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6G Vision, Value, Use Cases and Technologies from European 6G Flagship Project Hexa-X

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ABSTRACT

While 5G is being deployed and the economy and society begin to reap the associated benefits, the research and development community starts to focus on the next, 6th Generation (6G) of wireless communications. Although there are papers available in the literature on visions, requirements and technical enablers for 6G from various academic perspectives, there is a lack of joint industry and academic work towards 6G. In this paper a consolidated view on vision, values, use cases and key enabling technologies from leading industry stakeholders and academia is presented. The authors represent the mobile communications ecosystem with competences spanning hardware, link layer and networking aspects, as well as standardization and regulation. The second contribution of the paper is revisiting and analyzing the key concurrent initiatives on 6G. A third contribution of the paper is the identification and justification of six key 6G research challenges: (i) “connecting”, in the sense of empowering, exploiting and governing, intelligence; (ii) realizing a network of networks, i.e., leveraging on existing networks and investments, while reinventing roles and protocols where needed; (iii) delivering extreme experiences, when/where needed; (iv) (environmental, economic, social) sustainability to address the major challenges of current societies; (v) trustworthiness as an ingrained fundamental design principle; (vi) supporting cost-effective global service coverage. A fourth contribution is a comprehensive specification of a concrete first-set of industry and academia jointly defined use cases for

6G, e.g., massive twinning, cooperative robots, immersive telepresence, and others. Finally, the anticipated evolutions in the radio, network and management/orchestration domains are discussed.

INDEX TERMS 6G, Communication systems, Wireless communication, Tbps, AI/ML, Network architecture

I. INTRODUCTION

From 2019 onwards, the vision for the 6th generation (6G) of mobile networks and the effort to frame the 6G research agenda have begun, with several initiatives from around the globe. Majority of the key actors from academia and leading scientific and industrial research centers have identified that 6G will likely be commercially available from 2030 onwards. In order for this to happen, it is already timely to jointly shape the vision for 6G. As starting points, several academic papers have recently been published on visions, possible applications, core services, enabling technologies, and future challenges, see e.g., [1], [2]; in parallel, several industrial white papers and articles, e.g., [3]-[9].

In parallel, the geographical dimension has to be noted. In Asia, initial discussions have begun in China [10], [11] Japan [12]-[14], Korea [15], [16] and India [17], focusing on national strategies and fora. In North America, ATIS recently launched the Next G Alliance [18], and the National Science Foundation have opened a call for the upcoming Resilient & Intelligent NextG Systems (RINGS) [19], although these initiatives are still in a preparatory state. In Europe, several 6G initiatives have been launched [20]-[22]. In addition, the European Union (EU) is preparing for the upcoming ‘Smart Networks & Services’ (SNS) Joint Undertaking [23]. In 2020, EU begun funding several research projects aiming at smart connectivity beyond 5G, i.e., 6G [24]. Most of these projects will explore specific technology enablers, such as AI/ML or meta-surfaces [25]. With key industry stakeholders and academia in Europe the Hexa-X project is positioned to be the European 6G Flagship project with the ambition to strongly contribute to harmonizing the global 6G vision and define the foundations for the end-to-end 6G systems [26] in cooperation with key stakeholders worldwide [27]. On national levels, several programs and projects have been started in the last couple of years in Europe, North America and Asia, also in conjunction with various research fora.

Out of all these initiatives, there are certain trends that can be outlined. Most of the leading stakeholders have explicitly started formulating the 6G vision from use case, performance and value perspective, including objectives of societal and environmental sustainability. In addition, several actors have begun exploring prospective 6G technology enablers such as sub-THz communications to exploit spectral bands >100 GHz [28]-[31], localization and sensing [32]-[34], pervasive artificial intelligence (AI) [35], [36] and an initial architecture decomposition for the 6G era [37]. There is also work for defining KPIs; for instance [38], where the authors compare 5G and 6G from the perspective of supported KPIs in

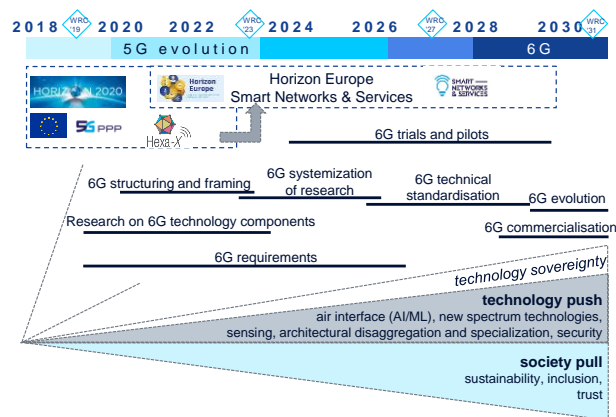


FIGURE 1. Timeline of 5G evolution and 6G framed by the dynamics of technology push and society pull. Evolution of previous generations continues usually long through the time of the successive generations.

identified 5G and future 6G related uses cases for verticals. However, there is need for work that will align the academia and industry views towards 6G, taking into account the initiatives in the world. Thus, the time has come for a concerted effort to streamline the various 6G visions and efforts, and go in depth in the specifications. Our work is an attempt in this direction, by: (a) taking steps towards the consolidation of the vision, values, use cases and key enabling technologies; (b) the identification and justification of six key research challenges that based on our analysis will be key features of 6G; (c) delivering a comprehensive set of use cases for 6G, e.g., massive twinning, cooperative robots, immersive telepresence, and others.

II. MOTIVATION FOR A NEW 6G SYSTEM

In the past, the realization of a new network generation has taken 8-10 years. Assuming a similar timeline for 6G and taking the schedule of ITU and WRC into account, the time to define the strategy and framework of 6G research is already here, as is evident from the global commencement of the 6G research. Fig. 1 shows the timeline of 5G evolution and 6G framed by the dynamics of technology push and society pull, which clearly shows that Hexa-X is well poised to contribute to the 6G structuring and framing as well as developing technological components and enablers and defining initial requirements for 6G, while still allowing for subsequent 6G systemization research projects ahead of technical standardization, targeting commercialization at the end of the decade.

Many of the market needs and requirements at the initial commercial launch of 6G may partially be met by 5G, especially as 5G Advanced will likely incorporate aspects

from 6G research. Some new applications envisioned for 6G will already emerge in the context of 5G Advanced. 6G's expanded and novel services and use cases, along with technological advancements will necessitate a new generation of mobile networks. These aspects can be divided into three distinct 6G motivators as described in the following.

Technology push: The advent of key technologies such as new radio technologies for sub-THz access, network-wide concepts of virtualization and architectural disaggregation as well as pervasive AI/ML and new security concepts to assure cyber-resilience, privacy and trust, promise to add important abilities and design dimensions for wireless networks. A timely start into a technology and concept evaluation is required, even if some of these technologies are still on a low level of technology readiness, to understand the potential performance and impact on the overall system architecture.

Society and industry pull: Climate change, pandemics, digital divide, social inequalities, as well as growing geopolitical tensions with an impact on technology markets are major challenges defining the environment in which 6G is currently developed. It is of utmost importance to tackle these challenges of global relevance and scale, while also creating opportunity for innovation-led growth and employment. Wireless networks, being a central component of a digitalized society, must reflect such complex needs and opportunities and proactively provide sustainable digital solutions to help address the United Nation (UN) Sustainable Development Goals (SDGs) [39] and the European Green Deal [40]. It is a top priority to guide and influence the development of 6G wireless networks to include values like sustainability, trustworthiness, and inclusion into the purpose and design of the networks.

