with large antenna arrays to spatially multiplex many layers of data using the same time-frequency resources, providing more reliable links and higher throughput with improved spectral and energy efficiency. The throughput of a massive MIMO system scales linearly with the number of layers, which is ideally upper bounded by the number of antenna elements. By using larger antenna arrays, ultra-massive MIMO can be employed to support more data layers. In addition, this can enable highly directive beamforming to overcome the large attenuation in high-frequency communications as well as enable high angular resolution for localization and sensing applications. However, there are new challenges with the implementation of such large arrays and their deployment for communications/ localization/sensing, and array technologies are necessary in 6G to enable such enhancement. When the antenna array aperture is extremely large, the near-field effect is strong enough to make the conventional beamforming ineffective, and near-field MIMO technology is necessary to provide array gains and limit interference. For instance, hybrid analog-digital architectures and fully digital architectures for sub-THz communication scenarios can be considered. Hybrid architectures can reduce complexity, while fully digital MIMO architectures have proven feasible with extremely low-complexity HW (e.g., one-bit converters) for sub-THz frequencies. For D-MIMO, coherent and non-coherent transmission strategies can be employed, depending on the quality of available Channel State Information (CSI) and synchronization, to coordinate distributed radio units and scale up the aperture without being limited by the HW constraints on a single-antenna array. This technology also benefits from high spatial diversity and provides for a more seamless UE mobility experience. Finally, MIMO technologies are expected to benefit from AI and ML capabilities in RANs to enhance efficiency and reduce complexity.

Multi-RAT spectrum sharing: 6G will usher in the seamless integration of heterogeneous RATs operating on both existing bands to be eventually migrated to 6G and potentially new bands for 6G, studied under WRC-27 AI 1.7. As with the 5G roll-out, spectrum availability is a crucial element for future 6G networks. Today, 5G deployments occupy a large portion of the licensed spectrum with the most favourable coverage properties. Naturally, the migration from 5G to 6G will be gradual, implying that the ability to share the same bands across RATs becomes a critical requirement. Static refarming, i.e., a hard splitting of the existing spectrum between 5G and 6G is a straightforward approach, but it comes with a severe drawback namely, there is no possibility to adapt the spectrum allocation to short-term traffic fluctuations. A more flexible alternative to allocate shared resources across different generations of wireless technologies is thus highly desirable. In retrospect, 3GPP introduced Dynamic Spectrum Sharing (DSS) to allow on-demand reallocation of resource blocks between 4G and 5G cells sharing the same carrier, but the frequent transmission of LTE Cell-Specific Reference Signals (CRS) led to significant fixed overhead. For 6G, the lean design of 5G can be leveraged to make MRSS a spectrally efficient native solution to ensure proper 6G coverage. It is expected that MRSS will be implemented in single-vendor deployments, where common, or co-deployed HW is used to schedule radio resources to either 5G or 6G, although longer time-scale multi-vendor MRSS may be supported. Thus, the impact on legacy specification and UEs is expected to be minimal, whereas the 6G specification would need to take into account the 5G specific aspects.

Reconfigurable intelligent surfaces: RIS is an emerging technology in the field of telecommunications, offering a novel way to enhance the performance of wireless networks, in particular for the higher frequencies expected in 6G. These surfaces consist of electronically controllable elements that can manipulate electromagnetic waves, allowing for improved signal propagation in wireless communication systems. At its core, a RIS is a thin layer of material with many small programmable elements. These elements can alter the phase, amplitude, and polarization of incoming radio frequency (RF) signals. By doing so, a RIS can effectively control the propagation environment, which is a major shift from traditional approaches where the environment is typically considered given and uncontrollable. The primary advantage of RIS is its ability to direct or reflect signals to areas that are otherwise hard to reach with direct transmissions, such as blocked indoor regions or non-line of sight regions [38][39]. This can potentially enhance signal coverage and reduce dead zones in a network. Moreover, RIS can be used to focus energy more efficiently towards intended users, improving in a cost-effective manner the overall energy efficiency of the network. A benefit which however still requires extended E2E validations to be verified. There are still challenges regarding the RIS integration into networks e.g., develop effective algorithms for dynamic configuration, understand the interaction with signal propagation environments, and integration with other technologies like MIMO and beamforming.

High-frequency technology: High-frequency technologies above centimeter-wave (cmWave), spanning from around 24 GHz to sub-THz (100-300 GHz), are all under research considerations for 6G. The use of sub-THz bands would bring vast bandwidth, but with extremely limited range and coverage, making them only suitable for line-of-sight operations in dedicated indoor scenarios, accurate sensing applications, and backhaul links (fixed and mobile). At THz frequencies the high pathloss prevents their usage from anything but very short-range links in e.g., data centres. World Radio Congress 2023 (WRC-23) down-prioritized the sub-THz range [40] and postponed sub-THz studies tentatively to WRC-31, to be potentially considered later releases of 6G.

Waveforms and multiple access: The introduction of waveforms and multiple access techniques revolutionized wireless communications by enabling increased simultaneous users and higher spectral efficiency. With 6G it is envisioned that the need for increased bandwidth can partially be addressed using sub-THz communication. However, the standardised waveforms and multiple access schemes, i.e., Orthogonal Frequency Domain Multiplexing (OFDM) and Orthogonal Frequency Domain Multiple Access (OFDMA) can suffer from distortion of the linear amplifiers due to the high Peak-to-Average Power Ratio (PAPR) as well as various frequency offsets and phase noise, degrading the signal by impacting the orthogonality of the subcarriers. Several novel techniques, e.g., Discrete Fourier Transfer spread OFDM (DFT-s-OFDM) can reduce the PAPR, and AI/ML based waveforms can compensate for various noise sources.

Furthermore, non-orthogonal waveforms are also explored, e.g., Non-Orthogonal Multiple Access (NOMA) or Rate-Splitting Multiple Access (RSMA) which can allow further improvements in non-orthogonal access to Physical Resource Blocks (PRBs) for UE groups (small clusters) of varying levels of SNR. This results in additional capacity available to far users (e.g., as signal in the power domain can be superimposed for the near/far users). If these techniques can be combined with a cell-free or D-MIMO deployment with a central scheduler, the potential interference can be minimised.

Advancements on coding and modulation schemes for sub-THz: To overcome the HW limitations at sub-THz e.g., power limitations or non-linearities, research is ongoing to develop novel coding and modulation schemes to achieve higher spectral efficiency and better energy efficiency. To achieve the former, high order coded-modulation schemes need to be employed. For example, a recent enhancement to Bit-Interleaved Coded Modulation (BICM) is Delayed BICM (DBICM), where latency and complexity is traded-off to improve capacity. Regarding the latter, energy-efficient and low-complexity physical layer designs need to be considered, such as improved Low-Density Parity-Check (LDPC) codes that deliver strong performance while reducing receiver complexity.

Random access for massive communication: Revising random access in 6G networks is a crucial action point to support for massive IoT and machine type communication. The main challenge comes from a large density of devices in a network and their sporadic low data rate traffic patterns. Devices are hence frequently required to go through random access to obtain transmission resources, which leads to overload and frequent preamble collisions. In 6G, potential addition and use of higher frequency bands and increasing directionality of communication pose further challenges for random access: While the probability of preamble collisions reduces with directionality, other problems such as deafness and blockage arise.

Potential enablers for massive random access are novel, lean, random-access procedures, grant-free access (including configured grants), and advanced random-access techniques, in particular those relying on NOMA. Periodic or semi-periodic traffic can benefit from configured grants, whereas lean random-access procedures can reduce the handshake overhead and hence the latency, but do not have any impact on the number of collisions. On the other hand, NOMA has a potential to massively reduce the number of collisions by multiplexing data transmissions from multiple users on the same resources at the expense of increasing receiver complexity. Such techniques have long been used in satellite networks and are thus well positioned to be deployed for NTNs. Coexistence of NOMA and conventional random-access channel poses further challenges.

Integrated Sensing and Communication: To enable the "beyond communication" services a promising technology is the ISAC, which extends wireless communication beyond data transmission, enabling systems to sense, interpret, and respond to the physical environment. In addition, ISAC can improve the communication performance of the network by sensing the surrounding environment. For example, network devices can detect blockage and perform fast beam switching or control transmission power. The ISAC system can either be deployed as a monostatic deployment, when the transmitter and the receiver sensing antennas are located in the same node, or as a multi-static deployment, when the transmitter and the receiver sensing antennas are located in different nodes. The accuracy of sensing is significantly better with line of sight (LoS) between the sensing antenna and the object being tracked, as each reflection of the signal in the environment introduces interfering scatter and uncertainty in the distance and direction of the object. In areas where such LoS is not provided by the base station, one or more UEs which have LoS to the object can be appointed to perform the measurements.

The sensing distance resolution is directly proportional to the signal bandwidth, while the angle resolution depends on the number of antenna elements. Making use of higher frequencies on the one hand, offers wider bandwidths and larger antenna arrays, thus providing a natural benefit to sensing, on the other hand their cost and complexity may be prohibitive.

Which radio resource is best suited for sensing is still an open research question, but a reasonable assumption may be based on some resource similar to a Positioning Reference Signal (PRS), which is used for downlink-based positioning measurements in 5G. Furthermore, in case multiple nodes are involved in sensing a common object, e.g., related to a service tracking a moving object, it will not suffice to simply detect it, but the radio resources across multiple cells may need to be coordinated to be able to track the object as it moves.

3.5. NEW ACCESS AND FLEXIBLE TOPOLOGIES

6G is expected to provide significantly improved coverage and capacity, while ensuring efficient and sustainable operation. To achieve this, it is envisioned to incorporate NTN and local subnetworks to extend the coverage, enable optimised local private networks, as well as enhance the multi-connectivity solutions for data aggregation.

Multi-connectivity: In 4G and 5G, there are two separate solutions to aggregate data from multiple cells, namely Carrier Aggregation (CA) and Dual Connectivity (DC). The former is controlled by one base station aggregating multiple carriers on the Medium Access Control (MAC) layer, whereas the latter splits the control between two base stations, a Master Node (MN) and a Secondary Node (SN) and aggregates the data at a higher layer, in the Packet Data Convergence Protocol (PDCP) layer. Performance-wise, both are comparable if the MN-SN transport delay is negligible, whereas a larger transport delay diminishes the benefits of the additional carriers as it is difficult to determine which node should transmit which data.

In 6G, only a single data aggregation solution should be pursued, to reduce the complexity and avoid market fragmentation, enabling both extreme reliability and excellent flexibility. By decoupling uplink and downlink, and integrating inactive connections which the UE only need to monitor, allow for customized configurations, suitable for the expected connectivity needs. Although data aggregation using DC from non-collocated sites doesn't bring any benefit compared to single connectivity due to the inter-site latencies, some aspects of it could still be beneficial in terms of robustness and reliability by providing redundant or back-up transmission paths.

Non-terrestrial networks (NTN): Since the TN and NTN are expected to be integral parts of the same 6G RAN, direct device-to-satellite communication should be supported by generic cellular protocols. This requires incorporation of NTN scenarios in the initial 6G design, including considerations for the data plane protocol stack, control plane connectivity, mobility procedures, resource allocation, handover management, user subscription, network slicing and orchestration, taking into account the specific characteristics of the fast-moving NTN nodes. For 3GPP Rel-17, a transparent architecture has been standardised, allowing data to be relayed via NTN. However, for 5G Advanced, a regenerative architecture is being explored, which could incorporate parts of the RAN and CN on the NTN nodes, laying the groundwork for a deeper integration between TN and NTN in 6G, with both components jointly optimised to forma 3D multi-layer system [41].

Special purpose networks: The 6G network is expected to be flexible enough to allow configuration, deployment, and management of special purpose networks what will be able to provide enhanced performance, security, or resilience in a local area [42]. These subnetworks should act autonomously, at least during a limited period of time, e.g., to provide life-critical services, but also be able to connect to the global 6G network as a network-of-networks. To enable this, a management node will connect to the main network and relay control and data signals to remote devices. The configuration of the subnetwork could either be initiated by the network, or by the devices. If the subnetwork is initiated by the devices, the subnetwork could be transparent, i.e., the network is unaware that the management node is acting as a man-in-the-middle (e.g., impersonating multiple UEs IDs). Since these subnetworks may be very densely deployed in e.g., a factory, the spectrum utilization must be optimised to minimise the interference, and the protocol stack need to be evaluated to see how best to enable these subnetworks.

3.6. EDGE-CLOUD CONTINUUM

The edge-cloud continuum in 6G networks refers to the integration of heterogeneous infrastructure devices and network services spanning different network domains (core to extreme-edge, i.e., UEs) that belong to multiple stakeholders, into a cohesive and dynamic ecosystem for service execution.

Management and Orchestration: The integration of the extreme-edge domain in the device-edge-cloud continuum presents significant challenges for network management and orchestration (M&O). This domain includes resources beyond a specific stakeholder's control, such as UEs, IoT devices, customer premises equipment, and external networks, which can be massive in scale, highly volatile, error-prone, mobile, and involve multiple stakeholders. Effective M&O must extend beyond traditional concepts, encompassing the entire device-edge-cloud spectrum, beyond the limits of the current orchestration methods.

AI/ML techniques are crucial for handling this complexity, enabling predictive orchestration and autonomous network adjustments. Cloud-native principles are a fundamental cornerstone for implementing the continuum orchestration paradigm, promoting programmability, flexibility, and scalability through modular service components orchestrated across the different domains, with robust exposed interfaces and adherence to data security and privacy standards. This approach facilitates highly decentralised M&O architectures, reducing bottlenecks and enhancing resilience as well as operational efficiency via CI/CD DevOps practices, reducing downtime and improving service delivery.

Serverless mobile networking: Communication networks are transforming as they shift from monolithic HW to SW-based functions running on shared computational, storage, and communication resources. This shift, known as network softwarisation, requires a cloud-aware redesign focusing on decoupling the tight interactions between functions, and enabling graceful service degradation when resources are scarce. While cloud computing solutions like microservices and serverless architectures offer efficient service provisioning, the mobile networking seems to lack similar solutions [43]. Prototypes show that applying these principles when redesigning networking functions for a serverless paradigm can boost the efficiency of network deployments [44] and reduce the overall network footprint [45]. The advent of 6G further motivates adopting this paradigm in various scenarios, including network monitoring [46], vehicular networking [47], or digital mobility [48].

Abstraction Layer: To fully leverage the edge-cloud continuum in 6G, the M&O framework must account for an expanded set of resource types and their characteristics, at a far greater scale and complexity than in previous generations. The M&O framework must handle the extreme heterogeneity of devices, including resource-constrained and ultra-low power far-edge nodes, while supporting AI/ML workload distribution across the network in real-time, seamlessly employing HW accelerators. Existing network management frameworks (e.g., NETCONF/YANG, etc.) need to be revisited as real-time adaptation, ultra-low latency, and dynamic DT modelling become critical for optimal service deployment/assurance, and resource management in 6G. Additionally, abstractions must encompass both HW and Virtualised resources (e.g., containers, microservices) to ensure holistic management across the device-edge-cloud continuum.

Utilizing the edge-cloud continuum in 6G will introduce a myriad of new resource types with specific interfaces, protocols, capabilities, and characteristics. To fully exploit them, the M&O framework must be aware of their specificities, such as HW acceleration and AI/ML workload support, moving beyond the typical abstraction of interconnected computing nodes. It is also crucial to represent characteristics like node mobility and battery capacity for far-edge devices. This enhanced view of the network infrastructure will be used during service deployment to guide service scaling and placement decisions. Additionally, these new views will foster DT modelling of the continuum resources. The realisation of this novel infrastructure representation calls for new models for resource abstraction that can adapt to a heterogeneous set of device types.

Function/Workload Offloading: Computationally intensive tasks, such as those in XR and AI applications, can exceed the capabilities of lean user devices. To address this, 6G networks aim to enable dynamic offloading of functions and workloads from mobile devices to wirelessly connected compute locations, balancing battery life, device heat, energy consumption, application performance, and network utilization. Efficient offloading requires exposing proper APIs to developers, designing resource-aware and mobility-resilient offloading mechanisms, as well as jointly optimizing connectivity, compute resources (at the device and the remote site), and application performance. Ensuring security and isolation of offloaded processes, as well as selecting user devices based on data availability and diversity, are also crucial for effective offloading in 6G [49].

Federation: As we advance towards 6G, the concept of federation becomes crucial, enabling seamless integration and cooperation across multiple domains and cloud environments. This multi-domain and multi-cloud federation will enhance network performance, reliability, and innovation by providing dynamic, scalable, and secure interactions. It facilitates collaboration among diverse network domains, including terrestrial, satellite, and aerial networks, creating a cohesive and resilient network fabric. This is essential for achieving the high data rates, reliable low latency, and massive connectivity expected from 6G. Advanced services and innovative business models, such as real-time AR, require handovers and integration across various network and computing domains. To this end, multi-cloud federation leverages the strengths of diverse cloud service providers, optimizing cost, performance, and resilience, and ensuring that no single point of failure disrupts critical services. It also enables data/application mobility, allowing services to run closer to end-users, thereby reducing latency and improving user experience. However, challenges such as interoperability, security, and privacy must be addressed. Robust federation frameworks must be developed - that can seamlessly integrate diverse technologies and services, including verifiable and auditable behaviours - with standardised protocols and interfaces, leveraging AI and ML for efficient resource allocation and enhanced security.

3.7. NETWORK SOFTWARISATION AND DISAGGREGATION

Network softwarisation is a promising trend aiming at advancing telecommunication industries by integrating cloud computing technologies and SW models into network services. The goal is to softwarise the network and to transform it into an open ecosystem where HW and SW are decoupled. Technologies like SW-Defined Networking (SDN), Programmable Data Planes (PDPs), Network Function Virtualisation (NFV), network slicing, cloud and edge computing are used for this purpose.

