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A flagship for B5G/6G vision and intelligent fabric of technology enablers connecting human, physical, and digital worlds

Hexa-X

Deliverable D1.2
Expanded 6G vision, use cases and societal values

– including aspects of sustainability, security and spectrum

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Editor(s):	Marco Hoffmann (NOG), Mikko Uusitalo (NOF), Marie-Helene Hamon (ORA), Björn Richerzhagen (SAG), Giovanna D'Aria (TIM), Azeddine Gati (ORA), Diego Lopez (TID)
Authors:	Giovanna D'Aria (TIM), Michael Bahr (SAG), Leonardo Gomes Baltar (INT), Riccardo Bassoli (TUD), Pernilla Bergmark (EAB), Carlos Bernardos (UC3), Serge Bories (CEA), Giorgio Calchira (TIM), Panagiotis Demestichas (WIN), Miltiadis Filippou (INT), Frank H.P. Fitzek (TUD), Christian Gallard (ORA), Azeddine Gati (ORA), Andeas Georgakopoulos (WIN), Marie-Helene Hamon (ORA), Bin Han (TUK), Marco Hoffmann (NOG), Vasiliki Lamprousi (WIN), Matti Latva-aho (OUL), Christofer Lindheimer (EAB), Diego Lopez (TID), Marja Matinmikko-Blue (OUL), Cedric Morin (BCOM), Markus Mueck (INT), Antonio de la Oliva (UC3M), Aarno Pärssinen (OUL), Antonio Pastor (TID), Cao-Thanh Phan (BCOM), Pekka Pirinen (OUL), Pawani Porambage (OUL), Rafael Puerta (EAB), Olav Queseth (EAB), Damiano Rapone (TIM), Björn Richerzhagen (SAG), Patrik Rugeland (EAB), Berna Sayrac (ORA), Peter Schneider (NOG), Hans Schotten (TUK), Aspa Skalidi (WIN), Vera Stavroulaki (WIN), Emilio Calvanese Strinati (CEA), Serge Bories (CEA), Elif Ustundag Soykan (EBY), Tommy Svensson (CHA), Emrah Tomur (EBY), Mikko Uusitalo (NOF), Mikko Samuli Vaija (ORA), Gustav Wikström (EAB), Volker Ziegler (NOG), Yaning Zou (TUD)
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Abstract

This report will describe the vision to guide the future research towards 6G. Use cases and key value indicators will be identified, providing high-level requirements and definitions of the deployment scenarios. An initial set of sustainability targets and spectrum requirements will also be included, as well as security guidelines.

Keywords

6G vision, use cases, services, key value indicators, performance, spectrum, sustainability, security

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Executive Summary

This report is the second deliverable of Work Package 1 (WP1) — "Expanded 6G vision, use cases and societal values – including aspects of sustainability, security and spectrum" — and focuses on 6G Hexa-X vision including novel use cases, services and key value indicators (KVIs) and performance, as well as impact of growth, sustainability, security and spectrum evolution aspects. This deliverable is an extension of the first deliverable of WP1 –- "6G Vision, use cases and key societal values".

Major societal and economic trends are analyzed one by one to help to guide research and design for human-centered communication networks in the 2030s. In addition, regulatory and technological trends are critical for the design and deployment of future networks of the 6G era and those are discussed. The **Hexa-X 6G vision is to connect** the worlds and revolves around their interaction: a **human world** of our senses, bodies, intelligence, and values; a **digital world** of information, communication and computing; **and** a **physical world** of objects and organisms. The vision has **three core values** setting the ambitions for the new interactions enabled by 6G: **trustworthiness** as a backbone of society; digital **inclusiveness** to connect the unconnected; and **sustainability** to make the largest possible positive impact on the global UN sustainable Development Goals and aspects such as energy efficiency and minimum CO_2 footprint. Six main **research challenges** were identified as integral parts of the 6G Hexa-X vision: **connecting intelligence, network of networks (e.g., millions of (specialized) subnetworks), sustainability, global service coverage, extreme experience, and trustworthiness**. The relevant principles expected to shape the business of 6G are identified as part of the vision: the convergence of data together with connectivity and local special purpose platforms; new business ecosystems and stakeholders; sustainable eco-systemic platform business models; future alternative business scenarios; and telecommunication and vertical-specific regulations (such as medical regulations).

An initial set of new use cases envisioned for the 6G era are described including their connection to the Hexa-X 6G vision. The ambition and methodology are presented, as well as a review of the state-of-the-art and existing work on use cases for 6G. **Families of use cases** are identified and described: **sustainable development, massive twinning, tele-presence, robots to cobots, and local trust zones**. Each family of use cases addresses several of the six research challenges. The set of use cases described in each of the use case families is representative of envisioned trends for the usage of 6G, but is not meant to be exhaustive and will be enriched throughout the project. An additional family is outlined, consisting of enabling services that harness new capabilities of 6G systems These services will enable the realization of the use cases identified in the project, and possibly new ones.

The **novel concept of KVIs** featuring the trustworthiness, inclusiveness and sustainability abilities is introduced and the effect of the key enabling technologies on value creation for products, services, and society is described. The state of the art on performance and value indicators is reported and research challenges for 6G are outlined across four dimensions: the evolution of Key Performance Indicators (KPIs) to address new use cases, the revolution of new End-to-End (E2E) measures, the need to capture new network capabilities, and the definition of meaningful and measurable KVIs to cover the aforementioned aspects.

A representative subset of Hexa-X use cases is presented to discuss deployment scenarios and associated KPIs/KVIs. One use case has been chosen for each use case family, according to the representativeness of these use cases of the characteristics of the use case family. The selected use cases are **E-health for all**, **immersive smart city**, **fully-merged cyber-physical worlds** and **interacting, cooperating mobile robots,** and **dynamic and trusted local connectivity**.

For each one a description of a possible deployment scenario and the definition of the corresponding sets of KPIs and key values is provided, to be used for assessment of the technologies being considered.

The extension of the usage of frequency bands is discussed, so as the promising opportunity it brings for addressing 6G service requirements and achieving both enhanced and novel applications, e.g., precision positioning and sensing applications and wireless power supply technology for e.g., energy harvesting. Current allocations beyond 52.6 GHz are provided as well as information on how the spectrum utilization can be improved in different bands in and across different frequency bands.

Sustainability is a main research challenge and a core value of Hexa-X. A first analysis of sustainability issues from a 6G perspective is provided, followed by the United Nations Sustainable Development Goals to comply with. Afterwards the report discusses how 6G can be made sustainable and how 6G could foster improved sustainability in various societal domains.

General aspects of trustworthiness are presented, followed by a description of the threat landscape, an overview of security technologies applicable for 6G and the Hexa-X approach to security.

The report concludes with an outlook on planned next steps.

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List of Acronyms and Abbreviations

2G	2nd Generation mobile wireless communication system
3D	Three-dimensional
3GPP	3^{rd} Generation Partnership Project
4D	Four-dimensional
4G	4^{th} Generation mobile wireless communication system
5G	5^{th} Generation mobile wireless communication system
5GC	5G Core
5G-PPP	The 5G Infrastructure Public Private Partnership
6G	6^{th} Generation mobile wireless communication system
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AIaaS	AI as a Service
AIMDD	Active Implantable Medical Device Directive
API	Application Programming Interface
AR	Augmented Reality
ARCEP	Autorité de Régulation des Communications Électroniques et des Postes
ATIS	Alliance for Telecommunications Industry Solutions
B5G	Beyond 5G
CAPEX	Capital Expenditures
D2D	Device-to-Device
DMO	Direct Mode Operation
DT	Digital Twin
E2E	End-to-End
eMBB	Enhanced Mobile Broadband
EMF	Electromagnetic Field
EU	European Union
eURLLC	Enhanced Ultra-Reliable Low-Latency Communication
FWA	Fixed Wireless Access
GDP	Gross Domestic Product
GNSS	Global Navigation Satellite System
IAB	Integrated Access/Backhaul
ICNIRP	International Commision on Non-Ionizing Radiation Protection

ICT	Information and Communication Technology
IoT	Internet of Things
IoX	Internet of Everything
ITU	International Telecommunication Union
IVDMD	In Vitro Diagnostic Medical Devices
KPI	Key Performance Indicator
KVI	Key Value Indicator
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
LTE	Long Term Evolution
MBB	Mobile Broadband
MDD	Medical Devices Directive
MEC	Multi-Access Edge Computing
ML	Machine Learning
mMTC	Massive Machine Type Communications
MNO	Mobile Network Operator
MR	Machine Reasoning/Mixed Reality
NFV	Network Function Virtualization
NGMN	Next Generation Mobile Networks
NTN	Non-Terrestrial Network
NR	New Radio
NWDAF	Network Data Analytics Function
OPEX	Operating Expenditures
OT	Operational Technology
PMSE	Programme Making and Special Events
PPDR	Public Protection and Disaster Relief
QoI	Quality of Immersion
QoS	Quality of Service
R&I	Research and Innovation
RAN	Radio Access Network
RF	Radio Frequency
RTT	Round-Trip Time
SDG	Sustainable Development Goal
SDN	Software Defined Networking
SDO	Standards Developing Organization

SDR	Software Defined Radio
SLAM	Simultaneous Localization and Mapping
SNS	Smart Networks and Services
TCO	Total Cost of Ownership
TSDCI	Telecommunications Standards Development Society
TSN	Time Sensitive Networking
TTM	Time to Market
UN	United Nations
URLLC	Ultra-Reliable Low-Latency Communication
V2N	Vehicle-to-Network
V2X	Vehicle-to-Everything
VR	Virtual Reality
VRU	Vulnerable Road User
WP	Work Package
XR	Extended Reality

1 Introduction

Hexa-X is one of the 5G-PPP projects under the EU Horizon 2020 framework. It is a flagship project that develops a Beyond 5G (B5G)/6G vision and an intelligent fabric of technology enablers connecting human, physical and digital worlds.

This report is the second deliverable of Work Package 1 (WP1) — “End-to-End Vision, Architecture and System Aspects”. It is a superset of D1.1 — “6G Vision, use cases and key societal values” — report and presents an extended analysis of the 6G vision, use cases and key societal values. The deliverable also includes an initial analysis of the sustainability targets, starting from the UN sustainable development goals to see how 6G can be made sustainable as well as how 6G could contribute to make society as a whole sustainable. It also includes an overview of the spectrum applicable for 6G, both the incumbent low-band, mid-band and mm-waves as well as the potential expansion into the sub-THz bands. The report also includes security considerations: what security threats that are expected in the coming decades and which potential security technologies can be used by 6G to address these.

1.1 Objective of the document

The objective of this document is to describe the vision to guide the future research towards 6G. Use cases, services and Key Value Indicators (KVIs) / Key Performance Indicators (KPIs) are identified, providing high-level requirements and early definitions of the deployment scenarios. An initial consideration of sustainability targets, spectrum and security aspects are included.

The document guides the work in the project (especially of all technology-enabling work packages) and will be disseminated globally.

1.2 Structure of the document

The document is structured in the following way: Chapter 2 introduces the overall Hexa-X project structure and the structure, main objectives, work plan, and deliverables of WP1. Chapter 3 describes the common vision including an analysis of current trends in society and technology, the Hexa-X vision on 6G and the identification of relevant principles impacting the business of 6G. Chapter 4 presents 6G services and use cases, the ambition and methodology of deriving them, followed by an initial description of Hexa-X use case families. Chapter 5 focuses on KVIs and KPIs. It includes a mission statement, a state-of-the-art analysis of 6G KPIs and KVIs, as well as a description of Hexa-X challenges and contributions regarding KVIs and KPIs. Chapter 6 describes five deployment scenarios and associated KVIs and KPIs. The deployment scenarios are E-health for all, immersive smart city, fully-merged cyber-physical worlds, interacting, cooperating mobile robots and dynamic and trusted local connectivity. Chapter 7 presents spectrum evolution aspects in 6G which includes the extension of spectrum boundaries, spectrum allocations above 52.6 GHz and spectrum utilization improvements. Chapter 8 focuses on sustainability targets. First the sustainability is described from a 6G perspective, followed by an introduction of the United Nations Sustainable Development Goals. Afterwards it is discussed how 6G can be sustainable and how 6G could be an enabler for a sustainable society. Chapter 9 presents security considerations, starting with general considerations in the area of trustworthiness, followed by a description of the threat landscape, an overview of security technologies applicable for 6G and the Hexa-X approach to security. The document concludes with the description of the planned next steps in Chapter 10.

2 Project and Work Package 1 Set-Up

In this chapter, the overall Hexa-X project structure, the structure and objectives of WP1, and the WP1 work plan and deliverables are introduced.

2.1 Project structure

The Hexa-X project is structured in nine work packages (see Figure 2-1) spanning a timeframe of 30 months: WP1 —"End-to-End Vision, Architecture and System aspects" — interacts with all the other technical WPs (WP2 – WP7), steering their work and including the research results into a common 6G Hexa-X End-to-End (E2E) view. The technical work packages are focused on design and evaluation of technical enablers and components for B5G/6G. WP8 and WP9 cover horizontal activities related to impact creation and project management, respectively.

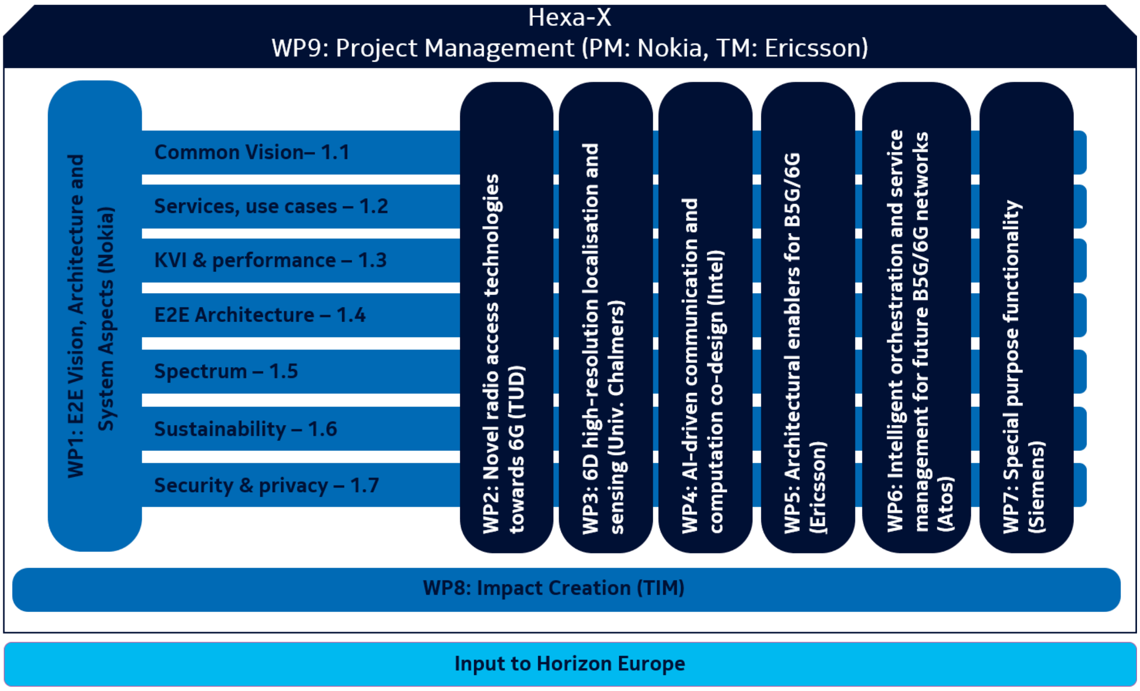

Figure 2-1: ***Hexa-X Project Structure***

2.2 Structure and main objective of WP1

This report is Deliverable D1.2 of WP1. WP1 has the main objective to define an overall vision, use cases, and an architecture of the x-enabler fabric capable of integrating the technology themes of research connected intelligence, sustainability, trustworthiness, inclusion, and extreme experience. WP1 will guide the work in the whole project and will provide requirements for all other WPs. It covers relevant E2E topics, such as architecture, security, spectrum, KVIs and KPIs. WP1 is split into seven tasks (Task 1.1 – Task 1.7, see Figure 2-1) to achieve its main goal.

2.3 Work plan and deliverables

The set of foundational elements on vision (Task 1.1), use cases and services (Task 1.2), KVIs/KPIs (Task 1.3), spectrum (Task 1.5), sustainability (Task 1.6) and security (Task 1.7) have been integrated to help build a seamless and cohesive 6G Hexa-X vision and architecture.

WP1 will provide the following deliverables:

- D1.1: 6G vision, use cases and key societal values (delivered: M02, month two after the project start). This report will describe the initial 6G Hexa-X vision including first use cases and KVI aspects.
- D1.2: Expanded 6G vision, use cases and societal values – including aspects of sustainability, security and spectrum (delivery date: M04). This report will describe the vision to guide the future research towards 6G. Use cases and KVIs will be identified, providing high-level requirements and definitions of the deployment scenarios. An initial consideration of sustainability targets, spectrum and security aspects will also be included.
- D1.3: Hexa-X architecture for 6G networks – initial release (delivery date: M14). This report will include an intermediate status update on use cases, KVIs, and spectrum, as well as achievements with respect to sustainability (final targets and progress of the project vs. targets). A draft of the E2E architecture will be delivered, including a draft security architecture and updated guidelines for security.
- D1.4: Hexa-X architecture for 6G networks – final release (delivery date: M30). This report will present the final Hexa-X vision for 6G, with final use cases, links to the technical work on enablers, final results on sustainability, the E2E Hexa-X architecture including the security architecture and related security guidelines. The document will be disseminated globally to support global discussion on 6G.

All WP1 deliverables are public.

3 Common Vision

3.1 Analysis of current trends in society and technology

3.1.1 Rationale

Since the invention of mobile telephony half a century ago, wireless network technology has undoubtedly transformed the everyday life of billions of people on the planet, and profoundly shaped the economy and the evolution of human society to date. Today, the world is facing several unprecedented challenges in parallel. The prosperity of human society and the long-term survival of mankind are in peril. From climate change, global pandemics, social inequalities to misinformation and distrust of democracy, every aspect that renders today's global economic, societal, and political agendas requires further and sustainable digitalization of the global economy and society. Infused by emerging and disruptive digital technologies on the horizon, wireless networks are and will be the keystone for enabling such a transformation. The evolution journey will carry on in the next decade, driving a large scale of adoption of current 5G use cases with significantly decreased deployment and operation costs and enabling new and innovative use-case-driven solutions with higher economic and societal values.

At the center of such an evolution is the design of future networks that convey and embody a human-centric (including human-in-control) approach involving human perspectives in all steps of the design [LUM12]. Such human perspectives shall take the environment aspect as a focal point in the consideration. The goals are to not only promote economic prosperity and sustainable growth but also act responsibly and to serve the individual and collective needs, interests and values of European and global society.

In this context, for guiding the design of human-centered future networks in Hexa-X, major societal and economic trends towards 2030 and beyond will be analyzed one by one in the following sections. In addition, regulatory and technological trends that are critical for the design and deployment of future networks will be discussed, ensuring the vision and the research work to be developed in Hexa-X will encompass all the essential elements and will lead to a future network design that is deeply rooted in reality and profoundly benefits humanity in the mid-to-long term.

3.1.2 Societal trends towards 2030 and beyond

3.1.2.1 Connectivity for a better and more sustainable world

In 2015, 17 interlinked Sustainable Development Goals (SDGs), as depicted in Figure 3-1, were collectively identified and set for "a better and more sustainable future for all" by the General Assembly of the United Nations (UN) [UN15]. Since then, all sectors of society have been called for working towards and delivering on these goals with a timeframe of 2030 and beyond. The Information and Communication Technology (ICT) and wireless network industry has positively contributed the goals so far. For example, it has been estimated that wireless networks have helped to lift two million people out of extreme poverty in Nigeria during 2010–2016 [GSM20]and a wide 1.5–2.5% growth of gross domestic product (GDP) can be triggered by a 10% increase in mobile broadband penetration [ITU18c], [ITU19a]. GSMA also estimates that network technologies enabled a global reduction of around 2,135 million tons of CO_2 emission in many other industries in 2018 alone, which is ten times greater than the global carbon footprint of the network industry itself.

