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Towards environmentally, socially and economically sustainable 6G – Key findings from the European Flagship Hexa-X-II

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Abstract – The European 6G Flagship project Hexa-X-II created momentum around 6G via 44 member organizations covering the entire value chain. The project lasted from January 2023 until June 2025. Here the key findings of the project are summarized, including requirements for sustainable, inclusive and trustworthy 6G, end-to-end system view and architecture, its validation, enhanced connectivity via 6G, network sensing, compute and AI for novel digital services as well as efficient network realization, implementation and management.

Keywords – 6G, AI, Hexa-X-II, KPI, KVI, ML, network architecture, sensing, sustainability, sub-THz, wireless communications

1. INTRODUCTION

As the fifth generation (5G) of mobile networks continues to be deployed, research on the sixth generation (6G) has been underway for half a decade and is now accelerating in the standardization arena. The International Telecommunication Union – Radio Sector (ITU-R), responsible for defining the requirements for mobile generations, prepared a Recommendation for the IMT-2030 framework, which serves as a roadmap for 6G research and development [1]. Meanwhile, the European 6G Flagship project Hexa-X was launched in 2021 with the aim of strongly contributing to harmonizing the global 6G vision and defining the foundations for End-to-End (E2E) 6G systems in cooperation with key stakeholders worldwide [2]. Hexa-X has contributed to 6G structuring and framing, as well as developing enablers and defining requirements for 6G with the vision to *connect human, physical and digital worlds,* while also considering the key societal values *sustainability*, *trustworthiness* and *digital inclusion*. The 6G vision and relevant use cases have been discussed in several prior publications (see, e.g. [2], [3], [4], [5]), and Hexa-X has contributed towards the 6G vision outlined in [3]. The succeeding European 6G Flagship project, Hexa-X-II, was launched in 2023 with the goal of further developing the foundation laid by Hexa-X and beginning to create the 6G E2E system. To accomplish this, the project consortium comprised 44 member organizations from across Europe, covering the entire value stack from hardware to system to platform to applications to service providers, and a strong academic presence, as can be seen in Fig. 1.

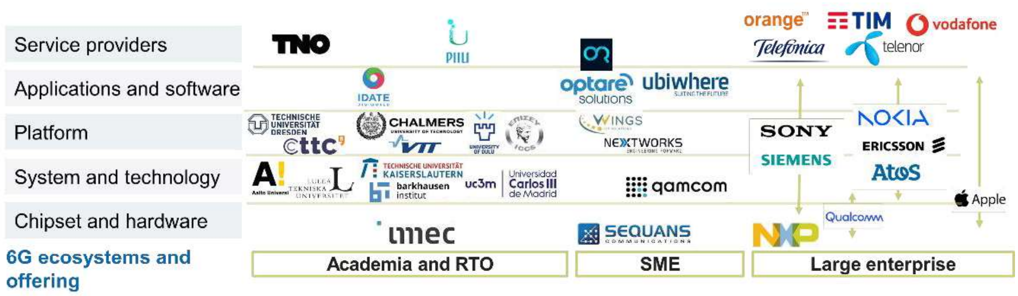

Figure 1 – Hexa-X-II project consortium

Hexa-X-II builds on Hexa-X by moving from foundational 6G research and architectural visions to a holistic system blueprint aided by practical validation and integration. Hexa-X identified key concepts, such as AI-native networking, joint communication, sensing and native trust/privacy. Hexa-X-II refined these ideas through further research, built the system level E2E view, cross-sectoral validation, proof of concepts, and standards-focused deliverables targeting scalability, energy efficiency and multi-stakeholder orchestration. Hexa-X's theoretical frameworks and gap analyses directly informed Hexa-X-II's use cases, KVI formulation, sustainability framework, implementation priorities and its emphasis on real-world trials and socio-economic-environmental sustainability-focused evaluation.

The Hexa-X-II project identified new 6G use-case families [6] that have been widely accepted. The work was based on earlier steps in Hexa-X, and the end results were used as a baseline for the joint European input to 3GPP SA1 workshop on IMT-2030 use cases in May 2024 [7]. Hexa-X-II has also continued to develop further technical enablers for 6G, tying them together under one E2E system view and architecture, as well as developing a new sustainability analysis and use case methodology. Hexa-X-II has provided a strong basis for further work in 6G on sustainability, including environmental, social and economic sustainability.

This paper shares insights from the European 6G Flagship project Hexa-X-II, detailing and assessing key candidate technologies for 6G, while acknowledging that it does not cover every potential technology. Section 2 discusses the requirements for 6G. Section 3 continues by tying together the 6G enablers to an E2E system blueprint and sheds light on the validation of the work. Section 4 presents the enhanced connectivity for 6G services. Section 5 describes the advances beyond connectivity for 6G, i.e. sensing, compute and artificial intelligence (AI) for new services. Section 6 describes network realization, implementation, and management. Finally, Section 7 concludes this paper.

2. REQUIREMENTS FOR A SUSTAINABLE, INCLUSIVE, AND TRUSTWORTHY 6G PLATFORM

The ITU-R Recommendation for the IMT-2030 framework outlines the research targets for the technical requirements envisioned for 6G [1] expanding the need for bitrate, latency, area traffic capacity and reliability beyond the requirements of IMT-2020 (i.e. 5G). In addition, it adds new required capabilities associated with new usage scenarios, *Integrated Sensing and Communication (ISAC), integrated AI and communication,* and *ubiquitous connectivity*. The enhanced and new capacities of IMT-2030 are presented in tables 1 and 2 respectively. Please note that the range of values given for capabilities are estimated targets for the research and investigation of IMT-2030.

The Hexa-X-II project further developed use-case-related requirements for each use-case family [6]. In addition, Hexa-X-II has identified the need to go well beyond the technical requirements and *Key Performance Indicators* (KPIs) to address and quantify the value the 6G system can bring and introduced the concept of *Key Value Indicators* (KVIs).

