Hexa-X

The European 6G flagship project

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***Abstract*— Hexa-X will pave the way to the next generation of wireless networks (Hexa) by explorative research (X). The Hexa-X vision is to connect human, physical, and digital worlds with a fabric of sixth generation (6G) key enablers. The vision is driven by the ambition to contribute to objectives of growth, global sustainability, trustworthiness, and digital inclusion. Key 6G value indicators and use cases are defined against the background of technology push, society and industry pull as well as objectives of technology sovereignty. Key areas of research have been formulated accordingly to include connecting intelligence, network of networks, sustainability, global service coverage, extreme experience, and trustworthiness. Critical technology enablers for 6G are developed in the project including, sub-THz transceiver technologies, accurate stand-alone positioning and radio-based imaging, improved radio performance, artificial intelligence (AI) / machine learning (ML) inspired radio access network (RAN) technologies, future network architectures and special purpose solutions including future ultra-reliable low-latency communication (URLLC) schemes. Besides technology enablers, early trials will be carried out to help assess viability and performance aspects of the key technology enablers. The 6G Hexa-X project is integral part of European and global research effort to help define the best possible next generation of networks.**

Keywords—6G, B5G, wireless, 6G vision

I. INTRODUCTION

During 2030 and beyond, Europe and the world will face opportunities and challenges of growth and sustainability of tremendous magnitude; to pro-actively tackle issues of green deal efficiency, digital inclusion and assurance of health and safety in a post-pandemic world will be key. A powerful vision is needed to connect the human world of our senses, bodies, intelligence and values; the digital world of information, communication and computing; and the physical world of objects and organisms, firmly anchored in future wireless technology and architectural research. The Hexa-X vision calls for an x-enabler fabric of connected intelligence, networks of networks, sustainability, global service coverage, extreme experience, and trustworthiness.

Wireless technologies are of critical relevance for our society and economy today; their importance for growth will continue to steadily increase with fifth generation (5G) and its evolution, enabling new ecosystems and services motivated by strongly growing traffic and trillions of devices [1-4]. The Hexa-X project ambition includes to develop key technology enablers in the areas of a) fundamentally new radio access technologies at high frequencies and high-resolution localization and sensing; b) connected intelligence though AI-driven air interface and governance for future networks, and c) 6G architectural enablers for network disaggregation and dynamic dependability.

Europe has been a leader in wireless network technologies for decades. It is now critical to initiate and consolidate our efforts in the joint research ambition of a "flagship" project to maintain and strengthen the global industry leadership for the 6G era. The Hexa-X flagship is a unique effort of vision, and an opportunity for disruptive impact in sustainable growth and technology experience leveraging the trustworthiness in Europe and worldwide.

This paper presents the European 6G flagship project Hexa-X that started beginning of January 2021 with a planned duration of 2.5 years. This is a first milestone in the development towards 6G, see Figure 1.

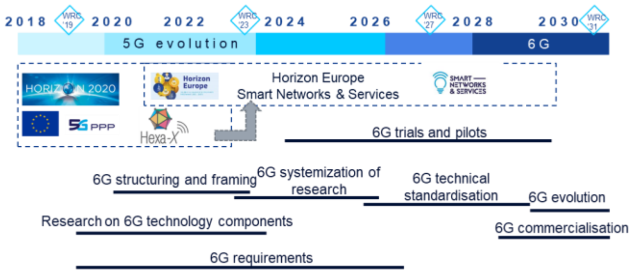

Figure 1. Expected 6G timeline.

The project brings together key industry stakeholders and academia in Europe to take the lead in advancing 6G. The consortium includes top representatives of all stakeholders involved in this value chain, ranging from vendors, operators, IT industry, and high-tech companies. They together create a unique ecosystem capable to realize the Hexa-X main objectives and take on a global leadership role, see Figure 2.

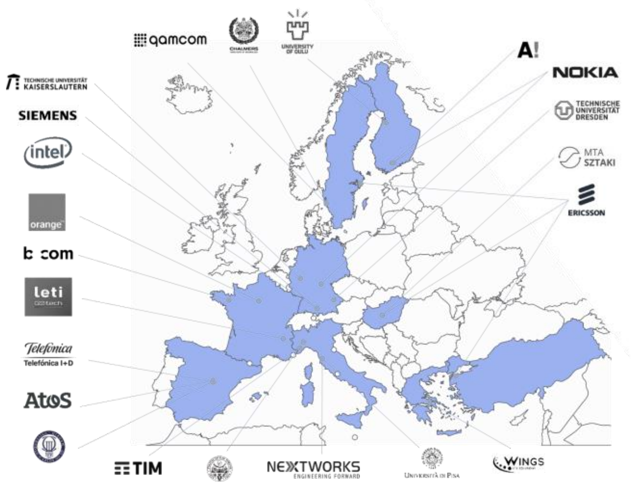

Figure 2. Hexa-X participants and countries in the consortium.