Developing future networks towards 2030, there is a clear and strong consensus among major stakeholders from industry, academia, and policy makers around the world: **network technology shall support and further accelerate this change for a better and sustainable world and network industry will increase its share of contributions and responsibilities to society, enabling significantly increased efficiency in the use of resources and facilitating new and sustainable ways of living in the next decades** [Eri20], [Nok20], [GSM20], [MAA+20], [Fet20], [Dem20], [Sam20], [NTT20]. The envisioned relations between future networks and the future sustainable development as outlined in the UN SDGs have also been thoroughly analyzed by a group of international experts led by the Finnish 6G Flagship initiative in [MAA+20].

Figure 3-1: ***United Nation's Sustainable Development Goals***

In particular, climate change is an issue that poses profound long-term threat to world population and will drive major decision making and actions of global governments, industries and citizens towards 2030 and beyond. For example, Europe has set up a Green Deal and announced its ambition to become the world's first climate-neutral continent by 2050 [EC19]. It calls for the development of technologies in a holistic way with least possible negative impact, e.g., on power consumption and carbon footprint, and even ideally with zero-waste and supporting companies net-zero ambitions [MAA+20]. In this context, the contribution of the network industry to SDG #13 Climate Action is emphasized with respect to energy performance and carbon footprint. To avoid accelerated energy usage triggered by foreseen exponential increase of traffic it is important to take measures to reduce energy consumption at every element of future networks [Nok20]. To maintain current development where exponential data growth it is critical to minimize the increase of energy usage in networks, striving for that zero power consumption at zero load [ML18]. Such reduction has to be further extended to resource and material usage where not only operational consumption but also the consumption of energy and resources during the whole life cycle will be counted for improving sustainability of networks and devices [Eri20], [ER20]. Future networks are also expected to have a significant impact on many more public and private sectors (e.g. automotive, industrial, transportation, agriculture, education) by means of complementary innovation, unleashed by the future network capabilities [CBH+20], [CBH+20a], [ITU14].

Meanwhile, it is worthwhile to notice that the SDG framework extends clearly beyond the climate issues, which calls for a holistic approach to all goals as they are interconnected. To address sustainability aspect, it will not be sufficient to focus on SDG #13 alone to support all environmental, social or economic goals [RRS+19]. For guiding the design of future networks further within the SDG framework, it is also important to take two additional aspects — trustworthiness and digital inclusion — into account as well, which will be discussed in detail in the next sections.

3.1.2.2 Built-in trustworthiness in an open society

As communication networks are servicing and intertwined with all everyday processes of social, economic and political life, the need for trustworthiness is apparent. Trustworthiness is also closely related to several of the SDGs, especially #16 and #9. It is a human-centric value and a broad term that comes from evidence, which is a key element to generate trust, a firm belief, among people. The characteristics of trustworthiness — security, privacy, availability, resilience, compliance with ethical frameworks — are foreseen to become new fundamental requirements for network design towards 2030 [Eri20], [Dem20]. Future networks have to consider trustworthiness from day one of their design, ensuring that humans will be in control in the age of automation and Artificial Intelligence (AI) and promoting openness, transparency, and mutual trust across different communities and eventually within the global society as a whole.

In addition, there will be increasing business and societal demands for delivering trustworthy computing solutions, secure handling of identities and protocols, and E2E assurance towards 2030, as networks evolve beyond connectivity platforms towards system platforms that will enable trusted services with special focus on security and privacy. For example, in the next decade or so, digital currencies and digital identities may become a new norm in society. The demand for delivering trustworthy services will be paramount [Nok20].

With future networks, beyond communications-enabled services, there will likely be a massive deployment of wireless cameras, radar, radio access with integrated sensing, and other sensing modalities like acoustics with supreme recognition capacity infused by AI and machine vision. The associated privacy concerns must be addressed by, for example, controlling access to data and anonymizing information [Nok20]. In general, data handling, network intelligence, ethics considerations and the trustworthiness of AI components will be major factors to be considered for designing built-in trustworthiness in future networks [Eri20].

3.1.2.3 Digital inclusion that serves all populations

Digital inclusion is one of the major enablers for addressing most UN SDGs [MAA+20] such as #1 #2, #4, and #10 by providing digital opportunities for the underserved population. It was estimated that nearly half of the world population, i.e., around 3.6 billion, had no internet access at all as of 2019 (among them 90 million in Europe). where roughly 62% of households in rural or remote areas and 28% of households in urban or metropolitan areas have no internet access at home [ITU19c], [ITU20e]. In Africa, the situation is even more dire with no internet access at 72% of households in urban areas and 93.7% households in rural areas. Meanwhile, global coverage that provides connectivity to wherever it is needed becomes to be very important to address the climate transformation of energy and transport infrastructure as well as for small and medium enterprises outside the metropolitan areas. This includes diverse elements such as support of smart automation services, for example, a fully autonomous supply chain, everywhere on the planet, connectivity for global sensors monitoring the status of forests and oceans, access to digital personal healthcare, financial tools and cultural platforms for everyone, and access to high-end services for institutions (such as schools and hospitals) everywhere [Eri20], [Eri20a], [Dem20]. More importantly, the global coverage has to be achieved with excellent energy and cost efficiency in both deployment and operation for supporting not only the service of today but also tomorrow [Eri20], [Dem20].

Evolving towards 2030, connectivity will likely be regarded as a basic human right for accessing equal education, business and health opportunities. Stressed by the pandemic beginning in 2020, there is currently a strong societal, economic, and political drive to continue the expansion of networks for providing full global coverage and closing the digital divide to urban, rural and remote areas [Dem20].

In addition to delivering technology solutions for all populations, it is of the same importance to clearly communicate the benefits and implications of future networks to the public with human-centric values in mind. The first deployments of 5G are facing more reluctance and opposition than previous generations infused by the spread of misinformation on 5G. In order to foster the smooth transition in the deployment of future networks towards 2030, it is very critical to frame 6G research and guide the subsequent design of future networks by clear societal value goals. To minimize the creation and impact of misinformation, the network industry shall involve more representatives of society, who will be end users of future networks, at each stage of their design, and communicate transparently on the expected added value and technical facts to society and to consumers, industry and enterprise customers, public communities, and governments, as suggested in [Dem20].

3.1.2.4 Pervasive AI for human-centric and trustworthy automation and intelligence everywhere

In the next decades, AI is expected to be deployed and used broadly in society for improved efficiency and enhanced possibility to solve complex real-life problems in, for example, healthcare and transportation, and for liberating humans from mundane tasks for a better quality of life as envisioned, e.g., in UN SDG #3, #8 and #9. This may lead to a simplification of lives where services can be provided automatically and without human intervention [Eri20], [Nok20], [NOK20b]. In the connectivity domain, future connected devices will become fully context-aware for more intuitive and efficient interactions among humans, machines and the environment, and the networks will become increasingly advanced at predicting needs, optimizing and simplifying processes and improving operation without or with minimal human participation and supervision [NOK20b], [ZVF+20]. Meanwhile, future networks will also act as a critical infrastructure that transports all the required data and enables the application of AI technologies everywhere.

The integration of such intelligent features in future networks will raise issues such as value alignment, i.e., “human control” and “human trust” in AI, as already mentioned in Section 3.1.2.2. The design of any digital technology that could potentially expand human possibilities, such as future networks and AI, has to respect and embrace human values, ensuring their positive impact on humanity in the long term [Rus15]. Frameworks for “trustworthy AI” have been developed in Europe (e.g., [EC19a]) and will continue to evolve. It is anticipated that legislation will follow in the next years (e.g., [EP20]), which designates that AI should be lawful, ethical and robust from both societal and technical perspectives. The design of future networks should revisit such works, shape actions based on human-centric and trustworthy AI, and propose enhancements to the frameworks accordingly.

3.1.2.5 Mobile communications as a global ecosystem and success story

Since its second generation, mobile communications and its research have become a true global success story driven by a worldwide joint effort and open collaboration by researchers, technologists, standardization organizations, and companies as promoted by UN SDG #17. Global roaming is, for example, one of the key attributes of mobile communications and an important prerequisite for global use of applications. Standardization is bringing together experts from all over the world, and the 3rd Generation Partnership Project (3GPP) is today one of the most respected standard-developing organizations of the world. The 5G Infrastructure Public-Private

Partnership (5GPPP) under Horizon2020 frame program has become a model of industry-academia open collaboration with wide participation from all European countries and significant contributions to the definitions, development and trials of 5G standards [5GP]. To address the sustainability aspect of networks, it would be beneficial to include the resource usage perspective, for example, energy and material to the global standardization.

This success story is challenged today by an increasingly polarized geopolitical context that is affecting the technology industry and global ecosystems to a level that we have not experienced with previous generations. Technology sovereignty, supply chain resilience, cyber security and national security arguments are brought forward and need to be considered. Regional societal policies, for example, with respect to privacy and sustainability, need to be reflected in framing the research agenda and subsequent system design, while at the same time not giving up the common ground for a global standard enabling true global services and benefits through economy of scale. In recent years quite a few organizations emerged, focusing on specific segments/applications and fostering an open architecture approach, e.g., open-radio access network (O-RAN) Alliance. Since 6G will target a wide variety of different applications, this trend is likely to continue, leveraging global standards (and associated economy of scale) through open interfaces to boost innovative and widely spread solutions.

Hexa-X has the ambition to guide 6G design in line with the best practice of research and innovation (R&I) principles in Europe, advocating the European position of open collaboration, standardization and precompetitive joint research.

3.1.3 Economic trends towards 2030 and beyond

Wireless network technology has long been regarded as an important engine for driving global economic growth. As projected in [Rac20], network technology that encompasses 5G and beyond will potentially trigger $13.2 trillion global sales across ICT industry sectors by 2035, representing 5% of global real GDP, while 6G value chain will be able to generate 22.3 million jobs globally by 2035. This estimation did not even include the impact of connectivity on non-ICT sectors. As recognized in [EC20], "the next era of industry will be one where the physical, digital and human worlds are coming together", facing great economic and societal challenges towards 2030. Future networks will be a key enabler for such a revolution with advanced technology capability and human-centric design.

3.1.3.1 Digital Technologies as Foundations of Recovery and Sustainable Growth of Global Economy

Rattled by the Covid-19 pandemic, global economy was pulled into a deep contraction of 4.3% in year 2020, - the 4th most severe global recession in the history of the industrialized world, only after the ones linked to the two World Wars and the Great Depression [WB21]. Similar to those major global events, social norms will be fundamentally shifted in the post-pandemic society with drastically increased amount of remote work and interaction. Considerably more distributed data are expected to be created and consumed globally. For enabling economic recovery and (re)-building global growth while building a sustainable future in next decades, digital technologies, in particular wireless technology, have been widely accredited as fundamental tools by global governments and industry. Wireless technology serves and will continue to serve the global economy as critical digital infrastructure for all possible industrial sectors (e.g., automotive, industrial, transportation, agriculture, education, health and entertainment) and inherently enable sustainable growth in all those sectors. In the newly published "2030 Digital Compass: the European way for the Digital Decade" by the European Commission [EC21], such a view has been fully expressed and will potentially guide decision-making, public and private investments and regulatory framework in EU toward 2030.

3.1.3.2 New applications, new functions, new business models, and new market segments

As in every generation of network evolution, new use cases will arise with 6G, stemming from new applications and new functions. Future networks will be able to integrate localization, sensing, and imaging functions into its system design and provide ultra-high data rates and capacity, which opens a new door for use case and business innovation, for example, holographic communication, future decomposed handsets and wearable devices, and other novel human-machine interfaces with immersive multi-sensory experience [Eri20], [Nok20]. Robots will be increasingly present in everyday life, and their usage will no longer be restricted to optimization and automation purposes in the industry, but will expand to various other areas. Integrating the Internet of Things (IoT), Tactile Internet, Internet of Senses and Internet of Robotics together, future networks will enable not only further deepening of digitalization in all industry sectors but also creating novel consumer products and services such as robotics and sensing-enabled "white goods" [Fet20]. Sustainability will not only become a societal goal but also drive new business cases and use cases for future networks. To serve billions of people who live in rural or in less privileged areas of the cities, new use cases and new business models must be developed along with technology development to provide economically viable and sustainable solutions. Better communication infrastructure and more resilience to harsh climate and harsh environment in remote locations will be essential to local economic growth in poor communities by lowering barriers to economic resources and supporting access to financial services and generating employment opportunities [MAA+20]. Meanwhile, with the expansion of cellular networks into new and specialized subnetworks, both public and private, with novel IoT use cases and future home and enterprise environments, there is an emerging trend to serve new and potentially niche market segments where much more specialized or even tailor-made connectivity solutions will be deployed [NOK20a].

3.1.3.3 Network as a powerhouse for twin ecological and digital transitions

Great challenges as well as great opportunities lie ahead of many industry sectors to progress towards a sustainable future and growth. The key to succeed will be to infuse both ecological and digital transitions simultaneously in those industry sectors [EC20], [ER20], improve their productivity, and upgrade their capability, efficiency, resilience, and competitiveness with advanced digital technologies and automation. Serving as digital infrastructure of the economy and supporting the flow of gigantic amounts of data, for example, petabytes per year for city areas, the network industry must carry out this twin ecological and digital transition itself, incorporate it into the design of future networks and empower all the other industry sectors for such a transformation towards a sustainable and circular economy [EC20]. To empower true and wide twin ecological and digital transitions, future networks shall be designed with great energy, cost and material/resource efficiency in both deployment and operation phases, and potentially address other important sustainability areas such as biodiversity perspective in its design.

3.1.3.4 Disruptive transformation of global education, skill and labor markets

As shown in the pandemic starting in 2020, many economic activities can continue during the lockdown thanks to advanced digital technologies, and interactions and operations may be handled remotely as easily as locally. Towards 2030, future networks are expected to enable immersive communication combined with a fully digital representation of the physical world, which can allow very precise interaction and feedback loops that can remove distance as a barrier to interaction [Eri20]. Together with global coverage and other emerging digital technologies, future networks might bring major disruption to global education, skill and labor markets. For example, all schools and universities have to re-think and re-invent themselves to fit into this digital age in terms of both contents and formats of education. Internet of skills may finally come of age, enabling global access in both supply and demand sides in the labor market.

Empowered by automation and intelligence everywhere as well as with new applications, new functions, new business models, and new market segments brought by future networks, new types of jobs will be created, and many existing jobs will be fundamentally transformed [MLC+17]. While global automation will lead to replacement of many jobs by AI and machines, it is of paramount importance to educate and promote the right set of vocational skills to all populations and help them prosper in the digital age and data economy.

3.1.4 Regulatory trends towards 2030 and beyond

3.1.4.1 Spectrum and operational trends

While the telecommunications sector has been liberalized and privatized in the 1990s, sector regulation continues to be important in conjunction with efficient spectrum access rules, aspects of EMF and assurance of level playing field with platform and cloud operators beyond telco context. Towards 2030, this trend will continue. For example, spectrum management is at the heart of future networks and any wireless technology development, and governments and regulators will have new opportunities due to a wide variety of spectrum bands with highly distinct deployment characteristics and spectrum access models with different levels and needs of spectrum sharing. Another rising issue is Electromagnetic Field (EMF) exposure. The deployment of 5G technology has started in different areas of the world, and in some regions (including Europe) concerns over EMF exposure fuel the opposition of the public to its rollout ([Arc20], [Con20]). The exposure to EMF is and will be regulated, based on guidelines from the International Commission on Non-Ionizing Radiation Protection (ICNIRP). But some cities or areas of Europe, such as Brussels or Paris or the whole of Italy, have defined more stringent limits, impacting the deployment of networks [GSM14]. Since the beginning of telephony, regulations have played an important role in shaping innovation and the operation of the telecommunications industry, for example, setting the industry to be monopolies in the 1960s, liberalizing the sector with privatization in the 1990s and setting up new regulations for 5G local and private networks. Future networks will likely combine a range of radio access network (RAN) technologies from macro cells to small cells with very high-capacity short-range links. This calls for refining regulations to resolve inconsistent local approval processes and frequency band assignments to enable dense small cell deployments. In this context, future network technology could bring unprecedented opportunity for a novel regulatory regime allowing advanced specialized networks in a network-of-networks topology [MAA+20]. There is also a linkage from climate action and SDGs to spectrum. For example, spectrum regulators have already started to look into climate issue and the benefits of access to spectrum from a perspective of 6G as a potential enabler of environmental, social and economic sustainability. See 3.1.4.3 for further details.

3.1.4.2 Ethical aspects

Networks are expected to encompass certain technologies and use cases that are likely to stress current ethical boundaries. For instance, it is envisioned that miniaturized energy-harvesting devices could be injected, ingested or implanted into the human body [Mit10], which would raise concerns of potential health implications, monitoring, and questions of corresponding data ownership. In addition, distribution of ubiquitous sensors and actuators could raise concerns related to their potential excessive resource usage in production, biodegradability, and any long-term effects. Another important aspect will be ethical considerations related to privacy as our lives become further digitalized, and sensors can track our every movement. For each of these aspects, ethics and regulatory actions will need to occur alongside the technological development and align with the values of EU civil society when deploying the technologies. Meanwhile, there is also rising ethical concern over the use of AI as mentioned in Section 3.1.2.4. To address the transparency and the explainability requirements, the European Parliament has recommended the creation of a regulatory body for algorithmic decision-making in 2019 [EP19].

3.1.4.3 Environmental aspects

There is a growing public awareness of environmental sustainability and the impact of technologies on energy consumption and usage of natural resources. Regulators are addressing the carbon footprint of networks and their related usages. At the European level, the EU Code of Conduct for Energy Consumption [ECC17] sets out the requirements for energy efficiency, and also following the EU’s Sustainable Development Strategy, policy background has been studied to facilitate the common methodologies for Product Environmental Footprint [EC12]. Also the European regulator Radio Spectrum Policy Group has established a sub-group to support action combating climate change [RSP20]. At a national level, several initiatives are established; for example, the French ARCEP is working on the definition of a *Green Barometer* in order to inform users of fixed and mobile networks about their consumer behavior as far as their carbon footprint is concerned [Arc20a]. New types of user devices are proposed, based on a modular architecture, allowing renewal of only part of the smartphone to address the demand of circular economy action [Fai21], [EC20b]. In Finland, the Ministry of Transport and Communications highlights the need to reduce energy and material consumption within the ICT sector itself and to harness the potential of the ICT sector as a facilitator of a more climate and environmentally friendly society in its final report of preparing an ICT climate and environment strategy [OMH+20].

3.1.5 Technological trends towards 2030 and beyond

3.1.5.1 Disruptive technologies that will shape future connectivity

Convergence of communications, localization, imaging and sensing: Localization was introduced in Release 9 of the 3GPPP specifications and is continuing to evolve. The possibility of transmitting haptic data together with audiovisual one brings about a Tactile Internet with Humans in the loop (TaHil) as preliminarily standardized in IEEE 1918.1. With the use of wider bandwidth signals coupled with high band spectrum (>100 GHz) as well as the incorporation of Simultaneous Localization and Mapping (SLAM) with communications at lower frequencies, future networks will be designed integrating high-precision localization (with centimeter-level accuracy), sensing (both radar-like and non-radar like) and imaging (at millimeter-level) capabilities. This requires the development of highly novel approaches and algorithms to co-optimize communications, sensing and/or localization. It will transform not only application layer aspects but also optimize the network performance, for example, with proactive radio resource allocation and management, and determine design choice of waveform to enable both extreme connectivity performance with ultra-high data rate and a full 6D map of the environment that captures information in all three spatial (latitude, longitude, altitude) and orientation (pitch, roll, yaw) dimensions. Combining extreme connectivity and such 6D maps with movement predictions and AI, novel applications and use cases will come to reality that are based on new immersive mixed reality experiences. This enables an intuitive way of interaction and a variety of use cases ranging from medical to industrial context [Eri20], [Nok20]. Security and privacy must be integrated into such applications and use cases to ensure that humans will stay in full control of the augmented and mixed reality.