Table 1 – ITU-2030 enhanced capabilities

Enhanced IMT-2020 capabilities for IMT-2030
Security and resilience (Enhanced protection against cyber threats and robust operation during disruptions)
Reliability (1-10^{-5} to 1-10^{-7})
Latency (Radio network latency reduced to 0.1–1 ms)
Mobility (speeds up to 500–1000 km/h)
Connection density (targets range from 10^6 – 10^8 devices/km²)
Area traffic capacity (targets include 30–50 Mbps/m² or more)
Spectrum efficiency (objective 1.5–3 times better than IMT-2020)
User experienced data rate (targets include 300–500 Mbps or higher, adaptable to various conditions)
Peak data rate (targets include 50–200 Gbps depending on specific scenarios)

Table 2 – ITU-2030 new capabilities

New capabilities of IMT-2030
Coverage (Improved cell edge service range through enhanced link budgets)
Positioning (High-precision positioning with accuracy of 1–10 cm)
Sensing (Advanced capabilities like object detection, localization, imaging, mapping, etc)
AI integration (AI-enabled features such as distributed learning, data processing and AI model inference, etc)
Sustainability (Reduced environmental impact through energy-efficient systems and resource optimization)
Interoperability (Seamless functioning across diverse systems with transparent standards)

2.1 Sustainability

Previous generations of mobile networks have primarily focused on superior performance and Return on Investment (RoI). However, as societies become increasingly reliant on digital services and mobile connectivity, their potential benefits have expanded, while costs, risks and vulnerabilities have also increased. As climate change and environmental sustainability have become some of the existential challenges facing our societies, it will be imperative to leverage the tools provided by a future 6G system to address these challenges. At the same time, the 6G system's own footprint in terms of energy consumption, material and resource use, and end-of-life waste must be minimized to avoid exacerbating the situation. This division can be classified as either *Sustainable* 6G or *6G for sustainability.* Furthermore, sustainability is often characterized as consisting of three pillars. Apart from *environmental sustainability*, *social* and *economic sustainability* are identified as equally important aspects that need to be addressed to make 6G a success. As many of these aspects can be diametrically opposed, e.g. optimizing throughput, minimizing latency, ensuring global coverage, with robust and secure operations, with minimal energy consumption and environmental impact, while ensuring economically sustainable operations, poses a complex multi-variable optimization problem.

2.1.1 Environmental sustainability

The most commonly known aspect of sustainability is *environmental sustainability*, in particular, energy efficiency and its relation to Greenhouse Gas (GHG) emissions and global warming. However, environmental sustainability encompasses much more, and includes, for example, the usage and waste of scarce materials and resources, pollution and impact on land and water use, as well as Life-Cycle Analysis (LCA) of all components. However, many of these aspects can only be assessed fully once the full 6G system is deployed.

On the other hand, 6G is poised to further enable the digital transformation of our societies, which can unlock unprecedented sustainability gains in a wide range of areas, improving efficiency and reducing waste in many different sectors.

2.1.2 Social sustainability

In addition to environmental sustainability, the United Nations (UN) Sustainable Development Goals (SDG) [8] identify many aspects that can be classified as social sustainability, such as *no poverty*, *zero hunger* or *reduced inequalities*. Although most of these targets are not directly addressed by 6G, digitalization and mobile connectivity can significantly improve their fulfilment. In Hexa-X-II, the concept of *social sustainability* is divided into two categories: *digital inclusion* and *trustworthiness*. Digital inclusion refers to all aspects of providing accessible and affordable access to digital services. This encompasses providing ubiquitous coverage through the integration of non-terrestrial networks and cost-efficient deployments to provide wide-area and indoor coverage, as well as ensuring that the devices and services remain affordable and easy to use. On the other hand, trustworthiness relates to the ability to provide reliable services that can address required characteristics, including specific security features, without interruptions and without compromising user privacy.

2.1.3 Economic sustainability

Even though, as a society as a whole, environmental and social sustainability are more important end goals, but without economic sustainability, technology will not be able to deliver that. If the user fees or hardware investments are too high in relation to the value it brings, the business models will be unsustainable and investors will not receive RoI; i.e. the technology will not be funded and, therefore, will not be developed or deployed. To avoid this, it is imperative to determine the detailed requirements and key technologies that there will be demand for and continuously strive for improved efficiency and cost reductions while fulfilling the requirements at an early stage.

2.2 A new use case and sustainability analysis methodology

The new challenge involves addressing all three pillars of sustainability, environmental, social and economic, to ensure the sustainability of the 6G system itself (i.e., sustainable 6G), as well as leveraging 6G to enhance sustainability in other sectors and verticals (i.e., 6G for sustainability). The current performance-based approach, which relies on technical and business KPIs, needs to be complemented by a value-based approach. To meet this challenge, Hexa-X-II has developed a new use case and sustainability analysis methodology that enables a structured and well-defined approach to addressing sustainability through use cases. Hexa-X-II began by formulating high-level Human and Planetary Goals (HPGs) related to all three sustainability pillars, such as ‘Curb climate change’, ‘Protect human rights’ or ‘Build long-term sustainable economic growth’ to name a few [6]. HPGs are fitted to the Information and Communication Technology (ICT) context and are connected to the UN SDGs [8]. Since HPGs represent specific goals, a 6G use case should aim to support or contribute to those goals. The influence of a particular use case and its associated technology on HPGs is expressed through Key Values (KVs). The process of establishing KVs involves identifying all potential positive aspects to be maximized (also known as sustainability handprints) and all potential negative aspects to be minimized (also known as sustainability footprints). Hexa-X-II recommends involving a representative set of stakeholders (of a given use case) to brainstorm all potential sustainability handprints and footprints. Although this process is subjective, by involving a representative set of stakeholders it should be possible to obtain a broad view and identify most KVs perceived as relevant as illustrated in Fig. 2. This exercise needs to be performed in all three sustainability pillars (i.e. environmental, social, and economic). As the obtained list of KVs may be huge, an assessment needs to be conducted to enable a focus on the most important KVs, which can be used to start the work. As the primary goal is to enhance sustainability and achieve the defined HPGs, it is necessary to have indicators that can evaluate the potential impact of these KVs. These indicators are referred to as KVIs, which may be qualitative or quantitative indicators. There is usually more than one indicator per KV. Furthermore, KVIs can be grouped into use case KVIs (to assess the impact of a use case or its application) and enabler KVIs (to assess the impact of the technical enabler, i.e. the 6G technology applied to a use case). The use case and sustainability analysis proposed by Hexa-X-II encompasses technical, business and sustainability evaluations. The first two are commonly known and are linked to technical KPIs and business performance. The last one adds sustainability considerations to the three sustainability pillars.

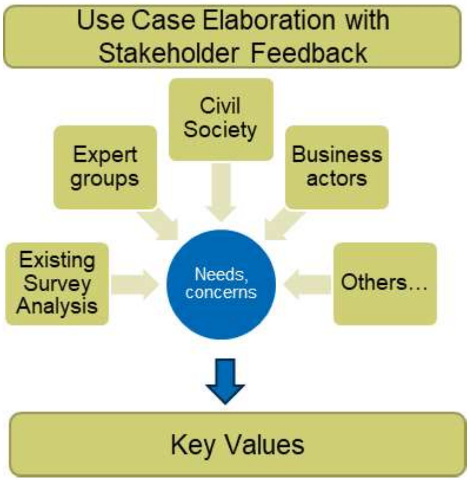

Figure 2 – Key Values finding

The involvement of various stakeholders, particularly civil society (e.g. through surveys), enables the consideration of specific perspectives and needs, leading to the identification of KVs in the realm of social sustainability. Sustainability analysis is an iterative process with stakeholders and business model analysis that allows for the continuous refinement of identified KVs. Although this process does not produce an exhaustive list of KVs, it effectively identifies the most relevant and expected KVs. Stakeholder input is also essential for establishing the relevant KVIs for each KV.