Network Virtualisation*:* Network virtualisation, has transformed the telco industry, making networks more flexible and agile by enabling abstraction, isolation, and flexible sharing of resources across different domains: wireless [50][51] and optical [52][53]. SDN and NFV [54] are two of the key technologies fostering this transformation. In 5G networks, virtualisation reduces the complexity of communication systems [55] and improves resource management, enhancing Quality of Service (QoS) [56][57][25]. With 6G bringing even more complexity both in terms of number of connected devices, sensors, computing units, with possible high mobility of these resources (e.g., autonomous vehicles), NFV and SDN are considered as de facto standards for network deployment, reducing HW needs, cutting costs, and increasing scalability. Additionally, the abstraction of resources facilitates unified resource representation, which can further simplify network resource and service management procedures, enabling full automation. However, 6G also brings challenges such as increased security issues that require enforcing robust policies and implementing intelligent monitoring and control techniques. Moreover, potential performance impacts due to virtualisation-induced latencies require sophisticated and agile management and orchestration solutions to optimise Virtualised resources and fully realise the potential of network virtualisation in 6G. Finally, end user virtualisation could be useful in 6G to address the challenges of providing QoS/QoE guarantees amid diverse and dynamic networks, and to support AI services and network management by efficiently collecting, managing, and processing extensive user data [58].

Network slicing: Network slicing groups Virtualised network resources to support specific services. Network slices are tailored to different services' requirements, allowing operators to create virtual segments for different business needs and efficiently allocate shared resources to enhance performance. However, the cloud-native approach of ensuring service availability using multiple replicas of network functions, can lead to excessive resource allocation and higher costs, necessitating careful planning to avoid overprovisioning computational resources. In 6G networks, E2E network slicing is crucial for providing service flexibility while enabling network technology diversity. Network slice lifecycle management involves interacting with multiple domain orchestrators, including those for access, transport, core network, and edge computing, Managing the dynamic life cycles of network slices across different administrative domains requires an overhaul of the E2E network slicing architecture to handle the complexity of multi-domain deployments.

Cloud-native networking: 6G aims to deliver an exceptional user experience with seamless connectivity and adaptability across various scenarios. This requires flexible and adaptable network architectures, leveraging cloud-native principles to enhance scalability, flexibility, and ease of deployment. Cloud-native applications use microservices architecture, virtualisation and containerization technologies to improve network performance. The SBA of 5G incorporated these cloud-native ideas but increased inter-NF dependencies, leading to higher signalling costs and latencies. For example, to perform a UE registration procedure more than six network function needs to interact with each other [20]. A modular approach, revisiting and optimizing the functional composition of NFs, can address these issues in 6G. By balancing NF granularity with interaction requirements, modular deployment allows for flexible, scalable, and efficient management of Virtualised NFs, enabling dynamic allocation of cloud resources, and the ability to migrate or clone NFs during network runtime for improved agility and adaptability.

Core Disaggregation*:* The disaggregation of 5G [59] and upcoming 6G core networks involves separating traditional monolithic network functions into distinct, modular components that can be independently deployed and managed. This approach enhances flexibility and scalability by allowing dynamic resource allocation based on real-time demand, leading to more efficient use of infrastructure. Hybrid solutions [59] combining HW-accelerated and SW components can reduce Central Processing Unit (CPU) usage, lower latency and increase throughput. Disaggregation also promotes innovation by enabling the integration of solutions from different vendors, fostering a competitive ecosystem and accelerating the development of new features and services. Furthermore, it improves resilience and fault tolerance by isolating faults, and facilitates edge deployment of network functions thus reducing latency and enhancing user experience. Disaggregation in the 5G, which is expected to be further evolved in 6G core unifies the concepts of cloud-native architecture, microservices, and HW offloading to enhance automation, reduce operational costs, and enable faster deployment and updating of network functions.

RAN Disaggregation: RAN disaggregation can be used to address the ultra-densification needs of future 6G networks [60]. Trends towards splitting RAN into more fine-grained modules (beyond RU/DU/CU) are progressing hand in hand with the decrease in an edge-cloud continuum resource orchestration granularity. This requires appropriate open SW architectures for efficient deployment and operation, mirroring the shift towards microservices and serverless architectures [61]. More flexible and granular RAN splits enhance resource allocation and efficiency, providing better scaling to meet user traffic demands, especially for novel use cases like XR, gaming, and holography. However, it is likely that the so called lower-layer split (LLS) which disaggregates the RAN in or above the physical layer into multiple radio units will be the dominating RAN disaggregation technique. Further disaggregated RAN can improve Network DTs (NDTs) (due to fine grained functional blocks) and tailored energy consumption control, necessitating adjustments in interfaces and protocols within 6G architecture. However, it will be important to not introduce bottlenecks by standardising multi-vendor interfaces [60] that split network control into multiple separate network functions, necessitating back-and-forth coordination between the functions to configure basic functionality in the devices (as was the case for the CU/DU split).

Deep network programmability: SDN decoupled the control from the data plane, introducing programmable control through standard and open APIs, but kept the packet processing logic fixed. With the advent of programmable data planes, deep network programmability has become possible. It has extended the SDN paradigm, enabling the data plane to be reprogrammed for customized packet handling. Now, the entire data plane, from header structure definitions to packet processing logic, can be described in SW. Various languages such as Programming Protocol-independent Packet Processors (P4) [62] or Network Programming Language (NPL) [63]) and frameworks such as extended Berkeley Packet Filter (eBPF) / eXpress Data Path (XDP) [64], Data Plane Development Kit (DPDK[7]), Vector Packet

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[7] https://dpdk.com/

Processor (VPP[8]) and Data Center-on-a-Chip Architecture (DOCA[9]) have emerged to support packet-level programmability, each suited to different levels of abstraction and specific use cases. Most of them are also supported by HW network devices like smart Network Interface Cards (smartNICs), Intelligence Processing Units (IPUs), Data Processing Units (DPUs), Field Programmable Gate Arrays (FPGAs), and switches, in addition to SW targets. In 6G networks, deep network programmability can be used for offloading network functions to HW accelerators, fine-grained and on-demand traffic monitoring, packet-level decision making, and may enable rapid innovation in the entire networking stack including the introduction of radically new protocols and mechanisms. This will bring forth challenges familiar from the SW world, such as ensuring consistency between management, control, and user plane views with programmatic validation of the network's behaviour [65], addressing runtime conflicts from distributed or federated reprogramming [65], and the need for some form of network garbage collection to manage orphaned allocations.

3.8. NETWORK INTELLIGENCE

AI-native 6G architecture: The concept of an AI-native 6G architecture is expected to transform the telecommunications industry, promising to deliver intelligent networks [66]. Unlike existing systems where AI is added as an afterthought, an AI-native architecture includes AI from the design phase, incorporating intrinsic trustworthy AI capabilities, where AI is a natural part of the functionality, in terms of design, deployment, operation, and maintenance [67]. AI-native implementations leverage a data-driven and knowledge-based ecosystem where AI continuously consumes and produces data, enabling new functionalities and adapting existing ones. Thus, 5G-Advanced considers AI as an overlay solution for its existing RAN /CN architecture, network functions, and protocol stacks: AI/ML is used as an optimization and automation toolset for selected network functions such as the CN-specific Network Data Analytics Function (NWDAF). 3GPP has begun exploring RAN AI/ML-based solutions for the air interface (CSI feedback, beam forming, and positioning) as well as for different RAN use cases (load balancing, mobility optimization, and energy saving). This approach, however, preserves the 5GS architecture without changing the RAN/CN interworking mechanisms. In 6G from a RAN protocol stack perspective, AI/ML based solutions will likely span multiple layers and modules and substantially extend beyond 5G-Adv use cases. Furthermore, a fully automated, customized use of AI/ML enablers across device, RAN and CN resulting in E2E AI/ML solutions is envisaged.

An AI-native 6G architecture is characterized by several critical aspects, namely (i) intelligence everywhere, (ii) a distributed data infrastructure [68], (iii) zero-touch management [69], and (iv) AI as a service (AIaaS) [70]. Intelligence is integrated across the network, from central nodes to edge devices, allowing AI/ML workloads to be processed where they are most effective. This requires a distributed data infrastructure for seamless data availability and processing. Zero-touch management enables autonomous network operations, with human operators setting goals while the system autonomously executes actions. AIaaS exposes AI/ML models, datasets, and tools as services through user-friendly APIs, enabling service providers and users to leverage AI capabilities without expertise in AI technologies, enabling new use cases where AI applications use the network as a platform.

Zero-touch management: Zero-touch automation, across multiple domains can reduce the complexity of network management and continuously optimise resource utilization, addressing the dynamicity of traffic, processing, devices and applications profiles. This eliminates manual interventions and limits operational costs while assuring Service Level Agreements (SLAs). Pervasive Closed Loops (CL) with specialized objectives, driven by AI/ML algorithms and supported by extensive monitoring data, are

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[8] https://fd.io/technology/

[9] https://developer.nvidia.com/networking/doca

enabling service and resource reconfiguration both reactively and proactively across different layers and domains, operating on varying timescales. CLs can be handled as a composition of programmable virtual functions, aligning with the SBMA model. Moreover, CLs have deployment requirements and lifecycles tightly coupled to their managed entities and their orchestration can be performed through CL Governance functions. CL Coordination procedures, whether hierarchical or peer-to-peer, are essential for consistent and scalable E2E network automation in multi-domain scenarios or across different stakeholders. Unified information models and standard interfaces would facilitate the integration of multiple, multi-vendor CL functions. Cooperation with network DTs can also help validate concurrent CL decisions in controlled sandboxes, verifying their combined impact in the medium/long term and with E2E scope before actual execution.

AI-Driven Air Interface: AI-driven solutions are expected to significantly impact the 6G radio interface in four key areas: signal optimization, CSI acquisition techniques (covering CSI estimation, compression, and prediction), MIMO transmissions, and compensation for RF HW impairments. AI can help in optimising waveform, modulation, and coding, enhancing existing methods and facilitating signal design approaches that improve spectral efficiency and reliability, e.g., by reducing reference signals. Advances in AI-based CSI acquisition emphasize intelligent compression and prediction techniques to minimise overhead while maximising spectral utilization. AI-enhanced MIMO transmissions address challenges such as beamforming with imperfect CSI, user pairing in multi-user MIMO, and pilot assignment in D-MIMO scenarios. Additionally, AI-enabled receivers can mitigate RF HW impairments, focusing on issues like power amplifier nonlinearities and oscillator phase noise, allowing for more energy-efficient operation. However, further work is needed to identify the HW requirements for efficient neural network inference as well as evaluate the energy, and processing costs associated with the AI optimizations on a case-by-case basis to determine where it will be beneficial to apply. Furthermore, in order to fully leverage AI on the physical layer in 6G, certain aspects of AI are expected to be needed to be standardised.

In contrast to the physical layer, where solutions are grounded in solid information-theory concepts, upper layer solutions in the radio protocol stack are often heuristic. The lack of provable solutions for combinatorial problems, like scheduling, presents an opportunity to uncover innovative solutions through data-driven methods. The less stringent runtime requirements of upper layers make them well-suited for deploying neural networks. 6G must be designed to support the training and inference of ML-based protocol solutions, including robust MLOps procedures and the flexibility to deploy both traditional expert systems and ML logic for specific protocol functions. This will enable the creation of highly tailored, context-aware protocol stacks. Promising research in this direction includes ML-based medium access control (MAC) protocols, Discontinuous Reception (DRX) control, Downlink Control Information (DCI) compression, resource scheduling, and power control.

Edge intelligence: It is envisioned that 6G networks will integrate mechanisms to support decentralized edge intelligence [71][72] where AI/ML models are trained and deployed on distributed and/or extreme edge devices (i.e., UEs) to manage the analysis of data where it is generated, and to ensure scalability, data privacy, and to reduce latency. Moving the intelligence towards the edge of the network will enable multiple 6G use cases involving intelligent devices such as communicating robots for industrial use cases, immersive XR. Finally, 6G optimization tasks e.g., traffic prediction, RIS-based channel shaping, will clearly benefit from edge intelligence. A typical application example is Federated Learning (FL) where compute could be potentially performed by UEs. On the one hand, protecting sensitive data and limiting its use to the legitimate purpose is a prerequisite for user acceptance. On the other hand, task distribution in such a distributed learning and aggregation campaign allows for coding schemes ensuring information-theoretic privacy. Another application example are UE-based subnetworks, where UEs autonomously customize AI/ML models in their group, collaboratively sense their environment, or jointly perform AI/ML inference. This will free the network from a flood of specific training and/or inference requests allowing for an overall resource optimization. Finally, low latency-bounded inference, e.g., for XR, is typically pushed to the network edge and may be split between an edge server and the UE. While this set-up minimises delays, split inference places still tight roundtrip latency requirements on the link between the edge server and the user device.

AI-enabled IBN: 6G will leverage AI across various layers, requiring knowledge exchange between them—such as Business Support Systems (BSS), service, resource layers—for seamless AI integration. This can be captured by IBN automation, where network, applications, and services are managed using high-level intents. These intents enable autonomous systems to communicate goals and requirements in an abstract way - as required by the integration of AI in the networks [73]. By utilizing AI, IBN simplifies network operation, optimises its performance, adapts to dynamic requirements in real-time, interprets intents, invokes the most suitable closed loops to fulfil the intent and automates the decision-making processes. This is achieved by abstracting the internal details of a network and allowing autonomous systems to reason on the expectations, goals, and requirements of users in the networks. Such abstraction allows users to specify needs without knowing the internal network procedures. The Intent Management Function (IMF) interprets these intents, while the closed loop within the IMF monitors and collects data, analyses and derives actions to meet user expectations, ensuring continuous and adaptive network behaviour.

Data Management: 6G will encounter a data explosion, necessitating advanced management strategies to handle a highly diverse mix of network- and application-generated data. A multi-tiered storage architecture-spanning on-premises, edge, and cloud storage - along with data lakes or data space**s** will be crucial to consolidate and manage vast amounts of structured and unstructured data, ensuring flexible access and real-time analytics. Granular access controls will safeguard data security, while anonymization techniques will support system development without compromising user privacy. Furthermore, effective data management in 6G requires protocols and standardised ontology tables, to ensure seamless interoperability, facilitating the storage, management, and transfer of data across various stakeholders. These strategies will be crucial for building a wide range of 6G related services and systems, and are key to enabling the AI-native 6G system architecture.

3.9. PHOTONICS

Photonics is a key enabling technology to access the higher bands of the RF spectrum delivering RF systems with unmatched performance [74] which will be needed to support the increased data rates in 6G. This includes both the low-loss distribution of microwave signals through optical fibre as well as RF signal generation and RF signal processing in the optical domain, providing functions that are very complex or even impossible to carry out directly in the RF domain [75]. This has led to the combination of RF and photonic technologies into a discipline known as RF Photonics [76].

Photonic-based RF Signal Generation is commonly based on optical frequency down-conversion, coherently mixing two optical wavelengths onto a high-speed photo-mixer (photodiode or photoconductor), generating an electrical signal determined by the frequency difference between the optical wavelengths. While its main advantages are its maximum achievable RF frequency (up to 2.5 THz) and the broad tuning range (from 5 GHz to 2.5 THz), the frequency stability is generally poor if the two lasers are free running, with wide linewidth and large frequency drift (> 10 MHz/h). This requires using additional phase locking schemes [77] to increase the signal stability.

Another key advantage of RF photonics is in the development antenna arrays, enabling the optical distribution of the signal to each of the individual elements of the array through low-loss optical waveguides. Due to the high gain required at these frequency bands (around 50 dBi), antenna arrays with large number (in excess of 100) elements are required. While electronic-driven arrays face the serious problems associated with the ohmic losses of the feeding network.

In the photonic approach this is no concern since is common, to exploit the broadband capabilities of photodiodes and photoconductors, to integrate them with planar antennas (such as bow-tie, patch, or slot antennas). This allows to reach higher frequencies, without the restrictions of the coplanar waveguides (CPWs). The full potential of photonic-enabled phase arrays to unlock scalable MIMO techniques is achieved when combined with optical beamforming networks (OBFNs) which enable independent steering many beams in 2D phased array antennae[10].

3.10. DIGITAL TWINS

DTs have recently emerged as a new concept that allows to generate a digital replica of a physical entity, which accurately represents its properties and behaviour. In the context of 6G, NDT are seen as one of the main enablers for the next generation of network technologies. Indeed, NDT are envisioned to enable further network automation and intelligence by providing an accurate and (near) real-time representation of the network state which can be used in the decision process for orchestration and resource management. NDT will be customized with different levels of granularity to include the properties and behaviours that are relevant for the use case and will encompass the technological domains for 6G (i.e., radio, extreme edge, edge, core, cloud, NTN), and may span across different administrative domains to provide an E2E view on the network state and the relevant KPIs.

NDT will be integrated into the orchestration and lifecycle management process as a “sandbox” environment for decision algorithms and models by simulating and assessing the effects of possible orchestration or configuration actions in different scenarios before applying the actions on the real network infrastructure. The NDT will also be used to predict the future state of the network at different timescales and trigger proactive mitigation actions when needed. As real datasets from telecommunication networks are difficult to obtain due to privacy concerns, and may not cover all of the relevant scenarios or features. NDTs will be further leveraged to generate synthetic data to augment or replace real datasets.

3.11. HARDWARE

High frequency transceivers: To achieve the expected high-frequencies e.g., sub-THz, in 6G, high - frequency transceivers will be needed. These can be seen at the intersection between optical and microwave circuit technologies. Many integrated circuit technologies such as silicon-based CMOS and SiGe, as well as III-V semiconductors based on GaAs, InP, and GaN, have advanced during the last years to have capabilities at higher frequencies. Different technologies have advantages in terms of integration rate, reliability, cost, efficiency, power consumption, frequency, power, and noise figure. The main enabler to gain benefits from different technologies is to mix them on the same package using heterogeneous integration.