Network intelligence: AI/Machine Learning (ML) will bring a major disruption to future networks from impacting the design of air interface, data processing, network architecture and management towards computing for achieving superior performance [Nok20], [NOK20b], [Dem20]. It will become essential for the end-to-end network automation dealing with the complexity of orchestration across multiple network domains and layers [ZVF+20]. Network intelligence will help to improve energy efficiency and ensure service availability by performing optimizations that are challenging for traditional algorithms with AI/ML approaches and carrying out system management tasks autonomously with AI/Machine Reasoning (MR) [Eri20]. However, an autonomous system can only be successful if it is trusted by humans and can be understood and explained. It is extremely critical to establish suitable mechanisms for trustworthy AI. For example: the system needs to be able to explain its actions and why it ended up in its current state; the intelligent system should i) act lawfully, respecting all applicable laws and regulations [EC19a], ii) be ethical, respecting the right principles and values, and iii) be technically robust while considering its social environment. Last but not the least, the system must involve humans when needed [Eri20].

Network of computing: Future network platforms will bring all physical things into the realm of computing. It will act not only as a connector but also as a controller of physical systems — ranging from simple terminals to complex and performance-sensitive robot control, and augmented reality applications — hosting computing intertwined with communication in a network compute fabric for the highest efficiency [Eri20]. Ubiquitous universal computing will be distributed among multiple local devices, sub-networks and clouds [Nok20], [ZVF+20]. Service providers can utilize their assets by integrating compute and storage into increasingly virtualized networks to provide applications with maximum performance, reliability, low jitter, and millisecond latencies. A network-compute fabric can provide tools and disruptive services that are supported beyond current connectivity solutions, such as accelerated compute and data services and new services that are enabled by disruptive technologies such as joint sensing and communications and digital twins for customer segments and verticals, including enterprises and industries [Eri20].

Resilience and security: Network resilience that helps the network provide and maintain an acceptable level of services facing faults or challenging situations will need to be addressed from different perspectives. Applications that demand resilience, both for their connectivity and their end-to-end communication, need to be supported. A distributed architecture may ensure that not all information (and not all risk) is centralized among a few parties. Similarly, the necessary internet infrastructure needs to be available, resilient, and resistant to commercial surveillance [Eri20]. It will be critical to ensure the integrity of the entire system including both RAN and Core parts [Fet20]. In addition, associated with their impact on the economy and society, future networks are expected to face more frequent and more sophisticated cyber-attacks and security breaches. New and efficient security and privacy schemes need to be developed [Nok20], [Fet20], for example, applying AI to predict problems, detect and automatically resolve attacks that are caused by either classical or AI-based approaches, [Dem20]. Last, but not least, resilience and security-enabled trustworthiness can only be fully realized when it is embedded in both the corresponding software and hardware implementations of the network technology [Fet20].

Digital Twin: A Digital Twin (DT) is a digital replica of a living or non-living entity. The virtual representation reflects all the relevant dynamics, characteristics, critical components and important properties of an original physical object throughout its life cycle. The creation and update of DTs relies on timely and reliable multi-sense wireless sensing (telemetry), while the cyber-physical interaction relies on timely and reliable wireless control [MLC20] over many interaction points where wireless devices are embedded. In future networks, DTs will be used as a valuable tool to create novel and disruptive solutions, especially for vertical industries, that are enabled by a large scale of real-time, robust and seamless interactions among, for example, machines, humans and environments. Particularly, DTs can be scaled up, which enables a large scale of sustainable living with systematic climate mitigation measures, improves the resilience of society in crisis situations by actively monitoring and simulating all possible scenarios and potentially helps transform the whole societal structure that is suitable for 2030 and beyond.

3.1.5.2 Technology evolution towards cost reduction and improved efficiency

Reimagined network architecture: New network architecture paradigms . for the 6G era are driven by a decomposition of the architecture into platform, functions, orchestration and specialization aspects [ZVF+20]. Future network platform will be associated with an open, scalable, elastic, and agnostic heterogeneous cloud, which is data flow centric and will include hardware acceleration options. Functionally, the convergence of RAN and Core Networks will help reduce architectural complexity. At the same time, options of flexible offload, extreme slicing and flexible instantiation of sub-networks will drive the increased level of specialization of the architecture. Of high relevance for the open provision of services and the monetization of resource will be the transformation of orchestration architecture; cognitive closed loop and automation are likely to become pervasive. All future deployment scenarios will rely on a superior transport network and network fabric that is flexible, scalable and reliable to support demanding use cases and novel deployment options, such as a mixture of distributed RAN and centralized/cloud RAN enabled by AI-powered programmability [Eri20]. The network architecture shall provide the capability to facilitate all the AI operations in the network.

Predictable latency and reliability: Future networks shall address the extreme performance requirements of more advanced vertical industry applications on latency, reliability and potentially, age of information and age of task [NOK20a]. To achieve such extreme performances with reasonable costs requires a joint design of communications, control and even computing [Fet20], [HYJ+20]. To address less extreme requirements, a deterministic latency end-to-end across the protocol stack will be important for enabling cost-efficient services.

New devices and interfaces: Future networks will be connected to multitudes of devices and interfaces beyond mobile phones or computers, enabling novel human-machine/machine-machine/AI-AI communications. New human-machine interfaces created by a collection of multiple local devices will be able to act in unison [Nok20]. In addition, the ubiquity and longevity of IoT devices will be further enhanced through zero-cost and zero-energy devices where printable, energy harvesting devices can be deployed anywhere.

Component and hardware: With advances in hardware development, it is now possible to employ generic hardware acceleration for faster service deployments through cloudification and virtualization. On the other hand, the use of non-generic hardware acceleration will still continue to address high performance required by AI and the real-time 6G physical layer, for example. Meanwhile, novel research on metamaterials promises potentially revolutionary new applications, questioning long-held presumptions based on classical components, for example, reconfigurable surfaces or novel antenna designs [Eri20]. Towards 2030, to minimize power consumption and enable novel use cases and seamless interactions, novel and advanced component/hardware technologies will continue to be developed.

Software: Application development for enabling functions and services will become easier than ever. There will be a need for the ecosystem to develop new, innovative applications once more things get connected. More development flexibility will be required to meet the increasing need for highly customized applications. Common APIs and abstractions, together with new programming concepts and simplified models, will be part of the solution [Eri20]. Open source and open APIs may play an important role to foster the growth of ecosystems.

Spectrum: More dynamic spectrum sharing methods are appearing (e.g., CBRS [Ong]) where spectrum resources are dynamically allocated in time and space. It is straightforward to follow this evolution forward into a more demand-driven system concept with a smaller granularity in spectrum allocation and a shorter round-trip time, while avoiding spectrum fragmentation drawbacks. This can allow for smarter use of resources complementing licensed and unlicensed bands and an opportunity for mobile services to use spectrum resources in bands occupied by other services [Nok20], [Eri20].

Network of networks: In order to capture local and specialized network and sub-network needs, 6G network-of-networks will cover multiple scales of – physical and virtual – networks. The evolution of private and 5G non-public network (NPN), such as campus networks, will expand to support many machines and process with strict requirements on Quality-of-Service (QoS) and connectivity, employing edge processing for further automation. With digital twins, massive data harvesting from local sensors build up capillary sub-networks handled by gateways, while in parallel the wide-area network must handle mobility and coverage. Verticals and enterprises (e.g., energy sector smart grids) will benefit from automated services with guaranteed performance in conjunction with as-a-Service (aaS) business model transformation. Such services will be based on various types of resources, including communication, data and AI processing, and will require tailored network functionality supporting new value chains in a controlled fashion.

Integration of non-terrestrial networks (NTNs): Integration of low-cost and power-efficient terrestrial solutions with NTNs will become one of potential solutions for addressing coverage in rural and remote areas, for example, with high-altitude platforms or Low Earth Orbit (LEO) satellites. Spectrum sharing with satellite frequency bands might be an attractive implementation option [Dem20]. The achievable latency, capacity, and reliability of NTN will be important aspects along with device energy consumption. Currently, in Release 17 3GPP is working on including NTN in the 5G New Radio (NR) scope [3GP20] and also started a study item on the use of NTNs for IoT operation in remote areas with low/no cellular connectivity in Release 17 [3GP20a]. Several LEO initiatives are actively promoting NTN as a useful coverage complement to terrestrial high-capacity systems [Eri20]. Such integration of non-terrestrial and terrestrial networks will require the development of design methods for 3D network [SBC+20]. vRAN may be introduced to enable virtualization of NTNs [BBG+20]. Different options of architectural evolution need to be examined for supporting both transparent and regenerative payload satellites.

Services and applications leveraging on richer context information: Future networks will enable the delivery of richer context information. Location information will be much more detailed. The context of service delivery will also be enriched by the much larger range of network capabilities, for instance, in terms of spectrum (which will go up to the THz range), network architectures, flexible software activation, following a disaggregation approach. In parallel, the introduction of special purpose networks and the emergence of new verticals-driven applications creates the possibility for richer user experience, depending on the time and place. Future networks will bring closer the vision of service offerings that will become different depending on requirements, user and application profiles, and the richer context. End-user devices must be able to proactively utilize varying content offerings. Moreover, from the system side, it can be envisaged that there will be various microservices, offered by different players, depending on the specific ecosystem and context.

Emerging trend on Semantic and Goal-Oriented communications: Towards 6G, there is a rising view in academia and industry that future services might induce to a radical change on how knowing and learning, guessing and discovering is independently implemented today. Whenever communication occurs to convey meaning or to accomplish a goal, what really matters is the impact that the received bits have on the interpretation of the meaning intended by the transmitter or on the accomplishment of a common goal [ECS21]. This may stimulate novel and innovative research directions based on Semantic and Goal-Oriented communications paradigms that will tackle fundamental opportunity resulting from interacting AI functionalities embedded in 6G networks.

3.1.6 Most significant global activities on future connectivity

With significant impacts on society, economy and politics towards 2030, the global race on the research of 6G networks has already started. The International Telecommunication Union (ITU) has established a focus group on Technologies for Network 2030 in 2018 [ITU18] and ITU-R Working Party (WP) 5D has started future technology trends work in 2020 and vision work in 2021 regarding IMT for 2030 and beyond [ITU21a]. Additionally, the Next Generation Mobile Networks (NGMN) alliance announced the launch of a project on visions and drivers for 6G in February 2021 [NGM20].

In Europe, with support of the academy of Finland, the world's first national 6G program, 6G Flagship, was established at the University of Oulu in 2018 [6GF], [6GF19]. In January 2021, nine EU 6G projects (including Hexa-X as the flagship) kicked off under the last call of Horizon 2020 [5GPa]. It is expected that these projects will carry out explorative research and pave the way towards 6G. Meanwhile, building on activities and results of 5G-PPP in Horizon 2020, a renewed European level private-public partnership on Smart Networks and Services (SNS) joint undertaking will be launched in the spring/summer of 2021 under the 2021–2027 European Research Frame Programme, i.e., Horizon Europe, targeting at R&I beyond 5G and towards 6G [SNS20]. In addition to network design, with 2030s on the horizon, Europe has also recognized the importance of strengthening its industry position and competence on connectivity chip design. A cross-industry initiative — COREnect — was launched in July 2020, bringing European major players in microelectronics and telecommunications together and targeting the reduction of Europe's dependence on other continents for suppling electronic subsystems and components towards 6G [Cor20].

Meanwhile, outside Europe, with "Secure 5G and Beyond Act" published in March 2020, the US administration has officially announced its intention to work with the private sector to facilitate the evolution and security of 5G [Cor20a]. On 13 October 2020, the Alliance for Telecommunications Industry Solutions (ATIS) launched Next G Alliance, an industry initiative that builds foundations for US leadership in 6G and beyond with 16 industry founding members [NGA21]. In Asia, as announced in September 2020, South Korea will target to invest €142 million over 5 years from 2021 to secure high-risk basic 6G technology [6GW20], while Japan published a paper on "beyond 5G promotion strategy – roadmap towards 6G" for public consultation in June 2020 [MIA20], and China's Ministry of Science and Technology made in a statement in 2020 that it will set up two working groups to carry out research on 6G covering both policy and technical aspects of 6G development [IF20]. Recently, the Telecommunications Standards Development Society, India (TSDCI) has started to establish a 6G initiative with focus on 6G use cases and requirements [Tsd20].

3.2 Hexa-X vision on 6G

During the last half century, driven by continuous wireless technology innovation and by market needs, mobile networks and the telecommunications industry have significantly transformed human society and the lives of billions. The primary focus has always been to meet peoples' needs to communicate anywhere/anytime and help the world act together. Since the time of 4G, the focus was on delivering a digital infrastructure that also supports professional services, vertical sectors and machine-to-machine communication. With the advent of 5G, this move has considerably been amplified. 5G is expected to pave the way for the digitalization and transformation of key industry sectors like transportation, logistics, commerce, production, health, smart cities, agriculture and public administration. This trend of digitalization, making industries more connected, automated and smart [Bar19] in conjunction with consumer interest in increasingly demanding services such as Augmented Reality (AR) and Virtual Reality (VR) will continue. Therefore, the need of services for connectivity is expected to keep growing exponentially [Eri20b], and will call for bit rates in the order of hundreds of gigabits per second to terabits per second. Several additional aspects of performance will be described below.

While 4G has enabled and 5G significantly enhanced our ability to consume digital media anywhere, anytime, the technology of the future should enable us to embed ourselves in virtual or *digital worlds*. In the world of 2030, human intelligence will be augmented by being tightly coupled and seamlessly intertwined with the network and digital technologies.

With advances in AI, machines can transform data into reasoning and decisions that will help humans understand and act better in our world. As the domestic and industrial machines of today transform into swarms of multi-purpose robots and drones, new approaches based on human-machine haptic and thought interfaces to control them from anywhere should become an integral part of the future networks. As illustrated in Figure 3-2, Hexa-X envisions a future in which everyday experience is enriched by the seamless **unification of the *physical, digital* and *human worlds*** achieved through a new ecosystem of networks, sub-networks and device technologies. Such a transformation will undoubtedly generate unprecedented economic opportunities towards the 2030 timeframe. To this end, 6G research should address studies into the technology fundamentals, usages and experience design, as well as social and market opportunities of future communications systems. Multiple key requirements must be reconciled to serve the massively growing traffic and the exploding numbers of devices and markets both in current deployment areas and for the currently underserved. At same time there is the need to accomplish the highest possible standards regarding sustainable energy and resource efficiency, low latency, strong security, and efficiency in deployment (coverage) and operation, for **enabling sustainable growth with trustworthy systems**. Despite increasing ambitions with more use cases and more performance, 6G should be an integral part of a fully sustainable and carbon neutral world. The main motivation factors for the 6G vision are:

Technology push: The advent of key technologies such as AI, radio access beyond 100 GHz, network virtualization, cloud native implementation and architectural disaggregation concepts 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 Technology Readiness Level, to understand the potential performance and impact on the overall system architecture. It is crucial to apply these new technologies to excel in new usage domains, and to make them useful in the future society.

There has been for a long time trend of growing interest how to provide in the best way local networks. One example of this are Campus Networks. At same time there has been increasing activity in providing connectivity via more affordable satellite solutions and there is possibility for better integration of space and terrestrial technologies for full 3D global coverage, reaching also remote locations and contributing to inclusion. 6G will look more closely at cooperation between humans and machines by fully merging all senses as necessary. Here for example tactile internet can help.

Society and industry pull: Climate change, pandemics, the digital divide, social inequalities, as well as distrust and threats to democracy, are some of the unprecedented societal challenges of our times. It is of utmost importance to mitigate these devastating challenges, 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 [WEF20] to help address United Nations (UN) [UN19] and European SDGs [EC19]. Digitalization of industry sectors will continue to improve efficiency, trust in and resilience of the economy, promote sustainable growth and create meaningful jobs, supporting the transformation of Europe to a strong circular economy.

Technology sovereignty is high on the agenda of the European Union to leverage future digital opportunities, guarantee jobs and livelihoods as well as to ensure the security of its citizens. Europe must build on the strength of its broad technology research and foster the digital transformation of its infrastructure and economy for the 6G era, while defending the continent's core democratic values. For the 6G era technology policies to reflect the societal impact and drive growth, it is decisive to focus on trustworthiness, sustainability and digital inclusion from the start, following a value-driven human-centric approach. Europe should build on its trusted public private partnerships to leverage on mutual strengths and cooperation. The 6G flagship initiative Hexa-X has identified technology sovereignty as a key value indicator, by bringing together the key industry stakeholders in Europe, along with the full value-chain of future connectivity solutions ranging from network vendors, operators, verticals, and technology providers, as well as the most prominent European research institutes and universities in this domain, streamlining expert forces and creating a critical mass to lead an integrated European led effort of research and development towards 6G.

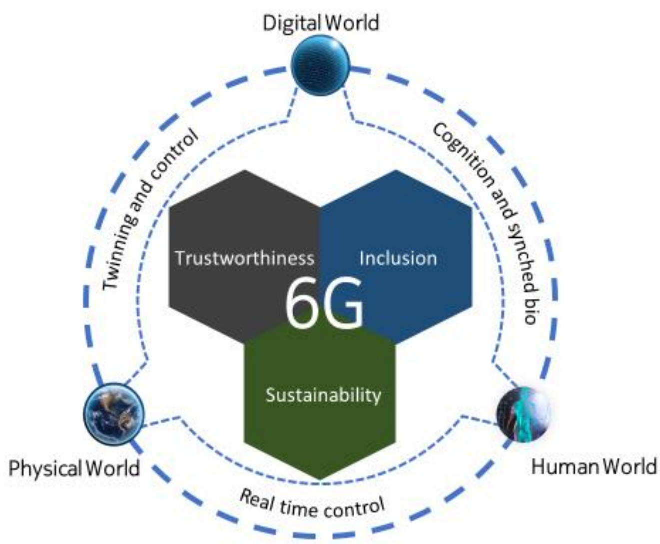

Figure 3-2: ***Hexa-X 6G vision***

The Hexa-X vision for 6G revolves around interactions between three worlds: a *human world* of our senses, bodies, intelligence, and values; a *digital world* of information, communication and computing; and a *physical world* of objects and organisms. The future 6G network system should make it possible for these worlds to tightly synchronize and integrate to make it possible to seamlessly move between them. Realizing these interactions will open up many new use cases, applications, and services that will benefit people on all levels: as consumers, parts of enterprises or societies.

Interactions between the physical and the digital world will enable digital twins of the world, where rich sensor information can be used for deep data mining and analysis. Intelligent agents can act on the digital twin and trigger actions in the physical world through actuators. Such actions would improve the efficiency and resilience of operation in the physical world via better planning and control as well as preventive actions, for example for maintenance before problems would emerge. This could lead to a massive scale of usage of digital twins and hence massive needs for communication.

Interactions between the human and physical world would enable efficient control and feedback between the worlds, for example based on efficient human-machine interfaces.

Interactions between the human and digital world enable assistance from AI to improve our lives, as well as empowering fully immersive communication between people. Collection of information on the state of the human bodies and synching this from the human world to the digital world would entail getting knowledge of the body through E-health applications, enabling, for example, preventive healthcare.

Importantly, the vision has three core values at its center, around which the three worlds revolve (see Figure 3-2), setting the ambitions for the new interactions enabled by 6G. These are: *trustworthiness* for 6G as a backbone of society; *inclusiveness* for 6G to be available for everyone and everywhere; and *sustainability* for 6G to play the largest role possible towards global development with regard to environmental, social and economic aspects. These three core values should influence the targeted 6G capabilities and requirements and should together with the three world interactions guide the project. Taken together, the vision points towards a set of research challenges to be addressed by the project, presented next.

To fully embrace such a vision, Hexa-X recognizes the necessity to expand the fundamental network design paradigm from mainly performance-oriented to both performance- and value-oriented. Here *value* entails intangible yet important human and societal needs such as sustainability, trustworthiness and inclusion. This will lead to a new class of evaluation criteria, i.e., KVIs [ZY20], which must be understood, developed and adopted in framing 6G research and the network design towards 6G. Hexa-X understands that the development towards 6G requires wide support and global efforts. It will strive for openness and collaboration among the European and global research community, standardization bodies, and policy makers through, for example, organization of public workshops, preparation of joint whitepapers, and active participation in major events. An open, modular and flexible framework — the x-enabler fabric — will be developed as a foundation, to integrate and weave together the technical enablers that address the six research challenges, from both the Hexa-X project itself and other 6G projects. “X” in Hexa-X refers to exploring the unknown and the x-enabler fabric adds the dimension of “x” as “cross-enabler”. The realization of a new network generation takes about eight to 10 years, and to guide the Research and Innovation (R&I) globally towards 6G during this time, Hexa-X will lay the foundation for the network of 2030 and develop long-term strategic roadmaps based on research outputs obtained within the Hexa-X project as well as from other 6G research projects under the H2020 5G-PPP umbrella.