Global alignment: Industry and academia need to work together in multiple constellations on forming the 6G vision considering these push- and pull factors. Table I presents an overview of the most notable initiatives world-wide, including Hexa-X. Several commonalities in topics, notably the focus on values of Sustainability and Digital inclusion, can be found. For the vision of 2030 a strong alignment towards aiming at cyber-physical interactions between digital and physical worlds is also seen. More diverging views are seen when it comes to research challenges to address. A critical task going forward will be to form a global consensus based on these separate views.

A. 6G VISION

Our vision for 6G aims to tightly couple and enhance the interactions between three worlds: a human world of our senses, bodies, intelligence and human values; a digital world of information, communication, and computing; and a physical world of objects and organisms. This will create a cyber-physical continuum, making networks a powerful tool to improve the quality of our lives. It is crucial, however, that future networks enabling the connection between the worlds are designed considering fundamental key values, such as

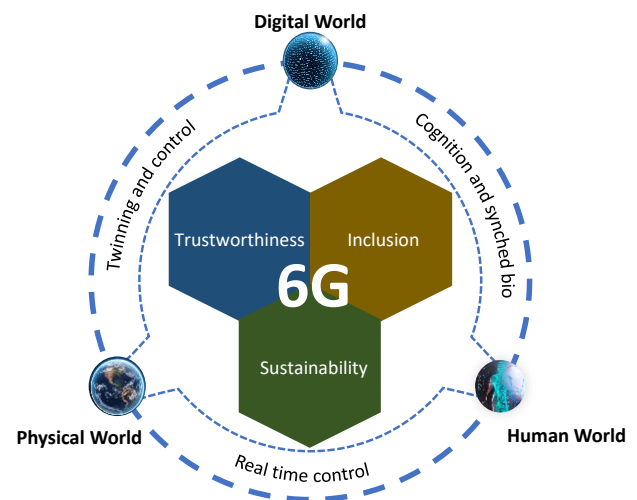


FIGURE 2. The Hexa-X 6G vision of connected worlds and key values.

sustainability, trustworthiness, and digital inclusion. The Hexa-X 6G vision, comprising the interactions between these three worlds and the fundamental key values that 6G shall address are presented in Fig. 2. The associated technological and societal transformation will likely generate unprecedented opportunities of economic growth and help tackle societal challenges towards the 2030s and beyond, as will be explored more in the following sections. Moreover, it will call for a fundamental shift in the way mobile networks are designed. Multiple key requirements must be reconciled: to serve the massively growing traffic and the exploding numbers of devices, sub-networks and markets, while accomplishing the highest possible standards regarding energy efficiency, security, privacy and trust, efficiency in deployment for coverage, densification and specialized operations, to enable sustainable growth and innovation across sectors and industries.

Furthermore, the trend of augmenting the human intelligence will continue, through a tighter coupling and seamless intertwining of the network and digital technologies. With advances in AI and machine learning (ML), machines will continue to transform data into reasoning and actionable insights, which will enable humans to understand and act better in our world. Interaction between the three worlds will pave the way for advanced sensing, powerful experimentation at the digital world, and high-performance and reliable actuation capabilities. As the dedicated domestic and industrial machines of today transform into large groups of collaborating, human-assisting multi-purpose robots and drones, new human-machine haptic and human intent interfaces to control and interact with them from anywhere will become an integral part of the future network.

B. DEFINING THE DIRECTION OF 6G RESEARCH

The realization of the 6G vision, based on connecting worlds and key values, sets the direction for the development of future networks and gives rise to a set of research challenges for 6G, forming the research plan of the project. This is a well-

motivated selection of topics; in the end these are the areas for 6G to tackle in order to get where we want to be in the 2030 era. It should be noted that this need and value-driven approach is strictly different from the casual expand and improve paradigm of previous mobile network generations.

As can be seen by comparing the visions from different 6G initiatives and fora in Table I, Hexa-X focuses on many of the challenges mentioned by other initiatives as well, and has the common focus on cyber-physical interactions, considering also the human aspects, placing the Hexa-X vision at the center of the current development. These Hexa-X research challenges are explored in more detail in the following:

Connecting intelligence: The 6G era will be about the cognitive and physical augmentation, which will require new solutions for coupling the human, physical and digital worlds. Therefore, there is a requirement and an opportunity for 6G to provide a framework to enable real-time control for trustworthy intelligence through, for example, advanced resource management and through the provision of AI/ML-generated supplementary data and functionality, therefore, transforming and enhancing processes, services, and products, while maintaining the human in control (“human in the loop”).

Network of networks: To enable the connection of the three worlds, the network is expected to consist of many specialized sub-networks. These sub-networks are essential to support the key values of 6G and the research challenges. The different specialized sub-networks are also needed to support the flexible deployments of nodes using a wide range of spectrum for maximum capacity and coverage, mesh networks for extreme reliability, cloud-native RAN and CN for efficient networks and in-body or intra-machine nodes for various factory scenarios (see section IV.C). 6G should be able to efficiently adapt any sub-network to support all these various flexible deployments and ultimately, support the three worlds. Further on, 6G should comply with the “network of networks” paradigm, for addressing mass-scale deployment, wide-area and specialized networks, and seamless operation fulfilling a large diversity of requirements with utmost (cost) efficiency, fostering business model and value chain transformation and economic growth.

Sustainability: 6G should be an energy-optimised digital infrastructure with relevance across a variety of industry sectors and consumers to help reduce global ICT related environmental and CO₂ footprint. In addition, 6G should be sustainable from a wider perspective, encompassing not only