The use cases identified by Hexa-X-II were grouped in six use case families. For each family a representative use case was selected to reflect the characteristics of the family. The new use case and sustainability analysis was applied to all six representative use cases. As an example, for the representative use case 'Cooperating mobile robots' (of the 'Collaborative robot' family), the KV 'Resource efficiency' (from the environmental sustainability pillar) can be mapped to the KVIs

- 'Overall GHG footprint of the materials involved',
- 'Virgin materials / material used in products'
- 'Percentage of produced products remaining in stock / not possible to sell/scrapped' or
- 'Energy consumption per process/overall'.

This KV addresses the HPGs 'Preserve natural resources', and 'Minimize waste'. Similarly, the KV 'Safer work environment leading to fewer injuries' (from the social sustainability pillar) can be mapped to the KVIs

- 'Number of injuries at work',
- 'Level of severity of work-related injuries
- 'Number of days on sick leave'
- 'Perception of risk' or
- 'Accident insurance premium',

which in turn address the HPGs 'Protect human rights' and 'Foster decent employment'. A full analysis of the relation between KV, KVI and HPGs can be found in [6].

The distinction between use case KVIs and enabler KVIs facilitates the identification of KV components related to both the use case and 6G system. This differentiation clarifies which KVs are beyond the influence of 6G design, which can be shaped by its technical design. Because enabler KVIs are associated with the 6G system, they may be mapped to existing technical KPIs, lead to the creation of new KPIs, or remain classified as enabler KVIs. An example within the social sustainability domain is digital inclusion, which can be represented (among others) by an enabler KVI linked to the technical KPI of "coverage."

3. BLUEPRINT AND SYSTEM VALIDATION OF THE SUSTAINABLE, INCLUSIVE AND TRUSTWORTHY 6G PLATFORM

The end-to-end 6G system architecture builds on well-proven experience from previous mobile systems. Many of its core components such as the network layer, Management and Orchestration (M&O), pervasive functions and cloud-based network nodes, already exist in today's systems to a large extent.

Beyond connectivity, an open question in 6G design is whether and how the network should evolve into a programmable platform that exposes its capabilities to applications through well-defined interfaces. While the first Hexa-X project explored early architectural directions, the concrete articulation of this platform concept, together with how architecture simplification can be achieved alongside new capabilities, are contributions introduced and validated by Hexa-X-II. The 6G system architecture is formulated as a flexible and adaptable platform that supports diverse applications and verticals. This platform can facilitate the development and deployment of innovative solutions by a broad range of providers. To guide the evolution towards a sustainable platform, the Hexa-X-II project developed an E2E system blueprint, as shown in Fig. 3, detailing the necessary components of the 6G system.

Ten key principles underpin this blueprint: (i) supporting existing and novel services (including sensing and offloading) via Application Programming Interfaces (API); (ii) achieving full automation and optimization through AI and/or Machine Learning (ML); (iii) adapting to diverse network scenarios and topologies; (iv) ensuring scalability across various deployments; (v) prioritizing resilience and availability; vi) maintaining persistent security and privacy; (vii) employing cloud-optimized internal interfaces; (viii) separating network function concerns; (ix) simplifying network architecture compared to previous generations; and (x) minimizing environmental impact through sustainable design and practices. These principles are aimed at a more efficient, adaptable and sustainable 6G network.

The **infrastructure layer** comprises the hardware of the devices, access network, transport, compute resources and data storage required to operate the 6G network. However, all of these aspects are interconnected in a cloud continuum, providing scalability across a distributed infrastructure and allowing functionalities and data to be placed where best suited.

The **network functions layer** comprises functions that operate on the infrastructure layer. User Equipment (UE), Radio Access Networks (RAN), and transport Network Functions (NFs) resemble those in 5G. However, the 6G RAN is deployed as standalone, and the Core Network (CN) will re-use existing 5G Core (5GC) NFs, while introducing dedicated 6G NFs where justified. This supports a smooth transition to 6G, thereby avoiding the multiple options developed in 5G. In addition, as 6G is expected to introduce novel services, such as sensing, AI-as-a-Service (AIaaS), or compute offloads, new functionalities are required in the network to support this.

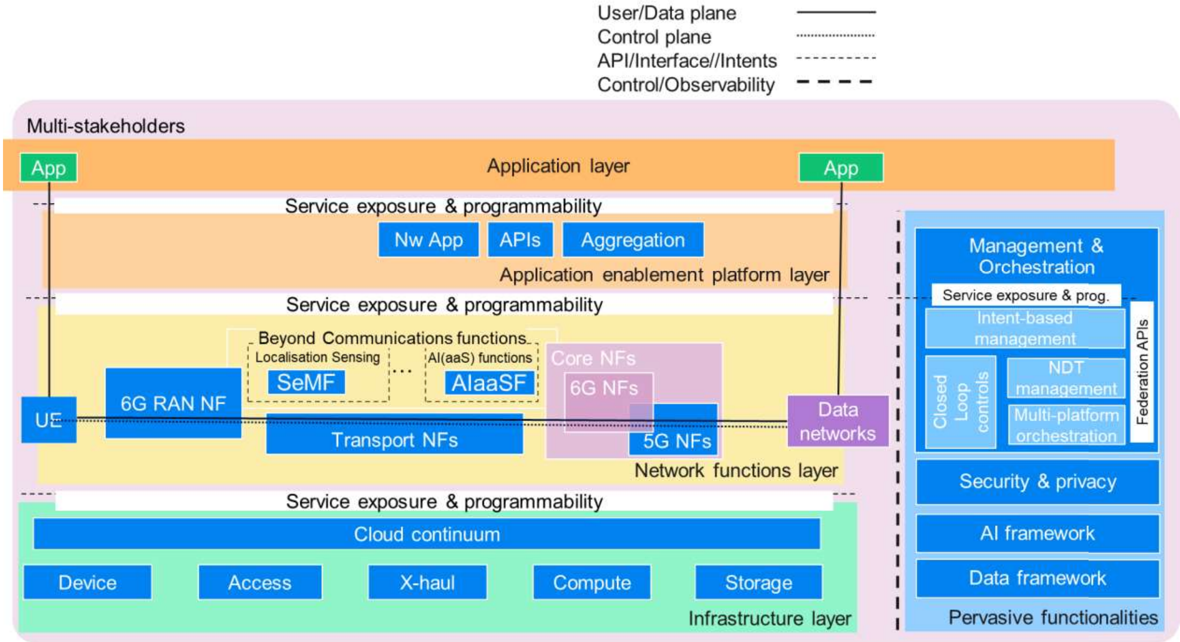

Figure 3 – 6G end-to-end architecture blueprint

The **application enablement platform layer** acts as the main access for service to the overall 6G system providing APIs, including simplified APIs, such as the Common API Marketplace and Repository Architecture (CAMARA) [9]. This layer also includes developer portals with the necessary developer tools, such as specifications, Software Development Kits (SDKs) and test environments, as well as network applications and aggregators that can provide aggregate services to application developers.