3.2.1 Research challenges

In order to ensure that the 6G research progresses in the right direction to fulfil the needs of 2030, it is important to focus on the most relevant issues. In this vision, six main research challenges were identified as can be seen in Figure 3-3. These challenges must be addressed to lay the technical foundation for the wireless systems of the 6G era:

Figure 3-3: ***6G research challenges***

1. **Connecting intelligence**: 6G shall assume a crucial role and responsibility for large-scale deployments of intelligence in the wider society. 6G shall provide a framework to support (e.g., through advanced resource management), enhance (e.g., through supplementary data, functionality, insights), and, ultimately enable real-time trustworthy control – transforming AI/ML technologies into a vital and fully trusted enabler for significantly improved efficiency and service experience, with the human factor ("human in the loop") integrated.
2. **Network of networks**: 6G shall aggregate multiple types of resources, including communication, data and AI processing that optimally connect at different scales, ranging from, for example, in-body, intra-machine, indoor, data centers, to wide areas networks. Their integration could result in an enormous digital ecosystem that grows more and more capable, intelligent, complex and heterogeneous, and eventually creates a single network of networks. It will serve various needs, support different nodes and means of connectivity, and handle mass-scale deployment and operation fulfilling a large diversity of requirements with utmost efficiency and flexibility, promoting business and economy growth and addressing major societal challenges like sustainable development, health, safety and the digital divide.
3. **Sustainability**: 6G shall transform networks into an energy-optimized digital infrastructure and will deeply revise the full resource chains of wireless networks towards sustainability and carbon neutrality. Its digital fabric shall, beyond providing unprecedented connectivity and coverage, also create the ability to sense and understand the state of the physical world in real time, and as such boost sustainability from the environmental, economic, and social perspectives and importantly deliver effective and sustainable digitalization tools for global industry, society and policy makers, help achieve UN SDGs and assist the implementation/operation of the EU Green Deal, in particular after the COVID-19 pandemic, towards a circular economy and a sustainable world.

4. **Global service coverage**: 6G shall put digital inclusion as one of the priorities and encompass efficient and affordable solutions for global service coverage, connecting remote places, for example, in rural areas and in transport over oceans or vast land masses, enabling new services and businesses that will promote economic growth [AEM12] and reduce the digital divide as well as improving safety and operation efficiency in those currently under-/uncovered areas.
5. **Extreme experience**: 6G shall provide extreme bit rates (access in the order of hundreds of gigabits per second to a few terabits per second), extremely low (imperceptible) latencies, seemingly infinite capacity, precision localization and sensing, pushing the performance of networks a leap beyond what is possible with 5G – unlocking commercial values of new technologies at sub-THz range, supporting extreme experience of services such as fully immersive communication or remote control at scale, and accelerating the pace of digitalization.
6. **Trustworthiness**: 6G shall ensure the confidentiality, integrity and availability of end-to-end communications, and guarantee data privacy, operation resilience and security, building trust of wireless networks as well as its enabled applications among consumers and enterprises — supporting and promoting European ethical values of trust and privacy protection as well as the technological EU sovereignty goal for fostering an open, trustworthy and democratic Europe in the digital age.

Naturally the requirements of cost-effective deployability and operability always apply in order to realize the results from these research challenges.

3.3 Aspects of 6G business impact

3.3.1 Background

The identification and development of future business opportunities will be an important aspect to guide 6G research and development to address the future needs of various vertical sectors that today are learning to benefit from 5G. This will call for filling in the requirements of scalability, replicability and sustainability in a legitimate way in a convergence and platform based ecosystem of connectivity, data and specialized services. Development of new ecosystemic platform business models has to be done in a sustainable way. New business ecosystems will appear to bring together stakeholders to solve systemic sustainability problems together with better monetization and higher profitability driving a faster deployment of open ecosystem. At the same time, sustainability of the 6G systems themselves will be an important design criteria in the ecosystem driving the future networks. Business objectives will include both aspects of value capture as well as sustainability impact. These business ecosystems will require an open ecosystem-focused value configuration and decentralized power configuration where there is no single dominating stakeholder, but the roles and positions will vary depending on the problem at hand. Focus will increasingly be on the long tail of specialized user requirements that crosses a variety of industries [YAM20a].

A major opportunity is in how 6G could potentially become a General Purpose Technology, i.e., pervasively affecting the world economy due to its dynamic improvements of technology enablers and fostering innovation complementarities across a wide range of industry sectors, instead of simply an enabling technology, to support countries, organizations and society in the journey towards a future of growth and sustainability. The achievement of the UN SDGs by 2030 calls for the whole ICT sector to support the verticals in renewing their operations to meet the increasing requirements for sustainability [MAA+20], [ZY20]. The deployment of 6G is expected to start in 2030 when the current SDGs should be achieved. The UN SDG framework itself is likely to evolve during the full deployment of 6G in the 2030s.

Convergence and platform based ecosystems : With the beginning of the 5G era, mobile communication networks have evolved into multi-purpose business platforms of cross-sectoral relevance. The mobile connectivity platforms of the Mobile Network Operators (MNOs) acquired from the network vendors are increasingly becoming converged with the data platforms of cloud service providers, giving rise to new platform-based ecosystems [AYM+20]. The convergence of data and connectivity platforms continues to be a major influencer for the business of 6G and the related value-capture in the 6G era requires understanding the dynamics of platforms and ecosystems [MYP20]. In addition to wide area networks based on distributed multi-stakeholder cloud architecture, we will see millions of subnetworks designed for both autonomous operation as well as operation in co-ordination with wide area policies. Operator-assisted service discovery and function offloading will enable an expansion of platform-based ecosystems beyond the dimensions of data and connectivity. Performance attributes such as extreme reliability and low latency can be associated with specialized and localized subnetwork platforms for the 2030s. Access to data and data ownership continue to be major factors shaping the 6G business and enabling stakeholders to develop control points in the ecosystem. Modularity and complementarity of technology solutions will redefine the competitive environment in the context of openness vs. transparency as well as collaboration vs. competition issues in the future 6G business ecosystem. The resulting complex multi-stakeholder ecosystem will be an arena of dynamic use case instantiation and monetization.

New business ecosystem and stakeholders: Combining various data platforms, connectivity and local special purpose platforms is a great opportunity to enable new business ecosystems beyond the mass market paradigm; but it is also a challenging task, especially in the real-life complex multi-stakeholder environments in verticals where different organizations typically have their own data, connectivity and special purpose operations time platforms with interactions with outside platforms being limited. The business ecosystem around future mobile communications is changing with evolving stakeholder roles and new stakeholders emerging [AYM+20], [ZY20]. Some of those stakeholders have dominant global positions being capable to impact the telecommunication market at large. The serving of different verticals with local and often private 5G networks has already introduced new stakeholders as local operators to complement the MNOs [MLA+17]. For example, local operators are appearing to serve a closed industry setting in a factory, MNOs' customers in a local public network, or a mix of both customer groups. Future 6G business ecosystems for solving sustainability problems need open value configuration and decentralized power configuration focusing on specialized user requirements that cross a variety of industries [YAM20a], [YAM20b]. Different sets of stakeholders with their specialized expertise and resources and a high level of automated integration processes and methodologies come together in the 6G ecosystem to solve specific sustainability problems.

Sustainable ecosystemic platform business models to address new opportunities of growth: In 6G the focus is on developing economically, societally and environmentally sustainable solutions and business models and with special potential for specialized solutions tailored to specific context and need. The solving of sustainability problems with 6G-based solutions will often involve interactions of multiple organizations emphasizing the business ecosystem level that brings the needed stakeholders together, instead of focusing at a single organization's level business considerations [YMA20]. As a result of the growing ecosystem level emphasis in 6G, the development of business models in the ecosystem level will be increasingly important, shifting the focus to ecosystemic platform business models. There the scalability and replicability of the 6G solutions' business models are key for growth. A scalable business model is agile and provides exponentially increasing returns to scale in terms of growth from additional resources applied, while a replicable business model can be copied to several markets simultaneously with minimum variations, aiming at growth through wide-spread adoption of 6G in society.

Alternative future business scenarios: Business scenarios present alternatives for the future, which is unknown. A set of twelve alternative business scenarios were developed for 6G in [YAM20a], [YAM20b], [ZY20]. From the scenarios, especially the most plausible "MNO6.0" Scenario and the most preferred "Sustainable Edge" scenario present highly distinct views for the future. The MNO6.0 scenario is built on the use of MNOs' wide existing customer base, with a growing demand for capacity through investments to maintain and strengthen their customer base and market position in connectivity, enhanced with customer data, relying on efficient spectrum usage and a variety of specialized attributes of performance. The sustainable edge scenario [YAM20a], on the other hand, describes a future where novel players take over both customer ownership and networks and MNOs play a role as a wholesale connectivity service provider. New, local, and specialized demands provide an opportunitity for novel business segments, specializing in governmental, municipal, vertical or enterprise customers and vertical differentiation with increasing requirements for sustainability in specific industry segments like education, healthcare and manufacturing. Also thinking and acting locally, close to the customer, promoting resource sharing, and utilizing the lowest cost spectrum and virtualized cloud infrastructure are key in the business scenario. In addition, we will see the proliferation of private and campus scenarios privately run and operated using either unlicensed or licensed spectrum.

Telecommunication and vertical specific regulation: A key factor in enhancing business of 6G continues to be regulation, which defines the rules and conditions for the telecommunication network as well as the different verticals making use of the data and connectivity platforms. The telecommunication sector is regulated, including, for example, spectrum regulation, access regulation, pricing regulation, competition regulation, privacy and data protection (see e.g. [MLA+18], [5GP20]). Additionally, the regulatory environment for 6G in vertical services is complex, encompassing both the connectivity-oriented communications market as well as specific vertical services offerings and performance attributes, so requiring a large variety of regulatory challenges to be addressed within the proper bodies. Moreover, the growing pressure from sustainability on environmental aspects, for example, will influence the development of future 6G networks. In Hexa-X we will consider the evolution of the spectrum requirements and of the current spectrum usages, in order to guarantee future-proof migration paths for vertical services, for example, and to enable new business opportunities.

3.3.2 6G business elements

Various elements from technology, service, standardization, and regulation perspectives will influence the 6G business. 6G aims to be developed as a "general purpose" technology and new business models will be developed accordingly.

New 6G services, based on zoning, twinning, slicing, on-demand security, brokering, matching, bridging, and "aaS", will trigger the emergence of new business roles for both current and new stakeholders. Also, service users will increasingly provide a compass for future business models due to their increasing demands and requirements in terms of e.g., "empowerment", user experience, security and privacy that go far beyond the compliance of often independent technical performance requirements.

Developing global harmonized technical standards will remain crucial for global services' availability and economies of scale, while taking into account the seamless network integration of emerging vertical domains. This development can accommodate and spur new business models where efforts are spent on sustainability and its implementation instead of technology push to prevent market failures afterward. In 6G, the current value capture mechanisms centered around broadband access will increasingly make use of innovations from converging information and communication technology application domains. To maximise the innovation for 6G it is essential that regulators protect the intellectual property contributions of developers and R&D practicing entities to incentivize R&D investments for the future. . Risk of fragmentation of standard defining organizations and other communities of collaboration needs to be actively mitigated to assure economy of scale in a global context. Furthermore, innovations may increasingly require access to new technological or technological-related infrastructures as public complementary assets, emphasising the role of public-private partnerships.

Sustainability and its implementation elements, such as measures for energy efficiency and reuse of materials, will need to be carefully taken into account since the beginning, when developing new systems and services. 6G will need to natively support the requirement of environmental efficiency and sustainability.

Limiting the consumption of highly scarce/limited resources, including radio spectrum and transmission power to limit EMF emissions, will be pivotal to reach that requirement. Technologies to enable resource sharing will increasingly develop to accommodate efficiency and sustainability principles, giving rise to new business models.

New regulations will also play an important role in providing guidance and make 6G business models both effective and attractive to all players, with respect to, e.g., security, data privacy, development of regulatory enablers for resource sharing, for the establishment of a large 6G market in terms of volume and adoption with equal coverage and opportunities in all countries, etc. Role of societies, i.e., expanding beyond B2B to explicitly include B2G (business to governments) could be recognized as a business case for public expenditure savings including the serving of challenge areas.

Finally, business models will need to prove affordable from the implementation cost point of view, and new roles of public-private partnerships (e.g., public funding) will need to be considered further in the appropriate bodies and at proper levels.

4 Services, Use Cases

This chapter outlines the set of use cases envisioned for the Hexa-X project, and their connection to the vision described previously. The list of use cases is not meant to be exhaustive, but representative of use cases envisioned for 6G. It will be updated and enriched throughout the project. A first set of use cases has been introduced in D1.1 [MUH+21] and is updated in this deliverable. In this report, the use cases have been refined and details are provided on a specific category, use-case enabling services. A subset of use cases will be further described in Chapter 6, introducing deployment scenarios. These additions are intended to provide more insights on how the use cases will be deployed and how these use-case enabling services will serve use cases, but should not be considered as a prioritization by the project.

4.1 Ambition and methodology

4.1.1 Mission statement

The 6G vision defined in Hexa-X is built on the interactions between the three worlds intertwined, namely the physical, digital and human worlds, and these interactions are driven by three core values, shared by European players and Hexa-X members, *sustainability*, *inclusiveness* and *trustworthiness*. In order to design the 6G system, which would realize this vision and play a crucial role in the development of society towards more sustainability, inclusiveness and trustworthiness, a first step consists in defining relevant use cases. Hexa-X use cases should not be only a simple extension of the 5G use cases, but should outline new usages, based on a more inclusive (along the geographical as well as the societal axis) and more sustainable use of the technology. To be in line with the vision, the set of use cases will relate to the six research challenges described in Chapter 3. These use cases will allow the requirements applying to the 6G network to be derived and the specification of the Hexa-X technical enablers to be driven to meet the target KPI/KVI values.

4.1.2 Terminology

The use cases considered in Hexa-X are real-life applications of the physical, human and digital worlds. Use cases may support one or more applications of the three worlds, through a clearly defined set of KPIs and KVIs (see Chapter 5) and should apply to one or more verticals. The "real life" aspect is highlighted in the use case descriptions, as this helps the wider audience appreciate the everyday life applications of the demanding technical KPIs that Hexa-X aims to achieve.

4.1.3 State-of-the-art

In 2020 (and even earlier), some stakeholders of the mobile ecosystem have started sharing their views about 6G. The white papers and other publications available already give some hints on use cases targeted with 6G. This section gives an overview of the most cited ones in the selected references.

Building on top of the 5G trend and the advent of VR and AR, Extended Reality (XR) will develop in many different areas such as "entertainment, medicine, science, education, and manufacturing industries" [Sam20]. Such techniques require not only huge data throughputs, low latency and positioning capability in order to provide a high-quality user experience but also specific device features like compute and battery, simultaneously. Such devices could be "lightweight glasses that project images onto the eyes" [AKN20]. Going a step further, holographic representations of objects and people are imagined [Sam20], [AKN20], [Eri20] [Nok20]. The “multi-sensory holographic teleportation” [AKN20] wording is even used, meaning that beyond 3D representations of distant objects or people, all the senses are also transmitted; for example, you could attend, remotely, a meeting with your colleagues, all being present in the same meeting room, hearing discussions, smelling as if you were physically yourself in the room [Sam20], [Flag19]. As mentioned in [Eri20], this could nicely help to cover the communication needs of the society, even in difficult situations such as the COVID-19 pandemic.

In order to support this holographic use case, a digital representation of the physical world, based on sensing and AI technologies, may be needed; this digital replica is called a digital twin. Actions in real life via interaction with its digital twin are even considered [Sam20]. In [Eri20], a 4D spatio-temporal interactive map of a city could enable the realisation of actions in the “real” city, such as sending commands to public transport, waste handling, or water and heating management systems.

One of the key concerns of the society coming with the development of new technologies is that its related services must be accessible for all and everywhere they are needed. This digital inclusion requirement does not only mean “global coverage” (at an affordable cost in terms of deployment and for the customer as well) but also “easy-to-use technology”, for example, for the elderly or people with disabilities.

Such a need is already nicely identified in 6G use cases such as high-grade digital oasis [Eri20] or distance education [NTT20], sensors monitoring the status of forests and oceans [Eri20], or telemedicine and healthcare in rural areas not properly connected yet.

Usage of telemedicine has indeed been generalized during the COVID-19 pandemic. One of the side effects of the COVID-19 pandemic is that, during lockdown periods, people are not keen to go to the doctor, even if they have health problems that would require a consultation; for instance, it is unfortunately expected that the number of deaths due to non-detection of cancers on due time will increase in the coming years (e.g. see [MSM+20]). In order to avoid such situations, the development of telemedicine and remote consultations appears as a good alternative, especially in rural or challenging areas [NTT20]. Beyond this simple use case, 6G is also expected to foster the development of E-health applications, thanks to in-body devices, such as biosensors to monitor health conditions such as heart rate or blood pressure [Flag19], [Eri20], [NTT20]. The network will allow remote analysis and processing to adjust the medical treatment accordingly.

5G allows for improved efficiency in industrial process, and connected robots represent one of the most emblematic use cases [ACI20]: mobile robots handling materials in warehouse and production plants, extremely large autonomous guided vehicles in chemical plants, etc. The usage of connected robots is expected to develop more in a 6G perspective and extend as well to other fields: collaborative industrial AI partners could take care of tedious or dangerous tasks, and even cooperate with human beings [Eri20a]; swarms of small robots will perform domestic chores in home networks [VM20].

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. Hexa-X will go one step further, beyond individual viewpoints, and will bring a unified view on these use cases for 6G, sharing the perspectives consolidated among a whole consortium of partners.

4.1.4 Methodology

This deliverable provides an initial set of use cases as a starting point for the technical work within the project. This set of use cases was reached from a combination of top-down (relying on the vision, the core values and research challenges as a basis to select use cases) and bottom-up approaches (collecting views from the ecosystem through proposals from partners, state-of-the-art, defining new use cases to illustrate the use of new technologies). The set of use cases has been clustered into families of use cases. These families of use cases describe use cases involving similar interactions and answering one or several of the six research challenges. The use cases grouped in one family are expected to share similar requirements. These families of use cases will be consolidated iteratively, among the partners and with the Advisory Group.

4.2 Hexa-X families of use cases

4.2.1 Overview of Hexa-X families of use cases

The Hexa-X vision describes the envisioned role of 6G in the evolution of society. The vision and the associated six research challenges lay the foundations on which relevant use cases for 6G can be forecasted, accounting also for the societal and economic trends (see Chapter 3). Hexa-X partners built on this vision to identify an initial set of use cases as a first baseline to guide the technical work within the project. This set of use cases is not exhaustive but a list of representative use cases, introduced in D1.1 [MUH+21] and updated in this deliverable, and which will continue to be refined and extended until the end of the project. These use cases encompass a wide range of usages, from evolutionary ones, extending and enriching the 5G usages with new capabilities, to more disruptive ones, opening up new horizons where 6G could benefit and transform society. These use cases are clustered into families of use cases, according to the type of usages, as well as the research challenges and values addressed, as pictured in Figure 4-1. Trustworthiness is a common value shared by all families of use cases, as well as sustainability.