TABLE I
COMPARISON OF 6G VISIONS FROM AROUND THE WORLD

Initiative	Vision slogan	Key values/drivers	Research challenges
<i>5G Forum</i> [16]	Connecting physical and digital world	Clean & safe society; sustainable society; fair & transparent society	Truly immersive experience; Distributed infrastructure for connected intelligence; Real-time interaction between physical and digital worlds
<i>5G IA</i> [22]	Convergence of physical, human and digital worlds	Sustainable development; Digital inclusion; Convergence of IT/OT; Trust	Digital twinning, immersive communication, cognition and connected intelligence; Programmability; Deterministic end-to-end services; Integrated sensing and communication; Sustainability; Trustworthy infrastructure; Scalable and affordable
<i>6G Flagship</i> [8]	Sustainable data-driven society	UN SDGs	Wireless connectivity; High-frequency transceivers and materials, distributed computing and ML, Sustainable user-centric services and applications
<i>Hexa-X</i> [26]	Connect human, physical, digital worlds	Sustainability; Trustworthiness; Inclusion	Connecting intelligence; Network of networks; Sustainability; Global service coverage; Extreme experience; Trustworthiness
<i>IMT-2030 Promotion Group</i> [10]	Intelligent connection of everything, digital twin society	Changes in social structure; High-quality economic growth; Environmental sustainability	Immersive cloud XR; Holographic communication; Sensory interconnection; Intelligent interaction – interactions of feelings and thoughts; Communication for sensing; Proliferation of intelligence – ubiquitous smart core; Digital twins; Global seamless coverage
<i>IOWN GF</i> [14]	Precise modeling of physical world in a digital twin system	Paradigm Shifts in Connected World; Smart and Connected World Applications	Data-centric communication and computing infrastructure; Full-stack communication acceleration; Computing scaling across device; network; Edge and center cloud; Sustainable growth with energy efficiency
<i>Next G Alliance</i> [18]	[Not published yet]	[Not published yet]	Minimizing environmental impact of future generations of wireless technology; Address spectrum issues of the Next G world; Societal demands and economic needs for sustainable 6G business case
<i>NGMN</i> [7]	Extend user experience across multiple physical and virtual platforms for immersive mixed realities	Societal goals; Market expectations; Operational necessities	Societal and environmental needs; New human-machine interfaces; Seamless multi-access continuity; Cost and energy efficient delivery of heterogeneous services with diverse requirements; Disaggregation and software-based agile, cognitive and autonomous networks; Support of AI by design; Harmonized and coordinated global standards and ecosystems
<i>NICT</i> [12]	Cyber-physical system	Inclusiveness; Sustainability; Reliability	Migration of information and communication networks; Integration of cyber space and physical space

energy related aspects, but also natural resources consumption, products lifecycles, social sustainability, etc. Its digital fabric shall also create the ability to sense and understand the state of the physical world in real-time and as such boost services that will lead to greater sustainability and cost efficiency and contribute to reach the sustainability goals.

Global service coverage: It is most important for 6G to provide "full" coverage. This is not intended for boosting human communications only. It is also most essential for enabling new applications (e.g., sustainable development, earth monitoring, twinning). Moreover, global digital inclusion will require efficient and affordable solutions for global service coverage, connecting rural areas, transport over oceans or vast land masses; in parallel, this will enable new services and businesses that will promote economic growth and reduce the digital divide, while improving safety and operation efficiency in areas currently underserved.

Extreme experience: 6G will provide extreme bitrates (in the order of hundreds of Gbps to few Tbps), extremely low (imperceptible) latencies, seemingly infinite capacity, and precision localisation and sensing, pushing the performance of networks well beyond 5G, many times in conjunction with specialized sub-networks. This will unlock commercial values of new radio technologies in sub-THz bands, accelerating the pace of digitisation across a variety of sectors.

Trustworthiness: Trustworthiness in the 6G era will be threatened and challenged in a variety of new ways such as from connecting billions of endpoints and millions of subnetworks that typically cannot be trusted, from open interfaces and architectural disaggregation, heterogeneous cloud environment as well as a mix of open source and multi-vendor software [37]. AI/ML based attacks and attacks against AI/ML based concepts are also likely to proliferate. To ensure cyber-resilience, privacy, and trust will require diligent research efforts on security technology enablers. Such enablers should include automated software creation as well as automated closed-loop security operations. Privacy preserving technologies such as homomorphic encryption as well as hardware and cloud-embedded anchors of trust will deserve dedicated attention. Security enablers to also be considered include quantum safe cryptography, physical layer security and distributed ledger technologies. Trustworthy wireless networks will be the foundation for trustworthy applications and use cases of the 2030s for consumers and enterprises alike.

III. 6G USE CASES

To better understand the 6G vision from the perspective of an end user and to characterize the 6G vision in terms of network usage, and gauge how 6G can meet the key values, use cases are developed as exploration tools. They are examples of the functionality foreseen for networks in the 2030 era and in turn drive requirements and point at new capabilities needed.

A. STATE-OF-THE-ART ON USE CASES ENVISIONED FOR 6G

In the 2030s, many new use cases can be expected, driven by societal demands and realized with emerging 6G technologies. Some of these will be widely enhanced experience of services available already today, while others will be innovative new types of applications of mobile networks. Several views, from industry as well as from academia, have already been shared in the ecosystem about the envisioned use cases for 6G. Some of the use cases foreseen build upon the trends initiated by 5G, such as the evolution of Virtual Reality (VR) and Augmented reality (AR), into Extended Reality (XR). XR video presence, going one step further in merging physical and virtual worlds, will open a wide range of applications in various fields (e.g., medicine or education). Holographic representations have also been extensively identified as a 6G use case, enabling 3D representations of distant objects or people, possibly with transmission of multiple senses [4], [5], [41], [42]. Another category of use cases frequently identified for 6G is the generalization of Digital Twins [4], [5], a digital replica of the physical world, allowing for actions in real life through interactions with the digital twin, with applications such as management of smart cities.

Building on the efficiency improvements enabled by 5G in industrial processes, the use cases involving connected robots represent a major trend in 6G use cases reported in [43], pursuing and increasing their usage in industrial context (e.g. mobile robots handling materials in warehouse and production plants), but also extending the usage of connected robots to other fields (including personal life, with for example swarms of small robots which perform domestic chores in home networks [3]), even cooperating with human beings [44].

There are also high expectations on 6G to foster the development of new usages with strong societal benefits, in particular use cases favoring the accessibility of services and digital inclusion. Telemedicine and healthcare services, as well as education, provisioned to remote areas not properly connected yet, are example of use cases deemed of high interest for 6G. Healthcare is considered as an important innovative area for 6G, with new precise monitoring of health conditions thanks to in-body devices such as biosensors [4], [8]. Another innovative usage involves 6G as a surveillance tool of the environment and prevention of disasters [4].

These use cases represent major trends in the literature for 6G, but the list is not exhaustive, as more and more actors share their vision on future usages for 6G. Several use cases have been prioritized and selected for further analysis in the Hexa-X project.

B. USE CASE FAMILIES

Guided by the values presented in section II, Hexa-X has selected a set of use cases to be further analyzed in the project. This set of use cases is not meant to be exhaustive, but representatives of use cases foreseen for 6G. This set of use

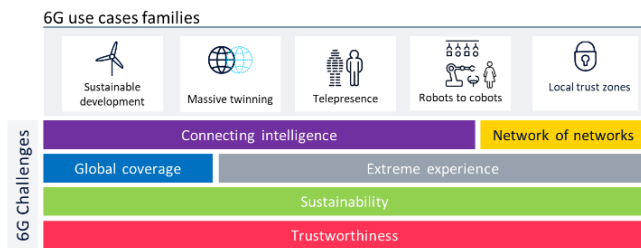


FIGURE 3. Use case families mapped to 6G research challenges.

cases lays the foundations for the technical work of the project, as technical requirements are then derived from the use cases as design target for the technical enablers. These envisioned use cases are clustered into categories, i.e., use case families, according to the type of usage and research challenges addressed as can be seen in Fig. 3. The clustering approach may be revisited in the future as more use cases are proposed for 6G.

The *Sustainable development* focuses particularly on the UN SDGs of reducing inequalities by providing global access to digital services as well as the objective of climate action by energy-neutral infrastructures and services. An example of use case is “e-health for all”, which will rely on 6G to provide healthcare services in every place, even in remote areas (e.g., rural areas or harsh environments, where deployment of fiber is not possible). Remote consultation with doctors and medical specialists, but possibly local analysis of samples based on new devices and sensors, will require global coverage in a cost-efficient way, and trustworthy connections to manage confidential information.