The **pervasive functionalities** represent functionalities that are embedded or interact with nearly all aspects of the network. The management and orchestration incorporate *intent-based management* of all network functionalities across multiple domains and platforms, while the *Network Digital Twin (NDT)* allows for monitoring and diagnostics of network operations. The *Data* and *AI frameworks* collect and analyse the data and control functionalities across the network. The AI and data collection functionalities are expected to consist of functions within, for example the network layer which can be controlled and initiated by the M&O.

For all layers, the *service exposure and programmability* framework allows functionalities and resources to be accessed and programmed from outside the layer.

Security, privacy and resilience aspects are incorporated in all layers to ensure that there are no security or privacy breaches or significant loss of functionality [10]. An analysis of the specific threats to security and privacy introduced by the new technologies considered as foundational for 6G was performed, along with key strategies to address these threats [11]. Consequently, specific *security controls* (pervasive functions that can be used in the context of any 6G enabler) have been identified, characterized and demonstrated. These include experimental features for Physical Layer Security (PLS), quantum-safe cryptography transition patterns, security and privacy patterns for Joint Communications and Sensing (JCAS), and privacy-preserving and explainability enhancements of AI/ML. In addition, the use of transparent notary services that provide reliable evidence for trustworthiness assessments has been considered, connecting it with the proposal of a network function for this assessment: the Level of Trust Assessment Function (LoTAF).

Hexa-X-II extended the foundations of its predecessor in four significant ways. First, it delivered a fully articulated, multilayered blueprint of a 6G platform with well-defined APIs enabling applications to seamlessly interact with the network. Second, it introduced a principled 5G-to-6G transition strategy through selective reuse of existing 5GC network functions combined with modular network function design, directly addressing one of the most critical practical challenges in 6G deployment. Third, Hexa-X-II also advanced the validation methodology of the enablers of the 6G system blueprint using an iterative, top-down and bottom-up design methodology [12]. The top-down approach derives a blueprint from use-case requirements and architectural principles; conversely, the bottom-up approach integrates 6G enablers based on the same principles. Naturally, a full validation of the entire 6G system necessitates a full-scale implementation. However, a comprehensive evaluation of individual 6G enablers (management and orchestration, network transformation, device capabilities, network control programmability and telemetry, radio protocols and sensing) using a knowledge graph and graph pruning framework guided by the objectives and constraints detailed in [13].

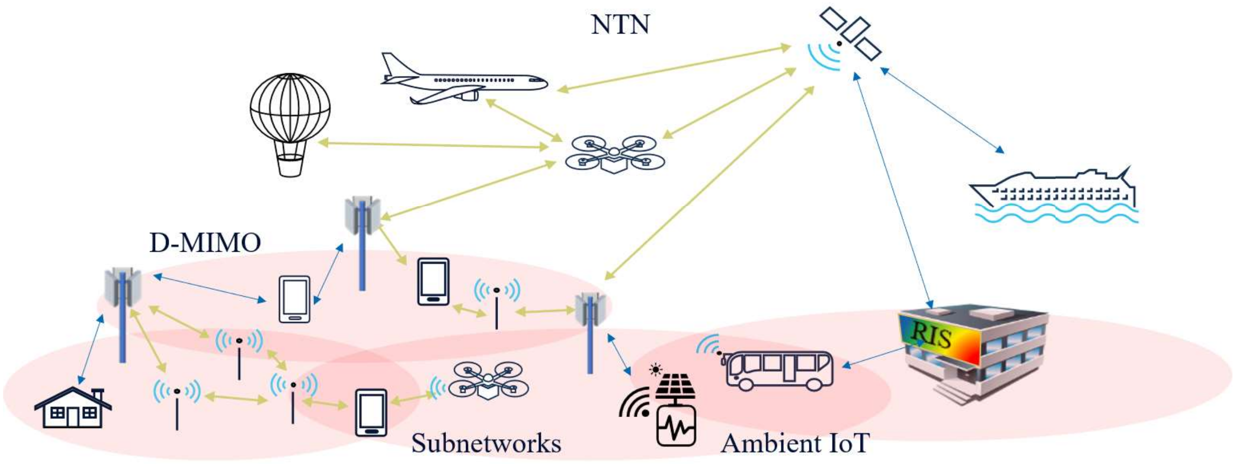

Figure 4 – Connectivity improvements for 6G

The evaluation considered KPIs (e.g. throughput, latency and scalability) and sustainability KVIs for the specific use case, enabler capabilities, design principles, enabler maturity and inter-enabler dependencies. Fourth, it provides concrete down selection evidence and iterative proof-of-concept validation. Approximately 30% of the initially proposed enablers were down-selected as not fulfilling either of these criteria for the collaborative robots use case, in favour of the remaining enablers. Proof-of-Concept (PoC) implementations, as detailed further in Section 6 progressively integrate advanced features from selected enablers, starting with single-domain management and orchestration and culminating in multi-domain configurations with flexible network topologies and novel radio and device capabilities. Feedback from these implementations iteratively refined the 6G enabler selection and overall E2E system blueprint.

4. ENHANCED CONNECTIVITY FOR 6G SERVICES

While 6G will include new services and functionalities, such as the 6G platform, AI, and sensing, it is of vital importance to improve connectivity for both existing and new services, as shown in Fig. 4.

6G networks require radio systems with enhanced capabilities that combine flexibility, scalability and sustainability, to support diverse applications. The Hexa-X-II project contributes to this vision by introducing a value-based holistic radio design framework that combines novel transmission techniques, advanced antenna systems, AI integration and spectrum management strategies across multiple frequency bands developed and validated through simulations and PoC demonstrations.