In semiconductor devices, one emerging trend is to use a Resonant Tunnelling Diode (RTD)-based technology for wireless communication transceivers. The potential of RTDs is based on their simplicity; a 1 mW 300 GHz source requires only a single RTD device realised using photolithography, while transistor-based technologies such as CMOS require an array of devices, sub-100 nm high-resolution lithography, and advanced circuit design techniques. Moreover, RTD-based front-end architecture is simpler than the more conventional transistor-based approach; RTDs can operate as both transmitter and receiver and in many cases, many RF blocks such as PAs, LNAs, and mixers can be omitted. Performance-wise, RTD-based devices can achieve comparable figures of merits. In the optical domain, there are several advances on both light source and detector technologies. Developing white LEDs that are energy efficient at the same time having a substantial bandwidth is a challenge. The use of highly

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[10] https://www.lionix-international.com/about-us/rd-projects/tera6g/

sensitive detectors also subject of research, as they will allow the design of more effective receivers. Many optical components support efficient transmission of data and energy using the same infrastructure.

Devices and their classes: Analysing different use-cases**:** the legacy 5G device classes e.g., eMBB, URLLC and mMTC, will likely continue to be relevant for 6G, but it is expected that further device classes will be introduced [78]. While one could consider different criteria for deriving device classes from use-cases, one approach could be based on the radio communication requirements [78] on a 6G network. For instance, Energy Neutral (EN) devices that rely only on energy harvesting will enable short-range energy efficient IoT deployments. The Reliable High Data Rate with Bounded Latency (RHDRBL) devices will provide immersive experiences with the help of reliable, high data rate communication with bounded latency. The High Reliability and Low Latency (HRLL) devices will combine seamless connectivity, autonomous operation and safety for human collaboration. Finally, the Enhanced Massive MTC (EmMTC) will expand on the 5G mMTC devices with improvements leading to slightly higher bitrates, wider coverage and potentially incorporating capabilities or AI/ML techniques. Application related features such as sensing, AI/compute capabilities etc. could be part of the above device classes, wherein low end EmMTC device may not support sensing due to limited compute capabilities, while high end devices such as cobots that belong to HRLL device class could support it.

HW accelerators: Traditionally, networking tasks such as packet processing, encryption, and load balancing have relied heavily on CPUs. However, the increasing complexity and volume of network traffic, coupled with the demand for lower latency and higher throughput, have exposed the limitations of CPU-based networking. This has led to the development of specialized HW accelerators designed to offload and optimise these tasks, thereby improving overall system performance. SmartNICs, also called Data Processing Units (DPUs), represent a prime example of HW accelerators. They are specifically engineered to handle network data processing at line rate. DPUs typically consist of general-purpose CPUs, high-speed network interfaces, and dedicated HW engines for tasks such as encryption, compression, and deep packet inspection, which offload intensive tasks from the main CPU, thus reducing latency and freeing CPU resources for other computing needs. DPUs offer several key data acceleration operations, including data packet parsing, RDMA over Ethernet (RoCE), TCP acceleration, network virtualisation (e.g., supporting VXLAN), traffic shaping accelerator, crypto acceleration for IPSEC and TLS etc. Such capabilities make DPUs especially valuable in data centres, where they enhance performance and efficiency. Furthermore, DPUs have significant potential for edge computing deployments, ensuring high-speed, low-latency communications while improving energy efficiency and security. To fully realise this potential, new HW-accelerated operations need to be designed and explored, such as offloading relevant 6G network functions, enhancing AI-based operations at the edge, integrating long-reach optical connectivity directly into DPUs, and enabling semantic communications and confidential computing in decentralized 6G environments.

Neuromorphic computing: 6G is expected to require increased computational power at the edge. Edge processing faces tight constraints on latency, battery life, and cooling infrastructure, which makes it a good match for neuromorphic computing (NC), an emerging technology which incorporates computational primitives of the brain to reproduce its real-time, energy efficient processing. While NC covers a diverse range of algorithmic and HW-related technologies, NC systems typically harness non-Von Neumann architectures [79], memory-compute integration, analog circuits, support for sparse communication, and/or asynchronous event-based processing. NC HW has been shown to outperform conventional HW on a range of algorithmic classes, with numerous applications in 6G. First, NC can lower the latency and energy consumption of Deep Neural Networks (DNNs). This can support 6G by boosting AI-based receiver solutions in channel estimation, equalization and demodulation tasks, increasing spectral efficiency. It further allows processing data at the edge, reducing the volume of data flow in the network. Second, NC can quickly and efficiently find solutions to optimization problems due to their memory-compute integration, which could for example allow the use of large antenna arrays in 6G, by increasing the symbol decoding accuracy in massive/multi-user MIMO cases. Third, NC can boost calculations on graphs (i.e., dynamic routing), by mapping the nodes and edges of sparse real-world graphs to neurons and synapses with sparse connectivity, respectively. NC promises to perform such algorithms and applications with unprecedented real-time speed and energy efficiency, bringing the edge processing power required for 6G to all nodes along the communication chain.

4. 6G ARCHITECTURE

This section aims to bring an updated vision on the 6G architecture concepts and potential innovations. As research in mobile networks is currently transitioning from 5G to 6G, we start with analysing and identifying a set of fundamental challenges in the current 5G architecture that limit efficient and global operations. Then we draw a vision to identify potential architectural innovation areas that can address those challenges and lay the foundation for 6G systems.

4.1. ARCHITECTURE CHALLENGES

This section provides a detailed analysis of various challenges we envision for the network architecture design of transforming 5G towards 6G, to meet the new objectives and requirements (KPIs and KVIs) of the six usage scenarios for 6G as defined by the IMT2030 framework for the year of 2030 and beyond, discussed in section 1. Accordingly, in the following we map these challenges into four groups based on the IMT defined six usage scenarios, namely: (*i*) Extension from IMT-2020 (5G) including Immersive Communication, Massive Communication, and Hyper Reliable & Low Latency Communication; (*ii*) ubiquitous connectivity; (*iii*) AI and Communication; (*iv*) and Integrated Sensing and Communication.

4.1.1. EXTENSION OF IMT-2020

Achieving advanced extended KPI such as the envisioned by IMT 2030 in a sustainable way involves overcoming various barriers across multiple network domains, including access, core, orchestration, management, and transport. In the following a structured analysis of these barriers and their impact on the deployment and operation of 6G networks is provided.

Unsustainable RAN Virtualisation. Virtualised Radio Access Networks (vRANs) can provide significant advantages over traditional hardwired RANs, such as mitigating vendor lock-in, streamlining upgrades, and enabling resource multiplexing. However, current vRAN solutions face substantial sustainability challenges. High-performance HW accelerators (HAs) necessary for industry-grade requirements are costly and energy-intensive. HAs like ASICs, FPGAs, and GPUs, while providing latency gains, raise concerns about long-term sustainability due to their high costs and energy consumption. Developing novel RAN virtualisation solutions is crucial for achieving sustainability in the RAN ecosystem [80].

Poor Interoperability of RAN components. Achieving 6G performance KPIs also builds on the seamless integration of Virtual Network Functions (VNFs) with the Radio Intelligent Controller (RIC) of O-RAN and 3GPP-defined automatic functions and algorithms. An SBA within the RAN can enhance network management processes and introduce a RAN bus for KPI collection and performance measurement. The API based design allows for an agile versioning of the specification, limiting the problem of ossification of standardised interface. However, challenges such as conflict mitigation, anomaly detection, and real-time AI implementation in the RIC persist. Improving the RIC architecture and xApp functionalities is essential for better interoperability and control.

Reconfigurable Multi Connectivity. Multi-connectivity can enhance reliability and reduce latency by using multiple traffic paths. Current 3GPP solutions lack flexibility, often leading to inefficient resource consumption. Supporting advanced multi-connectivity (either RAN based or multi-RAT) approaches in Multi-Access Edge Computing (MEC) deployments is fundamental for optimizing network performance. This involves dynamic control and configuration of traffic paths to ensure efficient use of radio resources and power [80].

Integration of localised Networks. Integrating localised networks with diverse characteristics, such as NTNs and subnetworks (like in-vehicle or in-robot networks), presents challenges in coverage, operational purpose, and spectra. Enhancing support for these networks can optimise their services and enable seamless integration. This requires flexible network architectures capable of accommodating the unique requirements of localised networks[80].

Non-Flexible Service-Centric Design. The current design philosophy of 5G/B5G networks prioritizes universal service offerings, limiting flexibility for diverse user needs and application demands. Transitioning to a more adaptable design that can accommodate various use cases and performance requirements is essential for the 6G era. This involves moving beyond the rigid hierarchical design of current network architectures.

Extreme MIMO Processing Complexity. MIMO communications are fundamental for spectral efficiency, but their high processing complexity remains a bottleneck, especially with increasing antenna elements. Developing high-performing, model-based processing methods that balance complexity and performance is critical for advancing MIMO communications in 6G networks.

Growing RU Energy Consumption. Radio Units (RUs) consume more energy than other network components, often due to inefficient operation. Optimizing energy consumption in RUs, especially during idle times, is essential for reducing overall network energy usage. This includes improving the efficiency of power amplifiers and ensuring optimal signal distribution.

High Volume of Control Plane Signalling. The SBA introduced in 5G aims to transform monolithic applications into independent services. However, the increased signalling traffic from direct communication between Network Functions (NFs) poses significant challenges, also due to stratified CP/UP interactions. The surge in signalling traffic leads to higher energy consumption and cost, limiting scalability. Optimizing signalling management is crucial for 6G networks, especially as mobile networks integrate into IT infrastructures. Enhancing resilience and reducing single points of failure in NFs can support network slicing and flexibility.

High Latency and Unreliable Network Intelligence. Traditional NI solutions often fail to leverage the unique capabilities of the underlying computing infrastructure, resulting in suboptimal network utilization and excessive data exchanges. A more tailored approach aligning NI solutions with network infrastructure specifics can significantly enhance efficiency. This involves optimizing interactions between NI algorithms, network services, and HW, reducing unnecessary data transmissions, and focusing on compact datasets. Leveraging edge computing and advanced learning algorithms can further enhance responsiveness and intelligence in network operations [80]. Additionally, current 5G/B5G networks are not designed with data-driven solutions and NI processing at the centre. This involves leveraging realistic datasets for training and evaluation and developing efficient NI algorithms to enhance network operations.

Efficient Orchestration. The transition to 6G involves creating an integrated communication and computation environment where network and application services can be seamlessly deployed and orchestrated [80]. Having different orchestration solutions across the compute continuum presents challenges in coordinating these orchestrators effectively. Developing cognitive coordination strategies is essential for efficient resource management in heterogeneous, multi-tenant, and multi-site topologies.

Orchestrating the Orchestrators. The high network programmability of 5G, driven by NFV and SDN, enables flexible and dynamic placement of VNFs across the network. As we move towards 6G, creating an integrated environment for seamless deployment and orchestration of services and resources becomes crucial. This involves managing the cognitive coordination of different orchestration solutions across various levels, from multi-site orchestration to fine-grain distributed task-level orchestration.

Energy-Efficient RAN Operations. Applying efficient NI algorithms to automate energy-efficient RAN operations requires realistic datasets for training and evaluation. The integration of AI/ML services with RAN control functions needs to be efficient, reusable, and explainable. Addressing the energy consumption of radio-related network components and ensuring optimal operation points are crucial aspects of sustainable network operations.

Tackling Latency for Seamless Connectivity. New technologies like terahertz (THz) communication bands and massive MIMO systems promise an increased bandwidth but also present challenges like severe attenuation and complex signal processing [81][82]. Managing the latency and the complexity associated with these complex computations is basic for meeting the hyper-reliability and ultra-low latency demands of 6G.

Quantum-Resilient Security Architecture. As quantum computing advances, transitioning to post-quantum cryptography (PQC) is necessary to protect against quantum-enabled attacks. Integrating PQC into 6G networks poses challenges, including larger key sizes, higher processing demands, and ensuring backward compatibility with existing networks [83][84].

Under-Utilized Modern Programmable U-Plane Transport. Programmable switches, smartNICs, and Network Processing Units (NPUs) offer novel compute resources for VNFs to operate on network traffic at packet level and line rate. Current solutions for user-plane inference are limited in complexity and feature support. Integrating more sophisticated models and demonstrating real-world use cases remain challenges. Additionally, coding and deploying current models for in-band computing is a manual process requiring expert knowledge, hindering the adoption of these solutions. Unlocking the full potential of programmable user-plane computing can lead to significant gains in latency and throughput.

Sustainable and Dependable Networks. Future 6G networks require architectural innovations for integrating subnetworks and ensuring reliable E2E service levels [85]. In-X subnetworks (e.g., in-vehicle, in-robot) need localised, cost-effective solutions with extreme requirements, featuring autonomous local data management and seamless integration with broader networks [86]. These subnetworks must maintain partial autonomy to stay operational during intermittent or lost connections with the 6G parent network, achieved through internal resource management and core network functionalities.

Privacy Preserving Network Operation. Processing data in a centralised way for operation such as orchestration or analytics production, may pose risks in terms of privacy, as one entity takes care of the data for all the other players in the ecosystem. This is of particular importance if the analysed data is Cyber Threat Intelligence.

By addressing these barriers within their respective domains, the transition to 6G networks can be made smoother and more efficient, paving the way for innovative applications and enhanced network performance.

4.1.2. UBIQUITOUS CONNECTIVITY

The following challenges and in part related opportunities have been identified to address the requirements of the ubiquitous connectivity.

Lack of Global, Open, and Easy-to-Use Service APIs. The possibility of realising actual global network operations that are natively open to tenants as well as external MNOs needs a unified approach for the service APIs. The current cellular architecture does not fully empower smaller-scale providers and global services, thus, limiting competition and innovation. Further, although the 5GS has been designed to support various industries, configuring networks and devices for specific verticals remains complex and time-consuming, hindering broader adoption. Several efforts have been made for the creation of an abstraction layer in the form of easy-to-use APIs (i.e., CAMARA and 3GPP SEAL); yet the main challenge with those ambitious approaches is that they have not been adopted in practice and we still lack open implementations [87].

Obsolete Trust Model Hinders Performance. Today, service providers expand their coverage globally only via pre-established agreements between two entities that define how they cooperate in authenticating and billing users. This relies on the assumption that users rarely cross boundaries between providers, e.g., country borders, which is not an up-to-date assumption.

Integration among Terrestrial and Non-Terrestrial Networks. The NTN technology has the potential to complement TNs and provide services to users in specific regions [88]. There are several fundamental challenges that need to be addressed in the integration of terrestrial and NTN [80][89][90], e.g., (*i*) supporting multi-connectivity, e.g., between TN and NTN; (*ii*) mapping services between different connectivity technologies; (*iii*) effective distribution of network functions across space and grounds segments; (*iv*) achieving E2E routing across diverse network domain; and (*v*) managing the increase of satellite edge devices, which also necessitates the modelling of inter-satellite communication in clusters and formations. Traditional concepts need to be upgraded to meet performance and resilient communication topology requirements including routing and packet forwarding challenges, and their applicability to satellite clusters, space-terrestrial distributed computing fabric as well as achieving a fully-distributed service oriented architecture with the exploitation of aerial, space, and terrestrial assets [91].

Lack of Integration among different AI-Based Deployments. AI-based deployments and systems are designed to operate autonomously, making decisions and taking actions without the need for human intervention. However, without a unified view, current approaches put the burden of integrating the automation of both AI solutions and infrastructure to majority of stakeholders that typically lack the specialization of both technologies at the same time.

Challenges in Federation. Federation related challenges relate to AI-based vertical federation to enable native integration of vertical services in mobile networks; edge computing resource federation across different stakeholders to enable the 6G vision of cloud continuum; and heterogeneous network domains federation, within the scope of Network as a Service (NaaS) including compute, transport and RAN, to provision an E2E network service and to enable the multi-tenancy [92].

Support for User-Centric Approach in Service Provisioning. Monolithic network services (both physical and virtual) could become significant bottleneck sources as the number of linked devices/users rises. The user-centric architecture in 6G implies altering how users, network services, and apps will communicate, which will have an influence on the ownership of personal digital assets, network access, and mobility management. In order to realise the user-centric 6G network, the main challenge is the architectural redesign of the core network, following the paradigm shift from “Network Function-focus” to “user-focus”, allowing users to participate in network service creation and operation, while also giving users full control over data ownership [93].

Management Plane Centralization. The 5GS, which was designed with centralized slice management support, has tightly integrated service management and slice management under a centralized OSS/BSS. This design does not scale to multi-tenant, heterogeneous, multi-stakeholder ecosystems. Management and orchestration of every aspect of the network and the services it delivers requires having a model that allows on-the-fly collaboration and adaptation, evolving to the M&O and distributed AI frameworks, Zero-Touch management enabling AI-driven dynamic reconfiguration for self-driven 6G infrastructures.

Support for Semantic Communications. Within classical communication systems, if a received packet contains errors, a retransmission is required until all bits are perfectly reconstructed. A possible paradigm shift may come from semantic and goal-oriented communications with the aim of enabling the recovery of the significance associated with the transmitted sequence or the fulfilment of the goal.

Hence, there is an urgent need for the amount of generated as well as transmitted data to be optimised for sustainable 6G networks [80].

4.1.3. AI AND COMMUNICATION

5G was not inherently designed for AI, neither AI for improving the network performance nor how to externally expose AI as a Service. In the following we list the main challenges to make 6G an AI-native system.

Enable an AI-Assisted Data Driven Architecture in 6G. 5G architecture lacks support of AIaaS, both in-network use and for external, and methods on how to both update and train AI models and collect and process data necessary for the AI model training. Another challenge is how to optimise the usage of computing resources and power consumption for ML models training and inference. Those challenges are even more key as AI can be employed in almost every aspect, segment and domain of a mobile network, enabling automated network operation and user service support [84]. Nevertheless, 6G systems need to be AI and computation pervasive to benefit and exploit the AI, implying a data driven architecture [93].