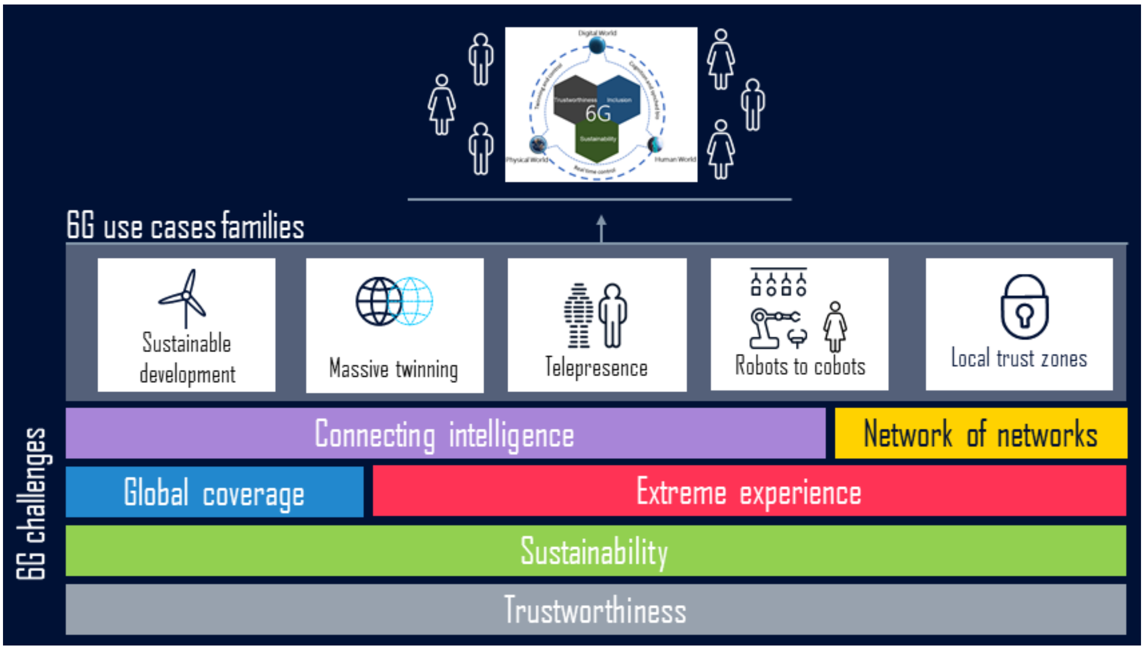

Figure 4-1: ***Overview of Hexa-X use case families***

Global service coverage is the other value emphasized in the Hexa-X vision, and different use cases, gathered in a use case family ***Sustainable development***, illustrate how 6G can contribute to the transformation of society, targeting UN sustainable development goals and the EU Green Deal, providing global access to digital services and energy-optimized infrastructures and services. ***Massive twinning*** is another use case family involving the massive use of digital twins to represent, interact and control actions in the physical world. The ***Telepresence*** use case family covers immersive telepresence for enhanced interactions, involving mixed reality or merged reality, providing extreme and fully immersive experience. The use case family ***Robots to cobots*** includes various use cases involving interacting robots, at home to facilitate everyday life as well as in professional environments to improve the efficiency of processes. 6G will also integrate multiple sorts of networks and handle the complexity and heterogeneity of a network of networks. The use case family ***Local trust zones (for human and machine)*** encompasses different use cases, involving in-body networks to wide area deployment of sensors networks. In this chapter each use case is described on a high level while Chapter 6 introduces the associated deployment scenarios for a sub-set of the use cases.

4.2.2 Sustainable development

The development of the 6G system heralds applications that go far beyond the user- and vertical-centric applications of current and former generations. To address the growing societal concerns of the sustainability of our environment and society, the 6G system will be very well suited to provide a meaningful impact, for example, by providing solutions contributing to meet UN SDGs or helping verticals to reduce their environmental impact. The core values of Hexa-X are trustworthiness, digital inclusion and sustainability. Naturally, these should penetrate through all design and development towards 6G and should be fundamental aspects of all use cases. Especially use cases contributing to dematerialization (telepresence, E-health for all, merged reality game/work), efficient resource usage (flexible manufacturing, AI partner), and optimizations (energy-optimized services) will have substantial beneficial impact towards these core values. However, enablers for sustainability (accounting for digital inclusion) also form a group of use cases of its own, focusing on sustainable development of society.

Sustainability is explicably the foremost research challenge addressed by this use case family, both in terms of environmental sustainability as well as sustainable development of human societies. However, in order to fulfil the UN SDGs, the use case family will encompass all the other research challenges to make the sustainable development come to realization. The extreme performance and global service coverage will be needed to empower the underserved and bridge the digital divide virtual-realistic remote experiences as well as provide means to monitor and counter-act current and impending environmental challenges. Connected intelligence and network of networks will enable operations to be optimized for sustainable performance. Naturally, any system addressing the societal and environmental challenges has to be trustworthy at its core in order to foster widespread confidence in their operation and execution.

4.2.2.1 E-health for all

We face a number of health challenges today, some of the most important ones to save lives are addressed in UN SDG #3 – “ensure healthy lives & promote wellbeing for all”. However, the demographic, economic and environmental development expected on a global scale the coming decade will add and emphasize additional challenges to address, while technology development will increase expectations.

The associated targets of UN SDG #3 aim to ensuring access to reproductive & universal healthcare, reduce maternal & child mortality, end epidemics such as acquired immunodeficiency syndrome (AIDS), tuberculosis, malaria and other preventable diseases (for example water borne parasites) as well as reduce death and illness caused by drug abuse, traffic, and pollution and to promote mental health.

In 2030 the demographic changes will in some rural areas give us a larger proportion of elderly in the population, with increasing numbers of people (primarily the young) living in urban areas.

The urbanization gives a rise in disposable income but also increasing welfare gaps, both leading to more “welfare diseases” such as obesity and diabetes. Moreover, growing inequalities in urban areas may also limit the access to universal healthcare in less privileged neighborhoods.

The climate change will put a growing pressure on the health system, not only by extreme weather conditions, draughts, flooding etc., but also due to the increased risk of new pandemics. Additionally, pollution and aerosols are identified as major health risks already today - whether this will increase or decrease as an effect of the climate crisis response is still unclear.

All these developments points towards remote and accessible healthcare becoming increasingly important. For all remote applications, trusting connected services to be reliable, keeping sensitive data private and information to be safe and trustworthy, is key to accepting technology to solve these challenges.

Finally, not only the network and connectivity open for new ways of addressing healthcare needs, the development of new and existing technologies and devices will impact this development. With emerging technologies providing new opportunities for remote care, and devices becoming accessible more broadly, cost and design which also drive new applications and services. For 2030 we expect smaller lightweight devices and sensors enabling on and in-body monitoring as well as AR, early adoption of haptic and neuro-based interfaces.

With trustworthy Mobile Broadband (MBB) connections to medicine expertise, basic E-health services can be delivered anywhere. Connectivity can be complemented by local analysis of samples, etc. with dedicated devices, and availability of expertise can be extended with AI agents giving first-line support. Local mobile E-health hubs can provide last-mile connectivity in areas with infrastructure challenges.

Providing virtual doctor visits to all who need it would be an enormous health benefit, requiring a full expansion of cellular network coverage capable of supporting these services. Reaching everyone in the world in a cost-effective way, and reaching areas where deployment of fiber is not an option (remote islands, rural areas, politically unstable regions) is a meaningful challenge for 6G networks. Sensitive medical data would need to be routed, stored, and processed throughout a network that may consist of multiple hops and access types, and service availability needs to be assured with affordable solutions.

3GPP Release 17 is already moving to this direction with NTNs, as documented in [38.821], for example, along with other satellite communication systems. In 6G we foresee that a tight integration between different topologies will allow for cost-efficient deployments and operations, even to underserved regions, which is currently cost-prohibitive.

4.2.2.2 Institutional coverage

The ultimate goal must be to include all communities with high-grade wireless services – this is true digital inclusion for networks. A more realistic goal is perhaps to make sure that schools, hospitals, etc. around the world can have access to full 6G services, even in developing countries and remote rural areas of developed countries. This goes far beyond video services and includes immersive and precise communication such as telepresence, remote virtual education and medicine. In many areas, deployment of fiber communication may be cost prohibitive, for example, due to long distances in remote areas or islands, or because of inaccessible areas due to political instabilities. By expanding and further improving the deployment and performance of 5G Fixed Wireless Access (FWA), for example, 3GPP Release 16 integrated access/backhaul (IAB) features and 3GPP Release 17 NTN features, backhaul based on 6G can be provided to dedicated localities that will act as full-6G digital oases. These key societal institutions connected to 6G services can spread connectivity locally, providing benefits for local companies and infrastructure, and make sure that society is included in the digital development.

3GPP Release 17 is already moving to this direction with IAB as documented, for example in [38.174]. In 6G, we foresee that the wireless backhaul capacity will be enhanced by orders of magnitude, enabling cost-efficient provision of 6G services even to remote areas that are currently cost prohibitive.

4.2.2.3 Earth monitor

By providing ubiquitous bio-friendly energy-harvesting sensors that can easily be deployed anywhere with cost-effective connectivity via, for example, NTN, long-range terrestrial or local mesh networks, a deluge of sensor data can provide near-real-time monitoring of system-critical environmental aspects such as weather, climate change, or biodiversity. Sampling of key data is made possible also in truly remote areas, far from infrastructure. This global telemetry system can be used to improve weather/climate models, provide surveillance and monitoring of environmental status and enable early warning systems for natural disasters such as flooding or landslides, or protect threatened ecosystems like endangered species from illegal logging and poaching.

Even though 3GPP Release 17 is already moving towards NTN, as documented, for example, in [38.821], this use case would require zero-energy and (near) zero-cost biodegradable devices that can effectively communicate with NTNs with very limited power.

4.2.2.4 Autonomous supply chains

To ensure a fully integrated autonomous supply chain, the demand of scoping, ordering, sourcing, packaging, routing and delivery must be automated using local and central AI agents continuously optimizing the process, for example, in relation to unexpected events such as natural events, disasters or political circumstances. 6G will enable fully automated supply chain, at reasonable cost and complexity. With global end-to-end lifecycle tracking of goods from production, shipping, distribution, usage and recycling, a higher resource efficiency and reduced material and energy consumption can be achieved. The use of 6G-connected micro tags on goods can simplify tracking, customs, safety checks, and bookkeeping, allowing it to be done without manual interference. Combined with the use case "Flexible manufacturing" in Section 4.2.7.3, the supply chain will need to become much more dynamic and flexible to cater to the much more varied needs for resources.

This use case builds on the work done with Narrowband Internet of Things and New Radio Reduced Capability with NTNs and integration of AI/ML. This will require a global system of systems, integrating different technologies into a unified, transparent, and cost-efficient access, which can orchestrate an optimal supply chain end-to-end, while also locally adjusting to any dynamic variations using the currently most appropriate connectivity solution. The system will also monitor the current statuses of businesses and factories in order to predict whenever something needs to be sourced, from where, what optimal and alternative delivery routes are available and to provide even the last-mile delivery. At every step of the way, the location and status of the goods should be monitored in order to facilitate a dynamic and responsive supply chain.

4.2.3 Massive twinning

Massive twinning, i.e., the application of the more fundamental Digital Twin (DT) concept in a wide set of use cases, will gain importance. Massive twinning is designed to lead us towards a full digital representation of our environment, extending the use in production/manufacturing (as it has started today), but also, for example, in the management of our environment, in transportation, logistics, entertainment, social interactions, digital health, defense and public safety.

Twinning is essential in various use cases. A DT is a virtualized model and real-time representation of an asset in the physical world, i.e., a representation within the digital domain, of the asset’s structure, role and behavior. Some example areas that are addressed in the remaining part of this section are manufacturing (so as to start discussing the progress from the situation of today), drastic enhancement of liveability of our cities (urban quality of life assessment based on various criteria), the enhancement of the productivity for addressing the “towards zero-hunger" goal, while maximizing the sustainability and the transformation of sectors like health or public security. From the discussion it will be shown that such areas will need the transfer of vast information volumes, low delays, high reliability, and capacity levels that will be pushing the current boundaries. Things will continue to evolve and be disrupted. More capacity will be needed (for example, for massive twinning), along with higher bit rates, and improvements in efficiency, reliability and security. Solutions should be characterized by sustainability, empower trustworthiness, and most often be suitable for global coverage.

In all cases, a fully synchronized and accurate digital representation of the physical and human worlds is key. This is costly in resources, as it requires precise representations of the physical world, enhanced means for generating insights and predictions, as well as for experimenting with “what-if” scenarios; furthermore, means to impact the environment are imperative. All these need the transfer of vast volumes of data, extreme performance (capacity, bit rates, low latency, compute power) and reliability, as well as sustainability, and also trustworthiness, at unprecedented levels. High-resolution and interactive 4D (spatio-temporal) mapping is needed, in conjunction with means to influence the physical world. High-resolution indoor and outdoor mapping will drive use case scenarios of dynamic DTs and virtual worlds in conjunction with real-time, multi-sensory mapping and rendering, movement prediction and real-time analytics. The availability of both the virtual and physical worlds will allow mapping and analysis of data and monitoring of systems to predict performance and operational issues to minimize downtime (predictive maintenance), and improve contextual awareness.

4.2.3.1 Digital Twins for manufacturing

The use of DTs will continue to grow in industrial/production environments, leading to Massive Twinnning. It will enable us to go beyond the current levels of agility of production, enabling more efficient interaction of production means to encompass a larger extent of the respective processes, and also to achieve the transfer of massive volumes of data, and, often, extreme performance and reliability. In the realm of production and logistics, DTs can be used for many beneficial applications. For instance, the following sub-cases can be identified:

(a) Managing infrastructure resources. The operator of the production facility is trying various scenarios through the DT’s “what-if” capability. The scenarios are supported through real-time interaction with the physical world. The operator decides to apply a certain configuration; it is applied with speed and reliability. A critical situation may also arise. The DT forms an accurate picture of the situation (based on advanced reasoning, ML/prediction mechanisms, etc., in conjunction with more traditional polling, alarm functionality), mitigation actions are found by the DT and are enforced at the highest performance levels and with the utmost security.

(b) New products need to be designed and automatically be linked to their DT. New products are designed, and then tested in a virtual environment (even today up to a point); the DT of the planned product is created and is tested in the digital world. Only when that equipment performs to exact specifications in the digital work environment, the physical manufacturing is allowed to start. Once manufactured, the physical build would be linked to its DT, for example, through sensors and actuators, so that the DT contains all the information that its physical counterpart possesses.

(c) The cooperation among multiple DTs in a flexible production process will also be needed, as it ensures anomalies in the real world are detected and mitigated through reconfigurations of the communication system or dynamic adaptations of the production process, or a combination of both. This means that due to the real-time, safety and privacy requirements of production processes, the respective DTs need to be executed in an environment guaranteeing these properties while ensuring access to all relevant data (production, sensing, communication) required to perform the necessary mitigation steps in case of anomalies or to increase efficiency. This use case is also tightly related to the use case family “From robots to cobots” (see Section 4.2.5).

(d) Another practical usage of digital representations is to follow the history through “digital threads”: the history of every part of the system can be used to learn, to replace parts, etc.

This use case demands low latency and high reliability, at capacity levels that will be much larger than those envisaged for such services in 5G, due to the growing adoption. Moreover, the highest possible level of efficiency is needed for increasing the chances of commercial success. Therefore, this use case requires the realization of Ultra-Reliable Low-Latency Communications (URLLC) grade services, at high capacity levels, and with the highest possible efficiency. The highest possible levels of trustworthiness will be needed (which are associated to the levels of performance, dependability, security, resource efficiency/cost) to ensure adoption at scale.

4.2.3.2 Immersive smart city

City liveability is a concept that is determined by large parameter sets, which are weighted. The sets correspond to wide application areas, relevant to the city infrastructure (for example, roads, rails, buildings, networks), the ambience/environment (for example, climate, air quality), healthcare aspects (for example, management of health system, quantified self), education and culture issues, the stability/safety, and many others. The effective management of all these factors, on various time scales, opens technical challenges, potential from a societal perspective, and business opportunities. Technical challenges are associated with aspects related to the volume of traffic that needs to be transferred, the associated time scales and reliability, etc. Societal value lies in the potential of perceiving, predicting and managing hazards or other less critical situations. Business opportunities occur for operators and other ICT players, by assisting cities in the accomplishment of their goals. Mapping and planning of smart cities will be another use case scenario for DT technology. A city in the 2030s will be a dynamic system of systems with many constituting elements such as people, infrastructure and events. In conjunction with real-time feedback from the physical world and its associated assets, the DT city model will be a powerful tool for future evolution and planning as well as enhanced and efficient operations of future smart cities. A digital replica of a real traffic scenario of the city, the automated train operations, the control of the utilities (energy, water, gas, etc.), air quality and more are some of the aspects of the implementation of massive twining to cities environment. An interactive 4D map can be used to plan utilities management such as public transport, garbage, piping, cabling, buildings, and heating, or to connect the many parts of a factory that can be inspected and steered in detail. By overlaying physical modelling, the 4D map can be used to forecast expected and predicted actions and behaviors of the environment and of other users, follow the history, and to check and control the function of parts. Human and AI operators can explore the rich data and simultaneously modify to manage and schedule activities, effectuating changes and tasks through actuators and controllers in the network. This optimized management of flows can also contribute to the transformation of cities towards sustainable models

This use case requires transfer of vast amounts of data within certain time limits (from ultra-low latency to vehicles or health, to “near” real-time). This is important for enabling actions that will influence the city operation and enhance its liveability. In parallel, the highest possible levels of sustainability are called for, while trustworthiness is most important and will be demanded by citizens.

4.2.3.3 Digital Twins for sustainable food production

One of the UN SDGs is to end hunger, to achieve food security, while maximizing the sustainability of the production. Massive twinning is a valuable concept in this direction, especially, in the light of the challenges for mankind in our time, for example, higher populations, climate aspects, and need for enhanced efficiencies.

The main challenge is that “remote”, “rural”, “in-sea, close to shore” areas need to be provided with higher network capacity and performance than today. This is essential for monitoring in real time the conditions at the level of micro-locations (microclimate, soil conditions), inspecting and developing optimized and targeted plant treatments (including disease combatting), experimenting with various actions or strategies (for example, removal of plants, alternate cultivations, spraying strategies), or enforcing actions, including the control of semi-autonomous ground robots. Human expert knowledge will benefit from the closely synchronized digital representation of the physical world, not only for inspecting, but also for experimenting with actions in the digital realm, and, ultimately, impacting the physical world. Therefore, in this use case, the fully synchronized digital representation is the key to optimize agricultural production through improved management and prevention of threats.

This use case requires the transfer of vast volumes of data, from areas that can be characterized as “underserved”, in terms of offered capacity and coverage. Nevertheless, close synchronization is needed. This will make possible the tackling of important challenges of our time, namely, those on sustainability, global coverage, inclusion and opportunity.

4.2.4 Immersive telepresence for enhanced interactions

This use case family consists in **being present and interacting anytime anywhere, using all senses if so desired**. It enables humans to interact with each other and with the other two worlds, and physical and digital things in these worlds. All human senses can be used exchanging sensory information and even extending the capability of the senses. This is well fitting the Hexa-X vision of a future in which everyday experience is enriched by the seamless unification of the physical, digital, and human worlds achieved through the new network and device technologies.

All the research challenges need to be met in order to provide this use case family. Extreme experience is needed to be able to meet the needed data rates. Low enough latency with high data rates and enough reliability is needed to avoid incomplete experience or even nausea. A network of networks is the basis for the connectivity. Connected intelligence improves the performance. This all needs to be done in a sustainable way and trustworthiness is also a fundamental starting point. Global service coverage enables provisioning of telepresence everywhere. Telepresence will have to be delivered in a sustainable way but can also contribute to sustainability and meeting UN SDGs by reducing the need for travel.

4.2.4.1 Fully merged cyber-physical worlds

Mixed Reality (MR) and holographic telepresence will become the norm for both work and social interaction. Via holographic telepresence it will be possible to make it appear as though one is in a certain location while really being in a different location – for example, appearing to be in the office while actually being in the car. Other example use cases include facilitating collaboration and performing remote home-working beyond office type of work by white-collar workers, improving diagnosis during tele-consultations and enhancing teacher-student interactions in e-learning classes. This can also mean virtual traveling to far-away places and telepresence meetings with friends and family. The user would experience the world where his/her hologram is, through very rich sensing of multiple sorts, synchronized to devices on his/her body for an enhanced sensory experience.

Users want to communicate with distant persons with a quality of interaction very close to reality. They want a better perception of body language (gesture, intonation, expressions, surrounding sounds, etc.), and also of other senses (for example, touching objects).

MR telepresence allows interaction with both physical and digital objects, which are near or far in physical reality. This experience and use case will be enabled by wearable devices, such as earbuds and devices embedded in our clothing and other novel user interfaces. Humans will carry multiple wearables, working seamlessly with each other, providing natural, intuitive interfaces.