Section 4.1 discusses the improvement in coverage, with emphasis on the network of networks paradigm, including Non-Terrestrial Networks (NTN), subnetworks and Reconfigurable Intelligent Surfaces (RIS). The second connectivity improvement, highlighted in Section 4.2, concerns throughput and capacity, with features such as Distributed Multiple-Input and Multiple-Output (D- MIMO) or spectrum sharing and advances in multi-connectivity. Section 4.3 describes solutions for hardware for new frequency ranges such as Frequency Range (FR) 2 (FR2) (24.25 – 71 GHz), FR3 (7.125 – 24.25 GHz) and sub-terahertz (THz) (above 100 GHz). The last connectivity area focuses on low-power connectivity, as described in Section 4.4, presenting ultra-low-power devices for Internet of Things (IoT) use cases.

4.1 Coverage extensions

No single technical solution can bridge the coverage gap, a mix of solutions and network types are required to fully meet the extensive coverage demands of future 6G networks. This was already evident for 5G, with more MIMO networks, small-cell solutions, initial steps of incorporating NTN, etc. In 6G, the coverage will be even more important, ushering in the network of networks paradigm.

One important enabler for 6G is the inclusion of NTN from day one. The architecture of the 6G NTN should follow the proposed 6G architecture (especially concerning RAN).

Therefore, the most likely options for 6G NTN architecture are "Radio Unit on board," "gNB on board," or possibly some sort of hybrid solution. A Terrestrial Network (TN)–NTN fast switch connectivity procedure was proposed in [14] which enables a swift switch to NTN in cases where TN coverage is lacking. High-Altitude Platform System (HAPS)-mounted networks can be a viable architectural option for TN-NTN integration in areas that are not well covered by existing satellite connectivity [15].

An important aspect to improve coverage and performance is to evolve 6G subnetworks, for example, networks operating in smaller deployments (e.g. private networks, ad hoc networks, or personal networks). A new lightweight subnetwork control plane between one UE and other (less) capable UEs in a subnetwork is introduced. This concept can improve both performance and lead to battery savings. Another concept is the Unmanned Aerial Vehicle (UAV)-assisted flexible network. This is a concept for addressing scenarios such as disaster recovery and outdoor events using UAVs to extend regular networks. It provides seamless network integration with functions such as the Network Exposure Function (NEF), Access and mobility Management Function (AMF) and Policy Control Function (PCF) for authentication, resource allocation and mobility management to ensure service continuity.

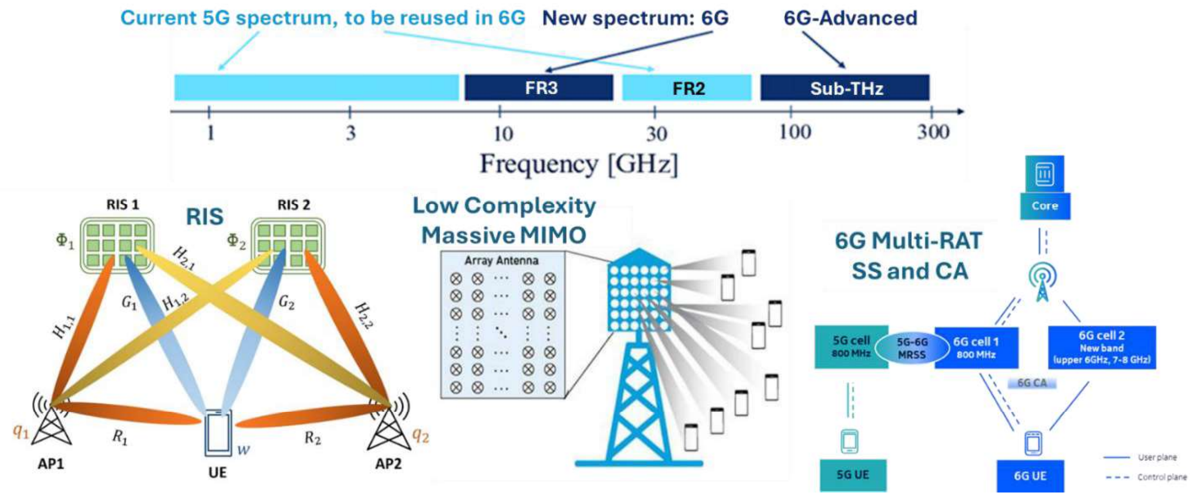

Figure 5 – Schematic depiction of various throughput improvement features of 6G: new spectrum, reconfigurable intelligent surfaces, low-complexity MIMO and multi-RAT spectrum sharing between 5G and 6G with 6G carrier aggregation

RIS is a promising solution to enhance coverage and support flexible deployments in 6G networks, particularly in environments with blocked line-of-sight. Evaluations showed that the RIS can boost performance even with low-precision phase shifters and contribute to cost-effective D-MIMO setups by reducing the number of active access points [16]. Reflection modulation techniques, particularly quadrature-based schemes with dedicated RIS subunits, can result in robust gains in both single and multi-user scenarios. RIS is also beneficial for backhaul links in Integrated Access Backhaul (IAB) networks affected by obstacles, such as foliage.

Despite these advantages, key challenges remain, such as acquiring accurate channel information under dynamic conditions, managing interference across operators, ensuring low power consumption and enabling real-time control.

The Hexa-X-II project also investigated the RIS control architecture and how 5G standards for Network Controlled Repeaters (NCRs) can be adapted for RIS control [17]. Three types of control architectures were investigated: (i) RAN-controlled, (ii) UE-controlled and (iii) third-party-controlled RIS. An RIS prototype consisting of 16 × 16 unit cell tiles was designed, fabricated, and tested. It operates between 24.25 and 27.5 GHz. Calibrated measurements in terms of bandwidth of influence showed a similar trend to the simulation results, with a shift of approximately 1 GHz in the control capabilities.

Furthermore, several mechanisms have been proposed to allow each network component to dynamically adapt to the context to ensure the expected enhanced E2E connectivity. One proposal focuses on improving connectivity of the transport networks. Improved utilization of transport resources and Quality of Service (QoS) can be achieved by creating an abstract view of transport resources and network functions, simplifying network management as the network scales. This can be combined with context-aware transport path selection, switching and packet processing using Programming Protocol-independent Packet Processor (P4) programmability based on the context (e.g. the QoS) provided by an SDN domain controller.

4.2 Throughput improvements

As the need for enhanced performance continuously increases, several technologies to increase the network throughput, both in the uplink and downlink, have been explored in the Hexa-X-II project, some of which are shown in Fig. 5. For instance, AI tools can be applied to improve the radio air interface in future wireless networks, especially in the context of complex scenarios where conventional model-based approaches fall short. AI can be applied to several key areas in 6G, such as designing flexible waveforms and coding to boost spectral efficiency and reduce overhead, compressing channel state feedback to support dynamic and multivendor environments, optimizing MIMO transmission with smarter power control, user pairing, pilot-free communication, and compensating for hardware imperfections such as amplifier nonlinearities. AI-based feedback compression can work across different vendors and can improve downlink throughput by lowering the signaling overhead. PoC demonstrations have shown that an E2E optimally learned AI-based transmission link that does not require pilot transmissions can achieve up to 30% throughput gain in emulated high-mobility conditions and 19.2% throughput gain in over-the-air tests [18]. These results confirm the value of AI-native air interfaces in making future wireless systems more efficient, scalable and adaptable.