AI Models Involved in Decision Automation Are Black-Box in Nature. The black-box nature of Deep Reinforcement Learning (DRL) models involved in decision automation jeopardizes their interpretability and trustworthiness. Moreover, human-in-the-loop workflows are challenging as black-box models complicate finding the root cause of various issues and anomalies and deriving possible solutions.

Learning at the Edge: The Scarce Resources Challenge. Edge intelligence, defined as the application of AI and ML at the network edge, has been identified as a key element in 6G, leveraging the multitude of data generated by the network and applications to learn and predict the run-time conditions and service requirements, thus enabling the proactive solutions for reduced latency and overall better performance and automation. However, the constraints on the training of such complex AI models over limited edge resources, the absence of sufficient local context information or data interpretation and the privacy concerns regarding the transfer of sensitive user datasets to the cloud, stress the need for decentralized learning solutions.

Sustainable data process and generation through learning representations of data collected at the edge and the far edge of the network, based on generative multimodal systems, which exploit the combination of multiple inputs, are expected to learn improved data representations, when compared to unimodal approaches [94]. Models that learn from multiple modalities have flourished. Although multiple modalities allow for building richer representations, several challenges exist, such as methodology to infer a joint multimodal representation and efficient approaches to enable the cross generation of missing modalities conditioned on available ones, how to define a suitable and efficient training and sampling procedure, and how to merge multimodal input sources and what are the relevant training objectives that contribute to cross generation properties.

Lack of a Unified E2E AIOps Framework and AI Conflict Management. AI at the edge has been used for proactive network management, such as channel modelling and prediction, traffic and mobility forecasting, network resource allocation, and task offloading. However, while most AI solutions have been designed to address stand-alone problems, the development of unified frameworks capable of overseeing E2E operations is not well investigated. In this direction, efficient collision-free AI solutions will be needed, able to work in a harmonized way when dealing with closely related problems, such E2E slicing, optimally splitting DU and CU functions across the edge-cloud compute continuum, or resource allocation of network and computation resources under edge constraints. Besides, AI techniques are expected to exploit the huge amount of data collected at the edge for achieving an optimised operation.

Efficient Application of AI/ML Algorithms for Automation of Energy-Efficient RAN Operations. The application of efficient AI/ML algorithms requires realistic data-sets for training and evaluation, which are usually limited to operators and hard to obtain for the developers, e.g., due to privacy concerns. Realistic emulation and digital twinning tools might help, though those entail the complexity of deriving realistic energy related KPIs. Finally, the exposure and integration of AI/ML services with RAN control functions with the goal of improving among others, efficiency, reusability and explainability, is still an open point.

Need for Self-Evolving, Autonomous, and Extendable Systems with Predicting Capabilities. Implementing AI technologies for both predictive network [80] and security management in a dynamic system is a significant challenge spanning all communication layers, from physical to application. Novel predictive approaches are needed to enhance traffic performance as well as support self-configuration, dynamic quality reinforcement, and predictive maintenance, while avoiding AI-related security issues [95][96].

4.1.4. INTEGRATED SENSING AND COMMUNICATIONS

ISAC is one of the key innovations of 6G, bridging communication and environmental sensing towards unlocking novel services and capabilities. ISAC transcends the boundaries of conventional dedicated sensing equipment such as radar and light detection and ranging (LIDAR). Its potential spans diverse industries, enabling applications from precise positioning to environmental monitoring and brings 6G networks into realms of comprehensive sensing and perception capabilities, paving the way for new applications and unprecedented user experience and interaction. Despite the promises of ISAC, several key challenges related to its integration in the 6G network are identified, as listed below.

Beyond Communication Network Services. The evolution of the mobile networks is pushing the boundaries, beyond conventional connectivity, into accommodating, supporting and exposing novel services, expanding the scope of the network by processing data, generating insights, and delivering added value from societal, innovation, and business perspectives. Sensing will be integrated as a fundamental capability in 6G, and in this sense ISAC characteristics should be supported, considering the seamless fusion of advanced sensor technologies with ultra-fast wireless networks, enabling real-time data collection and transmission for diverse applications needs [84][97].

High Data Volume Between Sensing Nodes and Network Core for Distributed Sensing Services. In 5G architectures, the volume of data transmitted between sensing nodes and the network core is considered to be overwhelming, leading to congestion and inefficiencies in data processing. This is primarily due to the centralized nature of data processing, where large quantities of raw data are sent from the sensors to the core network for analysis, taxing both bandwidth and processing capabilities.

Lack of Compact and Complete Data Representation. 5GSs would struggle with creating compact and complete representations of sensing data for efficient transmission and processing. This lack of optimised data representation leads to increased computational load and inefficiencies, particularly in distributed operations where adaptation to dynamically changing KPIs is crucial [98].

Lack of Sensing Control Functions. The absence of robust control functions for sensing in distributed operations is a significant barrier in 5G. This results in a lack of adaptability in control mechanisms to meet varying KPI requirements, which is essential for optimizing network performance and resource allocation in response to real-time environmental changes.

Lack of Standard Ways to Select and Configure Sensing Resource. ISAC is not only a network-based approach, it can also be both network-and UE-based. If UE-based, new challenges arise regarding how to select and configure the sensing resources and how to collect and analyse the sensing data.

Lack of Continuity of Service for Sensing Over a Large Area across Multiple Network Elements. When considering disaggregated or distributed networks, the interference cancellation problem between multiple distributed Tx and Rx antennas is more challenging. When considering state-of-the-art integrated solutions, most studies however only consider centralized implementations where sensing and communication functional pipelines are split, and the challenge is mainly how to distribute the sensing and communication functionalities across the multiple distributed network elements so they can share resources maximally. Moreover, joint communication and sensing not only requires distribution of the signal transmissions but also the computations should be distributed and shared effectively. Another important challenge is how to track and handle the mobility of the sensing objects or users across different domains/areas in a seamlessly manner, and hence to maintain continuity of sensing services over large areas. The design of 5GSs does not yet support wide area sensing services and therefore cannot seamlessly manage handovers on tracking sensing objects or users across extended spaces, impacting the reliability and accuracy of the sensing functions.

Lack of Synchronization Among Distributed Network Elements. For optimal resource distribution, it is necessary to consider the synchronization requirements for the different processing options, and adaptively learn the synchronization requirements and signals in the network as function of both communication and sensing needs. Sensing requires sending signals over long durations, and there are no solutions yet that minimise the synchronization cost.

Channel Modelling. The design and optimization of the new network architecture supporting ISAC call for accurate channel models for the complex propagation characteristics, including ray tracing and dynamic object and blockage modelling.

Waveform and Signalling Optimization. Meeting the envisioned communication and sensing performances requires new waveform and signalling protocols optimization across distributed transmission, while balancing the trade-offs between energy consumption, deployment costs, and spectral efficiency necessitates innovative solutions for efficient resource utilization. Moreover, the ISAC waveforms also need to consider the coexistence with the existing legacy waveforms, in choosing between OFDM and non-OFDM waveforms.

Non-line-of-sight (NLOS), Blockage and Misalignment. Overcoming propagation impairments such as NLOS, blockages and misalignment is essential for ensuring a ubiquitous service, especially sensitive for high spectrum bands. For instance, the mmWave spectrum is highly sensitive to blockages in the radio propagation environment, reducing its effective coverage compared to lower bands. This is one of the main barriers of adoption for higher spectrum bands, which also creates opportunities for smart network technologies (e.g., ISAC) that may alleviate this barrier.

Cost and Power Consumption, Constrained Physical Size, and Other Deployment Limitations. Cost and power constraints, along with physical deployment limitations, are critical considerations for implementing ISAC in 6G networks. To address this challenge, the cost and energy-efficient HW design and signal processing approaches, along with co-designed systems enabling ISAC integration is essential to increase overall cost and energy efficiency.

Lack of Object/Target Management Function. There is a critical gap in 5G architectures concerning the management of objects or targets being sensed. Specifically, there is often no dedicated function to monitor and ensure the accuracy and relevance of the sensed data, which complicates the tasks of verifying and tracking specific targets over time and space.

4.2. VISION ON ARCHITECTURE INNOVATIONS

This section is focused on providing a list of selected architecture innovations we envision to address the different challenges as described in Section 4.1.

4.2.1. EXTENSION OF IMT-2020

To overcome the challenges discussed before, a number of technical innovations have to be integrated into the future 6G Network ecosystem.

Advanced Network Design and Optimization. A new flexible 6G E2E system architecture view aims to support efficient mobile communication and beyond communication services by emphasizing AI integration, security, and modular design. In this context, novel learning frameworks are proposed to optimise wireless transmission chains with the goal of higher performance. Similarly, user-centric emerged communication protocols involve developing AI-based learning protocols tailored to specific users and applications. These protocols aim to bridge the gap between wireless KPIs and service-specific KPIs, enhancing the overall service flexibility.

To manage resources effectively, cognitive orchestration strategies are proposed to develop cognitive coordination methods for resource management in heterogeneous network topologies. Additionally, scalable signalling management offers new solutions to problem if increasing signalling traffic, which has been already an important issue in 5G networks, aiming to optimise energy consumption and scalability [80]. Finally, Dynamic multi-connectivity support with solutions for managing latency in technologies like THz communication bands and massive MIMO systems, ensuring ultra-low latency and hyper-reliable connectivity, will be integrated.

Addressed Challenges: Efficient Orchestration, Non-Flexible Service-Centric Design, Tackling Latency for Seamless Connectivity, Sustainable and Dependable Networks

AI and ML Integration. AI-empowered MIMO processing aims to develop advanced AI-enabled solutions for MIMO communication, improving efficiency and performance. DTs for 6G AI are proposed to provide virtual representations of physical systems to enhance NI. An AI-based joint communication, computational and storage resource allocation framework is needed to optimise resource allocation using semantic-aware information handling and predictive analytics. The predictive analytics engine employs real-time information and federated learning techniques to predict network capacity needs, ensuring QoS guarantees. Additionally, AI-driven energy-efficient RAN operations aim to apply AI and ML algorithms to automate energy-efficient operations in RAN and shall be supported by a data driven architecture as discussed in Section 4.3.

Addressed Challenges: Extreme MIMO Processing Complexity, High Latency and Unreliable NI, Energy-Efficient RAN Operations.

Architectural Support for New HW Infrastructure. Vertical-aware edge computing with cross-domain coordination aims to expand the MEC paradigm to support advanced B5G systems, simplifying interactions between service layers and 5G networks. HW enablers for 6G AI involve developing novel HW implementations using advances in neuromorphic computing to support efficient AI services. Intelligent RAN virtualisation is proposed to address sustainability issues by developing intelligent, energy-efficient alternatives to current RAN virtualisation solutions. Additionally, programmable transport resource optimization aims to unlock the full potential of programmable transport resources for better network performance.

Addressed Challenges: Unsustainable RAN Virtualisation, Reconfigurable Multi-Connectivity, Under-Utilized Modern Programmable Transport.

Interoperability and Integration. Developing scalable interfaces between applications and networks, provides flexibility for consistent performance across domains. Advanced conflict mitigation for RAN components improve the interoperability by among different network functions operating in the same domain (e.g. RAN). Enhanced support for localised network integration requires flexible network architectures supporting their diverse characteristics. Seamless integration of TN and NTN focuses enables direct-to-satellite connectivity and resilient operations [80]. Additionally, a self-organised network architecture can target seamless network transitions and effective adaptation to traffic conditions.

Addressed Challenges: Poor Interoperability of RAN Components, Integration of Localised Networks.

Security and Resilience. Quantum-resilient encryption methods aim to develop post-quantum cryptography solutions to secure 6G networks against quantum-enabled attacks [99][83]. Beyond communications network services are designed to enable new 6G applications such as sensing and compute offloading, focusing on secure and efficient data management. An E2E control plane framework aims to demonstrate deterministic multi-technology and multi-stakeholder network orchestration, ensuring QoS metrics like latency constraints are met.

Addressed Challenges: Quantum-Resilient Security Architecture, High Volume of Control Plane Signalling.

Energy Efficiency as an Enabler for Sustainability. Optimised RU power management introduces innovations to optimise energy consumption in RUs, including improved power amplifier efficiency. AI-driven energy-efficient RAN operations aim to automate energy-efficient operations in RAN using AI and ML algorithms. An AI-aided network architecture provides optimization frameworks for resource allocation, multi-connectivity, and network slicing, enhancing overall network efficiency and sustainability [80].

Addressed Challenges: Growing RU Energy Consumption, Energy-Efficient RAN Operations.

Privacy-preserving decentralized and distributed networking. Enabling a Decentralized Security Analytics system enhances network security by distributing data processing to edge devices, utilizing Federated NWDAF for tasks such as anomaly detection, and integrating privacy-preserving AI models. Also, the integration of Explainable AI with Distributed Attestation allows to enforce a Zero Trust model, leveraging cloud-based FPGAs and Distributed Ledgers for secure and auditable verification, which can also be applied to Cyber Threat Intelligence sharing.

Addressed Challenges: Privacy Preserving Network Operation

4.2.2. UBIQUITOUS CONNECTIVITY

The following solutions aim at addressing the challenges pertaining to ubiquitous connectivity.

Vertical Integration, Open Global APIs, and New Trust Models. Existing service APIs shall be further advanced and opened up to transform them into a vertical-oriented ones that: (*i*) expose network capabilities to verticals; (*ii*) provide vertical-information to the network; and (*iii*) enable verticals to dynamically request and modify certain network aspects, in an open, transparent and easy to use, semi-automated way. For example, Cooperative Awareness Messages (CAM) verticals can provide different types of information from the CAM services, e.g., planned route or current vehicle position and status, that could be useful for the communications system. Moreover, currently, APIs are exposed from the network core (e.g., through the NEF), edge (e.g., MEC APIs), and access domain (e.g., RIC APIs of O-RAN architecture). Thus, there is a need for a unified API framework due to the plethora of APIs and to realise the interactions in a secure and interoperable manner.

In terms of new trust models, distributed ledger technology (DLT) can be leveraged to enable dynamic partnerships in the ecosystem, focusing on real-time billing, automated dispute resolution, trust, and confidentiality. Accordingly, blockchain solutions can enable direct interaction among mobile operators and supports different charging models. For example, such a new trust model marks a significant change, requiring a shift to a paradigm where IoT device identities, e.g., pertaining to connected cars or logistics operating on a global scale, are not tied to a single operator. This approach, grounded in decentralized identity, separates user authentication from operator services, paving the way for innovative business models and dynamic customer charging strategies.

Addressed Challenges: Lack of Global, Open, and Easy-to-Use Service APIs, and Obsolete trust model hinders performance.

Seamless Integration Between TN and NTN. Advancements in NTN assets (both satellite and aerial components) and aerial device/flying node management can be capitalized on to ensure a seamless integration between TN and NTN elements. This allows for the creation of a unified and cost-efficient network configuration that can dynamically move functionality and adapt to different network topologies, including both terrestrial, aerial and space nodes [80][89]. A multi layer network architecture is envisioned to support TN-NTN integration by considering a set of different radio cell types including femto, micro, macro, super, HAPS based, NGSO based and GSO. This requires for effective multi connectivity across the different access technologies between orbit layers and with terrestrial network to enable seamless mobility. On the one hand, routing across the different access layers associated to each cell types, shall take into account a wider set of constraints compared to 5G including QoS and latency requirement, congestion state (network and spectrum), energy consumption [89]. On the other hand, efficient implementations for multi-connectivity [100] involve application of multipath protocols such as MPTCP [90], MPQUIC (Multipath QUIC) and new Active Queue Management (AQM) strategies (e.g., CAKE, Codel, SQM,) possibly casted into the evolution of the 3GPP ATSSS framework. Moreover, fully softwarised space segment owing to the design of more advanced NTN-regenerative payloads will pave the way towards a more effective and flexible ubiquitous connectivity, achieved through space and terrestrial assets in more sustainable way. On the other hand, dynamic mapping service needs to the current network infrastructure are enabled by new E2E protocols. Service developers can make use of the provided APIs that can be jointly orchestrated via AI-based algorithms. This involves exploiting Virtualised network functions that can be dynamically deployed in a distributed manner across TN and NTN nodes, hence necessitating effective and sustainable cross-domain orchestration frameworks. Further, inter-PLMN scenario with NTN/TN hybrid access can strengthen the scope of TN and NTN seamless integration [91]. Another key challenge on the TN and NTN integration is how to handle the service disruptions (interruptions and declined quality) in constellations of Low Earth Orbit satellites and how to cope with high densities of ground terminals and the high E2E delays of satellite constellations. Besides, not only the end devices on the ground may move, but also the satellite “base stations” move and appear and disappear in short time frames base on their path around the Earth. This can be handled through middleware services that can mitigate this effect, by estimating the receive/transmit situation and it must be able to derive proper actions at the right place, specific including satellite selection, caching or other means depending on the application [101].

Addressed Challenges: Integration among Terrestrial and Non-terrestrial Networks.

Native AI Integration Towards Intent-Driven Lifecycle Management (IDLM) Demonstrated via Testbeds and Experimentation Processes. Large Language Models (LLMs) as part of an E2E AI framework can be leveraged to deliver the IDLM for Federated Experimentation infrastructures, providing great benefits in terms of making simpler to perform experimentations in 6G. The experimenters can simply express their desired experimental intents and, consequently, steer the conduction of experiments towards the extraction of maximised utility and insights from the experiments. Auto-constructed workflows are executed from natural language prompts and adapted in an autonomous manner that is transfused from the IDLM service towards the testbeds. Explainable foundation models use neuro-symbolic AI to address traceability and interpretability, hence further improving reasoning and root cause analysis via explainability. Edge Intelligent agents deployed at the testbeds adopting MLOPS and AutoML workflows are closing the IDLM loop via zero-touch drift detection, self-configuration and self-optimization of research infrastructures. Zero-Touch management enabling AI-driven dynamic slice reconfiguration for self-driven 6G infrastructures is translated in a unified approach for service and network management, following a DRL approach, architecture, where a centralized decision engine addresses convergence and stability problems by making arbitration decisions to solve conflictive decision making or race conditions of DRL. Network automation and self-optimization via closed-loop orchestration in multilayer and inter-computing scenarios with multiple cooperating stakeholders is needed in 6G networks. AI/ML techniques are expected to be the key to achieve more effective close loop optimization strategies combining the knowledge of the current network condition with predictions on future traffic trends and service demand [102].