Massive twinning expands on the use of digital twins by leveraging on this intertwining to be able to represent and control any aspect of the physical world in order to improve efficiency in several areas, from optimization of automation in production and manufacturing, to prevention of threats or diseases in agriculture. The concept of twinning can therefore be extended to the management of smart cities. An example use case is the “Immersive smart cities”, where the Digital Twin will enable to manage the various flows (e.g., public transportation, traffic) and utilities in cities (e.g., water, energy), or monitor different environment indicators (e.g., air quality). The Digital Twin will model all these flows and will allow to forecast events, manage and schedule accordingly the different flows.

Immersive telepresence by means of mixed reality or holographic telepresence, provides extreme and immersive experiences, blurring the boundary between the digital and physical worlds. The quality of interactions between distant persons is enhanced for professional as well as personal purposes. An emblematic use case is the “Fully merged cyber-physical worlds”, where Mixed Reality (MR) and holographic telepresence will become the new communication tools in everyday life, at work and at home. The user will experience being in a different place of his actual location, with enhanced

rendering of the interactions (e.g., gesture, touching the objects).

From robots to cobots includes use cases involving interacting robots and autonomous systems and the human interaction with those systems, at home and in society to facilitate everyday life as well as in industrial environments to improve the efficiency of processes and to enable new value chains. An example of use case is “consumer robots”, where presence of robots at home will increase and generalize, performing the various domestic chores, but also allowing elderly people to stay at home, managing the different tasks that they cannot perform anymore. In these types of use cases, trustworthy communication and coordination among the different robots will be essential.

Local trust zones encompass different use cases with specialized sub-networks and network of networks, requiring extreme reliability, availability, and resilience on a local scale, from microscale in-body networks for example, for health monitoring purposes, to wide area deployment of sensors networks. An example of use case is “sensor infrastructure web”, in which networks will advertise and share information locally available from third-party sensors, when relevant. The sensors data will therefore be aggregated by the network and distributed among many entities and devices.

IV. TECHNOLOGICAL ENABLERS FOR 6G

The success of mobile communications as key enabler for mobile services and the respective global ecosystems is based on an internationally harmonized standard, a vital global ecosystem and high-quality product qualifications processes.

Hexa-X believes that it is essential for 6G to defend this unique positioning in the global technology ecosystem. To accomplish this, Hexa-X focuses on essential functionalities and technological enablers that it believes could define the 6G key characteristics and become mandatory parts of a 6G standard. Hexa-X recognizes that there are a number of promising additional technologies that might well become important complements to 6G, such as quantum technologies, satellite communication, visual light communication and reconfigurable intelligent surfaces. However, these topics are not in the focus of Hexa-X’s work, but may develop in parallel and might be integrated into the 6G ecosystem at a later stage. To address the challenges and use cases described in Sections II and III, the Hexa-X project has grouped the identified technological enablers based on the mutual interaction into three research areas, where each will be pivotal in realizing the 6G systems. In section IV.A we explore extreme radio performance offered by the higher carrier frequencies in the upper mmWave band (100-300 GHz) which enables both seemingly infinite capacity and data rate as well as highly accurate joint communication and sensing. In section IV.B, we explore means of connecting intelligence, both for enhanced network orchestration and service management as well tight integration of AI into the radio access network for enhanced network performance and provisioning of AI services. Finally,

in section IV.C, we explore architectural enablers that will enable more flexible and efficient networks with, for instance, cloud-based architecture and flexible networks of networks. It will also address specific special purpose functionalities such as human-machine interfaces (HMI) and develop methods to sustainably extend coverage and connectivity to the currently underserved.

A. Extreme Radio Performance

The evolution to a new mobile network generation have previously always included significant improvements to the air interface. Among the envisioned use cases, several require radio performance far beyond what 5G can deliver [45], either in terms of communication metrics (rate, coverage), localization and sensing metrics (accuracy) or joint metrics (latency, energy efficiency). For example, massive twinning of cities and factories will require further densification of urban networks through more flexibility for backhaul, provision of high-speed local wireless access with link rates exceeding 100 Gbps, e.g., in public spaces/buildings, accurate situational awareness, with location errors varying from 1 meter down to 1 cm with high scalability (devices per cubic meter). Moreover, twinning will combine localization (i.e., determining the position and pose of connected devices) and sensing (determining the state of passive objects, including walls, people etc.). To support fully merged cyber-physical worlds for immersive telepresence, radio access should be capable of carrying short-range bidirectional streaming of video data with unprecedented resolution and refresh rates for AR/VR applications with beyond 20 Gbps per display and fully immersive holographic communications with required data rates up to 1 Tbps. From localization point of view, immersive telepresence is an exceptionally tough use case, requiring not only location accuracies below 1 cm, but also sub-degree orientation accuracies, with latencies below 1 ms, in order to meet the strict requirements on visual and haptic feedback. Fusion of location and sensing information will likely be needed to support this use case. Robots to cobots will be equally challenging, though in a different sense, given the safety-critical nature and fine precision needed for robots to collaborate and to move in their sensed environment. In industrial settings, similar accuracies as in immersive telepresence may be needed, though with looser latency requirements, but with higher mobility and integrity requirements. Finally, local trust zones, by their very nature, will rely on locality and will need flexible localization capabilities and potentially extreme data rates in the confined area.

In order to provide such extreme radio experiences, it requires: (i) improvements in the spectrum efficiency and localization and sensing accuracy compared to current communications systems; (ii) a move towards higher frequency bands for exploiting the abundance of spectral resources. During the World Radiocommunication Conference (WRC)-19 in November 2019, three separate

mmWave bands were identified as globally harmonized International Mobile Telecommunications (IMT) bands [46], although with a limited total bandwidth of only 17.25 GHz. Activities are ongoing in several standardization bodies [47], [48] and there is now an emerging consensus that communication, radar, and localization are converging [49], [50]. Targeting access data rate above 100 Gbps and localization accuracy at 1 cm range, arguably the only way to provide such radio performance is to transition to the use of bandwidths on the order of 2 – 20 GHz, which are only available at higher carrier frequencies. While 5G operates at the low band (< 6 GHz) and of the lower mmWave band (30 – 100 GHz), the needed bandwidths are available in the upper mmWave band (100 – 300 GHz) and the THz band (300 GHz – 1 THz). Due to the very short wavelengths, massive arrays can be packed in a very small form factor (e.g., a 20x20 array at 300 GHz is only 1 cm²), providing potential for high-gain beamforming and fine angular resolvability. While 6G will not be limited to such high carriers and instead a combination of different frequency bands will be needed to provide the required coverage and performance flexibility, operation at 100 GHz – 1 THz presents the most urgent scientific, engineering as well as commercialization challenges in terms of radio technology, and should therefore be carefully studied in the coming years.

In particular, the radio design at upper mmWave and THz bands will be severely constrained by the hardware capability and the propagation channels [51]. Together with the rising concern on energy consumption, it is utmost of importance to design 6G radio taking these two challenges into account [52].