Touchscreen typing will likely become outdated. Gesturing and talking to whatever devices are used to get things done will become the norm. The devices we use will be fully context-aware, and the network will become increasingly sophisticated at predicting our needs. This context awareness combined with new human-machine interfaces will make our telepresence interaction intuitive and efficient.

4.2.4.2 Mixed reality co-design

Mixed reality co-design means remote collaboration and "experience before prototyping". This may for example apply to a factory scenario where two people are remotely designing something intricate together with some physical objects and some virtual objects.

A MR reality co-design system will allow designers to cooperatively design innovative virtual products in a virtual-real fusion of worlds. Context awareness as an integral part of the MR co-design process will allow designers to focus on the design itself and its relationship with the external environment. MR co-design will link into new forms of man-machine interaction such as capturing the designer’s head or eye movement, emotional state, facial expressions, and body parameters such as heart rate or blood pressure. Such an approach can be subsumed under the term “spatial computing”. Moreover, the co-design context can be captured by spatial mapping and imaging technology. In the 2030s, we expect designers’ behavior and vital parameters to be included in the co-design process and task.

With the leverage of machine learning and AI, the MR co-design use case will be greatly enhanced. The decomposed and advanced user equipment in conjunction with wearables will transform the next generation of Industrial IoT.

4.2.4.3 Immersive sport event

Current sport simulators utilize motion capture technology to create life-like renderings of real players. With the advent of XR gaming, this will be further expanded to allow 3D rendering of any simulated sports event. With 6G, it will be possible to motion capture actual games in real time to create a DT of the whole game, which can be experienced live from any angle, by hundreds of millions of people worldwide. The majority of viewers would likely be satisfied with a classical overview, determined by professional camera operators and thus, the bulk of the information can be broadcasted single-to-multipoint. However, the 3D rendering also allows end users to experience the game from any angle with a 360° view, for example, following a specific player, or watching the game from the ball’s point of view. In these cases, the processing would have to take place locally to allow high fidelity rendering of the interesting field of view. AI models could also assist in predicting the near-future motion of the players merging real-time footage with pre-rendered models. The experience could be to watch the game from a virtual bleacher while interacting virtually with your friend while watching the game.

4.2.4.4 Merged reality game/work

Gaming in a public or in a dedicated space is experiencing a shared merged reality with a massive amount of people where the distinction between reality and virtuality has been blurred. Some objects or other players in the game are present in the physical world, others are digitally enhanced with visual, haptic or olfactory sensation while yet others are fully digital but appear to be real. Players in the same game share a common merged experience and exchange synchronized sensory information that is authentic or synthetic. Digital meetings can take place where the user participate with a hologram avatar of himself/herself, making him/her appear fully present. Tactile and sensory feedback can be delivered to participants, and visual information is immersively experienced through a smart contact lens, for example. Digital co-creation is easily handled in the virtual domain, simplifying remote work and training.

Concerning the four use cases described in this section, 3GPP Release 17 is already moving to this direction, as documented in [26.928] and also addressed via the ongoing 3GPP RAN Rel-17 Study Item, whose outcome will be reported in [38.838]. In 6G the efficient interaction among all the three worlds is of high interest, using all senses in a massive scale.

4.2.5 From robots to cobots

The 6G system provides the technical fabric to go beyond pure command-and-control of individual robots. Instead, it empowers robots to become “cobots” in that they form symbiotic relations among each other to fulfil complex tasks efficiently or better cater to the needs and demands of humans in day-to-day interactions. Trustworthiness and digital inclusion are core values in human-machine and machine-machine interaction. By collaborating and building symbiotic relations, complex tasks can be fulfilled in a sustainable fashion: rather than devising more and more complex machinery and allocating more and more resources, intelligent and flexible utilization of existing capabilities to the benefit of society is at the core of this use case family. This also enables new business models for verticals: with increased flexibility in production and resource utilization and connected intelligence, machinery can perform highly individualized on-demand tasks, enabling lot size one production and fully utilizing novel production methods such as additive manufacturing.

A number of research challenges are targeted with this use case family. *Trustworthiness* is at the core, especially as use cases in this family depend on *connecting intelligence* and coming to joint decisions. This requires flexibility in network topologies and resource allocation, targeting the *network of networks* challenge. Some use cases, for example in the industrial context demand *extreme performance*, for example in terms of latency, dependability and positioning. Sustainability is an underlying challenge, especially when dealing with extreme performance use cases. Having meaningful AI partners and human-machine interaction addresses the challenge of inclusion.

4.2.5.1 Consumer robots

Numerous consumer robots will go beyond the automated vacuum cleaners and lawn mowers that we know today and become an essential part of future living. These may take the form of a swarm of smaller robots that work together to accomplish tasks or autonomous robots that provide convenience. Enabled by 6G, the robots will be, for example, equipped with video cameras streaming to a local compute server for real-time processing as well as equipped with advanced sensing and positioning features for seamless and intuitive interactions among users, robots and environment. Robots will utilize the connected AI capabilities offered by 6G for situation-aware cooperation and collaboration and assistance. Thus, we will see an increase in the number of devices and higher capacity requirements within our home networks, further demanding seamless connectivity across the resulting network of (local) networks. In the big picture, domestic robots will enable the elderly to stay in the comfort of their homes for longer and improve their quality of life.

This use case extends existing 5G functionality into more challenging scenarios with an increased number of devices, increased latency demands, positioning and computational requirements with higher integration needs when it comes to sensing and utilization of AI, as later detailed for the use case enabling service “AI as a Service” (see Section 4.2.7.2).

4.2.5.2 AI partners

With the advances in AI and its embedding into 6G systems, AI agents will become more prevalent and ingrained in society, alleviating more and more tasks from humans. However, many tasks will still involve human operators actively interacting with AI partners to jointly solve tasks, not only the AI assisting the human operator, but the AI and human working as equal partners. Instead of relying on dedicated machines or specific autonomous system, the AI agent can be much more general-purpose and act as a partner which autonomously and adaptively interacts with other agents (humans/machines), by interpreting intents and surroundings, performing challenging and risky tasks. This AI agent could be a simple stationary machine in a factory, software controlling the illumination wherever you are by communicating with other AI agents in the vicinity, either in your home, in the office, or in a public space, or it could be a group of drones autonomously collaborating to solve various tasks. This requires trustworthy cyber-physical systems able to smoothly cooperate with groups of humans and intelligent machines with precise action. In case the AI partner interacts with other AI agents, the nature of communication may shift to a new breed of user plane communication, to benefit from and enable a distributed compute functionality.

This use case focuses on broad integration of AI capabilities in 6G communication systems and their offering as a service to applications, such as broad applicability of AI for cooperation with humans. It relies on use case enabling services w.r.t. AI functionality (“AI as a Service”, see Section 4.2.7.2).

4.2.5.3 Interacting and cooperative mobile robots

In consumer-oriented use cases with multiple robots as introduced above, machines need to identify others, connect, exchange intent and negotiate action through automated communication. Examples of where robots need to coordinate with each other are, for example, awareness such that your personal butler doesn't step on your robot vacuum cleaner; in construction/building scenarios where different robots need to sync/coordinate their movements of lifting, etc.; Automated Guided Vehicles (AGVs) outdoors that need to avoid collisions; swarms of simpler robots coordinating among themselves to perform tasks through emergent action. In industrial environments, going beyond flexible modular production cells (i.e., specific areas where mobile robots and machines collaborate on a production task), some production tasks can be conducted by collaboration among mobile machinery, for example, robots collaboratively carrying some goods while being mounted on AGVs. This coordination will be conducted in three dimensions, to avoid collision and enable collaboration of robots evolving in the air, such as drones. In this use case, in addition to the coordination among the interacting entities, process data among involved entities needs to be exchanged, meeting real-time requirements and requiring synchronization: with (static) machinery when departing from a modular flexible production cell, among collaborating machines while on the move, and when reaching the target production cell for the next process steps. Reliability, functional safety, latency and positioning requirements as well as high-energy performance need to be met during all steps and even if trajectories are blocked or need to be altered.

This use case extends existing 5G functionality into more challenging scenarios with an increased number of devices, increased latency demands and a high share of local communication. It moves central tasks of coordinating interacting entities to the entities themselves. 3GPP Release 17 moves into this direction through capability exposure for time-sensitive communication and QoS and a fully distributed configuration model for Time-Sensitive Networking (TSN), for example. Sophisticated coordination among entities relies on use case enabling services related to distributed AI functionality exposed to applications.

4.2.5.4 Flexible manufacturing

With increasing personalization and modularization of production (for example, lot size one production of a single, highly customized product) and flexibility of manufacturing systems (for example, mobile robots) comes the need for powerful wireless communication and localization services as well as flexible, dynamic configuration of communication services in the network. The machinery and associated communication will be configured dynamically for each production task, either by a production system or even in a self-organizing way by direct collaboration among (mobile) production machines. This involves the orchestration of AGVs, as higher flexibility in the production process requires higher flexibility in logistics. Dynamic configuration of real-time communication services is required, potentially initiated by end systems themselves and executed in a distributed fashion. Respective communication resources and capabilities (for example, local compute, D2D communication, frequency ranges) need to be assigned through a flexible framework. High availability and functional safety requirements need to be met, and data from the production process needs to stay secure and private.

This use case extends existing industrial 5G functionality in more dense industrial environments with higher flexibility, self-organization capabilities, local processing and direct communication among entities. As stated for “Interactive and cooperative mobile robots use case” (see Section 4.2.5.3), 3GPP Release 17 moves into this direction. The use case enabling service “Compute-as-a-Service" as another enabler for this use case details additional requirements for local compute capabilities on constrained devices.

4.2.6 Local trust zones for human & machine

“Mobile” communications are up to today often “cellular” communications. Many use cases, however, require local or private communication capabilities for very sensitive information that are tightly integrated in wide-area networks. Here, network topologies beyond cellular topologies and security concepts beyond classical security architectures are required. Local trust zones protecting individual or machine specific information and independent sub-networks such as body area networks enabling advanced medical diagnosis and therapy or on-board networks of AGVs have to be dynamically and transparently integrated in wide area networks, or remain on-premises as private networks, as needed..

The work towards research challenges “Connecting Intelligence”, “Network of Networks”, and “Trustworthiness” will contribute to building communication solutions for these use cases. Private and often local sub-networks are integrated in the classical cellular networks, trust zones for sensitive information – often under very specific regulation – are implemented, and AI functionality is integrated. Local trust zones can be dynamically reconfigured with autonomous and intelligent enabling of service capabilities, to adjust to the type of network coverage required for the services (e.g. specialized network, wide area or network).

4.2.6.1 Precision healthcare

Today`s medicine typically follows a one-size-fits-all approach, in which disease treatment and prevention strategies are developed for the average person. In contrast to this, precision medicine is "an emerging approach for disease treatment and prevention that takes into account individual variability in genes, environment, and lifestyle for each person," according to the Precision Medicine Initiative. In order to understand the environment and lifestyle of persons, 24/7 monitoring of vital parameters for both the healthy and the sick through numerous wearable devices will be useful. Persons interested in their personal analytics, or “quantified self”, will be able to perform self-tracking and monitoring thanks to in-body devices.

In general, health monitoring, diagnosis and therapy, for example, based on precision medicine, will enable personalized diagnosis and treatment. Here, in-body devices communicate with wearables outside, which in turn can transport the data to the internet. Using topical, implanted, injected or ingested sensors and devices, continuous health monitoring can be performed and adjustive measures can be implemented if needed, such as medicine dispensers. Bodily and sensory reactions like organ malfunction and pain can be represented and analyzed in the digital domain. A 6G tele-medical paradigm will be enabled by in-body sensing and analytics in conjunction with a wide area connectivity option. Obviously, very high privacy requirements including the need for local anonymization and pseudonymization will require local protected signal processing capabilities. Logging activities and environment of persons might require the access to information of the Cyber-Physical Environment. Application domain-specific regulations have to be considered.

This use case requires the interaction of a local trust zone with the wide area network security, access to information available in other networks under pre-defined filtering rules, and a split of network transport, control and security. From a regulatory perspective, in addition to the difficulties to adjust to regulations of the medical sector, the integration of medical devices in wide area networks is today at least challenging and is disruptive.

4.2.6.2 Sensor infrastructure web

A simple autonomous vehicle (with no or limited sensor capabilities) is moving around the environment, while relying on external third-party sensors as if they were on-board sensors. The vehicle obtains external data from externally available sensors, or navigation commands through the network with utmost confidence in the reliability, timeliness and confidentiality of the data, and can as well share its own sensor data. This allows aggregation of sensor data across different systems, even to devices lacking their own sensor capabilities.

The network can advertise locally relevant and trusted sensor information that all connected devices, for example, vehicles, can access.

3GPP today does not allow diffusion or sharing of sensor data in predefined local environments and to networks or network parts under external security management. Depending on the implementation, this use case might require the split of network ownership, network control, network transport and network security. Finally, today it is not possible to allow a network to advertise and distribute third-party provided sensor data in well defined local areas.

4.2.6.3 6G IoT micro-networks for smart cities

The expansion of smart cities usages (for example, energy management, traffic control, citizen safety) will entail massive deployment of communicating objects. Administrators of smart cities want to deliver the required coverage for smart city networks with minimized energy consumption and without multiplying base stations. They need self-adaptive networks, relying on objects as relays. These micro networks would manage the flows of information from objects, robots, etc, locally interacting in a complex system.

Network slices and private networks bringing their own network nodes exist in 5G. Here, micro-networks of potential different ownership and with a potentially external security management might share parts of the infrastructure with wide area networks, i.e., a private network with partly owned infrastructure and a private trust policy is integrated in a public network.

4.2.6.4 Infrastructure-less network extensions and embedded networks

At the edge of network coverage, a temporary network coverage extension is required, for example, for providing connectivity between several agriculture vehicles during harvesting campaigns. The connectivity should remain even when the vehicle platoon is leaving the network coverage completely while still in the harvesting campaign.

An industrial vehicle manufacturer has a fleet of its shop-floor vehicles deployed in a factory. While all or some of them are connected to the wide area network, the manufacturer wants to have reliable networking solutions between his vehicles not using the local network, i.e., a local private infrastructure-less network being established. This network might have authorized access to the spectrum of a local non-public network or a public network, thus external network control should be enabled.

D2D solutions exist in LTE and 5G. Direct Mode Operation (DMO) is a typical requirement for Public Protection and Disaster Relief (PPDR). Construction work, agriculture, and tactical services — often operating at the edge of network coverage — regularly ask for coverage extending concepts beyond D2D and autonomous operation of island solutions. Mesh networks, multi-D2D might be options. Temporary, ad-hoc security solution deployments are required. Networking islands of several devices re-joining the cellular networks shall be seamlessly re-integrated. D2D could be seen as a first step, and DMO solutions are known from several standards.

4.2.6.5 Local coverage for temporary usage

PPDR and Program Making and Special Events (PMSE), roadwork and harvesting campaigns benefit from applications as massive video transmissions that often require local networking coverage fulfilling high requirements. When cellular coverage is insufficient or unavailable, local, semi-permanent, temporary, or moving network nodes enabled e.g. mounted on vehicles, drones, high altitude platforms or other means can be used. Automated licencing processes can help to guarantee access to the required spectrum resources.

Today temporary deployments for PPDR and PMSE are already used. However, lowering the costs of the deployment and the administrative burden, for example, by automated licencing, might help this option to become more widely used.

4.2.6.6 Small coverage, low power micro-network in networks for production & manufacturing

A machine manufacturer wants to mutually connect a large population of sensors in his machine using – for reliability reasons – non Industrial, Scientific and Medical spectrum. This can be done with very low-power devices and very limited coverage as an underlay network, potentially with one of the sensors getting the authorization out of the public or non-public network of which the spectrum is used.

This could be seen as a shared spectrum access concept under full control of the incumbent. The incumbent might have the option to disable the spectrum usage by signalling.

4.2.6.7 Automatic public security

There will be a massive deployment of wireless cameras as sensors. With advances in AI and machine vision and their capacity to recognize people and objects (or more generally, automatically gather information from images and videos), the camera will become a universal sensor that can be used everywhere. Privacy concerns will be addressed by limiting access to data and anonymizing information. Also, radio and other sensing modalities like acoustics will be used to gather information on the environment. In short, advanced techniques will be used in security-screening procedures to eliminate security lines. A combination of various sensing modalities will be used to screen people as they move through crowded areas rather than only at entrances. Radio sensing will be an essential component of achieving this; supported by the communication systems of the future the network can sense the environment. For example, it could be programmed to automatically detect metallic objects of certain kinds that people or robots may be carrying in a crowded square. The network can sense and identify potential threats.

4.2.7 Enabling services harnessing new capabilities

In the initial collection of use cases, some ideas have emerged, that may not be categorized as use cases according to the definition above, but that deserve to be shared to the 6G ecosystem. They can be considered as services useful to address the use cases proposed above and, possibly additional ones. This set of novel services will develop 6G beyond the data pipe, leading to a convergence of communication, computing, data and sensing, including Artificial Intelligence.

The services identified and detailed below enable the realization of the use cases described in the previous sections. For instance, scenarios falling under the massive twinning and robots/ cobots use case families can benefit from the Compute-as-a-Service (CaaS), general-purpose AI-as-a-Service (AIaaS) and AI-assisted Vehicle-to-Everything (V2X) concepts, as these use cases may involve resource-constrained devices and may need to be based on data-driven decisions, respectively. More globally, CaaS or AIaaS can be considered as examples of a more global category of service, Service Provisioning as a Services (SPaaS), focused on fulfilling a given service request, originating from any device or network infrastructure equipment. In another example, a service dedicated to addressing the challenge of multiservice devices with heterogeneous requirements may be applicable to immersive telepresence scenarios characterized by both extreme data rate and ultra-low-latency requirements. Also importantly, use cases related to sustainable development may benefit from energy-optimized "green" connectivity services and "Internet-of-tags" services aiming to limit the incurred environmental footprint.

Additionally, these services are, in their turn, enabled by key technologies that are building blocks of systems, subsystems and components, and which will be studied in detail in different WPs of Hexa-X. Some of these key technologies are: distributed computing, AI/ML and network intelligence, radio access beyond 100 GHz, as well as further enhancements and optimizations of service-based network architecture. The aim of such architecture will be to provide needed interfaces outside network infrastructure (for example, user devices) entailing network virtualization and disaggregation concepts. Moreover, energy-efficient networking solutions are essential to ensure a sustainable digital world. Each of the services described here is connected to one or more research challenges identified in the Hexa-X 6G vision.

4.2.7.1 Compute-as-a-Service (CaaS)

CaaS can be applied for storage and processing of large sensory data in an industrial environment to address specific needs, such as: (i) production process customization involving, e.g., AGV trajectory planning and moving/ static robot coordination; (ii) enhancement of production process dependability e.g., by guaranteeing full synchronicity of actions and reactions in the system. This service is aimed to be used by any devices (static or mobile, IoT, handhelds, etc.) or network infrastructure equipment that choose to delegate demanding, resource-intensive processing tasks to other parts of the network providing more powerful compute nodes, which are also of higher availability at the time of workload generation; these service-offering compute nodes can be either onboard other devices or, for example, edge cloud servers at the infrastructure side. A first example is the one of a worker performing equipment maintenance. The worker uses special equipment (glasses, gloves, vests, etc.) useful to capture information (for example, video footage, images, sensory information) of the process. The respective workload for data fusion, sensor data processing, etc. needs to be processed in a reliable and timely fashion; however, the computational/ memory/ storage resources of the special equipment are limited. As an alternative, instead of a human, any kind of small robot (for example, AGV, unmanned aerial vehicle) of limited energy, storage and computational resources can play the role of the maintenance entity. Workload delegation to powerful nodes at the network will be essential for the stability of a closed loop system involving measurement capturing, processing, issuing an actuation policy and implementing it. Another example is the one referring to the collection of data and remote processing for Earth monitoring; examples are small robots/pathfinders/probes and ground stations deployed in forest/arctic areas collecting sensory information or analyzing (air, water, ground, etc.) samples. A third example of the CaaS concept is the one of multi-player gaming, where complex computer games may be processed on computational resources in the network, which will be able to address high computation load requirements and meet low latency requirements for multi-player gaming. The service tightly relates to the Extreme Experience, Sustainability and Connecting Intelligence research challenges.