The new 6G spectrum range in the FR2 (24.25 – 71 GHz), FR3 (7.125 – 24.25 GHz) and sub-THz bands (above 100 GHz) will require re-evaluation of the waveform and modulation schemes with a focus on power consumption, Phase Noise (PN), Out-Of-Band (OOB) radiation and energy efficiency. The results presented in [16] show that standard 5G NR waveforms, such as cyclic prefix Orthogonal Frequency Division Multiplexing (OFDM) and Discrete Fourier Transform-spread-OFDM (DFT-s-OFDM), remain suitable across these bands, offering backward compatibility without significant performance loss. In particular, DFT-s-OFDM with a larger subcarrier spacing (960 MHz and 1920 MHz) at 140 GHz and 300 GHz effectively mitigates the PN. Alternative constellations, including polar and Geometry-Shaped (GS) schemes, demonstrate greater robustness to PN and Doppler effects than the conventional M-Quadrature Amplitude Modulation (QAM). Zero-Crossing Modulation (ZXM) also proves to be more energy-efficient than M-QAM, particularly in wideband scenarios. Additionally, improvements to standard Low-Density Parity Check (LDPC) codes through optimized parity matrix design significantly reduce decoding complexity and latency, contributing to more efficient communication.

MIMO technologies, including multiuser MIMO, massive MIMO and D-MIMO, are important for meeting the performance requirements of 6G networks. For massive MIMO, hybrid beamforming designs supported by signal models that help select suitable beamforming settings can lower energy use while maintaining good performance.

In multi-user MIMO, simple data-driven methods can estimate the channel in situations where pilot signals are limited or the channel changes quickly. For low-resolution MIMO, 1-bit Analogue-to-Digital Converters (ADCs) and Digital-to-Analogue Converters (DACs) can result in significant complexity and energy consumption reduction, albeit at the cost of some performance reduction. However, the performance degradation can be minimized by: (i) optimizing the UE transmit powers and managing noise levels at the transmitter and (ii) improving the detection accuracy for higher-order QAM in massive MIMO systems by compensating for quantization distortion that leverages the expected received constellation to refine the signal recovery [19]. These methods helped reduce the effects of quantization and showed a performance close to that of full-resolution systems, making them a possible option for energy-efficient design.

An extremely large MIMO is required in sub-THz systems to meet link budget demands [16]. Link budget analysis at 234 GHz and 318 GHz showed that data rates of 10–100 Gbps are possible at approximately 80 m with a typical transmit power and 512 antennas. To comply with Electromagnetic Field (EMF) regulations, the expected compliance distance under worst-case assumptions range from 1.5 to 4.7 meters, based on existing safety guidelines. When realistic operating factors are considered, such as beam scanning and duty cycles, compliance distances drop to 0.6–1.7 meters, which is similar to FR2 systems.

D-MIMO, encompassing both coherent and non-coherent beamforming, is a viable solution to improve coverage and capacity in different deployment scenarios. Noncoherent methods are useful when detailed channel information is not available. The use of movable and rotating antennas adds flexibility to the system and helps improve signal quality, especially in complex environments. Analogue fronthaul can support better timing and signal quality, helping to reduce errors and improve link reliability. In addition, D-MIMO deployments can reduce the EMF exposure. For example, simulation results at 3.5 GHz showed that the measured exposure levels were below 0.1% of international safety limits [16].

Hexa-X-II proposes to only have one architectural option for Multi-Connectivity (MC) in 6G, based on an improved Carrier Aggregation (CA) solution using Radio Units (RUs) connected to the same gNB using a lower layer split and where the RUs can be non-co-located. The main reason for basing 6G MC on CA is that CA is believed to be more efficient than Dual Connectivity (DC). However, to make the 6G CA more reliable, new functionalities may be needed, for example, functionality for better reliability and improved uplink and downlink decoupling. In [14] proposals for coverage extension or increased reliability via Wireless Local Area Network (WLAN)-based UE relays for remote UEs were also described.

Spectrum sharing and coexistence are key areas for ensuring efficient use of available frequencies across different technologies and services. Mechanisms such as Multi-Radio

Access Technology (RAT) Spectrum Sharing (MRSS) enable the coordinated operation of 5G and 6G networks, with initial results showing less than 10% capacity loss in worst-case scenarios. For latency-sensitive use cases, a two-step coordinated access scheme using a low-band RAT to assist high-band access can reduce the access latency. Simulation studies reported in [16] demonstrated access latencies as low as 100–150 µs, which guaranteed the lower end of the 6G latency target.

4.3 Hardware for new frequency bands

Novel transceivers are required to satisfy the evolving data rate and energy efficiency requirements of 6G by exploiting the available bandwidth in the FR3 and sub-THz (above 100 GHz) frequency ranges. Hexa-X-II has studied the design of transceivers in both the FR3 and sub-THz bands, studying and solving a variety of challenges, such as power amplifier nonlinearities and phase noise mitigation [16]. The project further investigated the UE power constraints in the FR3 band to satisfy the EMF exposure limits. The power consumption of the analogue and digital components of the sub-THz transceivers was investigated. This allows dimensioning the transceiver in terms of energy efficiency, trading off between power consumption and the maximum data rate [20]. Finally, a novel sub-THz transceiver based on resonant tunnelling diodes was investigated, offering a compact and low-power alternative to the classical transistor-based approaches.