Hardware: Stemming from the laws of physics, the inherent physical constraints, cost- and power-efficiency, and hardware imperfections will limit what is practically achievable at higher carrier frequencies. Technologies that are currently widely adopted in commercial 4G/5G radios in antennas, packaging and especially in integrated circuits are not mature enough to perform well in large scale systems [51], while radio electronics towards THz range are not easily scalable to mass production. 5G technologies have paved way towards complex phased array solutions with high integration rate in the lower mmWave region, supporting data rates of several Gbps but not much more. In academic trials, short range, simple radio links have been demonstrated at ~100 Gbps data rates [53]. Similarly, radars especially for automotive industry, are available already in the market as CMOS chips up to 78 GHz band, though are not optimized for joint communication and sensing. Finally, 5G studies have shown that accurate positioning and sensing is possible, provided large bandwidth or large antenna apertures are available [54]. Hardware imperfections beyond 100 GHz will require efforts in terms of modeling, design, and mitigation strategies. Impairments such as IQ imbalance and antenna coupling that were relatively frequency-flat at 5G bands will become highly frequency-dependent at higher bands. Phase noise will reduce observed coherence of the channel, while

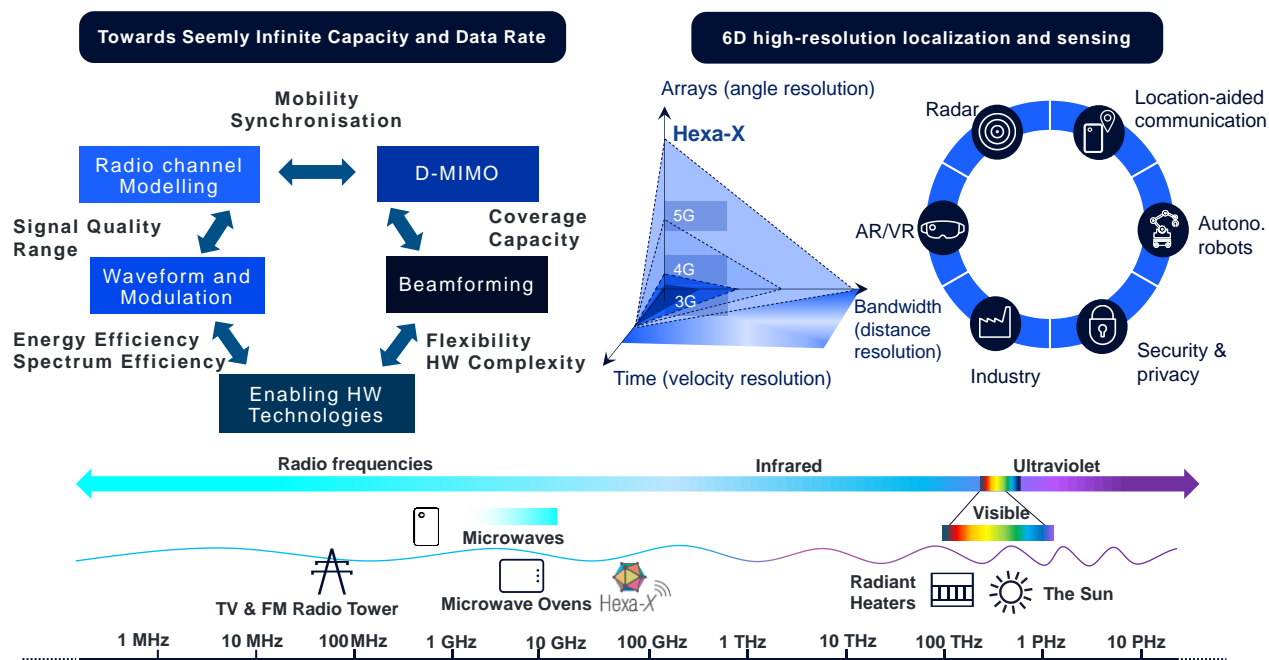


FIGURE 4. 6G radio technologies, targeting enhanced radio capacity and data rate as well as 6D (3 spatial, 3 rotational dimensions) high-resolution localization and sensing explored in the Hexa-X project.

amplifier nonlinearities and fundamental output power limitations will constrain the signal types and link ranges. Several of these impairments will be more challenging for localization and sensing than for communication, as the latter relies on the end-to-end radio channel, while the former must consider each impairment separately to understand the impact on estimation of delays, angles, and Dopplers. The increased data rate will require higher clock speed, higher bandwidth [55] and potentially more energy consumption in digital modems. Therefore, the usability and potential of upper mmWave and THz bands will heavily rely on the current and future development of semiconductor technologies.

Propagation: Radio channels at different frequencies lead to different propagation effects, depending on the ratio of the wavelength and objects sizes [56]. In 5G mmWave, this leads to few propagation clusters, while at higher frequencies, the number of available propagation paths will be even more limited. In particular, the line-of-sight and reflections from metallic objects will dominate in received power. The high degree of resolvability of multipath in delay and angle domain, which will be a main enabler for extreme radio localization and sensing, requires new and site-specific models with spatial and temporal consistency. Conventional characterization of small-scale and large-scale fading will be insufficient in design and evaluation of 6G systems. A final aspect of the propagation channel is the effect of molecular absorption, which will affect communication links, while simultaneously providing information about the propagation medium (e.g., for pollution monitoring or imaging) [57], [58].

In addition to technological challenges stemming from hardware and propagation, to accommodate the associated

system complexity and the large variety of use cases, it is critical to provide the capability to scale data rate, positioning, and performance efficiently in a large network and over different radio protocols to optimize not only a single radio link but the system performance. The realization of scalability will require efficient (in terms of energy consumption and hardware reuse) management of spectrum and utilization of radio technologies and networks.

Hexa-X will tackle the challenge to achieve extreme data rate and extreme performance, e.g., >100 Gbps achievable rate for access and cm-level localization precision by jointly studying radio access, hardware-enabling technologies, propagation channel models up to at least 300 GHz, and key elements of future wireless networks, while accounting for sustainability aspects. As many of the technologies cannot be taken as granted, the system design towards Tbps radios for 6G communications and sensing requires much more careful balancing between opportunities and practical constraints foreseen still in the 2030 timeframe, than in case of 5G. As can be seen in Fig. 4, the specific research topics studied in Hexa-X towards extreme radio performance include:

- Hardware implementation complexity, hardware impairments, available semiconductor technology offers in the considered timeline. Pushing the upper limit of data rate while keeping energy efficiency, implementation complexity and cost in a reasonable level.
- Hardware-friendly waveforms for both communications and sensing are needed.
- Advanced beamforming schemes for tracking users and scanning the environment.