Addressed Challenges: Lack of integration among different AI-based deployments.

Scalable Federation. A scalable federation architecture provides access to vertical application developers and experimenters to heterogeneous computing resources without a centralized orchestrator or resource manager. It leverages intelligent, decentralized paradigms and emerging federation standards, where platforms are interconnected with an overarching federator plane that spans the entire path between testbeds, via east/west APIs, thus allowing an easier onboarding of new testbeds that support a high scalability of the federation.

Addressed Challenges: Challenges in federation.

User-Centric Architectural Design. The realisation of the user-centric 6G network motivates a paradigm shift from “NF-focus” to “user-focus”, allowing users to participate in network service creation and operation, while also giving users full control over data ownership. To this end, the network architecture can be separated into user service nodes (USNs) and network service nodes (NSNs), which will be adaptable for activities, such as collaborative sensing and distributed learning to spread AI applications on a broad scale across the edge-cloud continuum. This user-centric redesign of the core architecture is driven by the distributed edge-cloud continuum and the openness of the 6G system, following the paradigm of the 5G core openness and its exposure capabilities with standardised 3GPP APIs, such as CAPIF/NEF, as well as the Network Apps paradigm. The cloud continuum in 6G will allow the realisation of the USN and NSN services in a distributed and adapted way closer to users, tenants, applications, data sources, and regulated processes. New services can be easily created, placed, subsequently scaled and moved between the clouds of the continuum (i.e., far edge, near edge, and central cloud).

Addressed Challenges: Support for User-centric approach in 6G service provisioning.

Disaggregated Management Plane of Domain Manager Orchestrators. Interoperable modules can enable a fully decentralized management plane. This simplifies onboarding of third-party infrastructure domains (e.g., cloud and edge nodes, abstracted via the intelligent cognitive compute continuum framework) or connecting NFs in the form of O-RAN compliant elements (i.e., CUs, DUs, and RUs).

Addressed Challenges: Management plane centralization.

Semantic Communication. In this paradigm, the boundaries between communication, computation, and intelligence are blurred, where a more structured goal-oriented design paradigm is followed. This paradigm further makes communication converge with computation in a jointly data- and model-driven manner, which changes the current content-blind-transmit-without-understanding approach, where data is transmitted without a prior understanding on whether and how it is informative for AI algorithms.

The intelligence model at communicating devices and/or network elements can be utilized to overcome the limits of the traditional separation of source coding and transmission (channel coding), offering: (1) new models and concepts for semantic data transmission and processing; (2) new theoretical bounds and algorithmic solutions that approach those bounds; and (3) new architectural requirements, concepts and new blocks that enable implementation of the semantic transmission techniques at scale. In addition, semantic-aware information handling can significantly reduce the amount of unnecessary data both generated and transmitted, thus contributing to sustainable 6G networks. It is worth noting that implications of the use of AI on the overall energy consumption shall be studied, as well. In parallel, traffic prioritization techniques can benefit from metrics such as Age of Information and Value of Information, leading to highly sustainable resource allocation solutions [80][88].

Addressed Challenges: Support for Semantic Communications.

4.2.3. AI AND COMMUNICATION

We claim that there is the need to design and implement a novel 6G system architecture that integrates a distributed AI framework for combined communication, computation and control and empowers the convergence of networks and systems to enable new future digital services [103]. A 6G architecture should inherently support AIaaS both in-network use and for external use to improve the injection of automation and distributed intelligence characteristics. The following explains the main innovations in this area.

Data Driven Architecture, Enablers and Framework. A 6G architecture should inherently support AIaaS both for in-network use and for external use to improve the injection of automation and distributed intelligence characteristics [84][97]. The main AI enablers for the 6G data-driven architecture comprise of the MLOps, DataOps, AIaaS, and management. MLOps focuses on making ML models operational by ensuring smooth deployment, versioning, and monitoring within the overall architecture. The architecture requirements for MLOps are access to high-quality data, scalable data storage, computation for data processing and model training and finally security and trust. The high-quality and scalable data storage is enabled by the DataOps. The DataOps enabler must ensure an efficient data collection and integration, serving MLOps with data at the right time and with right quality. DataOps require an E2E data pipeline that can serve MLOps with data, and a version control for the collected data. One of the in-network use of AI is the ability of much improved management of the network with the goal of making zero-touch management and automation [104]. This can be enabled by a so called closed-control loop together with explainable AI (XAI) and Machine Reasoning (MR) mechanisms [105]. The latter are used in parallel to ML models to ensure their explainability and hence ensure trust in their inputs. Besides, XAI combined with MR allow finding the root cause and deriving possible solutions. At the same time, the XAI-DE helps DMO managers to detect intent and policy conflicts and create rules to generate optimal and trusted decisions.

Finally, the AIaaS framework builds on MLOps, DataOps and management to provide AI services to different parts of the network and to end-users. The AIaaS framework requires new APIs for exposure in-network and to end-users. It is also identified that AIaaS requires security measures and compliance with regulations and feedback loops for continuous improvement and resource optimization.

Addressed Challenges: Enable a data driven architecture in 6G and AI models involved in decision automation are black-box in nature.

Network Automation. There is a need to enhance the level of network automation in control and management of 6G networks. A fully automated network involves applying multi-layer self-optimization and self-configuration strategies supported by distributed AI, monitoring metrics and data, AI agents and trained AI models.

The management architecture enables a closed loop and AI-driven automation of the network at different time scales, coordinating real-time control reactions with medium- and long-term optimization, decisions, and combining local- and global-scope re-optimization strategies [97][94].

To enable an automated management and optimization of communication and computing resources, one possible solution is the provision of an intelligence layer, especially for the edge. This layer specifies the model-specific methods for: (*i*) AI/ML training and validation; (*ii*) AI/ML model monitoring and management (e.g., retraining if needed), including the AI conflict resolution module; and (*iii*) AI/ML model inference. Furthermore to ensure Security, Privacy and Trustworthiness for AI [106], there is a need to include methods for formal verification, data privacy, causal AI representation, explainability and trustworthy RL and data sharing, specifically taking into account the challenges present in edge scenarios.

Addressed Challenges: Lack of a unified e2e AIOps framework and AI conflict management [107] and Lack of an AI-assisted and Data-driven architecture.

Subnetwork Integration. The subnetwork ecosystem is characterized by a flexible, softwarized, and virtualised environment, which allows for high freedom in the local distribution and allocation of tasks and functions to computing HW resources in pursuit of deterministic service provisioning. There is also a clear trend towards the integration of subnetworks and (edge-)cloud infrastructures as part of the specialized 6G 'network of networks' vision. Tasks/Functions offloading from subnetworks to the 6G parent network computing infrastructure requires architectural innovations leveraging AI/ML that enable predictability, dependability and a seamless integration and scheduling of the communication and computing technologies [80].

Addressed Challenges: Need for self-evolving, autonomous, and extendable systems with predicting capabilities, and Integration of Localised Networks.

Intelligent Architecture for Coordination/Cooperation in the RAN. The RIS-to-BS requirements can be processed in the non-real time unit of the RAN architecture leveraging the use of AI to organize and provide cooperation/coordination among RISs [108][109]. Further on, the RIS-to-UE requirements can be processed in the real time unit of the RAN architecture leveraging the use of AI for codebook selection. As low latency is the priority, this function can be located very close to the users.

The proposed Intelligent Plane incorporates an AI Engine, which will provide a serverless execution environment hosting the AI/ML models, offering inference and training services to the control plane applications such as rApps or xApps by following a loosely coupled approach. The Intelligence Plane will facilitate energy efficiency enhancements by exploiting control and monitoring functions of the radio and edge compute domains [110]. The Intelligence Plane also aims at integrating the control of RIS, fixed relays or relay User Equipment (i.e., UEs with relaying capabilities).

Addressed Challenges: Need for self-evolving, autonomous, and extendable systems with predicting capabilities, and Efficient application of AI/ML algorithms for automation of energy-efficient RAN.

Distributed Trustworthy AI Engine Based on Federated Learning. A distributed trustworthy AI Engine based on federated learning approaches, will allow intensive computation to take place in a disaggregated fashion without promoting the spread of sensitive information through the network [111]. The security will be driven by AI to provide enhanced cognitive capabilities to detect, mitigate and prevent from Cyber-threats [112].

Addressed Challenges: Need for self-evolving, autonomous, and extendable systems with predicting.

4.2.4. INTEGRATED SENSING AND COMMUNICATIONS

ISAC emerges as a transformative force in the 6G innovation, offering a cost-effective pathway to drive sustainable digital transformation. By amalgamating sensing, reflective surfaces, and intelligence, ISAC systems extend the boundaries of connectivity beyond traditional communication paradigm, encompassing network and service infrastructures, devices, and microelectronics. This heralds a new era of multifunctional connectivity, wherein operators and stakeholders are compelled to redefine performance metrics and key indicators to ensure scalability, sustainability, and resilience in the face of evolving technological landscapes. Moreover, ISAC plays a pivotal role in reinforcing connectivity, offering competitive solutions to the challenges associated with deploying and managing distributed sets of devices and infrastructures. The ISAC vision aligns seamlessly with the trajectory towards 6G, facilitating the realisation of an intelligently interconnected world where the physical, digital, and human realms converge, as envisioned in Section 1.2. Beyond technological advancements, ISAC places a strong emphasis on improving the energy efficiency by reusing the same communication spectrums and resources for sensing as well, driving the green transition by reducing the energy needs of high-performance connectivity and enabling energy-efficient solutions across diverse vertical applications. One of the key research questions is to investigate its potential energy saving and resource utilization gain while considering additional overhead and computation cost by ISAC. In the following, we introduce the related innovations to enable and support ISAC.

Distributed ISAC Architecture Design. The distributed network architecture is envisioned to embed native support for distributed processing. The distributed architecture allows for a flexible balance between local and central computation and storage, significantly reducing the need to transmit high volumes of raw data and improving the representation and adaptation of these data to meet various KPIs. By doing so, it enhances control functions and improves target management by decentralizing processing and reducing latency.

Addressed Challenges: Lack of Continuity of Service for Sensing Over a Large Area across Multiple Network Elements and High data volume between sensing nodes and network core for distributed sensing services.

Semantic / Goal-Oriented Plane. One of the main challenges in ISAC is to efficiently collect sensing data and process them along with the communication. Accurate data interpretation and representation are essential aspects of ISAC applications. To this aim, the inclusion of a semantic/goal-oriented plane operations can help to interpret the transmitted/received sensing data and encode them into proper semantics to optimise efficient communications [113]. This innovation not only reduces the volume of data to be transmitted by focusing on relevant information, but it also enhances the compactness and completeness of data representations. It adapts dynamically to varying KPIs and provides advanced control functions tailored to the specific needs of the network.

Addressed Challenges: Lack of Compact and Complete Data Representation.

Object/Target Management Function for Extended Tracking. To overcome the lack of continuity in service for sensing over large areas, it is required to incorporate robust architectural support that can facilitate target tracking and handovers across extended spaces and times. This ensures that the service remains seamless and efficient, even beyond the field of view of a single transmission - reception point (TRP). In this regard, an Object/Target Management Function (OMF) is envisioned as a novel component designed to effectively manage target sensing within the network architecture. This function can be integrated within the network or exist as a third-party entity, enhancing the capability to monitor and confirm the identity and status of the targets continuously, thus directly addressing the previous limitations in object management.

Addressed Challenges: Lack of Continuity of Service for Sensing Over a Large Area across Multiple Network Elements and Lack of Object/Target Management Function.

Waveform Engineering for ISAC. Two families of waveforms are considered within the framework of an ISAC, highlighting their distinct objectives and characteristics. The former encompasses *pulse waveforms*, prioritizing energy efficiency in transmission, particularly crucial for battery-powered devices and radar systems. Pulse waveforms optimise energy consumption through techniques such as narrow-width pulses and strategic pulse repetition intervals, aiming to achieve maximum performance while conserving energy. In contrast, the second family consists of *continuous waveforms*, emphasizing spectral efficiency for maximising data throughput within limited bandwidth. Techniques such as Orthogonal Frequency Division Multiplexing (OFDM) and coding algorithms enhance spectral efficiency, though these waveforms may prioritize communication data rates over radar performance metrics. We underscore the importance of understanding each waveform's objectives and recommend comparing waveforms within their respective families rather than across families to achieve optimal ISAC solutions aligned with specific KPIs.

Addressed Challenges: Waveform and signalling optimization, Cost and power consumption, constrained physical size, and other deployment limitations.

Cell-Free Network Architecture for ISAC. Recent research has begun exploring the use of observations from multiple sensors across various base stations or access points (APs), yet the adoption of cell-free architectures and the integration of RIS as performance enhancers remain underexplored [114]. The 6G network architecture should ambitiously extend ISAC design to embrace cell-free network architectures. This approach will allow different APs or remote radio heads to not only provide communication services but also to serve as transmitters or receivers for radar functionality. The architecture could leverage hybrid relay RIS (HR-RIS) to enhance channel properties and navigate around blockages, thus boosting overall system performance. These advancements are critical in pushing the boundaries of traditional network designs and capabilities, particularly through the implementation of ray tracing and dynamic RIS-based sensor measurements in the DT form for predictive AI-based network management [115][116].

For mitigating blockage in RIS and cell-free networks, [117] proposes innovative cell-free multi-band technologies targeting the mmWave spectrum for practical cell-free deployments to address its sensitivity to blocking. [118] also proposes innovations for the RIS, which also helps address blocking following a different approach that involves user tracking via ISAC technologies.

Addressed Challenges: High data volume between sensing nodes and network core for distributed sensing services, NLOS, blockage and misalignment.

Novel Solutions for Sensing Performance Assessment and power Consumption. In terms of performance assessment, the ISAC-supporting network architecture should focus on sensing performance bounds and errors for positioning and object location accuracies, alongside evaluating communication performance through supported rates or spectral efficiencies. This analysis, considering capacity constraints of front-, mid-, and back-haul networks, guides the development of ISAC algorithms. These algorithms, drawing from traditional model-based and data-driven approaches, reflect the hybrid nature of the architecture in addressing complex network challenges [119][120]. Moreover, the network architecture should address energy efficiency (EE) by modelling the power consumption of APs, user equipment, and novel RIS architectures. The EE criterion is not only used for performance assessment but also for refining algorithms, emphasizing the architecture's commitment to sustainability in its designs. This, combined with advanced AI strategies, should exemplify the role of the ISAC-supporting network architecture in pioneering the next generation of intelligent, efficient, and multifunctional wireless networks that are vital for the agility and autonomous operations expected in 6G and beyond.

Addressed Challenges: Cost and power consumption, constrained physical size, and other deployment limitations.

ISAC for Improved Non-Terrestrial Network Performance.

Achieving ubiquitous service requires full interoperability between TNs and NTNs, as a key direction for 6G. Current NTNs, such as low Earth orbit satellites, use higher frequency bands (Ka and Ku) that are prone to blockages. Future NTNs, including drone-based networks, will also use mmWave bands shared with 5G and 6G. However, obstacles like buildings, especially in urban areas, can limit sky visibility, reduce NTN connectivity, hinder seamless interaction between NTNs and TNs, and offload capabilities. ISAC capability to sense the environment offers a powerful solution to enhance NTN performance. By leveraging ISAC for local skyline sensing, networks can dynamically map the environment, identifying optimal pathways for NTN signals, even in dense urban areas. This approach ensures that NTN connectivity can be maintained despite potential blockages, as ISAC enables real-time detection of environmental features, such as building heights and positions.

Thanks to ISAC, users can benefit from enhanced NTN performance, as the technology allows for adaptive beamforming and link optimization to moving NTN nodes. Indeed, following the sense-to-communicate paradigm, real-time environmental awareness from sensed information can guide signal transmission and adjust communication parameters, maximising connectivity and offloading rates. However, operational costs may arise from skyline sensing and processing overhead, leading to a tradeoff between sensing cost and communication benefit.

Addressed Challenges: NLOS, blockage and misalignment, Cost and power consumption, constrained physical size, and other deployment limitations.

Microelectronics. The role of microelectronics development cannot be underestimated to achieve co-designed ISAC systems with HW reuse. The co-design leverages on communication systems available today in wireless networks at different frequency bands. However, to converge mono-static radars into a time-division-duplex system requires a holistic approach to reduce self-interference [121][122]. At the same time, an adaptive and reconfigurable approach for front-end development [123] can be key to cost and power effective HW solutions in infrastructure and personal space (namely, internet of senses). This can also be a game changer for in-band full-duplex communication systems that are cable of radar sensing as well.

Addressed Challenges: Cost and power consumption, constrained physical size, and other deployment limitations.

RIS-As-A-Sensor. RIS is constructed from metasurfaces, versatile elements utilized across various frequency ranges from microwaves and terahertz to visible light. Many types of RISs have been designed recently for different applications going from Wi-Fi, sub-6G, 5G, B5G and 6G. One of the most relevant questions is how to integrate the RIS into wireless communication systems. In literature, many publications and campaigns have contributed to answer this essential question [124][125].

RIS is being under intensive investigation in pilot projects and initial deployments. However, there are still many areas were RIS need to be addressed and, corresponding answers need to be provided. The main open questions related to such devices range from new EE and cost effective RIS Design, Localization and tracking applications [126], Interference mitigation and SINR improvement [127], to multi-beam communication and fast beam-steering capabilities.