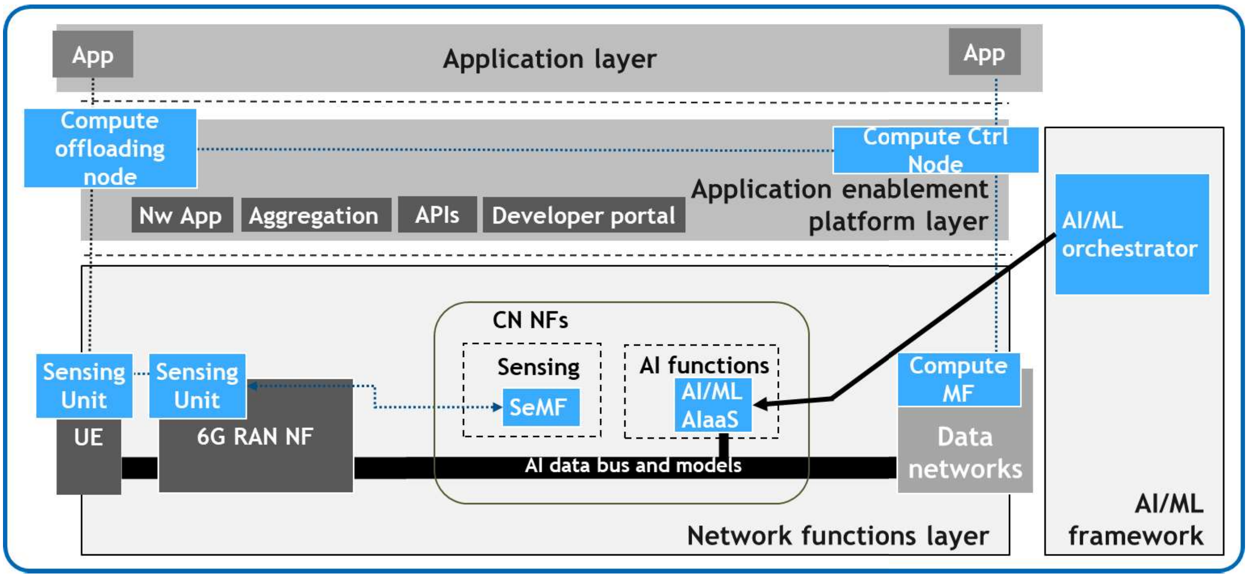

Figure 6 – AI, Sensing and compute services depicted on the 6G E2E system blueprint

4.4 Low-power connectivity

6G is expected to incorporate ultra-low-power connectivity capabilities for ambiently-powered IoT devices (also known as “zero energy devices”). Such devices make use of backscatter, RF Wireless Power Transfer (RF-WPT), or ambient energy harvesting, and have a power budget on the order of milliwatts or less [21]. Hexa-X-II presented several zero-energy device prototypes, including an active battery-less device relying on solar power, a passive ambient backscatter device developed using a cost-effective printed electronics manufacturing process, and a multisource energy harvesting circuit with built-in power monitoring capabilities [16]. Energy-efficient lightweight protocols have been proposed to support the connectivity of zero energy devices. The benefits of fast uplink grant-based channel access in terms of scalability and energy efficiency were demonstrated, as compared to random and grant-free access [22]. A backward-compatible protocol with a reduced signaling overhead was designed to avoid PDU session establishment (an energy-consuming and complicated procedure). Finally, an energy-aware uplink/downlink scheduling protocol was presented, which adapts the data transmission and reception rates of devices based on the harvested and stored energy.

5. NETWORK SENSING, COMPUTE, AND AI FOR NOVEL DIGITAL SERVICES

The 6G platform is expected to support several novel services, with capabilities beyond connectivity. In particular, network sensing, compute offloading and AI will be prominent features in 6G, which may require modifications to their architecture, functionality or implementation, as shown in Fig. 6.

5.1 Sensing

Supporting sensing in 6G requires new functions, such as handling sensing requests from applications and functions, routing through the Sensing Management Function (SeMF) in the core network to the sensing units (UEs and BSs), and sensing control near gNBs [14]. In addition, the sensing data must be processed using a processing function and the exposure of the processed sensing data. The Hexa-X-II project has explored JCAS [23], reusing communication signals for sensing and localization in monostatic and bistatic setups, including UE-based sensing without centralized infrastructure, as illustrated in Fig. 7. Indoor bistatic sensing achieved sub-10 cm accuracy at 100 GHz in 85% of cases with comparable performance at 60 GHz (80%) and 10 GHz (58%), with outdoor UAV tracking showing position error dependent on coverage and geometry from a few centimetres to over 4 m in low-coverage areas.

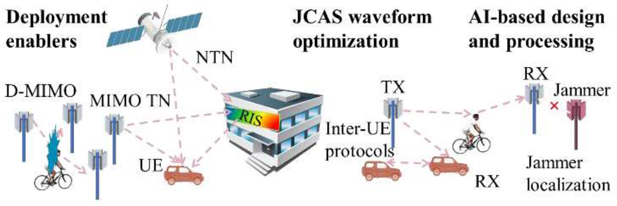

Figure 7 – Holistic JCAS: using common infrastructure and signals for communication and sensing functions

Enhancements to OFDM waveforms and AI-assisted signal design improve sensing range and accuracy. RIS and NTNs further enable sensing in obstructed environments, with improved satellite handover and control signaling to enhance positioning. Energy analyses confirmed the feasibility of the bistatic JCAS within practical power budgets. Security and privacy concerns are addressed through secure sensing protocols, jammer localization and privacy-preserving analytics, ensuring trustworthiness aligned with 6G goals.

5.2 Compute

The compute offloading architecture proposed for 6G is loosely integrated and over the top, avoiding major modifications to the RAN and Non-Access Stratum (NAS) protocols for faster market adoption. However, new procedures are required via Application Functions (AFs) and NEF for offload node discovery, registration, and management [14]. In the Hexa-X-II project, a scalable E2E Extended Reality (XR) testbed was developed, which enabled offloading of video rendering from an Augmented Reality (AR) device to the network using adaptive rate matching [24].

5.3 AI/ML

To integrate AI resources within 6G networks and for consumers, three interconnected enablers are considered essential: Data Operations (DataOps), Machine Learning Operations (MLOps) and AIaaS [14]. DataOps ensure reliable, scalable data pipelines by aggregating data across network nodes (UEs, RAN and CN) using protocols such as Prio within Network Data Analytics Function (NWDAF), supporting intelligent air interface models. MLOps operationalize machine learning workflows, supporting techniques such as federated learning and split learning, and enabling scalable distributed AI deployment. AIaaS builds on MLOps to deliver AI-native services with APIs for data exposure and QoS, dynamically orchestrating AI models to meet user and network demands [14].

Efficient 6G devices require scalable hardware with dedicated AI accelerators. Hexa-X-II developed a low-power accelerator optimized for inference, achieving 6.144 Tera Operations Per Second (TOPS) at 1 GHz with 0.65 TOPS/W energy efficiency [16]. In addition, the Hexa-X-II smart network management framework [25] integrates AI/ML into the orchestration and management of computing and digital services. It uses decentralized orchestration with AI/ML for proactive resource allocation across the extreme edge and cloud, multiagent systems for cluster coordination and AI-driven zero-touch control loops for real-time adaptive automation. Monitoring also leverages AI/ML for advanced decision making on heterogeneous data, with privacy-preserving analytics protecting sensitive information. Security is enhanced by AI/ML agents defending against adversarial attacks [26], [27].