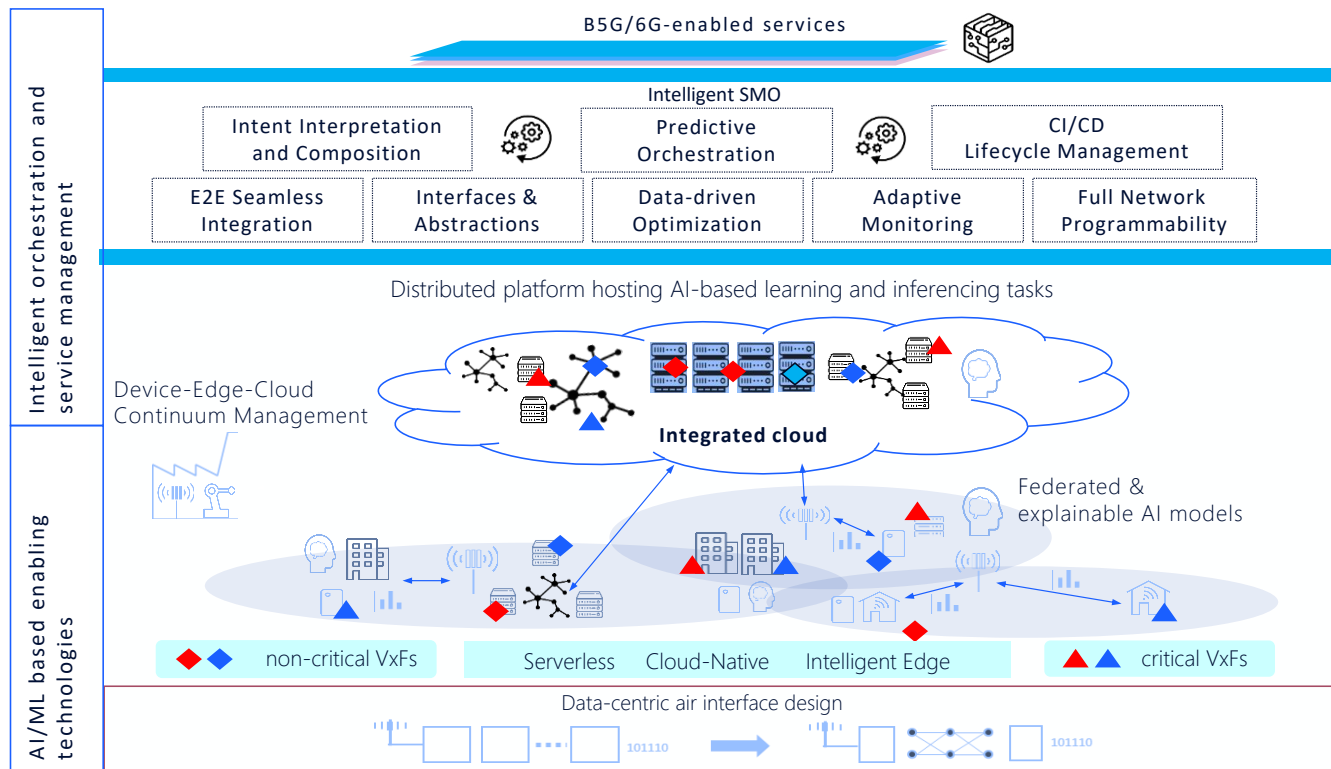


FIGURE 5. Technological enablers for integrating intelligence into 6G networks; AI/ML is pervasive across the network protocol stack from air interface design to intelligent network orchestration and management.

- In-depth understanding of the radio channel and environment with reflective surfaces at frequencies up to at least 300 GHz.
- Systems concepts from beam tracking to multiuser access utilizing scarce radio resources efficiently.
- Selected trials, careful follow-up of technology development in different areas and advance modelling methods to analyze the system properties from performance to power consumption are needed to facilitate 6G research in layers up to networking and applications.
- Use of data-driven AI-based method for hardware impairment compensation.
- Joint treatment of radar, communication, computation, localization and sensing for certain extreme use cases.

B. CONNECTING INTELLIGENCE

Hexa-X envisions 6G as a critical infrastructure for enabling large-scale application deployments, exchange of unprecedented data amounts and seamless integration of new system capabilities, including intelligence and local compute to the wider society. This can be achieved by delivering methodology, algorithms and architecture redesign to support AI-driven air interface design and AI governance towards realizing a network of automated operation. It entails: (i) introducing AI enablers, for wireless transceiver and signal transmission/ reception design involving distributed massive antenna setups and radio resource management exposing benefits in performance, complexity, adaptivity to the wireless

environment, robustness to hardware impairments and energy efficiency; (ii) delivering sustainable, secure, privacy-preserving and trustworthy governance of AI mechanisms, functions and agents, along with explainable AI-powered network operation, given system-wide constraints of processing, storage, memory, data and networking resources, and (iii) employing AI for the use of predictive orchestration, seamless management of the device-edge-cloud infrastructure and full network programmability, by developing new methods, interfaces and technology enablers. Contrary to initiatives in various parts of the globe, such as the DARPA Spectrum Collaboration Challenge [59] in the U.S. and the ITU AI/ML in 5G Challenge [60], internationally, where the focus is on optimizing specific functionalities of wireless networks based on data-centric approaches, Hexa-X aims to cover the area of AI-driven communication & computation co-design holistically, both by designing the air interface using an ML-based toolbox and by concurrently redesigning the overall communication network to address the Connecting Intelligence research challenge. The latter can be viewed as designing the network for more efficient, sustainable, and trustworthy AI or "communication for better AI".

As wireless networks have grown substantially complex, different air interface designs have been proposed using AI/ML-based methods. In terms of utilizing the network as a learning platform, Distributed Deep Neural Networks (DDNNs) save cost when deployed in an end-device-edge-cloud hierarchy, as end devices hardly achieve model fitting with the required accuracy, due to memory and power

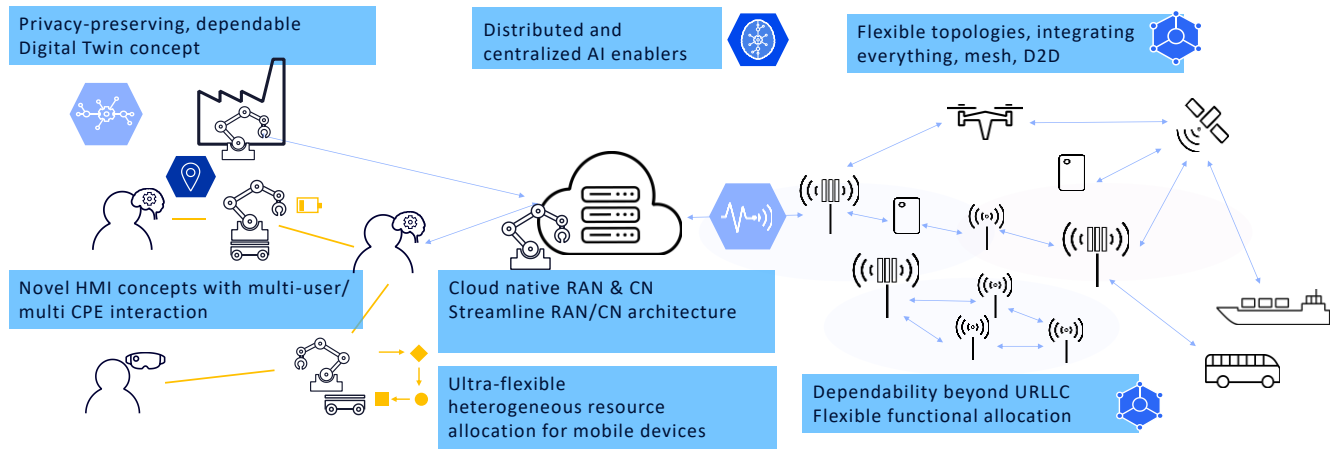


FIGURE 6. Technological enablers for a 6G architecture creating a flexible network of networks that is able to support a wide range of future deployments such as mesh networks, NTN and nodes using sub-THz. This enables vertical use cases such as ultra-flexible resource allocations for devices, HMI and digital twins etc. All this requires cloud-native Radio Access Networks (RAN) and Core Networks (CN).

limitations. Recently, the concept of Federated Learning (FL) was investigated, consisting in multiple network nodes collaboratively training a shared ML model in a distributed fashion with no exposure of "raw" device data [61]. FL is motivated by limitations in uplink bandwidth, along with network coverage and data privacy restrictions. Focusing on AI algorithm output explainability, [63] provides design approaches for highly interpretable Fuzzy Rule-Based Systems (FRBSs) to make AI-based models more transparent, while maintaining high-performance levels of accuracy and precision.