Moreover, RISs have been recently seen as enablers of the ISAC paradigm. Indeed, their ability to dynamically shape the wavefront, while considering various environmental factors and usage scenarios, unlocks a realm beyond traditional communication applications. In this new frontier, communication nodes transcend their conventional roles, becoming versatile tools for environmental sensing, obstacle detection, mapping, object presence detection, power focusing, localization, mobility tracking, and navigation. In this environment, RIS will be used as cornerstone for ISAC. Leveraging the unique capabilities afforded by RIS-based sensing, we RIS technology can be applied to enhance RAN coverage and environmental awareness, thereby fostering seamless integration across disparate network layers. Moreover, beyond its primary function in providing controllable reflected paths, recent works slightly modifies RIS HW enabling them to serve jointly as channel optimisers as well as passive sensors [128]. This, in turn, can be exploited to add a “sixth sense” to the network at a limited HW and management cost. This dual-purpose functionality not only optimises resource utilization but also enables novel applications in environmental sensing and monitoring.

Addressed Challenges: NLOS, blockage and misalignment, Cost and power consumption, constrained physical size, and other deployment limitations.

Wavefront Engineering. Wavefront engineering allows the concentration of the signal energy to a specific area of a specific size, increasing the power at the receiver or the sensing target and consequently the energy efficiency of the system [129]. Furthermore, transmission beams can have properties that allow them to reconstruct behind obstacles or bend around them to avoid them entirely [130]. As ISAC systems are expected to use highly directional links at high frequencies, blockages will become an important restriction for service availability and the sensing field. Therefore, the aforementioned capabilities will make them substantially more robust, while offering them more possibilities for the placement of base stations, relays, and RISs. As a result, ISAC systems can be more cost-effective, and energy-efficient in comparison to placing a new network radio component (e.g., a base station or RIS) in all locations where LoS is not possible with the existing nodes.

Addressed Challenges: Cost and power consumption, constrained physical size, and other deployment limitations.

ISAC in Disaggregated Networks. Active research work on ISAC towards 6G are exploring the capability of O-RAN compatible functionalities. The envisioned sensing pipeline will be partitioned in real-time and near-real-time functions, mapped to the O-RAN architecture. Focus is on relevant control, user and sync plane functions. Real-Time user plane functions are focused on spatial processing for minimizing interference between sensing and communication signals. Moreover, near-real-time control functions are focused on resource allocation policies for ISAC, where the challenge is how to effectively schedule sensing and communication signals. Finally, ISAC requires tight synchronization over long sensing durations, so low-cost over-the-air sensing methods to reduce the synchronization cost are imperative to make resource-friendly ISAC systems. To reduce synchronization cost, SUNRISE-6G will exploit AI based techniques to relax oscillators’ performance requirements.

Addressed Challenges: Sensing and communication functionalities distribution across multiple network elements, and Lack of synchronization among distributed network elements.

ISAC and RIS for Energy Efficiency. To reduce the energy footprint of the overall network and specifically in RAN, ISAC and RIS can be used to improve the energy efficiency of the system. Therefore, it is worth investigating the possibilities of using ISAC information for improving physical layer energy efficiency while taking into account any additional energy costs associated with ISAC and RIS. This would address mainly optimisation of the beam-training algorithms, being the primary goal to reduce the wireless medium usage during the beam training phase. A secondary goal would be to offer an efficient solution for beam training, which, in turn, will allow for higher usage of systems supporting beamforming and beam-tracking. These systems generally require less transmit power for a given link budget, therefore increasing their energy efficiency. In addition to this, ISAC solutions may also be integrated with RIS to reduce energy consumption. This may be achieved by using ISAC solutions to estimate users' location and leveraging RISs coverage extension capabilities to turn off active RUs that may not be needed.

Addressed Challenges: Cost and power consumption, constrained physical size, and other deployment limitations.

ISAC-Related Data and Service Exposure, Provision and Management. The exposure and data management enabler aims to reduce the overhead from data exposure by aggregating and fusing data while ensuring data privacy and trust. This enabler supports the creation of novel services that contribute to societal benefits like safety and sustainability, supported by its capability to efficiently handle and expose data from various producers, including the RAN and sensing nodes. Any network entity with proper access rights should be able to access data or model(s), stored from another entity. A form of authorization and/or authentication should be performed when a network entity is trying to access, update or share data, analytics and model from another entity. Security should be enabled E2E for any operation of the data collection services, including access, exposure, storage, cleaning, processing and encoding. The network should be able to identify energy-aware data collection services and facilitate their operations. Data collection and exposure can be based on a local configuration, or a configuration received from the requester. Different data consumers exist in the network (defined as general network entity), such as UEs, RAN nodes, CN NFs, AFs, 3rd party applications, OAM. Discovery, configuration and in some cases evaluations of such data sources are among the functionalities to cover in 6G. Further on, there is a need to develop novel APIs, enabling both internal network functions, as well as 3rd party applications to request, receive and manage data securely and efficiently, thereby reducing data traffic and overhead significantly.

The provision of sensing services by next generation communication systems necessitates the introduction of a Sensing Management Function (SeMF) that will be responsible for facilitating an efficient coordination of sensing procedures, considering various aspects such as sensing requirements, sensing capabilities, sensing constraints, etc. The SeMF can be designed as a dedicated NF, since it is enabling a new functionality for next generation networks. An alternative option would be to integrate the SeMF services as part of the location management function of 5G.

Addressed Challenges: Beyond communication network services.

4.3. VISION ON THE 6G ARCHITECTURE INNOVATION AREAS

The analysis of the challenges and solutions performed throughout this section identifies the need for potential 12 architectural innovation areas on 6G Architecture that should be researched to support the solutions discussed in Section 4.2. They are elaborated in the following.

1. Interoperability: designing network architecture in a silo-way, with specific frameworks for every domain in the network (i.e., access, RAN, Core, Management, Orchestration) shall be avoided. The main drivers in this context are the consistent integration of AI/ML solutions and the open circulation of data through APIs.

2. Resource Awareness – Resource Brokering: owing to the need of integrating: i) new technologies that were not available at the 5G design phase; ii) data gathering solutions for AI/ML training, that enforce iii) closed control loop directly with the infrastructure, resource awareness shall be introduced in the architecture. That is, architectural modules that enforce the cloud-continuum functionality, efficiently brokering the underneath available resources. Especially for the u-plane related activities these features will be very important. Most of the rigidity and hence the lack of sustainable operation come mostly from that area (i.e., energy consumption at RAN level), hence the possibility of directly integrating network operation and resource utilization is important and shall be enforced using specific interfaces.

3. Service-Awareness. In the same way there is the need of directly integrating data and computing and network infrastructure throughout all the network architecture; such need is also critical at the service level. The network slicing framework proposed in 5G is a solid starting point that need to be further extended to be more programmable and accessible from the vertical application service providers. Leveraging ongoing activities such as CAPIF or CAMARA will be fundamental to extend the architecture towards this direction. Hence, as the 6G system should include a generic exposure functionality, e.g., simplified APIs to expose capabilities to E2E applications facilitating seamless integration of beyond communication network functions and HW capabilities.

4. Enriched exposure for multi-tenant federation. A way of enhancing the integration of external entities (either vertical application service providers or other network operators) is to enhance the federation capabilities of the network through an enriched exposure interface. Ideally, all the network planes like CP and UP can be federated among operators to build a global operator model. Analogously, other novel planes that arise in the recent years such as NI planes or integrated sensing planes should be exposed to other stakeholders in the network, to achieve a comprehensive and effective coverage of the solutions deployed throughout a network of networks.

5. Deeper integration of the UE in the network architecture. When dealing with overarching aspects such as security or sustainability of the system, the role of the UE is fundamental. Optimizing aspects such as mobility and authentication, leveraging data coming from the terminals in a scalable way will require architectural support. Moreover, the future design of 6G services is more towards UE driven and thus the inclusion of UE into the E2E network and service management becomes essential. In this sense, the extension of a SBA toward the UE is a possible way forward.

6. Architectural Support for AI/ML. 6G architectural components shall support the open circulation of data. However, data harvesting is just one enabler of the ML pipeline. Other aspects of its lifecycle management shall be directly integrated in the architecture, offering network functions the capability of selecting, changing, re-training or re-configuring the AIML models running in the network.

7. Support for dependable communications. Reliability and dependability are factors that must be implemented in 6G independently of the provided services. Thus, specific modules shall be designed to enforce these aspects, providing configuration APIs to the different 6G network players (i.e., operators and providers).

8. Support for ISAC. The 6G network architecture should ambitiously extend and support ISAC design to integrate advanced AI-driven architectures for supporting ISAC, embracing advanced radio technologies including multi-functional RIS and cell-free architectures to enhance system performance and energy efficiency while addressing the complexities of dynamic environments and interference management. The convergence of advanced 6G wireless communications and radio frequency sensing systems will be significantly advancing with the incorporation of AI-enabled architectures for ISAC in 6G networks.

9. Seamless integration between TN and NTN. The integration of NTNs poses disruptive challenges for the 6G architecture design to support a new unified 3D multi-layer and multi-connectivity paradigms, exploiting flexible onboard processing space nodes embarking full and/or distributed RAN deployment, hence enabling networking in space and ultimately allowing for direct-to-satellite connectivity. This will address a few key innovations, especially on flexible radio interface and RAN design to support flexible NTN-regenerative payloads, effective routing, multi connectivity management and traffic steering support to enable seamless mobility across TN and NTN.

10. Enhanced Support for Security, Privacy and Trustworthiness. Trustworthiness is one of the fundamental requirements for 6G, which can be divided into 5 taxonomies of Safety, Security, Privacy, Resilience, and Reliability. Novel solutions and APIs need to be developed to ensure Security, Privacy and Trustworthiness E2E (including UEs) for any operation of the data collection services, including access, exposure, storage, cleaning, processing and encoding. Another trend is to explore Quantum-resilient encryption methods to develop post-quantum cryptography solutions to secure 6G networks against quantum-enabled attacks.

11. Network simplifications: There is a need to avoid many standardised deployment options and protocol splits to minimise complexity and cost. The focus is on simplifying protocols and minimizing UE Network (UE-NW) signalling as well as avoiding unnecessary inter-node signalling, e.g., which occurs in the case of CU-DU split.

12. Sustainability: The 6G architecture should allow the network to optimise both energy consumption and costs for enhanced sustainability and operational efficiency. A wider sense of sustainability and how it inter-relates with 6G have been outlined in Section 2.1.5.

Figure 7 summarizes the above listed 12 innovation areas we envision for the forthcoming 6G architecture, based on an initial vision of the architecture view for 6G [131]. These identified architecture innovation areas will serve as a foundation for sketching the baseline design of the 6G architecture. Such architecture will be based on the 5GS but greatly extending it with breakthrough design concepts and novel functional building blocks along with new interfaces, which we envision in this section, to support a brand-new set of 6G technology enablers (Section 3) and 6G use cases (Section 2).

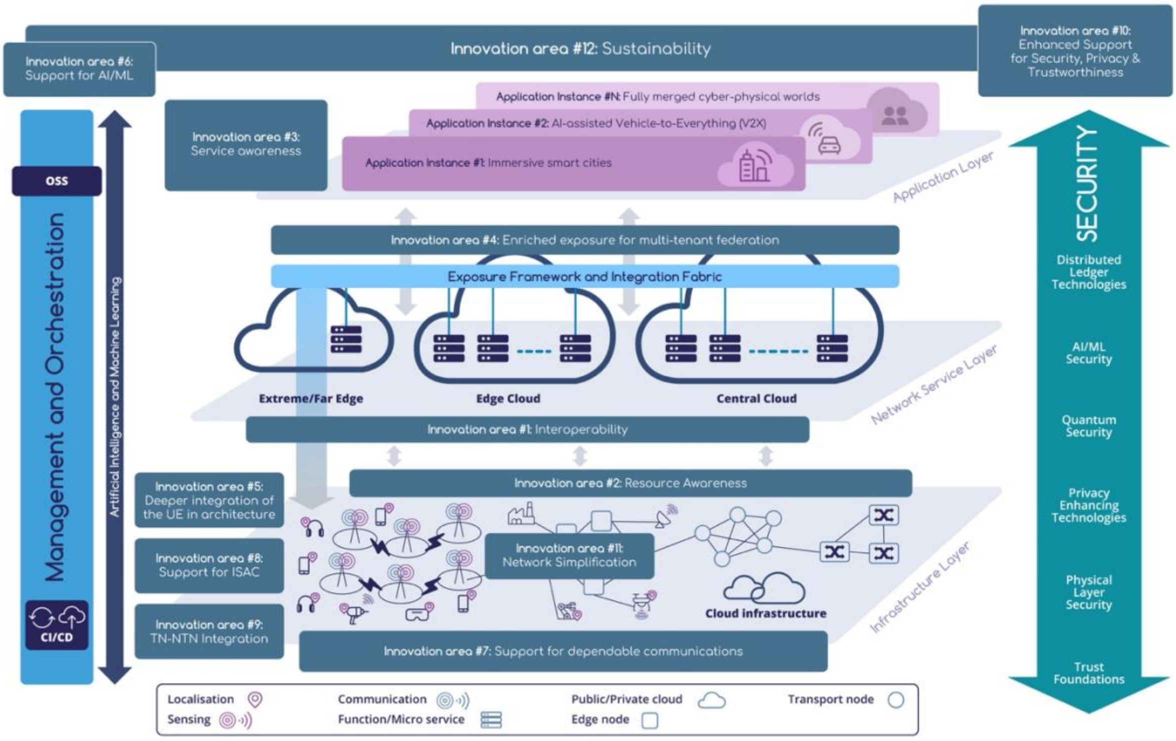

Figure 7: Vision on the 6G Architecture Innovation Areas

5. MAJOR DIFFERENCES WITH RESPECT TO 5G

The **envisioned usage scenarios for IMT-2030** [132] build upon those defined in IMT-2020, which included enhanced Mobile Broadband (eMBB), Ultra-Reliable and Low-Latency Communication (URLLC), and massive Machine Type Communication (mMTC), featuring broader and evolved capabilities (see Figure 1 in Section 1.1). IMT-2030 also introduces new usage scenarios, namely, (i) Immersive Communication, which extends eMBB to cover interactive immersive experiences; (ii) Hyper Reliable and Low-Latency Communication, expanding URLLC to meet even more stringent reliability and latency requirements; Massive Communication which extends mMTC to connect a massive number of devices or sensors; Ubiquitous Connectivity, enhancing connectivity through interworking with other systems; Artificial Intelligence and Communications, to support distributed computing and AI applications across the edge compute continuum, including the creation of DTs; and Integrated Sensing and Communication which enables new applications and services based on wide area multi-dimensional sensing.

To accommodate an expanded range of usage scenarios, IMT-2030 is anticipated to offer **enhanced capabilities beyond those outlined for IMT-2020** [133]. Additionally, each capability may have varying relevance and applicability across different scenarios. Figure 8 illustrates this extent as per Recommendation ITU-R M.2160-0 [132] and Table 3 provides a more detailed comparison of the KPIs for both technologies. Notably, the specified range of values serve as estimated targets for research and investigation of IMT 2030, and future ITU-R Recommendations/Reports may refine these values. Furthermore, achieving these capabilities may not occur across all usage scenarios or simultaneously in a specific usage scenario.

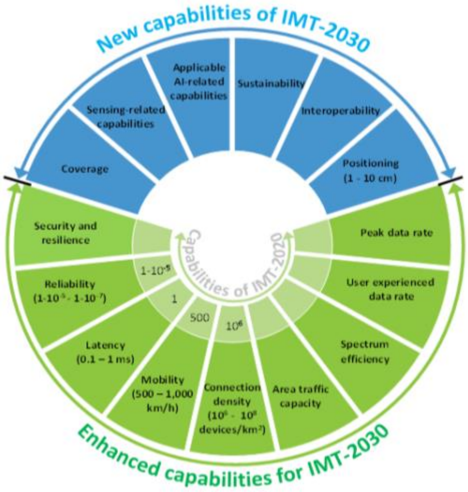

Figure 8: Capabilities of IMT 2030 vs. IMT-2020 [132]

Table 3: IMT-2030 vs. IMT-2020 associated KPIs [132]

Capabilities	IMT-2030 (6G)	IMT-2020 (5G)
Peak data rate	50-100-200 Gb/s	20 Gb/s
User exp. data rate	300-500 Mb/s	100 Mb/s
Spectrum efficiency	1.5-3 x IMT-2020	
Area traffic capacity	30-50 Mb/s/m^{2}	10 Mb/s/m^{2}
Connection Density	10^{6} –10^{8} dev/km^{2}	10^{6} dev./km^{2}
Mobility	500 – 1 000 km/h	500 km/h
Latency	0.1 – 1 ms	1 ms
Reliability	10^{-5}- 10^{-7}	10^{-5}

It is evident that IMT-2030 KPIs are significantly more demanding than those for IMT-2020. Achieving such stringent KPIs may involve enhancements to existing IMT, the **integration of new technology components and functionalities**, and/or the development of novel radio interface technologies. Additionally, **interworking between diverse access networks**—especially NTNs like satellite communication systems, high-altitude platforms, and UAVs—could contribute to achieving these objectives and, notably coverage. However, integrating these platforms with TNs presents challenges in network architecture, latency management, and energy sustainability.

Apart from the strict requirements implied by a new set of use cases, there are other aspects such as sustainability, trustworthiness, and inclusion which 6G is expected to support. The philosophy behind 6G is not just about higher speeds and lower latency, but also about transforming the way we interact with technology and the environment. 6G will place human well-being at its core and aims to create technology that serves people in an intuitive manner.