Latest information is available from the project website https://hexa-x.eu/.

The rest of the paper is outlined as follows. Section II presents the vision of the project including key research challenges, which was jointly defined by the 25 participants in Hexa-X. Section III introduces the planned demonstrations that will showcase the tackling of research challenges, while Section IV presents the project in the context of the external activities towards the 6G definition for establishing its role as a flagship project within the European 6G research and industry community.

II. PROJECT VISION

Hexa-X will define a vision for the 6G connectivity forming the backbone of a hyper-connected, data-driven society in beyond 2030 where sovereign citizens will be supported by a network of senses, autonomous things, and an increasingly intelligent environment. Protection of climate and environment, resource efficiency, enabling participation and inclusion, improving productivity, ensuring trustworthiness, and creating new business opportunities are key design criteria. To frame the challenges of research for communications in the 2030s, Hexa-X starts from the bold vision to connect and enhance interactions of the three worlds, Human, Physical, and Digital, as illustrated in Figure 3. The 2030s will offer tremendous opportunity and challenge to society and mankind worldwide. Contributing to objectives of global sustainability, trustworthiness and digital inclusion are a key part of the Hexa-X vision for the 6G era.

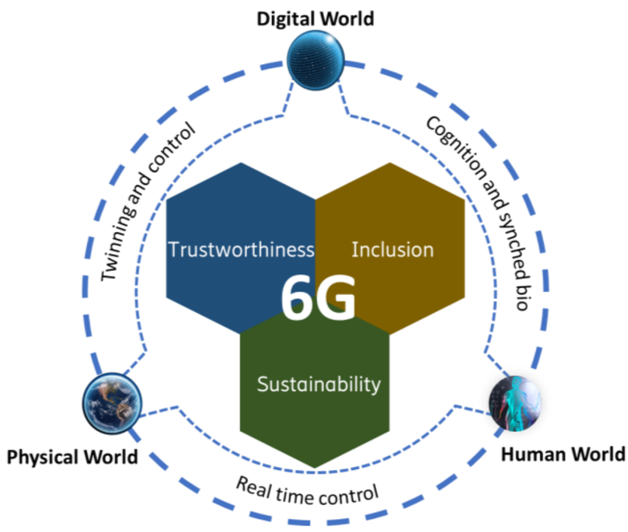

Figure 3. Hexa-X vision of 6G

The Hexa-X key challenges aiming at both technology advancement and societal values of research have been formulated accordingly: **Connecting intelligence**, cognitive and physical augmentation with the human in control; **Network of networks**, integrating millions of sub-networks with resources such as communication, data- and AI- processing, and localization and sensing optimizing the connectivity at different scales; **Sustainability**, addressing the critical challenges such as energy efficiency and CO_2 footprint of network infrastructure [5] and to be complemented by innovation across industry sectors and use cases [6]; **Global service coverage**, where digital inclusion will be a key driver and enhanced by efficiency and affordability of solutions extending the coverage by employing non-terrestrial networks and enhanced integrated access/backhaul (IAB) nodes; **Extreme experiences**, pushing the boundaries of mobile connectivity in terms of bit rate, latency, capacity, and localization accuracy and co-design for sensing; **Trustworthiness**, building on novel technology building-blocks and trust foundations to assure security, privacy, reliability, and resilience for the networks of the 6G era.