Considering network orchestration and management, aided by technologies of Network Function Virtualization (NFV) and softwarization, a set of network services can be composed inside a network slice characterized by given QoS demands. Network function placement is an important mechanism of NFV to jointly optimize network performance and resource utilization. The characteristics of NFV as cloud-native are framed in resiliency, monitoring, scaling, decomposition, modularity, and their design suitability for network automation. In terms of latency and throughput, the Edge Cloud is crucial in bringing processing proximity and innovative applications closer to end-users [64].

Hexa-X has the objective to develop concepts and solutions enabling AI-driven communication and computation co-design in 6G as can be seen in Fig. 5. It targets to:

- (i) design 6G wireless transceivers and air interface functionalities in a cost and complexity-efficient manner, either by replacing specific model-based parts of the transmission/ reception chain by their AI/ML counterparts, or by adopting an intelligent end-to-end optimization approach;
- (ii) develop data-driven methods adaptive to the wireless environment and enabling radio hardware impairment mitigation to maximize radio access flexibility and configurability and
- (iii) propose design concepts for a 6G learning platform capable of supporting:

- Semantic and goal-oriented communication [62] and involving thousands of dynamically collaborating AI agents capable of optimally supporting and addressing distributed edge workloads and learning and inferencing mechanisms, with respect to latency, reliability, energy efficiency (via reduction of a factor of 10 in network energy consumption and of a factor of 100 at the device side as a result of AI-based workload offloading), security, manageability, explainability to avoid biased AI-based decisions (by tolerating an up to 10% inferencing accuracy reduction as compared to DNN performance) and knowledge sharing requirements.
- Develop ML applicability contexts for predictive management and orchestration for use in Software Defined Networks (SDN) and Operations, Administration and Maintenance (OAM) towards increasing service continuity by reducing the downtime by more than 80% and reducing the time to onboard new resources from other domains by more than 90 %.

C. NETWORK EVOLUTION AND EXPANSION

Although the network architecture of previous mobile generations has provided good performance, development and expansion, there are several aspects that could be improved to address the research challenges and provide the use cases described in the previous sections, as can be seen in Fig. 6.

Hexa-X considers cost-efficient enhancement of performance and service coverage as a vital element for the development of 6G. New technical components will be required for enabling novel flexible network deployments and the future use cases. 6G is envisioned as a flexible network of networks that supports the integration of nodes using sub-THz spectrum, mesh networks, non-terrestrial networks (NTN), device-to-device (D2D), cell-free multiple-input, multiple-output (MIMO), network procedures exploiting AI, and millions local device sub-networks to allow the integration of all new capabilities and meet the requirements of 2030. A key enabler for such a flexibility paradigm will be the extended use

of enhanced application of radio access virtualization methods. It requires to advance the current state-of-the-art with solutions enabling fully cloud-native Radio Access Networks (RAN) and Core Networks (CN) using common platform functions and distributed cloud infrastructure for maximum service independency, flexibility, and re-usability, applying data flow centricity and alternative compute paradigms such as “serverless”, abstracting away cloud servers. This goes beyond 5G concepts such as separation of User Plane (UP) and Control Plane (CP) functions, network slicing, convergence of fixed and mobile communication, and local breakout mechanisms. By designing the 6G architecture considering this from the beginning, it is expected to significantly increase flexibility and cost efficiency and decrease the overall complexity of 6G.

In addition, to enable a network of networks across different verticals, the associated value chains and special-purpose networks need to be considered. It is a must to explore mechanisms for high dependability, addressing reliability, availability, safety, integrity, and maintainability as a crucial prerequisite for mission-critical applications. This includes analyzing the potentials and limitations of cross-layer technologies such as communication-control co-design and spatiotemporal network design. It is crucial to understand the implications of increased flexibility on the dependability of the system, therefore, novel KPIs to measure dependability in vertical scenarios will be studied. These KPIs do not only consider the communication service, but also computation and AI-related resources offered as a service by the 6G system, leading to an end-to-end perspective on dependability with the ambition to increase productivity of the respective applications and use cases. This goes well beyond the work on ultra-reliable, low-latency communication (URLLC) introduced in 5G, where KPIs (e.g., packet error or loss rates) were considered in an application agnostic fashion. An initial application-centered assessment shows how the application can dynamically signal the required level of reliability to the network, enabling a more efficient resource usage [65].

Hexa-X has the ambition to develop a fully converged smart connectivity platform for a wide range of network topologies, devices and sub-networks, and a multitude of special-purpose solutions for specific segments of existing and potential new value chains. This connectivity platform will enable flexible assignment of heterogeneous resources and dependable network services as well as an execution environment with guaranteed high levels of privacy, user transparency, and availability. Solutions for enhanced human-machine interfaces (HMI) and human cyber-physical interaction will need to be evaluated to enable the integration in wireless networks and reach performance goals with several closely interacting HMIs. Hexa-X will also innovate methods to extend connectivity and coverage in a sustainable way through flexible heterogeneous resource sharing, predictions and management of resource and spectrum needs, applications of zero-energy devices and energy harvesting technology, taking

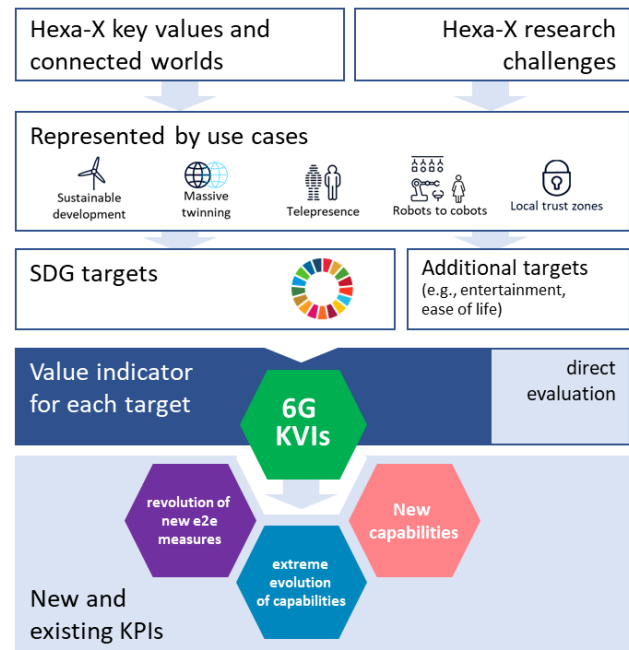


FIGURE 7. Methodology to capture the value of 6G.

existing works on energy harvesting and backscattering to the next level [66]. Thus, Hexa-X will deliver a 6G functional architecture that utilizes a fully cloud-native RAN and CN, supports an intelligent, secure, smart, and flexible network and inherently reduces the complexity of network integration and implementation and, thereby, the TCO.