It is worth noting that 6G has a significant focus on sustainability. This emphasis is driven by not only the need to address environmental challenges, reduce energy consumption and promote more efficient use of resources, but also by the 17 UN SDGs introduced in 2015 for achieving a better and more sustainable future for all (see Figure 9) [134]. Since then, all sectors of society have been called for working towards and delivering on these goals with an ideal timeframe of 2030.

Figure 9: United Nations' sustainable development goals

The development and deployment of 6G technology have the potential to significantly contribute to the achievement of these goals in various ways. In the following, some examples of 6G contributions on selected goals are given:

- Goal #2 Zero hunger: End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
    - 6G contribution: Precision Agriculture in the sense of being able to enhance agricultural productivity through IoT devices, use of network of networks, and data analytics for efficient resource use and crop management.
- Goal #3 Good health and well-being: Ensure healthy lives and promote well-being for all at all ages.
    - 6G contribution: By providing a high-speed, low-latency connectivity for all, even in remote areas, 6G can make the access to medical care possible. Additionally, by using health monitoring devices and remote check-ups, 6G can help to prevent the advancement of various diseases.
- Goal # 11 Sustainable cities and communities: Make cities and human settlements inclusive, safe, resilient, and sustainable.
    - 6G contribution: Enhancing urban planning and management through connected devices, data-driven decision-making and usage of DT. Moreover, by improving the communication

and monitoring system, a higher level of resiliency and accelerated response in disaster management can be provided.

6G technology holds immense potential to support and accelerate progress toward these goals. Subsequent sections are aimed at outlining the **key innovations** that, to a large extent, were **not present in previous generations and are expected to be introduced in 6G networks**. Innovations in both radio access and core networks are covered.

5.1. KEY INNOVATIONS IN THE RADIO ACCESS NETWORK

The Rel-18 RAN1-led study on AI/ML for NR Air Interface explores the benefits of augmenting the air interface with support of AI/ML-based algorithms for enhanced performance and/or reduced complexity or overhead [135]. This includes functionalities such as channel state prediction and feedback, beam prediction, and precise positioning, for which the use of AI/ML algorithms has been proven beneficial in improving performance. Although 5G-Advanced addresses AI/ML-based improvement on selected aspects, 6G wireless networks are expected to natively incorporate AI/ML in the air interface design from the onset, i.e., an AI-native air interface. This will allow for instance [136] learning spectrum-efficient waveforms matched to propagation conditions or HW impairments/limitations, or the adoption of fully learned transceivers avoiding the very costly time-consuming traditional process of algorithm design and HW implementation and, to large extent, their detailed standardisation. The integration of MEC and Edge AI (EAI) is another significant development, enabling real-time, low-latency processing at the network edge for e.g., advanced robotics, and immersive virtual reality (VR) and augmented reality (AR) experiences.

6G is expected to utilize a combination of various frequency ranges to meet coverage and enhanced capacity requirements and to serve new emerging 6G use cases. While low bands remain essential for nationwide coverage, bands between FR1 (Sub-7 GHz) and FR2 (above 24 GHz) are currently being considered and studied for IMT-2030/6G, as they would balance wider bandwidths for high-speed data transmission compared to lower frequencies with better urban propagation properties compared to FR2. Hence, work has been initiated under WRC-27 agenda item 1.7 to study the 4.4-4.8 GHz, 7.125-8.4 GHz and 14.8-15.35 GHz bands for IMT-2030/6G. While still emerging, this range (proposed in 3GPP to be called FR3) holds promise for 6G as existing bands approach their limits.

Another potential paradigm shift of 6Ghowever in the very long-term is to study the use of **Terahertz** (THz) **communications**, offering vast bandwidth and spatial resolution for ultra-high-speed data transfer and advanced sensing. However, due to economic constraints, 6G should start from the existing cell site structure, leading to focus towards FR3 and FR1. To optimise spectrum utilization, in this multi-band communication scenario, spectrum sharing techniques across services, providers, and technologies has also been identified as a key enabling feature for 6G.

Operating at higher frequencies allows us to fit more antennas into a given aperture size. **Extremely Large Antenna Arrays** (ELAA) and Near-Field Communications (NFC) offer improved spatial multiplexing and reduced interference. However, they present design and performance complexities.

Another innovative approach in the 6G radio interface is ISAC that combines communication and sensing within a single network infrastructure to enhance wireless communication performance and enable new and enhance existing services with location/contextual-based information and, by doing so, add value to the 6G system.

5.2. KEY INNOVATIONS IN THE CORE NETWORK

5G has been the first mobile network generation designed to not only operate in the traditional CSP ecosystem, but also to address the requirements of the industrial and other vertical environments, e.g., for replacing wired connectivity. As the demand on the network rises, industries will require even more advanced features that can support increased flexibility and specialization.

5G core network went through disruptive changes in comparison with 4G. Introducing a SBA in the core and its cloud native deployments are a few of such changes. These changes, among others, facilitated network deployments in heterogeneous cloud environments involving a mix of private, public and hybrid clouds. Such design and deployment are expected to lead to reduction of total cost of ownership (TCO) [137].

6G core network is expected to follow similar principles as the previous network generation and hence presumably will be an evolution of 5G core network. Moreover, the architecture of 6G system and in particular 6G core network is expected to **support a range of innovative technologies** (e.g., joint communication and sensing) as well as providing enhanced performance, flexibility, scalability, and sustainability [138].

The **integration of AI/ML in the 6G core network** and the possibility of having AI-native network functions promise to improve levels of efficiency, security, and intelligence. With that, there is a possibility of dynamically managing network resources and optimizing performance. Furthermore, AI-driven analytics provide deep insights into network traffic and user behaviour, enabling personalized services and proactive security measures [139].

While 5G laid the groundwork for the fundamentals of, e.g., network slicing for flexible and efficient network resource management, it is envisioned that **future slicing** will be able to elevate this concept with **enhanced granularity** beyond eMBB, URLLC and mMTC, **superior performance** in some cases even real-time resource allocation, deeper **AI integration** for slice management, demand prediction, self-optimization, etc., and advanced security measures.

The innovations for the 6G core network focus on achieving higher performance, better flexibility, enhanced security, and improved sustainability. By integrating advanced technologies, 6G aims to create **a robust and future-proof network architecture** that can meet the demands of next-generation applications and services and that is ready for deployment in evolving telecommunications and cloud infrastructures.

6. NEXT STEPS

This section reflects on the next non-technical steps and provides some recommendations to be considered towards making 6G a reality by 2030. On the one hand it draws attention on the technical specifications (TSs) produced by standards, which define the functionality and the interwork among devices, and on the regulatory frameworks issues by different authorities, the compliance with which is necessary to be able to sell any future 6G product in the European market. On the other hand, it discusses the envision next steps related with business aspects and picks the important topic of sustainability as the main guiding factor in the forthcoming definition, development and finally deployment of the forthcoming 6G system.

6.1. STANDARDISATION

When focusing on the standardisation landscape that provides the TSs to implement 6G systems, the main internationally recognised institution to refer to is the International Telecommunication Union (ITU) [140], a United Nation specialized agency for digital technology. In November 2023, the Radiocommunication sector of ITU, i.e., ITU-R, defined “IMT-2030” as the name of the next generation of International Mobile Telecommunications (IMT), also known as 6G, and issued the Recommendation ITU-R M.2160 “IMT-2030 Framework” [141] with the aim to clarify and plan the next steps of the 6G standardisation process.

As illustrated in Figure 10 the next step for ITU is to work on the technical performance requirements for 6G, which are expected to be finalized mid-2026. Based on those requirements, and in parallel to their definition, standards Developing Organisations (SDOs), such as the 3rd Generation Partnership Project (3GPP), will then start working on normative documents that will define what can be called a 6G-compliant system.

Figure 10 also shows relevant European R&I activities for 6G networks (i.e., the work of the SNS Joint Undertaking), in terms of phases and scope, main EU funding program run by the SNS JU and key international events where 6G networks can be launched and showcased. The shown standardization and research activities provide the complete timeline for the design, testing and eventually 6G deployment and commercialisation.

To briefly touch on the main difference with a 5GS, it is worth mentioning that the IMT 2030 vision describes 6 usage scenarios the next generation of mobile systems should enable: 3 are evolved 5G ones, i.e., Immersive Communications (evolved from eMBB), Massive Communications (evolved from mMTC) and Hyper Reliable & Low Latency Communications (evolved from URLLC); 3 are new, i.e., Ubiquitous Connectivity, AI and Communications, and Integrated Sensing and Communications [142].

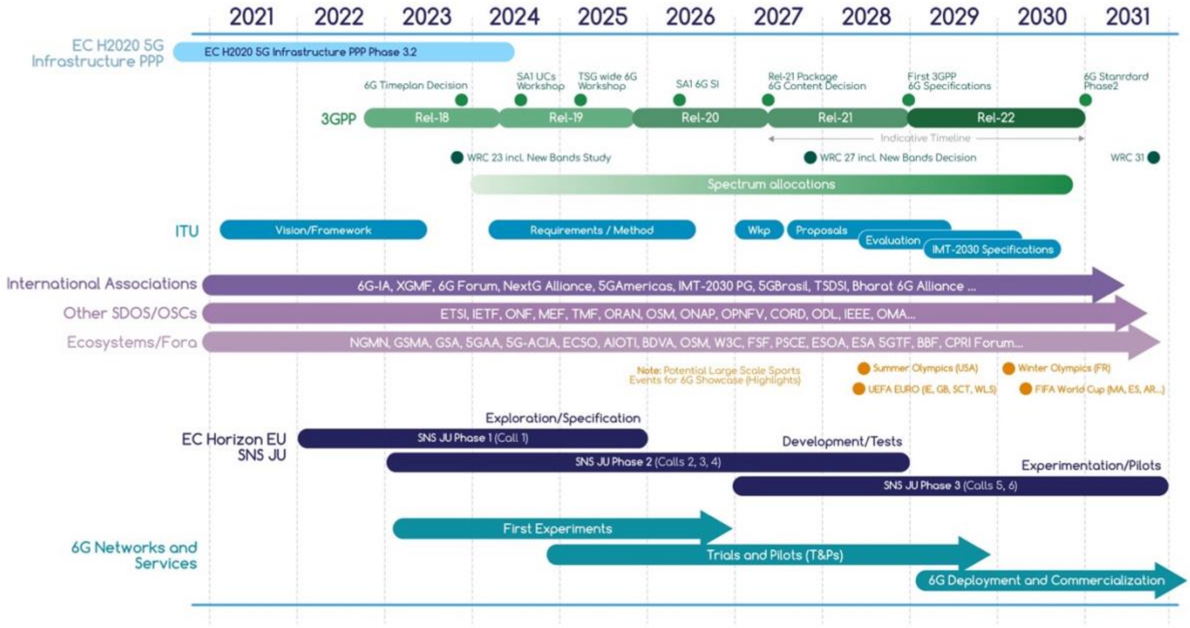

Figure 10: Standardisation Timeline for 6G and other related key activities at the European level

As a matter of fact, 3GPP already started in its Release 19 (Rel 19) some preliminary work on 6G; in May 2024 a workshop driven by 3GPP SA1 to discuss the definition of the 6G use cases was organized, during which some key 6G stakeholders provided their views on what 6G should look like and shared a set of interesting presentations for the benefit of the broader public [143]. In the next couple of quarters, more structured work on 6G will be conducted in the form of study items to finalize on the definition of the 6G use cases, and then work items under the future 3GPP Rel 21 are expected to produce, not before 2028, the first normative documents on 6G, i.e., TSs.

The definition of a single global standard for communication systems compliant with the IMT-2030 framework and requirements is key to foster the growth of a healthy and global telecommunication ecosystem, ensure backward compatibility, allow for interoperability among the different equipment and terminal providers, and facilitate scalability, adoption and easy re-use in future systems [144].

Such standard, covering interfaces among Integrated circuits (IC) and HW components, infrastructure equipment and terminals, SW and applications, goes in pair with global markets and economies of scale and unleashes business potentials for HW manufacturers and SW developers, thus potentially reducing costs for network operators and end customers. It can also enable new players' products and services to enter the ecosystem, thus making the supply chain more robust to potentially disruptive market and geopolitical events and the telecommunication infrastructure more resilient and efficient, providing the reliable backbone needed for the full adoption of a digital society.

As the work on the IMT 2030 vision includes contributions from a broad range of stakeholders, it is expected to see various pre-standardisation or related-to-standardisation efforts taking place in parallel to the work done in SDOs (see Figure 10). Such efforts are driven by international associations and mainly happen in their WGs focusing on different aspects of a 6G system (e.g., the pre-standards WGs in 6G-IA, AIOTI, BDVA) or are crystallized by the publication of white papers from industry-driven organisation like the Global System for Mobile Communications (GSMA, representing the interests of mobile operators) [145], the 6G IA and the European Flagship project Hexa-X-II, the first ever research program in 6G, i.e., 6G Flagship [146], the Next Generation Mobile Networks Alliance (NGMN) [147], the Next G Alliance [148], the one6G association [149], or the 5G Alliance for Connected Industries and Automation (5G-ACIA) [150]. Furthermore, a range of Industry Specification Groups (ISGs) and SW Development Groups in the European Telecommunications Standards Institute (ETSI) are actively working on technologies with future standardisation potential, e.g., the recently started ETSI ISG on ISAC [151], addressing the IMT 2030 vision usage scenario with the same name.

In addition to ETSI and 3GPP as the main providers of global standard for mobile communication networks, other SDOs work on technologies that are equally important for the definition of 6G systems, for instance The Internet Engineering Task Force (IETF) [152], e.g., on the required protocols of the IP suite, or the Institute of Electrical and Electronics Engineers (IEEE) [153] on other access network technologies (Wi-Fi) and protocols and solutions outside of IETF and below the IP stack (MAC, VLAN), and the Open Mobile Alliance SpecWorks (OMA) [154] focusing on defining an agreed-upon common framework for applications and services.

Although not an SDO as the ones mentioned above, the activities of the Open-RAN Alliance [155] cluster more than 300 members among mobile operators, equipment vendors and research institution. O-RAN mission is to have RAN industry to be open, intelligent, virtualized and fully interoperable. O-RAN issues specifications and white papers proposing several RAN optimisation use cases, thanks to the massive use of AI, and defines open interfaces aimed at improving disaggregation, interoperability, and fostering a more competitive supplier ecosystem.

Finally, it is worth mentioning the increasing importance of the open-source ecosystem in providing de-facto standards in several domains of 6G interest. For instance, the Free Software Foundation Europe [156], the Open Source NFV Management and Orchestration (OSM) [157], and the World Wide Web Consortium (W3C) [158], focusing on the continuous evolution of the web.

We also observe that the standardisation timeline and cycles may vary. While the 3GPP and ITU-R specifications develops over many years (consider the 10-year cycle of the previous generations of IMT), e.g., due to HW dependencies, there are specification areas that are purely SW- based and where the standards or standardization cycles may develop much faster.

It will be the collective set of standards developed by all the above mentioned SDOs that will provide the specifications to implement 6G-compliant systems, standardized 6G enabled service offerings, and related operations support.

6.2. REGULATION

Whatever new system defined by SDOs is going to be introduced or enhanced in the forthcoming years, including its features and functionalities, in order to be deployed in networks it will have to be compliant with an always growing number of public regulations, issued by the European Commission, sometimes even by its Member States, and, looking outside of the EU, also by other governing bodies of other countries.

Broad transformational activities (e.g., the ongoing paradigm shift of digitizing all aspects of society) of such important sectors like telecommunications need to happen in a manner that is aligned and agreed-upon by all major stakeholders, if social cohesion, resilient supply chains and better access to business are to be ensured, as recognised in a recently published white paper "*a new approach to regulation is needed [which] should radically reshape the governance of the sector to foster investment and innovation, unleash a true Single Market for telecoms, and achieve Europe's vision for 2030*" [159].

To address the need mentioned above, the Radio Equipment Directive (RED) and several other European Acts (finalized or still under work) take the lead in setting the legal frameworks, which all equipment, products, services and applications will have to be compliant with. In what follows a very short introduction of the main legislations is provided.

The RED [160] is built upon the previous EU radio and telecommunication terminal equipment directive (1999/5/EC) and ensures a single market for radio equipment by setting essential requirements for safety and health, electromagnetic compatibility, efficient use of the radio spectrum, protection of privacy, personal data and against fraud, interoperability, access to emergency services, and compliance regarding the combination of radio equipment and SW. The first version of RED was published in 2014 (Directive 2014/53/EU [161]), and, since then, periodic updates are issued, the latest one in December 2022 [162] controlled by the telecommunication conformity assessment and market surveillance committee (TCAM), a committee related to the Regulation (EU) No 182/2011. Voluntary harmonised standards in support of the RED have been and are being prepared by CENELEC and ETSI.

The Data Act [163] answers to a set of rather complex issues related to how, in general terms, data is produced, shared, processed and stored along the E2E business value chain by the several involved actors in all market segments. Among other aspects, it focuses on "*laying down a harmonised framework specifying who is entitled to use product data or related service data, under which conditions and on what basis*" All those aspects are of uttermost importance for forthcoming 6G systems, as data creation and processing will be at the core of all services and applications in a 6G implementation. Future mobile systems and their parts related to the treatment of subscriber data might need additional interfaces and APIs to be conform. On the other hand, the Data Act enables a multi-provider cloud, which can be an essential enabler for the unhindered execution of 6G network functions and 6G services over a territory.