This service goes beyond 3GPP Rel-17 specifications on support for Edge Computing in 5G Core network (5GC) (see [23.748]). It also expands beyond the task offloading use case, as documented by [EGM18].

Considered in the context of an exemplary application, “Interacting and cooperating mobile roblots”, the operation of this service can be further described:

- **Need to consume the service (precondition)**: the use case involves devices of local compute/ memory/ storage capability which is insufficient to complete a processing task reliably and with energy efficiency, such as robots (static or mobile), wearables used by humans working in a production environment, tools and machinery.
- **Service consumer**: human user or machine operating the device of limited capability. Humans (e.g., system administrators) may consume the service, as processing of "raw" data is needed for process monitoring and optimization. Robots may, in their turn, consume the service as the output of a processed workload (e.g., item positioning) may be considered to apply an actuation policy for productivity improvement and/or worker and facility safety.
- **Service provider**: CaaS provider offering a service identifying compute nodes, either as part of another end user/ machine device or onboard an edge cloud server at infrastructure side, as part of the industrial environment's infrastructure.

- **Needed message exchange to consume the service**:
    1. The service consumer issues a request to evaluate possible delegation of a challenging processing workload to a jointly available, capable and trusted compute node in the production environment.
    2. The most appropriate compute node (i.e., trusted, available and with sufficient resources) for workload offloading is identified by the CaaS provider.
    3. The workload is delegated to the identified compute node.
    4. The obtained processing output is forwarded to the service consumer that will take proper corrective actions, if needed (e.g., AGV trajectory update).
- **Impact of service consumption (postcondition)**: The elapsed time from task generation to output reception is reduced when consuming the CaaS, as compared to the case of locally addressing the processing task. Also, the combined energy consumption (i.e., involving radio transmission/ reception and partial local processing) at the device side when CaaS is consumed is lower, as compared to the case of local processing, while the energy consumption at the infrastructure side is minimally altered.
- **Technical enablers essential for efficient service operation**: data-centric workload-compute node association, network architecture to support service enablement and operation in a private network, as part of a Wide Area Network.

4.2.7.2 AI-as-a-Service (AIaaS)

AIaaS can be applied for intend classification and prediction in human-to-human and human-machine interactions, based on criteria/ features, such as: gesture, intonation, expressions, surrounding sounds, touching objects etc. This service can be consumed by applications instantiated at either user and IoT devices, or at network infrastructure submitting requests for ML-based inferencing decisions to the network (for example, to other devices or to edge cloud hosts with already trained models). A first example relates to inclusiveness of the elderly and people with motion/vision impairments, in which, for example, a person with vision impairments is equipped with wearables including sensors collecting environmental/ surroundings data. These sensory data are exploited to infer and identify objects, street furniture and possible hazards so that the user can be informed in advance and take proactive measures. Such environmental identification via object classification is useful to improve the inclusiveness and quality of life per the UN SDGs. A second example is the one of in-advance QoS predictions based on a plurality of data (for example, from the Uu and PC5 interfaces but also from vehicle sensory (RADAR, LiDAR) information); a driver/ machine (for example, used for tele-operated driving) planning to perform a journey would like to be informed of any V2X service degradations along the planned route. The reasoning of such needed notifications is the possible prioritization or postponing of software over-the-air downloads, the activation/de-activation of autonomous driving functionalities and features, etc. Towards 6G, these QoS predictions should support very demanding use cases providing very high accuracy, with an enlarged sets of KPIs to be predicted potentially including service-tailored predictions (e.g., quality of experience – QoE – tailored for the specific service) and supporting from extremely short to long time windows of predictions. Computational intelligence is needed, in this case, which can be provided by an ML-based prediction function instantiated anywhere at the network. An additional example is the one of AI-based high-resolution image/video processing in which a user is able to take a high-resolution image or video of a large crowd such as an audience in a soccer stadium. A remote AI agent may be used to identify specific persons or objects, including friends, family, an unattended child, etc. The service primarily relates to the Connecting Intelligence research challenge.

On top of 3GPP Rel-17 specifications (e.g., [29.520] on Network Data Analytics Services), where, the consumer of the service provided by the Network Data Analytics Function (NWDAF) is a

Network Function (including an Application Function implying also a third part application), per AIaaS concept, the service producer can be any AI agent reachable, as part of the network, even instantiated at the UE side (in case the latter one is of needed inferencing capability).

Considered in the context of an exemplary application, "Fully-merged cyber-physical worlds", the operation of this service can be further described:

- **Need to consume the service (precondition)**: the use case involves handheld and wearable devices, such as smart clothes, gadgets etc. as well as on-body and on-object sensors useful to generate large amounts of data, however, lacking context awareness during a MR telepresence session.
- **Service consumer**: MR telepresence application used by humans or machines. Purpose of the application is to create, synchronize and update a holographic MR environment depending on session purpose (e.g., business meeting, entertainment session etc.).
- **Service provider**: third party AIaaS provider providing a service which is consumed to enhance device/ wearable context awareness in the holographic MR telepresence session environment by means of human/ machine intend classification and/ or prediction. An essential component of the service is the discovery of an AI agent containing a ML model properly trained to perform such inferencing-based perception receiving as input the various available environmental data coming from wearables, handheld devices and sensors.
- **Needed message exchange to consume the service**:
    1. The service consumer issues an environment context awareness request to the AIaaS provider accompanied by relevant datasets coming from user and machine sensors, wearable devices etc.
    2. The service provider receives the request and identifies a proper AI agent to process it. The AI agent issues an inference-based output which is forwarded to the service consumer via the service provider. Such output can be exploited for human and environmental perception awareness.
    3. The service consumer receives inferencing output which is useful to take possible action (e.g., to update the holographic environment accordingly).
- **Impact of service consumption (postcondition)**: as a result of AIaaS consumption, the application implementing the holographic MR telepresence session will be seamlessly updating features of the session (e.g., background) per the perceived gestures and haptics-based signals.
- **Technical enablers essential for efficient service operation**: Human-Machine Interface (HMI) interfaces augmented with context awareness features, network interfaces and discovery/ selection methods of the ML model to be used for context awareness enhancement.

4.2.7.3 AI-assisted Vehicle-to-Everything (V2X)

Safety and security are of high importance for any transport system, especially road transport due to the prevalence of accidents. Several initiatives have been conducted to promote rules, technical standards and awareness campaigns to decrease the number of fatalities caused by road accidents, (refer to the European Commission' Road Safety website [ERS21]). Moreover, studies and trials proved that AI can be exploited for making roads safer, as reported in [FSN19] and [MSN19]. This motivates the need to further explore the potentiality of the AI algorithms for enhanced automotive services provided by future 6G networks. The novel AI algorithms, applied to the big data collection gathered by sensors (in and outside of the cars) as well as radio stations in the operators' networks, will allow dynamic shaping, monitoring and suggesting actions/recommendations to connected vehicles' drivers — or, potentially, to directly control the automated vehicles in order to reduce the traffic caused by them. This will have an important societal impact allowing a safety improvement for drivers and passengers as well as minimizing traffic congestion. With respect to C-V2X technologies already developed and based on LTE and NR, the processing of the massive amount of data gathered through the automotive services offered by communications networks is far to be managed properly and this creates room for the introduction of AI-based algorithms to dynamically control and shape the traffic, generating a digital replica of the real traffic scenario. The real-time creation and adaptation of such digital replica encompassing an entire urban area is very challenging and requires network capabilities not currently available; in addition, the intertwining of digital and physical worlds, as foreseen in Hexa-X, will improve not only safety but also the mobility's sustainability in a human-centric fashion. Latency and location accuracy are essential for these AI algorithms in order to control real-time-like the type, the evolution and the shaping of the traffic in large scenarios like today's cities.

Considered in the context of an exemplary application, "Immersive Smart City", in V2X environment, the operation of this service can be further described:

- **Need to consume the service (precondition)**: continuous and dynamic improvement of mobility's sustainability in a crowded urban scenario
- **Service consumer**: vehicles' drivers, where the term 'vehicle' encompasses not only cars but also (motor)cycles
- **Service provider**: a communication network operated by the MNO providing mobility services being able to generate and adapt a real-time digital replica of the traffic scenario within an entire urban area
- **Needed message exchange to consume the service**:
    1. The service consumer provides the service provider with information regarding e.g. its own location within a certain urban area for which a digital replica of the traffic scenario is developed
    2. To support the service consumer, the most appropriate network node, e.g. the road side unit or the operator's base station, collects and elaborates all the information provided by a multitude of service consumers as well as other relevant actors (e.g. pedestrians) and entities (e.g. infrastructure monitoring, traffic lights, etc.), all located within a portion of the urban area under the network node's service coverage; such network node may be chosen e.g. by considering the workload of the node itself along with its own AI processing capability
    3. The network nodes within the concerned urban area coordinate among each other by sharing the AI-processed data elaborated by themselves in order to define actions/recommendations to be then provided to the service consumer in order to dynamically control and shape the traffic in the whole urban area aiming at reducing the traffic itself
    4. The above-defined actions/recommendations are forwarded to the service consumer in the concerned urban area
- **Impact of service consumption (postcondition)**: big data collected by sensors located not only within the vehicles and pedestrians' devices but also distributed in the infrastructure deployed in the concerned urban area (e.g. road infrastructure, traffic lights, etc.) are processed by an AI-based communication network which, in turn, suggests actions/recommendations to the service consumers in order to reduce the traffic caused by them; this will allow a significant minimization of the traffic congestion. It is worth to note that such AI algorithms may also process data provided by different vehicle typologies in the concerned urban area such as cars and (motor)cyclists as well as vulnerable users e.g. pedestrians

- **Technical enablers essential for efficient service operation**: AI algorithms elaborating big data gathered by sensors within the service consumers and those located in the surrounding urban environment; access network infrastructure being able to properly collect sensors' data as well as delivering actions/recommendations to service consumers; network architecture to properly manage these data (e.g. at the Edge Cloud) and to operate with such AI algorithms for generating and adapting a real-time digital replica of the traffic scenario.

4.2.7.4 Flexible device type change service

The service may need to be consumed when robots or humans enter or leave a specific group of collaborating entities that act on a common task. In this case, the respective communication entity needs to adapt to the communication requirements within the respective group, potentially differing from previous device configurations. This service will enable devices to effectively and flexibly change their device type, for example, from a consumer device (like today's smartphone) to an industrial IoT device to a V2X device. As an exemplary user scenario, we consider the case that a user owns a consumer device (such as today's smartphone) that is typically used for voice/data communication in a non-safety-related context. When the user is entering an area where V2X communication is being used (for example, on a road, on a side-walk close to a road), the user device changes its purpose (and, therefore, its type) and will enable safety-related communication; a Vulnerable Road User (VRU), such as a pedestrian, will be warned in case of danger, a vehicle will have access to Vehicle-to-Network (V2N) services through the smartphone, etc. Another example could be an industrial robot toggling between critical and non-critical actions, such as switching from welding, requiring very high localization accuracy and low latencies, to long-range movement only requiring moderate localization accuracy and latencies. This requires that a device can flexibly change its type and configuration depending on the currently active service needs. Sensing capabilities will be an advantage to predict the need for such change and appropriate timing. This service is mainly relevant to the Network of Networks and Trustworthiness research challenges.

This service goes beyond the current status of 5G standardization, as device assignment to a network slice is static in today's 5G specifications; for example, a consumer device is assigned once to a (set of) specific network slice(s). The challenge for 6G systems lies in the extremity of performance requirements for new applications, for the addressment of which current 5G solutions may need to be enhanced. Flexible device type change may evolve today's network slicing concept in 5G to the one of "device slicing".

Considered in the context of an exemplary application, "Interacting and cooperating mobile robots", the operation of this service can be further described:

- **Need to consume the service (precondition)**: one example highlighting the need to consume this service is the one of humans spontaneously assisting robots for a given task. When approaching the respective robots, communication devices like HMIs need to be configured such that interaction with local networks under the respective requirements for the task at hand (e.g., latency, dependability) is possible. At the same time, additional services might still need to be consumed (e.g., video-based live assistance), potentially through the same HMI (in the case of AR, for example).
- **Service consumer**: the respective automation/assistance application within the OT context of the factory.
- **Service provider**: (non-public) network management capable of orchestrating and authenticating the required reconfigurations.

- **Needed message exchange to consume the service**:
    1. A request for inclusion of an entity into a local collaboration group is issued by the OT application, indicating the desired communication characteristics and participating entities.
    2. The service distributes the request to involved network management entities, informing the OT application of success or failure.
    3. In case of failure, the OT application needs to take care of finding alternative means of interaction to reach the goal of the task, potentially aided by AI.
- **Impact of service consumption (postcondition)**: After the service has been consumed, the new communication entity is able to participate in the collaborative task (e.g., a human operator can assist through direct local interaction with the robots) as the required communication capabilities of the end device are enabled for the specific task at hand.
- **Technical enablers essential for efficient service operation**: HMI interfaces carrying messaging formats on device capabilities and performance requirements of the collaborative environment to join; also, a network architecture for (non-public) network deployments extending the network slicing concept to the device side.

4.2.7.5 Energy-optimized services

Users want to be given the choice of consuming "green" ICT services, with reduced environmental impact with respect to traditional services, in a holistic manner, considering not only the applications, material, etc. but also the technology and the E2E network design. As environmentally friendly users, they will be invited to consider possible trade-offs between performance, cost and environmental impact, enabling them to monitor the overall environmental impact of their products/services. Such services aim to mainly address the Sustainability and Global Service Coverage research challenges.

This service considers the energy consumption end-to-end, considering the environmental impact of all the elements involved in the service: application, network, terminal, etc. These energy-optimized services will require not only energy-optimized networks, but also energy-optimized applications, appropriate upcycling of materials, etc. Providing a holistic view will require new indicators of the environmental impact and an aggregation of these indicators to reach a global view.

Considered in the context of an exemplary application, “E-health for all”, the operation of this service can be further described:

- **Need to consume the service (precondition)**: as the use case implies delivering E-health services everywhere, even in remote areas, it is required to minimize the environmental impact of such global coverage.
- **Service consumer**: User of E-health services, in any part of the world.
- **Service provider**: service identifying most sustainable connection to the user, thanks to new indicators, aggregating different indicators of the environmental impact, in order to reach a global view. When there is no infrastructure yet to reach a given location, the service can also be used to define the most sustainable connectivity to deploy and deliver these E-health services at this location.
- **Needed message exchange to consume the service**:
    1. The service consumer issues a request to start using the E-health service
    2. The most sustainable solution is selected by the service provider, and the services are delivered to the consumer through this solution

- **Impact of service consumption (postcondition)**: The global environmental impact of global coverage is reduced thanks to the service, considering not only end-to-end energy consumption, but also materials…
- **Technical enablers essential for efficient service operation**: sustainability KPIs and KVIs, energy-efficient features at all levels (radio, transport, core networks, as well as devices and applications)

4.2.7.6 Internet-of-Tags

Tags will be present everywhere to facilitate everyday life. The tags will enable multiple operations: collecting information through tracking of label-tags and monitoring and acting on the environment through smarter tags, with sensing or actuating capabilities in addition to communication capabilities. For instance, tracking merchandise with basic label-tags can improve logistics; tags capable of sensing temperature/light, etc. can be monitored to optimize energy consumption for heating/lighting, etc.; tags that are activated with the manual pressure of a button can be used to switch on/off light or heating. To limit the impact on the environment, tags will not be powered but will rely on energy harvesting to enable communication between tags or between tags and network, sensing, actuating, processing of the data collected. Energy harvesting will be performed through re-using ambient or renewable energy, for example, using surrounding (already existing) or dedicated RF waves, solar energy, wind, vibration, mechanical push. Finally, "zero-environmental-cost" tags can be considered, utilizing for example printed electronics to enable ubiquitous tags, while still ensuring sustainable handling at end-of-life of tags (e.g., bio-degradable).

This service generalizes and extends the use of tags and the concept of energy harvesting, relying on multiple possible sources (RF waves, solar, …), going into massive deployment. It also includes communications of the tags with the network and will enable monitoring and controlling the environment.

Considered in the context of an exemplary application, "Immersive Smart City" especially in logistics environment, the operation of this service can be further described:

- **Need to consume the service (precondition)**: The use cases involved the presence of tags at all relevant locations in the cities to enable efficient monitoring and control of city flows
- **Service consumer**: City utility managers, in charge of controlling and managing these city flows
- **Service provider**: operator of the infrastructure of tags
- **Needed message exchange to consume the service**:
    1. The tags regularly collect and report to city utility manager the status of the flows / utilities, to allow monitoring
    2. In case of abnormal value for a given utility, the city utility manager can decide of a specific and corrective action. Information is sent to the tag
    3. Thanks to actuation and sensing, the tag can deliver the corrective action
- **Impact of service consumption (postcondition)**: thanks to the wide deployment of tags, management of flows / utilities are improved: problems are detected earlier (or tags can improve detection capabilities and detect issues not identifiable before) and corrective actions are taken.
- **Technical enablers essential for efficient service operation**: availability of tags, energy harvesting, low-energy communications

4.2.7.7 Security as a service for other networks

Any kind of connected device will become able to establish trusted local connections, request and verify the on-demand deployment of security functions and assess the security of the end-to-end path by the composition of trusted segments. Local access provider collaborates with other network, security and application providers by means of dynamic trust links, always verifiable by end users.

- **Exemplary application**: Providing dynamic and trusted local connectivity to network, composable to end-to-end-scenarios.
- **Need to consume the service (precondition)**: Access applications, network functions and security management infrastructure able to manage dynamic trust and on-demand security deployments.
- **Service consumer**: End users and application providers in all sectors, at the edge or any level in the cloud hierarchy
- **Service provider**: Network service providers, security function providers, security service integrators
- **Needed message exchange to consume the service**:
    1. The user and/or device authenticates to the access provider and requests a security service policy
    2. The access provider deploys security functions, and establishes the required trusted links with other segment providers, collecting evidence of the deployments
    3. The deployment evidence is collected by the connected device and evaluated to establish the level of trust with respect to the required policy
- **Impact of service consumption (postcondition)**: The user/and or device use a trusted link to access the required network-enabled services
- **Technical enablers essential for efficient service operation**: Attestation procedures for infrastructure, functions, and topologies. Dynamic trust fabrics and reputation systems.

4.2.8 Hexa-X use cases: Summary

The project identified five main use case families, and an additional family of use-case-enabling services. This initial set of use cases, summarized in Figure 4-2, is a starting point for the project, and will be enriched, accounting for developments in the ecosystem, new findings in the project and from other projects.

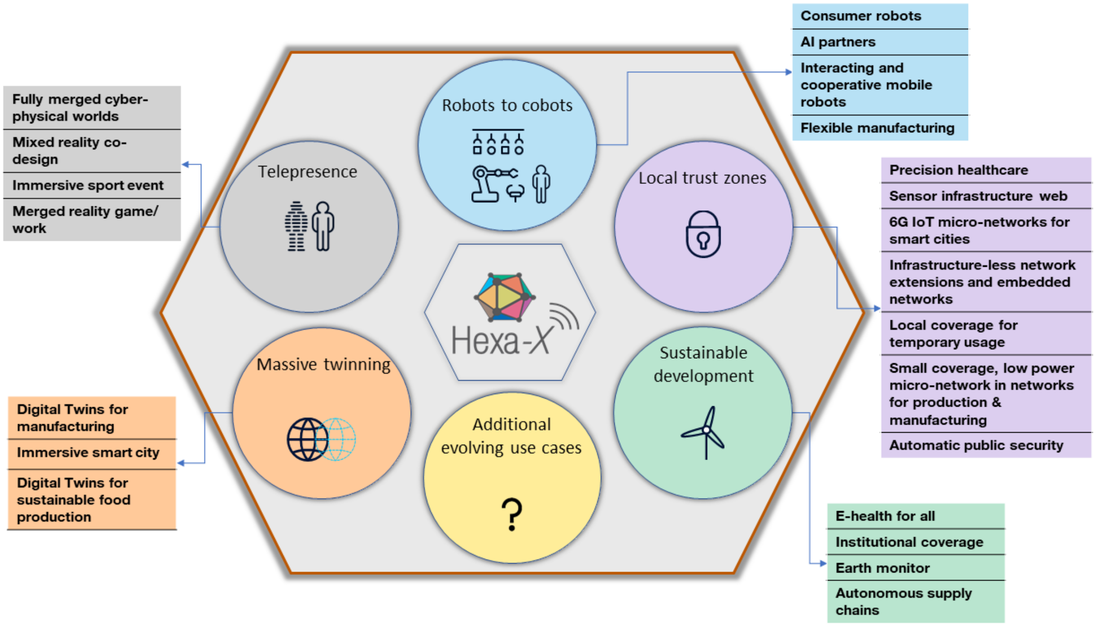

Figure 4-2: ***Summary of Hexa-X use case families and use case***

5 Key value and performance indicators (KVIs/KPIs)

In this chapter, the reasoning behind introducing Key Value Indicators (KVIs) and their role in assessing the effect of the key enabling technologies is detailed. State of the art on performance and value indicators is reported and research challenges for Hexa-X are outlined.