V. DEFINING THE VALUE THAT 6G WILL BRING

Hexa-X expands the traditional performance- and cost-oriented network design paradigm with a novel value-oriented approach. The key values sustainability, inclusion, and trustworthiness and their inherent research challenges are embedded in the use cases outlined in Section III. To a high degree, these values can be mapped to several of the UN SDG targets and thus be placed in a global context as is described in section VI. For some, the delivered value might not directly be associated to a UN SDG target, but can be related to, e.g., entertainment or ease-of-life, as illustrated in Fig. 7.

For each relevant target, novel key value indicators (KVI) are derived to quantify and compare the contributions of technical enablers to the respective target. In some cases, these novel KVI might be evaluated directly, but usually they are associated with a set of KPIs serving as proxies for the respective KVI. Such (new or existing) KPIs represent characteristics or capabilities which are required to realize the respective use cases and their associated values. Hexa-X proposes to cluster the underlying KPIs into three areas: (i) the extreme evolution of capabilities, (ii) the revolution of new end-to-end measures, and (iii) new capabilities.

Extreme evolution of capabilities: Novel use cases and new technology require traditional KPIs to be expanded. For specialized use cases, some metrics such as bit rate are

expected to be expanded to extreme values (e.g., 1 Tbps data rates). In addition, measures, such as the maximum sustainable data rate in a given context gain in importance compared to peak or achievable data rates. Additional requirements arise from novel capabilities, e.g., joint communication and sensing approaches that aim to provide 6D (three spatial and three rotational degrees of freedom) positioning and mapping information with cm-level accuracy.

Revolution of new end-to-end measures: Motivated by the use case-centric view and the additional capabilities of the 6G system, new end-to-end measures need to be defined to quantify performance in a 6G system. One previously mentioned example is dependability, which needs to be considered in a network of networks and across several types of services comprising a single application (e.g., compute, AI-as-a-service, communication). Similarly, sustainable (spatial) coverage needs to be further quantified also in relation to energy efficiency of the network and resource utilization.

New capabilities: 6G is expected to integrate several new capabilities currently not covered by wireless communication systems, such as co-design for sensing, integrated AI functionality, specialized sub-networks or using embedded zero-energy, zero-cost devices. This will bring several new domain-specific performance indicators (e.g., sensing resolution, AI model convergence time and fidelity or computational round-trip time), while also affecting the scope of end-to-end measures, e.g., related to dependability.

Assessing the ability of these different types of KPIs towards quantifying a target (UN SDG target or additional targets motivated by the use cases and societal needs) leads to the definition of KVI. These KVIs will finally enable us to quantify the value that 6G will bring to society beyond pure communication KPIs. This methodology is also applied to address sustainability in the context of 6G, as discussed in the following section.

All of the KVIs, as described, will foster and contribute to economic growth and value expansion. Within this decade, the increase of ICT investment is forecast [67] to increase global GDP by USD 8 trillion in 2030; extrapolating such numbers by leveraging 6G performance and value attributes into the 6G era yields promising scenarios of economic growth [68]. Physical industries are expected to increase their ICT investment significantly to exploit the associated gains in safety, productivity, efficiency and resiliency. Moreover, as for Hexa-X, connecting intelligence is one of the key research challenges for 6G networks, data monetization is expected to impact multiple stakeholders, from content generators, enterprises, application developers and edge service providers to mobile network operators and end users. Data can be categorized into network data and application data. In a 6G system, network data can be seen a “commodity” owned by the network operator, while application data may be either owned by the data creator or by the application provider, as part of a service subscription. Exemplary services are the ones of data lifecycle management and sharing or specialized

services for efficient acquisition and maintenance of learning data. Business agreements among various stakeholders on data ownership and usage are expected to lead to different implications with regards to data monetization and structure of data-centric economies [69].

VI. SUSTAINABILITY

Sustainability is one of the three key values, cornerstone for the 6G vision of the project, and has been identified as a main research challenge. To tackle the concept of sustainability from the various angles (environmental, societal and economic) and come within the scope of the UN SDGs, Hexa-X has defined a global framework to address sustainability: define “sustainable 6G” on one hand, and “6G for sustainability” on the other hand.

First 6G must be sustainable *per se*, to meet the global objectives of reduction of the environmental footprint of the ICT sector (representing 1.4% of the total carbon footprint of society [70], and expected to reduce it by 50% from 2015 to 2030 [71]). Energy efficiency of mobile networks have been improved by a factor 10 from generation to generation, mainly thanks to enhanced spectral efficiency, and 6G should target at least similar improvements. Sustainability should be built-in, not only regarding energy consumption, but also in the use of materials (from conception to end-of-life management), as well as utilization of renewable energy. Sustainability must be embedded at all levels of the system design, leveraging on all possible solution: use of Artificial Intelligence, softwarization, hardware levers, etc. The project natively integrates these targets and objectives into use cases and KPIs / KVIs.

6G, as a pillar infrastructure, widely used in various economic sectors, can also be turned into a powerful tool for these different economic areas to boost their own sustainability. These sectors will have the opportunity to build upon 6G to provide new services contributing to the UN SDGs, such as providing health services or educations to remote and underserved areas. They can also employ 6G as a means to monitor their own sustainability indicators. GSMA estimated that ICT has an enablement effect, and can contribute to the reduction of greenhouse gas emission by a factor 10: Compared to the global carbon footprint of mobile networks themselves, the level of avoided emissions enabled by mobile communications technologies is 10 times greater [72].

VII. CONCLUSIONS

As it has been explained in this paper, the Hexa-X vision is to connect human, physical, and digital worlds while at the same time considering sustainability, trustworthiness, and digital inclusion. Based on this vision, the six key research challenges identified by the project include connecting intelligence, network of networks, sustainability, global service coverage, extreme experience and trustworthiness.

Additionally, an important first milestone reached by the project is the identification of five use case families for 6G,

namely the sustainable development, massive twinning, immersive telepresence, robots to cobots as well as local trust zones. In order to serve these use cases, Hexa-X is going to expand and transform the fundamental network design paradigm from mainly a performance oriented one to both performance and value oriented, where the technical KPIs are complemented with KVIs to drive the network design.

Specific critical technology enablers for 6G are developed in the project and connected in a framework of x-enabler fabric, including: sub-THz transceiver technologies, accurate stand-alone positioning and radio-based imaging, improved radio performance, AI/ML inspired radio access technologies, future network architectures and special purpose solutions.

Having so far set the foundations of the work and a joint vision of 6G research, the European 6G flagship project Hexa-X will lay the foundation for future 6G projects aiming at overall system concept as well as influence the global IMT system vision.

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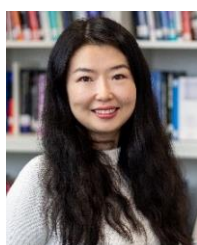
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