6. EFFICIENT NETWORK REALISATION, IMPLEMENTATION AND MANAGEMENT

Three PoC systems demonstrated 6G network management capabilities in challenging scenarios. PoC #A focuses on automated inventory management in a warehouse using autonomous robots and drones to optimize service placement and resource allocation [28]. The PoC results demonstrated improvements in the performance of the management and orchestration processes, reduced energy consumption, and increased trustworthiness. PoC #B extended this work by incorporating the AI-assisted end-to-end lifecycle management of latency-sensitive services across a distributed computing environment [26]. Specific advancements include multi-cluster orchestration using multiagent reinforcement learning for service migration and scaling, zero-touch automation via reactive closed-loop control in a cobot-based video surveillance scenario, and enhanced warehouse inventory management with business intent-driven resource allocation and flexible topologies. The PoC confirms that multi-cluster orchestration combined with closed-loop automation enables efficient lifecycle management of latency-sensitive services, as well as gains in trustworthiness and energy efficiency. A third PoC (#C) further integrated a multidomain orchestration framework, leveraging an integration fabric for scalable and secure communication [24]. This PoC also advanced closed-loop automation to include AI-driven predictive analytics for proactive resource planning and implemented intent-driven orchestration using a business intent hierarchy. The PoC demonstrated that integrating multidomain orchestration and predictive analytics significantly enhances scalability, reliability and proactive resource management.

Altogether, these PoCs showcased the system's ability to operate intelligently and securely across multiple stakeholder environments while supporting future 6G services, such as XR and robotic collaboration. They validated the technical advancement but also demonstrated the alignment with broader societal, environmental and economic goals, paving the way for real-world 6G applications.

Several implementations have been performed, focusing on the Hexa-X-II smart network management framework [25]. Some aim to showcase how certain technical enablers in the framework itself can be implemented, while others are implementations *based on* the framework, targeting the showcasing of how this management framework could be used in practice.

Among the former, different solutions have been implemented associated with real-time zero-touch control loop automation and coordination systems, including (i) an AI-enabled real-time zero-touch control loop analysis function based on an Adaptive Neuro Fuzzy Inference System (ANFIS) [29], (ii) a penalty-based management of concurrent service control loop, addressing the challenge of managing distinct closed loops running different services with unique KPIs to be fulfilled, (iii) a conflict detection system for reactive activities that may be requested by closed loops, intended to identify potential conflicts between different management plans and to ensure that the best combination of these plans is selected for execution, and (iv) an algorithm to support the human-assisted training of cognitive closed loop functions for network automation based on casual reasoning on information taken from the network. Other implementations targeting how certain technical enablers in the framework can be implemented are sustainable MLOps assets aimed at supporting different stakeholders (operators, software providers, data providers, AI/ML model providers, etc.) to train and deploy AI/ML-based artefacts in a highly automated manner considering sustainability metrics, as well as certain implementations for the Open-Source ETSI TeraFlowSDN asset [30].

Regarding the implementations *based on* the management framework, different demos have been implemented: (i) an implementation showcasing the Management Capabilities Exposure (MCE) functionality, where the MCE concept is applied to two different use cases: the integration of a vertical industry, and a failure detection and recovery scenario; (ii) a demo showcasing the Management and Orchestration (M&O) of network services on the network continuum, with different M&O scenarios that include the proactive migration of service components, MLOps techniques, services federation, and trust-based management; (iii) a demo showcasing the functionality allocation feature, and how it could be applied to a cobot-powered warehouse inventory system; (iv) an ML-based configuration recommendation system for energy saving, which targets a fully automated CL-based solution for fixing flow misconfigurations in a scalable way in deterministic networks by taking autonomous decisions for network cells to disconnect or wake-up; (v) a resource assignment demo for federated learning-based systems, which extends the capabilities of the service and resource management functions described in [31] enabling the network to efficiently allocate compute resources for federated learning; (vi) a demo showcasing a flow reconfiguration scenario via dynamic monitoring and closed control loops for deterministic networks [32]; (vii) another demonstration targets the concept of edge convergence over federated resources, targeting the exploration of the capabilities of the CAMARA EdgeCloud APIs [33] in the management of computing resources in the network continuum, and the possibility of extending them to be used with federated resources of external administrative domains.

7. CONCLUSIONS, AND OUTLOOK

The Hexa-X-II project has made significant steps towards realizing a sustainable, inclusive and trustworthy 6G platform by advancing foundational technologies, architectural blueprints and validation methodologies necessary for next-generation mobile networks. Building on the vision and groundwork laid by its predecessor, Hexa-X, this project has developed a comprehensive E2E system architecture blueprint that integrates enhanced connectivity, advanced sensing, compute offloading and AI-native capabilities, all designed with a strong emphasis on environmental, social and economic sustainability. The project's iterative design and validation approach, which combines top-down requirements with bottom-up enabler integration, has ensured a flexible, scalable and secure 6G system blueprint. Through numerous PoC demonstrations, Hexa-X-II has showcased practical implementations of smart network management, zero-touch automation and multi-domain orchestration, highlighting the feasibility and benefits of 6G technologies in real-world scenarios. Naturally, several of the implementation challenges will only arise once the 6G systems begin to be deployed at large scale, such as validation of the multi-stakeholder, end-to-end system, or implementation of the proposed novel hardware such as sub-THz frontends, RF amplifiers, zero-energy devices, etc., as well as the constraints on capacity, latency and energy for compute at the edge for example, for AI-native functions. Similarly, the integration fabric and intent-based/AI orchestration reduce some complexity but add coordination overhead, whereas joint communication and sensing, flexible topologies and trust assessment show promise but require larger testbeds and further maturation before large-scale, multi-vendor deployments can be considered production-ready. These aspects were not possible to address due to the limited time and budget of the Hexa-X-II project. Ultimately, Hexa-X-

II sets a robust foundation for the upcoming standardization, development and deployment of 6G systems, not only providing envisioned use cases and technologies, but also addressing environmental and social sustainability challenges. However, many challenges remain, such as

– developing energy efficient AI at scale that consumes low power during training as well as inferencing,
– exploring how mature AI models can best optimize and operate the 6G networks,
– designing robust end-to-end orchestration for distributed, multi-stakeholder environments handling intent-based policies, scalable deployments, resilient and federated MLOps and verification for SLA/Latency guarantees,
– maturing JCAS deployments and applications to explore how they can best be integrated into the 6G system,
– investigating socio-economic-environmental sustainability trade-offs based on the developed 6G KVIs,
– PA design and use of non-CMOS technologies for FR3 transceivers,
– need for standardized protocols for both active and passive ambient IoT devices,
– carrying out the required standardization and productization.

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