To address the 6G research challenges, the Hexa-X project will design, develop, and evaluate a wide range of technological enablers, illustrated in Figure 4 a) **Radio performance** including advances in radio access technologies towards Tbps and high resolution localization and sensing by exploring sub-THz frequencies [7]. This includes aspects such as performing measurements and developing channel models as well as designing waveforms, modulations and beamforming techniques taking the hardware limitations of sub-THz components into account. It will also consider cell-free distributed MIMO deployments at all frequencies for scalable network densifications. Joint communication and sensing will allow leveraging on existing infrastructure to employ ubiquitous sensors for localization, mapping and sensing. b) **Connecting intelligence** by means of native integration of artificial intelligence (AI) for e.g. network orchestration and service management as well as dynamic data-driven air-interface design. This will consider how AI can automate and optimize network performance at all levels while maintaining sufficient level of explainability and data privacy. and c) **Network evolution and expansion** to increase the flexibility and efficiency of networks, including specific verticals as well as facilitating the application of intelligent agents in the network by identifying and addressing roadblocks in the design. This includes exploring extensions of the Service Based Architecture (SBA) to the Radio Access Network (RAN) as well as flexible integration of the plethora of access types, e.g. non-terrestrial network (NTN), device-to-device (D2D), mesh networks, etc. The specialty networks will consider applications of digital twins and human-machine interactions (HMI) in industry and society at large and enhancements to the latency and reliability of the communication by considering communication-control-co-design.

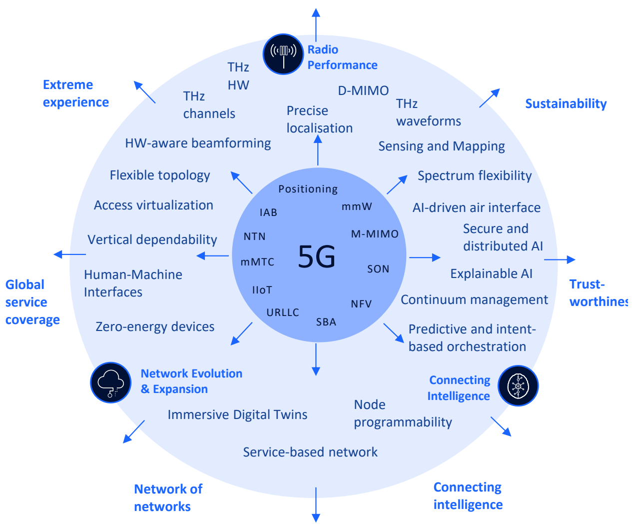

Figure 4. Hexa-X ambitions going from 5G to 6G.

These technological enablers will be tied together in a framework — the **x-enabler fabric** — which will be translated into a roadmap for future a 6G end-to-end system.

A. *Key use cases*

Hexa-X will identify use cases stemming from this vision and addressing the above six research challenges. In an initial step, five use case families have been identified, clustering various representative use cases as illustrated in Figure 5. As sustainability is a main driver in Hexa-X, this challenge is addressed by all families, and in particular in a dedicated one, **Sustainable development** where aspects such as global environmental monitoring can facilitate sustainable development and cost-effective extreme performance connectivity to underserved regions can help bridge the digital divide. Trustworthiness is also an underlying challenge for all use case families, and more specifically for **Local trust zones** where local sub-networks catering to use cases requiring utmost performance, reliability, or security with assistance from a wide-area network. **Telepresence** clusters use cases characterizing extreme experience, where users can experience virtual, augmented, or merged realities with all senses, blurring the line between the physical and the digital world. **Massive twinning**" involves different use cases building on the interconnection between the physical and digital worlds, where digital representations of physical objects and entities in all aspects of industry and society can be used to plan, monitor, manage, and predict their behaviour. This could help to optimize operation of cities or industrial complexes as examples. "**From robots to cobots**" encompass use cases leveraging on the advent of the AI functionalities, involving various robots or autonomous systems which closely collaborate with other robots or human operators. Use case identification will continue during the lifetime of the project to refine and upgrade with relevant use cases.