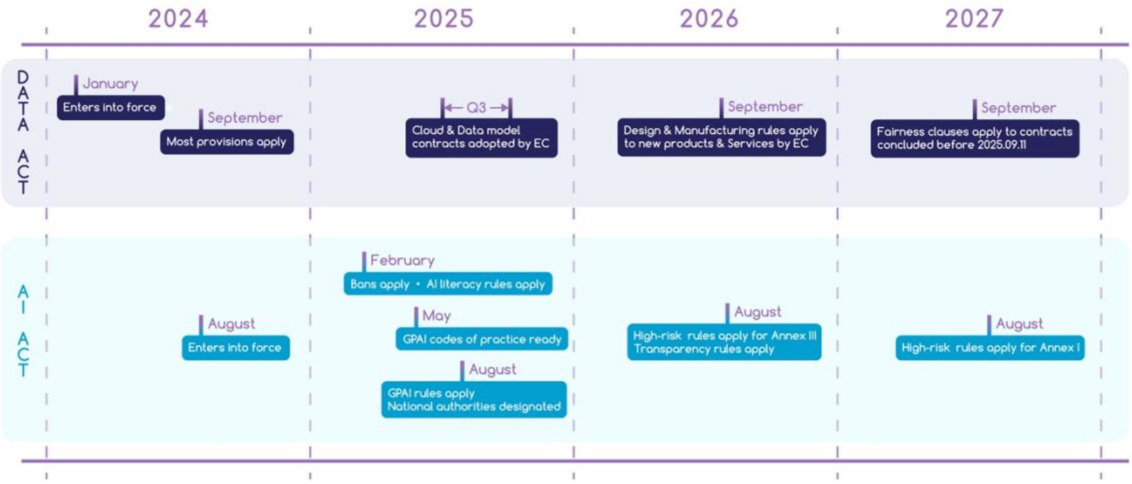

Figure 11: Timeline of the implementation of the Data Act and the AI Act.

The AI Act [164] has been published in July 2024 in the EU Official Journal and have entered into force on Aug. 1, 2024, with a roadmap of key obligations applying from August 2025, 2026 and 2027. The Act states it objective as "*The purpose of this Regulation is to improve the functioning of the internal market by laying down a uniform legal framework in particular for the development, the placing on the market, the putting into service and the use of artificial intelligence systems (AI systems) in the Union*" and therefore is relevant to almost all 6G-related functionalities, as AI will be at the core of most of the internals of 6G systems. The ongoing implementation of the Data Act and the AI Act and its next steps are shown in Figure 11.

The Cybersecurity Act [165] entered into force in 2019 and has the charter of establishing a cybersecurity certification framework for products and services for the European market. The latest amendment to the original Act was issued in April 2023 and focuses on "*enabling, by means of Commission implementing acts, the adoption of European cybersecurity certification schemes for* *'managed security services', in addition to information and technology (ICT) products, ICT services and ICT processes, which are already covered under the Cybersecurity Act*".

Finally, it is also worth mentioning that, as a central part of the EU Green Deal, the EU has decided to adopt and implement the Digital Product Passport (DPP) concept, i.e., a digital identity card for products, meant to share with all stakeholders vital product information and foster the broadest possible adoption of virtuous environmental practises. This initiative is driven by a new regulation called Ecodesign for Sustainable Products Regulation (ESPR) [166] and aims at mandating a structured way to ensure better transparency of the components of each product sold in the EU, providing detailed information on how to dispose a product, what is the origin of its components and materials, and providing an overall assessment of its environmental impact. The DPP aligns and supports the open data initiative, stressing transparency and accessibility of all steps needed to create a product. The adoption and the publication of the first working plan for the ESPR is expected in Q2 2025, with the enforcement of the regulation supposed to happen not before 2026.

6.3. INDUSTRIAL BUSINESS ROADMAP

In the global 6G landscape, Europe has a strong position in terms of infrastructure as two out of the three world-leading network vendors have their headquarter in the EU. However, in the 6G evolved value chain (c.f., subsection 2.2), there is an ongoing trend in which market share and revenues of European technology enablers and connectivity providers could be decreasing in favour of dominant non-European streaming and content providers, hyper-scalers or other online service providers (e.g. social networks). A better market balance will be required by means of introducing the principle of "same rules for same services" as well as dispute resolution mechanisms that ensures fair commercial outcomes.

Besides, there are many other aspects around 6G that should be considered in order to maintain European sovereignty, so Europe is able to ensure prosperity of its businesses and the wealth of its citizens, as well as to decide independently while operating in the global environment, for instance, related to the fact end to end 6G architecture builds on AI and cloud technology. The European position in both cloud technologies and AI is currently not so prominent; also consumer telecommunication devices is currently less strong, therefore a dedicated effort will be needed regarding chipset technologies.

In terms of emerging opportunities, the new use cases for 6G (c.f., section 2.1 for details) on Immersive Experience, Collaborative Robots, Physical Awareness, DTs, Fully Connected World and Trusted Environments can open the ecosystem for new European players. New business opportunities are expected to emerge in specific industrial communities associated with the new use cases (manufacturing, infrastructure, transport, etc.), which will extend the market with new services. Furthermore, evolved services in 6G would be created both bottom-up, designed by the provider, but also top-down, with vertical customers expressing their requests through intents. Value creation opportunities in any case should be explored from the various players, including vertical industries, to maximise economies of scale. Moreover, the cooperation between companies at European level is highly recommended to avoid fragmentation that could put at risk the existence of a real common market for network services.

New business models and new regulatory policies will be also needed, from highly distributed cloud service providers who host both the applications and networks, to a federation of MNOs with applications and networks on private edge cloud infrastructure. This ubiquitous distributed computing will also require more and more disaggregation of the services as well as the capability of orchestrating distributed resources across different stakeholders and business models. Besides, more widely standardised interfaces will be needed to ease consolidation and stronger collaboration of the different stakeholders in a multi-domain ecosystem.

Moreover, open architecture and interfaces will bring new possibilities of innovation. This development aims to bring more choices for operators and manufacturers to mix and match components for different vendors thus diversifying their dependencies, while bringing greater automation and flexibility for operational efficiency in network roll-out.

As AI is becoming an intrinsic part of 6G (native AI), technological sovereignty will be starting also from the integrity and resilience of the data infrastructure, as well as from data computation integrity and data-controlled distribution. Data has become a key factor of production. Businesses in 6G will need strong enough data frameworks that allow them to start up, scale up and use data, to innovate, compete or cooperate (see the Data Act related information in Section 6.2).

Security, trust and privacy will also need to get a greater dimension in 6G, versus previous generation 5G, as explained in previous sections, which will have consequently related business implications. There are still important challenges that need to be solved in this field to make 6G a reality. The dependence of the economy and societies on telco networks will deepen in the 6G era, so embedded trust should be the target, and a holistic 6G network security architecture planning is needed, reinforcing the involvement of security stakeholders.

The integration of TN and NTN is another key feature of 6G, with the purpose of addressing the Digital Divide between rural and urban areas. Though NTN is already being treated in 3GPP since Rel.17 from the radio access architectural perspective, there are still many challenges to be addressed regarding capacity, sustainability, resilience, security and reliability for NTN to be a reality as part of 6G. Both MNO and Satellite Network Operators (SNO) are collaborating in 3GPP for the definition of the unified infrastructure recognizing the TN-NTN integration as part of the future 6G system, however new business models will be required for both MNOs and SNOs in this regard. The success of achieving the full integration by 2030 will depend not only on the successful technical validation or on the regulation and standardisation decisions, but also on the actual manufacturers business plans.

Sustainability is definitely one of the key differentiators in 6G, from the previous generation 5G, which will have its impact also from the business perspective, since 6G will act as a catalyst to improve sustainability in other vertical sectors (6G for sustainability). Next steps and recommendations regarding sustainability are covered in Section 6.4.

Finally, regarding human resources capacities, it will be needed to design new workforce development strategies and incentives to increase number of students in Science, Technology, Engineering, and Mathematics (STEM) degrees. More professionals are needed from engineering schools and high-level university programs in technologies enablers needed for 6G, like communication protocols and SW, virtualisation and cloud, cybersecurity, microelectronics. Even new STEM degrees shall be considered, which should be combining multiple disciplines across computer science, telecom, cyber and AI/ML. Moreover, a specific effort is needed to attract female students / develop female talents, in the mentioned topics since generally digital science suffers from a lack of attractiveness to female students, and therefore creates a very significant gender unbalance. In general, Europe needs to be more attractive for people to move and stay to contribute to the European economy. Finally, it is important to highlight that the potential lack of investment in advanced networks could put in risk the EU digital decade connectivity targets.

6.4. SUSTAINABILITY ROADMAP

Section 1.1.3 explained how the 6G system itself must be sustainable, "**Sustainable 6G**", and also ensure that 6G contributes to the sustainability of other sectors, "**6G for sustainability**". The sustainability goals for 6G will align with the UN's 17 SDGs, often summarized in social, environmental, and economic 6G sustainability goals. Section 2.1 above elaborates on perspectives and importance of sustainability as an integral part of developing and analysing use cases or use case families.

Looking ahead, we see three main challenges for the 6G community:

i) to find good ways to assess and measure sustainability aspects of the 6G system and the sectors using it;

ii) to take analytic workload of the shoulders of 6G system users by integrating sustainability into the 6G technologies and services as the default alternative; and,

iii) to reveal and handle the dilemmas and trade-offs that will emerge between sustainability goals and technological and economic efficiency.

For 6G systems, any assessments of technology development and use must be expanded with environmental, social, and economic aspects. Aspects regarding e.g., safety, reliability, and availability must be taken into considerations of social costs and benefits, and likewise, social exclusion or inclusion in a more digital world. KVIs, and ways to assess KVIs for specific use cases, is introduced as a way forward, however, the frameworks are still in the making. A methodology in Europe is already being created in the way that KVIs can be quantified and therefore it is possible to assess the performance of 6G solutions in relation to sustainability aspects; details can be found in the 6G-IA position paper released in September 2023 [3].

Within the domain that the telco industry controls, "Sustainable 6G", it is needed to identify technology enablers that independently meet sustainability requirements, and not inflict costs on users and use cases. For instance, the 6G system must cater to sustainable power consumption. The deployers and operators of 6G systems must consider new constellations, investment, and business models to optimise use of materials and resources. In this way, the continuous assessment of the sustainability of 6G is taken off the shoulders of users by integrating the sustainable choices into the technology itself.

Sustainability assessments must on the one hand cater to sustainability aspects for a concrete use case, e.g., decrease in emission consumption and increase in societal inclusion, and on the other hand capture how 6G systems perform on environmental, social, and economic aspects, e.g., increased power consumption and waste. Thus, there may be many trade-offs considering 6G uses and 6G. In other words, it is a non-negotiable requirement that a 6G use case with sustainability benefits should only be realised if 6G technologies and services can offer it in a way that is beneficial according to sustainability aspects. For 6G providers, it cannot be argued that additions of use cases to social inclusion justifies, e.g., power-greedy solutions. 6G circularity achievements cannot justify ever increasing consumer device turnover. For the 6G community, it will be important to reveal these trade-offs to make informed choices and decisions, for all 6G stakeholders.

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8. ABBREVIATIONS AND ACRONYMS

3GPP	3rd Generation Partnership Project
5G	5th Generation
5GS	5G Systems
6G IA	6G Infrastructure Association
6G	6th Generation
AI	Artificial Intelligence
API	Application Programming Interface
BICM	Bit-Interleaved Coded Modulation
CA	Carrier Aggregation
CNC	Centralized Network Controller
CPU	Central Processing Unit
CRS	Cells-specific Reference Signal
CSA	Coordination and Support Action
CSI	Channel State Information
DBICM	Delayed BICM
DC	Dual Connectivity
DFT-s-OFDM	Discrete Fourier Transfer spread OFDM
DL	Downlink
DLT	Distributed Ledger Technology
D-MIMO	Distributed MIMO
DPU	Data Processing Unit
DRL	Deep Reinforcement Learning

DSS	Dynamic Spectrum Sharing
DT	Digital Twin
E2E	End-to-End
EH	Energy Harvesting
EmMTC	Enhanced Massive MTC
EN	Energy Neutral
FSO	Free-Space Optics
GSO	Geostationary Satellite Orbit
HAPS	High Altitude Platform Stations
HRLL	High Reliability and Low Latency
IBN	Intent-Based Networking
IoT	Internet-of-Things
ISAC	Integrated Sensing and Communications
KPI	Key Performance Indicator
KVI	Key Value Indicator
LDPC	Low-Density Parity-Check
LEO	Low Earth Orbit
LLM	Large Language Model
LoS	Line-of-Sight
MAC	Medium Access Control
MBB	Mobile Broadband
MIMO	Multiple Input, Multiple Output
ML	Machine Learning

mMIMO	Massive MIMO
MN	Master Node
MPQUIC	Multipath QUIC (Quick UDP Internet Connections)
MPTCP	Multipath Transmission Control Protocol
MRSS	Multi-RAT Spectrum Sharing
MTC	Machine Type Communication
MU-MIMO	Multi-User MIMO
NDT	Network Digital Twin
NGSO	Non-Geostationary Satellite Orbit
NI	Network Intelligence
NIC	Network Interface Card
NLoS	Non-LoS
NOMA	Non-Orthogonal Multiple Access
NTN	Non-Terrestrial Network
OFDM	Orthogonal Frequency Domain Multiplexing
OFDMA	Orthogonal Frequency Domain Multiple Access
OWC	Optical Wireless Communication
PAPR	Peak-to-Average Power Ratio
PDCP	Packet Data Convergence Protocol
PLMN	Public Land Mobile Network
PRB	Physical Resource Block
PRS	Positioning Reference Signal
PLS	Physical Layer Security

PTP	Precision Time Protocol
QoE	Quality of Experience
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RHDRBL	Reliable High Data Rate with Bounded Latency
RIS	Reconfigurable Intelligent Surface
RSMA	Rate-Splitting Multiple Access
RTO	Research and Technology Organisations
RTD	Resonant Tunnelling Diode
RU	Radio Unit
SBA	Service Based Architecture
SDO	Standards Development Organisations
SIM	Seamless Immersive Reality
SME	Small and Medium Enterprise
SN	Secondary Node
SRG	States Representatives Group
TAF	Trust Assessment Framework
TN	Terrestrial Networks
TSN	Time Sensitive Networking
UE	User Equipment
UL	Uplink
URLLC	Ultra-Reliable Low Latency Communication

VLC	Visible Light Communication
WPT	Wireless Power Transfer
XR	Extended Reality

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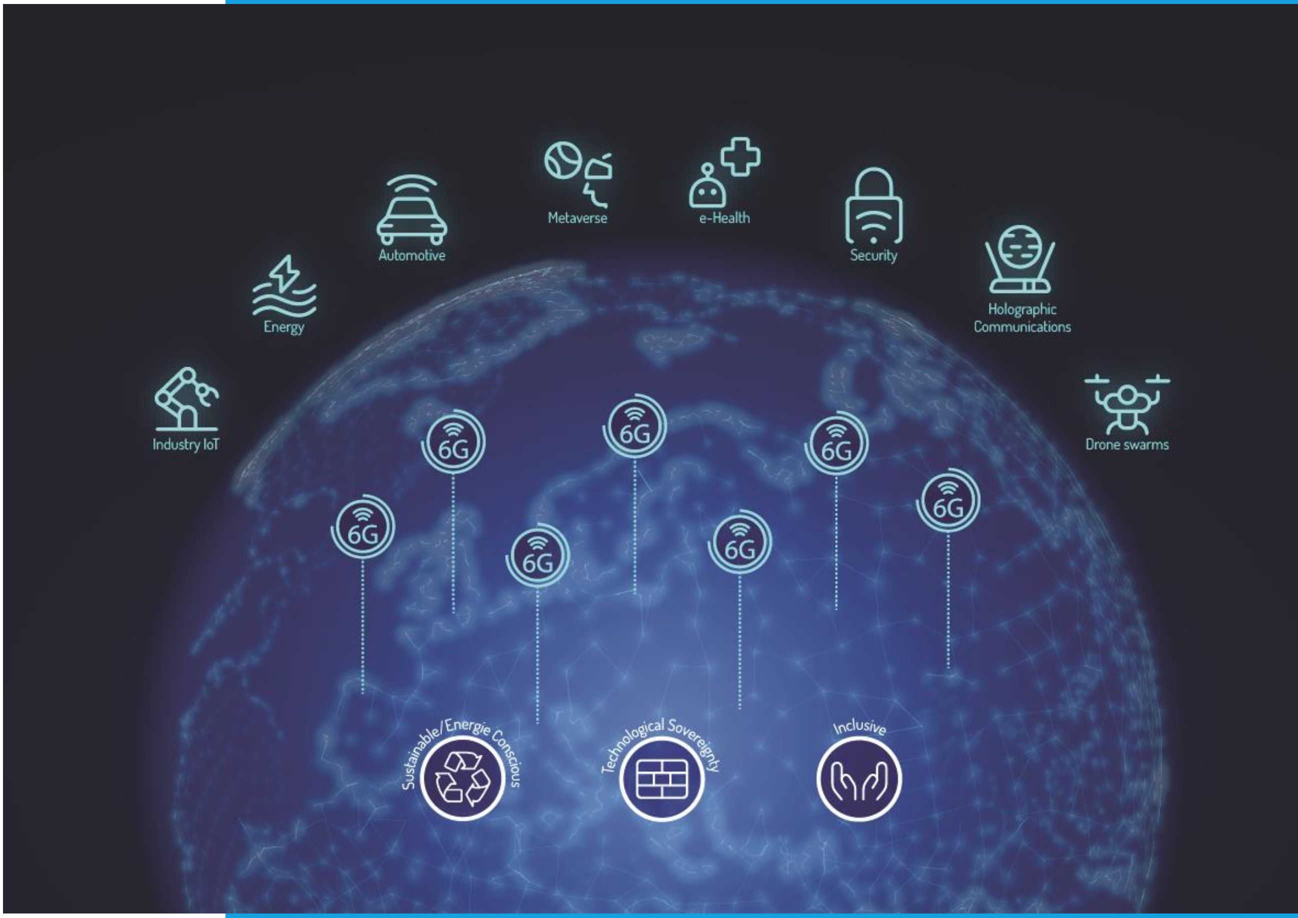

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