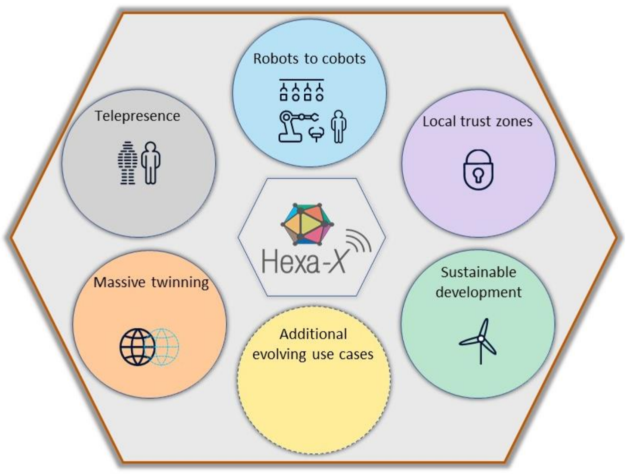

Figure 5. Hexa-X use cases families

B. *Key values and performance indicators*

In a 6G world, some of the existing key performance indicators (KPIs) will need to be extended to capture future needs, such as bit rate or connection density. But merely extrapolating the KPIs will not suffice to frame the 6G agenda of research, which needs to be considered end-to-end (E2E) to include some other aspects, such as energy efficiency or service availability. To scope 6G, key-value indicators (KVIs) will represent the dimensions of impact that go beyond the scope of deterministic performance measures into full account, such as sustainability, digital inclusion and trustworthiness. It is expected that 6G systems will incorporate novel aspects, such as integrated sensing, artificial intelligence, local compute-and-storage, and embedded devices. These aspects will both facilitate enhancements to existing KPIs, as well as require a range of new KPIs and KVIs which have not traditionally been associated with mobile networks, such as sensing accuracy, computational round-trip-time, AI model convergence time, etc. Moreover, as a foundational objective for all future technology, the United Nations Sustainable Development Goals (SDGs) will be important for Hexa-X and as an inspiration as well as a measuring stick. The Hexa-X project foresee a substantial enabling impact on most of the SDGs. Pull from new use cases and push from novel technologies will also impact a set of expanded and new set of capabilities in 6G, as illustrated in Figure 6.

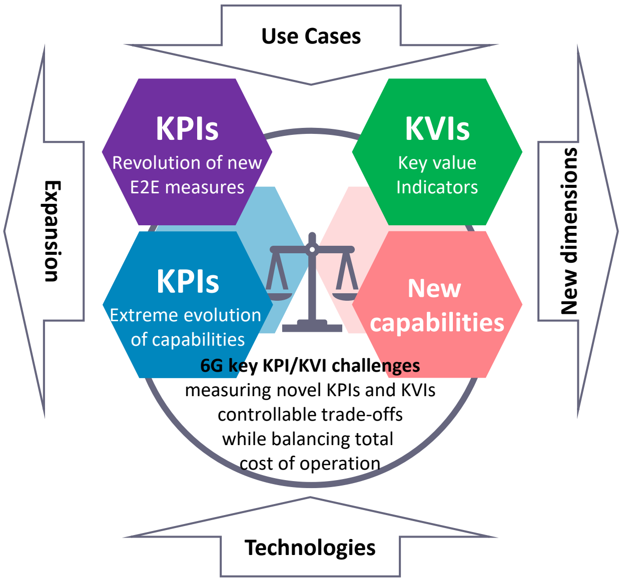

Figure 6. Key value and performance indicators.

III. DEMONSTRATING 6G

The Hexa-X project will showcase the technological enablers and the progress towards accomplishing the 6G vision by setting up five separate demonstrations (demos).

Demo #1: 6G OTA - Waveforms in action: The demo verifies selected 6G candidate waveforms designed in Hexa-X and evaluates their performance over the air (OTA) in real-world environment with non-ideal radio frequency (RF) and radio channel as seen in Figure 7. The work will be carried out by connecting three testbeds provided by Qamcom, University of Oulu, and TU Dresden within the project in three progressive phases using 6G waveform candidates: a) Non-real time demonstration of radar sensing performance at mmW; b) Non-real time demonstration of communications and sensing performance at 200 GHz region; c) Real-time demonstration of communications and sensing performance. The testbeds verify and evaluate the candidate waveforms in realistic environment to help select the best candidates for future studies. As waveforms strongly impact also RF transceiver performance and power consumption the results will be applied to radio system design for communications and sensing in all aspects studied in the Hexa-X project.

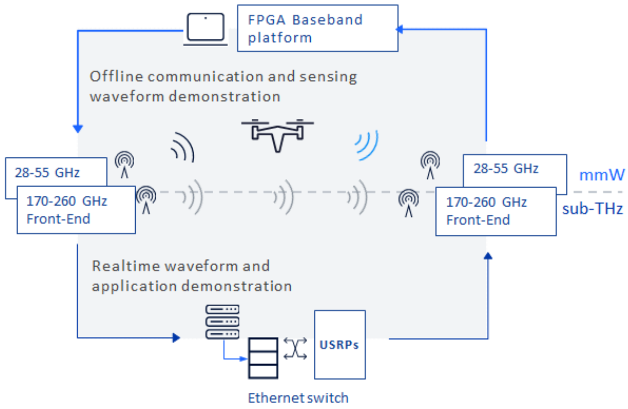

Figure 7. 6G OTA - Waveforms in action, demo #1.

As sensing will be a prerequisite for many 6G use cases, such as Telepresence or Massive Twinning, to get an accurate digital representation of the actors and environment, this demo will showcase the potential for joint communication and sensing allowing for abundant cost-effective sensing by re-using existing hardware and infrastructure. As this represents a new capability integrated into the mobile networks, the demo will mostly address KPIs associated with sensing, e.g. accuracy and resolution.

Demo #2: FED-XAI – Federated XAI demo:

Hexa-X will demonstrate the developed framework for the federated learning of eXplainable AI (FED-XAI) models [8], along with the related signalling, using a real-time network emulator and real terminals as seen in Figure 8.

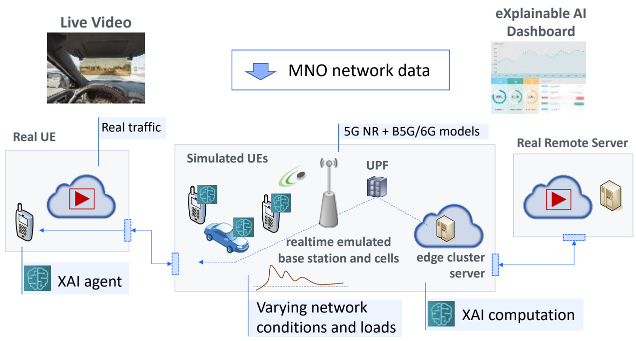

Figure 8. FED-XAI – Federated eXplainable AI demo, demo #2.

End-user agents will sense local data and collaboratively train an XAI model with the goal to make predictions, e.g., on Quality of Service (QoS), without exposing their data to other agents. The model obtained from the federated learning process will be transferred to other agents, which will adapt it locally to perform predictions. Moreover, an edge side-agent, federated with the end-user ones, and possibly with agents from other Mobile Network Operators (MNOs), will display in real time a dashboard, showing the predicted QoS in the federated domain and explaining how these have been achieved. As AI is expected to play a crucial role in 6G, in network operations and in end-user applications, it will be imperative to maintain the explainability and privacy to avoid introducing new cyber-threat vectors. This demo will showcase examples of connected intelligent machines from the use case family "From robots to cobots". As this represents a new capability integrated into the mobile networks, the demo will mostly address KPIs associated with AI/ML, e.g. response time and explainability.

Demo #3: Flexible topologies (FLEX-TOP) for efficient network expansion and complementary means for global coverage, sustainability and trust:

The demo will deliver insights on the efficiency of the flexible topologies concept as seen in Figure 9.

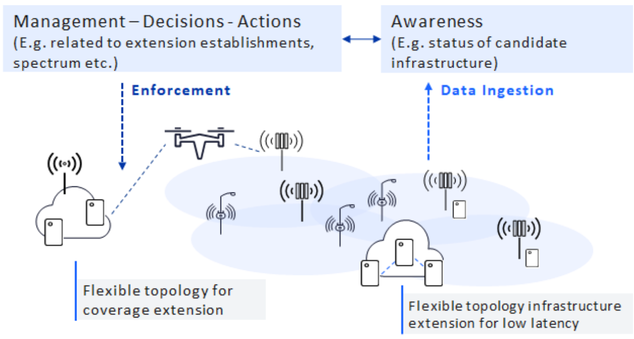

Figure 9. Flexible topologies (FLEX-TOP), demo #3.

The key benefits of a flexible topology will be coverage extensions; service provision with lower latencies, since local structure is terminated at the infrastructure edge; security as the engagement is limited to selected devices; and lower energy consumption at the infrastructure. This will be applicable to e.g. the sustainable development use cases, where cost-effective global service coverage is a prerequisite for affordable digital inclusion and global monitoring of system critical environmental indicators. The management of the flexible topology will leverage on mesh/ad hoc/device-to-device (D2D) networking, disaggregated devices with the ability to flexibly allocate functionality or computing resources, as well as usage of ultra-high spectrum also in coordination with the infrastructure. As this demo intends to show the application of the flexible topology which is applicable to the broad sustainability KVIs, the primary KPIs tested in the demo will be the traditional KPIs of throughput, latency, and reliability as the sustainability targets are not testable at this small scale.

Demo #4: Extreme performance in handling unexpected situations in industrial contexts:

The demo will target the handling of unexpected situations in industrial environments through 6G enablers as seen in Figure 10, involving infrastructure and mechanisms for emulating impairments. The infrastructure will be a set of robots (e.g., swarms), cooperating on a task, and 6G connectivity. Impairments will be faults in the network, robotic devices, or functionality. Several cases will be shown: a) using flexible topology, advanced network infrastructures, and predictive orchestration for mitigating impact of a faulty device by redistributing functionality and roles; b) using 6G to deliver high rate, low latency, and reliability supporting human-machine interfaces (HMI) [9]; c) using advanced radio and positioning to address impairments. This demo will showcase examples from the use case family "From robots to cobots". The main KPI to be tested by this demo is the reliability, the ability to provide expected performance and latency even in case of faults.

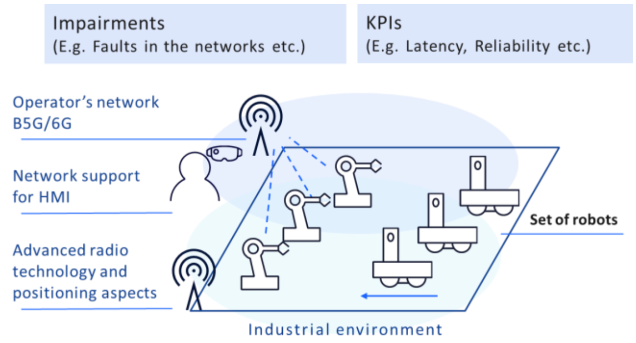

Figure 10. Extreme performance in handling unexpected situations in industrial contexts, demo #4.

Demo #5: Algorithms for data-driven device-edge-cloud continuum management:

A set of algorithms are required to support zero perceived latency in 6G networks. This demonstration will showcase the prediction of a future state of a device and necessary actions that will be taken for the service self-adaptation, to ensure lowest possible latency, reliability, and efficiency (in terms of resources, means used). In this regard, the algorithms will predict the next device state, based on its context (see Figure 11), e.g., user profile, network hints, application and IoT aspects. The actions will relocate the service as close as possible to the device.

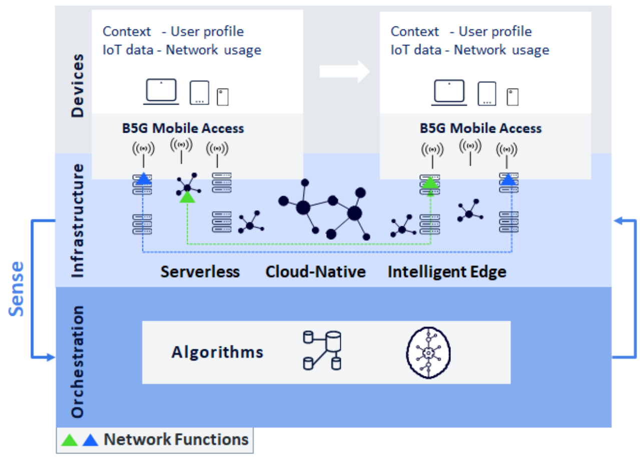

Figure 11. Algorithms for data-driven device-edge-cloud continuum management, demo #5.

IV. Outlook

As the flagship project of the European 6G research and industry community, Hexa-X will actively exchange and align its vision with the concurrent research activities in the European and international context (see Figure 12).

Building on the novel x-enabler fabric, Hexa-X will be able to learn from other 6G- related research projects and integrate their inputs together with Hexa-X research outputs for achieving maximised impact among the research community, regulatory and standardisation fora.

Figure 12. Relation of Hexa-X to major stakeholders.

Hexa-X will collaborate with a wide range of stakeholders at the European and international levels: from national R&I Action Plan for 6G in Europe (e.g., 6G Flagship initiative in Finland), national 6G programs outside Europe (e.g. in the US, China, South Korea and Japan), policy makers (e.g., the European Commission), standard development organisations, (e.g., 3GPP, ITU and ETSI), to Hexa-X Advisory Group with top experts from society and sociology (UN, Uni Luxembourg), business verticals (BMW, SNCF, Thales) as well as other major 5G/6G industry representatives (Apple, CMRI, Facebook, IIT Kanpur, KT, Marvell, NTT DOCOMO, Qualcomm, Sony and Vodafone). The forthcoming Smart Networks & Services Joint Undertaking in the framework of the 5G Industry Association is a natural environment where the activities of Hexa-X will be fundamental for the success of the European 6G partnership [10].

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