5.1 KVI and KPI mission statement

Hexa-X recognizes the necessity to expand the fundamental network design paradigm from performance-oriented to both performance- and value-oriented in order to fully embrace the 6G vision. Here, *value* entails intangible yet important human and societal needs such as growth, sustainability, trustworthiness, and inclusion. Based on the Hexa-X key values and vision and the derived research challenges as outlined in Section 3.2, the core values of 6G are embedded in the use cases discussed in the previous chapter. To a high degree the values delivered by the Hexa-X use cases can be mapped to the UN SDG targets and thus be placed in a global context. For some use cases, e.g., those selected to focus on a technical research challenge, the delivered value may not be directly associated with an SDG target, but can instead be related to another target, e.g., entertainment or ease-of-life, as illustrated in Figure 5-1. Consequently, there is a need to also look wider and consider additional targets besides the SDGs.

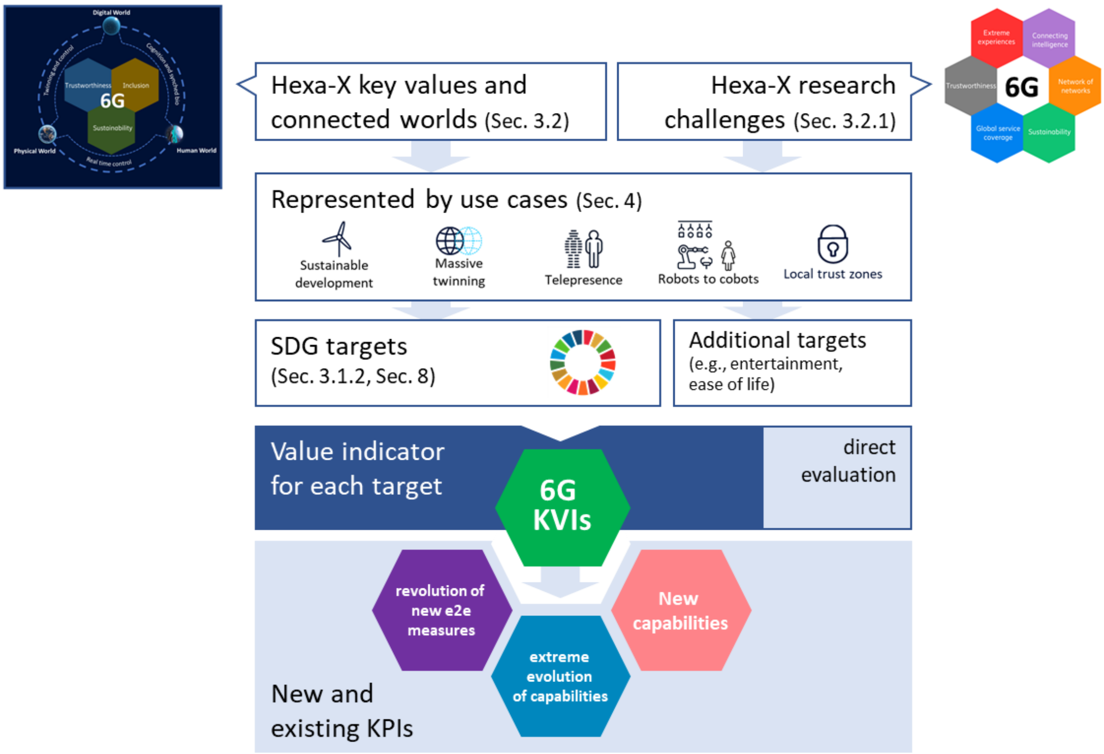

Figure 5-1: ***Mapping of targets to KVIs and new or existing KPIs***

This leads to a new class of evaluation criteria, i.e., KVIs for each target, that must be understood, developed and adopted in the network design towards 6G. For the SDG targets, as further discussed in Chapter 8, established indicators exist although mostly only applicable for national follow-up. Hexa-X will thus define value indicators that are relevant for 6G both for SDG targets and for other targets, as further discussed in this section. These KVIs might in some cases be possible to evaluate directly, but are usually to be associated with a set of KPIs serving as proxies for the respective KVI. Such (new or existing) KPIs then represent characteristics or capabilities which are required to realize the value as outlined by the targets and the KVIs. This approach has not yet been fully implemented but an example is available in Section 6.1.

Figure 5-2 illustrates the key value areas as stated in the Hexa-X vision and associated KPIs and capabilities. Each key value area reflects multifaceted aspects for which KVIs need to be developed. The key values are sustainability, inclusiveness and trustworthiness, where sustainability is explicitly considered from two perspectives in Hexa-X as further discussed in Chapter 8: 6G in itself needs to be sustainable, which could, for example, be mapped to the network energy efficiency as a KPI. In addition, 6G is an enabler for sustainability and sustainable growth in other markets and value chains, potentially covering aspects of inclusiveness and trustworthiness. This distinction and the resulting measures are further discussed in Chapter 8. Trustworthiness as another core value for Hexa-X is further discussed in Chapter 9 in the context of security considerations for 6G. In addition, the value of new capabilities enabled with 6G needs to be captured; this includes integrated sensing, embedded devices, local compute integration and integrated intelligence, as illustrated in the lower right. *Flexibility* is seen as a core capability. As core capability, flexibility covers, for example, the applicability of 6G to a new value chain, including ease of deployment and operation in that environment and, consequently, the goal of enabling new business opportunities. Flexibility as new capability of 6G impacts, for example, AI-based network management and operation.

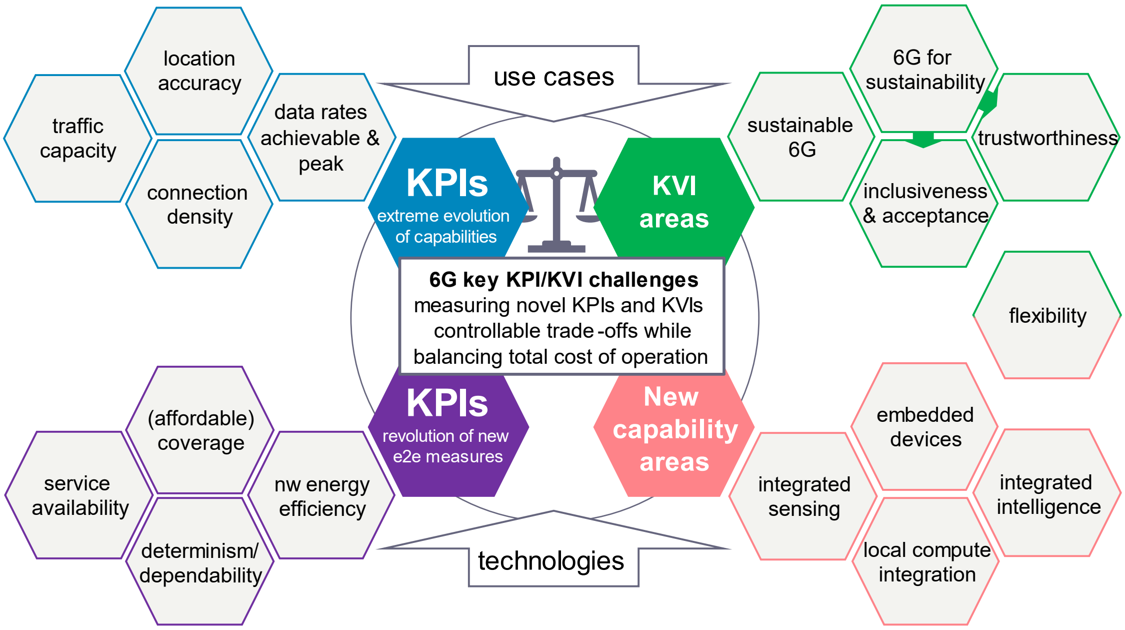

Figure 5-2: ***Clustering of KPIs and KVIs***

In addition to the novel concept of KVIs, KPIs and performance goals need to go beyond what 5G can do to address new use cases discussed in the previous chapter. This includes increasing peak data rates and data rates achievable at the cell edge, density of connections, traffic capacity, and location accuracy to a substantial extent. For some performance goals, for example, dependability and determinism, service availability, affordable coverage, and network energy efficiency, the focus will shift more towards new end-to-end KPIs in specific use cases, and extreme performance in terms of data rates might be confined to specific scenarios rather than being a general, system-wide goal. Depending on the use case, novel KPIs for this end-to-end perspective will be defined. In addition, the relation between the fulfillment of KPIs and the associated total cost of operation becomes increasingly complex, given the number of stakeholders involved and the potential of networked intelligence and service-oriented ownership and business models on a local and global scale.

The *evolution* of KPIs and the *revolution* of new end-to-end KPIs and new KVIs in 6G is tackled on a use-case basis and from the viewpoint of individual technical enablers in Hexa-X (WP 2-7), as outlined in the following sections.

5.2 Literature on 6G KPIs and KVIs

This section outlines how KVIs and KPIs and related concepts have been used in other projects to provide input to future identification of the KVIs and KPIs applicable to Hexa-X.

In [ACI20], an open ecosystem for Operational Technology (OT) networks in industrial environments is motivated: Openness relates to interoperability with other hardware used in OT networks, compatibility with commonly used technology like Time-Sensitive Networking (TSN), and sustainable integration with the existing installed base. To quantify the required and achieved level of openness in this regard, novel KVIs are required. Local and remote use cases are distinguished in [ACI20], with aspects such as isolation for automation networks and machine safety, but also regarding data privacy (for example, data is not allowed to leave the premises). Here, requirements originating from the automation application such as packet loss rates below $5*10^{-7}$ and no consecutive packet loss motivate the need for novel cross-layer dependability metrics. Such dependability metrics need to take application characteristics such as recovery times into account. Additionally, reliable time synchronization within microseconds is a key requirement for automation networks. Regarding security, the potential for integration into existing security frameworks is a requirement that needs to be supported.

In [ZY20], the authors described how KVIs are broadly clustered into (i) growth and (ii) sustainability and efficiency domains. They propose for this setup to measure 6G impact for growth by measuring economic growth and new value chain, ecosystem and business models. Sustainability and efficiency objectives should then utilize the following value indicators, according to the authors: total cost of ownership (TCO), time-to-market (TTM) and flexibility, open collaboration, security, privacy and trust, energy consumption, serving the underserved, megacity impact, and Public Protection and Disaster Recovery (PPDR).

According to [ZY20], 6G performance indicators with very high impact on economic growth include the expected high number of 6G private and dedicated networks as well as the number of devices including sensors. Furthermore, network slicing and network of networks automation as well as sensing will show high impact on economic growth. Ecosystemic business models and platform transformation are found to be a key value drivers enabled by very high number of private and dedicated networks and 6G flexibility, automation and granular slice instantiation. Besides impact on scalability and replicability and therefore growth, sustainability and efficiency targets deserve attention. Six performance indicators were identified with likely very high impact on efficiency and sustainability targets: new business models will be greatly boosted by a fast growing number of private networks; TCO will be significantly reduced by zero energy devices and by flexible automation of network of networks; flexibility and automation and capability to instantiate thousands of network slices will also have a positive impact on TTM. Open collaboration can be considered both a means and a goal – flexibility as required to build network of networks architecture and technology will leverage vehicles of openness including Standards Developing Organizations (SDOs), open source and white box. Key enablers to help reduce energy consumption may well come from making trillions of devices and sensors consuming zero energy. The key performance indicator with single-most important impact on driving smart megacity transformation may well be density of devices per square-kilometer, whereas coverage and non-terrestrial coverage will help deliver on the objective of serving the underserved.

In the white paper [Eri20], the vision of *Ever-present Intelligent Communication* is discussed based on the drivers of trustworthiness, sustainability, extreme applications, and simplified life. Looking at the use cases that are expected to come from these drivers and to appear in the 2030 timeframe, [Eri20] sees two directions of expansion going from 5G to 6G; the first being to continue improving the current set of capabilities pointing at targeting quantitative parameters like capacity, data rates, E2E latency, and connecting massive amounts of devices; while the second is to aim at new capability dimensions with more qualitative nature such as security, local compute integration, service availability, and positioning and sensing capacities. In between those two sets of capabilities, one can place energy efficiency and coverage, which have been targeted by previous generations of mobile networks but where the interpretation and ambitions should be scaled up to cover the whole network system and the whole world, respectively. Important is also to consider a sustainable level of total cost of ownership or operations as a basic ambition.

The white paper [NTT20] presents 6G as focused around *Cyber-physical fusion*. The main areas for 6G to address are solving social problems, communication between humans and things, expansion of communication environment, and sophistication of cyber-physical fusion. The 5G use case areas of Massive Machine Type Communications (mMTC), URLLC, and Enhanced Mobile Broadband will evolve into new combinations with more specific use cases and extreme requirements. The capabilities needed for delivering this around 2030 are mainly seen as expansions of those of 5G, aiming at going further in the directions of data rate, capacity, coverage, low energy consumption, low cost, low latency, high reliability, and massive connectivity, but with the last two pointing in partly new directions of security/privacy and positioning/sensing.

The white paper [Sam20] envisions 6G to *bring the next hyper-connected experience to every corner of life*, with a focus on the megatrends of connected machines, AI, openness, and societal goals. The new services brought by 6G will revolve around the key areas of immersive XR, mobile holograms, and digital replicas, which will require improvements in the 5G KPIs of data rate, energy efficiency, spectral efficiency, latency, connection density, reliability; but also an expansion into the new capabilities of communication and computing convergence, and new requirements in the domain of security.

The first Finnish 6G Flagship white paper [LL19] addresses key drivers and research challenges for 6G. Many of the technology-driven KPIs developed for current and emerging 5G technologies (for example, peak data rate, ultra-reliability, traffic increase) are seen valid for 6G with respective increments in capability. However, they should be critically reviewed and new KPIs need to be seriously considered. Initial 6G KPIs have been divided into *technology- and productivity-driven KPIs* and *sustainability- and society-driven KPIs*. The former can be further categorized to latency, jitter, link budget, extended range/coverage, 3D-mapping fidelity, existing tuned 5G KPIs, position accuracy and update rate, cost, and energy related KPIs. The latter covers inclusion of vertical players in definition of requirements and standardization, transparency KPIs (for example, related to AI), privacy/security/trust KPIs, global use case-oriented APIs, UN SDG inspired KPIs, open source everything, and ethics KPIs.

The next round of the Finnish 6G Flagship white papers [6GC20] go deeper in the following thematic areas: 6G drivers and the UN SDGs, business of 6G, validation and trials for verticals towards the 2030's, connectivity for remote areas, networking, machine learning in 6G wireless communication networks, edge intelligence, research challenges for trust, security and privacy, broadband connectivity in 6G, critical and mMTC towards 6G, and localization and sensing [6GC20]. Performance and value indicators are considered more closely from each topic's own perspective. As an example, [Pou20] compares industry mMTC, industry eURLLC, mobility, eHealth, energy, finance, public safety, and agribusiness verticals and their respective KPI and KVI requirements. It is noteworthy that KPI assessment is highly use case dependent with a large variation between verticals. Also, setting numerical values for KVIs is hard and the assessment of them is only indicative at first. The use case dependency of KPIs is also stressed in recent technical reports by the ITU on representative use cases and their requirements [ITU20, ITU20b].

In [Ora20], the importance of defining societal requirements is stressed, in addition to the "traditional" performance KPIs (data rates, capacity, latency, reliability, connection density, etc.). Defining 6G should build upon the lessons learnt from 5G deployment, and more specifically the real adoption of extreme requirements, before defining new performance requirements. In order to ensure societal relevance and acceptance, the needs and expectations from end users must be accounted for, through the formulation of societal requirements, associated with target values for 6G. These societal requirements should be considered with equal importance as performance requirements, and can include energy efficiency, aiming at gains as high as capacity gains with respect to 5G, very low end-to-end environmental impact, higher EMF-awareness, higher digital inclusion (with improved affordability, coverage of low density areas), higher security and much higher resilience.

5.3 Hexa-X challenges and contributions regarding KVIs and KPIs

The main challenges with respect to KVIs and KPIs are illustrated in Figure 5-2: being able to measure novel KPIs and KVIs, and being able to provide controllable trade-offs while balancing the total cost of operation. In the following, we provide a more detailed discussion on the challenges ahead and on the planned contributions in Hexa-X.

When developing towards 6G we should move in multiple dimensions: expanding the set of capabilities, aiming at key values, and redefining as well as advancing on an existing set of capabilities. The capabilities in turn can be mapped to measurable KPIs, whereas key values are mapped to KVI (see 6.3.4).

5.3.1 Advancing on existing KPIs

Bringing 6G forward, it remains important to advance on the fundamental capabilities of delivering extreme data rates, capacity, location accuracy, and connection density, which will continue to serve both the existing use cases with better performance and reliability as well as novel use cases relying on similar capabilities.

Data rate

Peak data rates are important in certain scenarios for extremely demanding services, while in a general scenario, it is more important to consider the user experienced data rate. Both should take a significant step from the 5G levels. For instance, fixed wireless access (FWA) and integrated access and backhaul (IAB), are expected to operate at peak data rates, as the stationary nature of the use cases can enable full utilization of line-of-sight communication without restrictive battery operation, whereas handheld or other devices will be highly mobile with stringent power consumption restrictions. In all scenarios, it will be imperative that the performance delivered suffices to fulfil the service requirements of the applications in use.

Capacity

Compared to 5G networks, the total traffic capacity per area should increase several times to support demanding services with a multitude of concurrent users. As both, the peak and average date rate and the connection density are expected to rise significantly for addressing extremely demanding multi-user use cases, the traffic capacity must be extended for all, the access, transport, and core networks.

Localization

Precision and accuracy in positioning services should by far exceed that achievable in 5G and GNSS. Although current systems allow for meter precision in positioning, e.g. for map services or localization for emergency calls, 6G will enable applications that rely on much stricter positioning accuracy.

Connection density

The number of served/connected devices in an area should be much higher than supported in 5G to enable embedded devices everywhere. With the advent of near zero-cost, near zero-energy devices, the marginal cost of introducing additional devices will plummet, adding additional requirements on the network to support the connections while still maintaining service for the high-performance devices.

5.3.2 Redefinition of existing KPIs

A set of capabilities have been in focus for previous generations of communication networks, but should now be considered in a comprehensive, end-to-end perspective. By shifting focus from enhancing the best-case peak performance to improving the worst-case guaranteed performance, a new slate of critical services can be enabled.

Service availability

As applications and services become even further ingrained in our societies, the expectations of ubiquitous and interminable service availability will rise. Important aspects are here: the fraction of device population for which a service can be delivered with a certain availability; minimum service interruption due to events or mobility; and network survivability over time.

Deterministic services and dependability

It should be possible to deliver guarantees for: achievable data rate; maximum end-to-end service latency; bounded jitter; and end-to-end packet reliability with robust mobility, in order to enable, for example, use cases from the automation domain or in human-machine interaction (c.f. use cases in Section 4.2.5). This could include novel end-to-end definitions of dependability metrics, taking application specifics in such domains into account.

Coverage

The key aspects to consider here are: fraction of global surface covered; fraction of population covered; total cost of coverage per area; and traffic volume while providing 6G performance and services.

Network energy efficiency

The end-to-end perspective should be considered for energy consumption. Relevant parameters are: total energy per delivered bit; signaling overhead; total energy consumption per service area; and total resource consumption per delivered bit.

5.3.3 New capabilities leading to new KPIs

6G is targeted to introduce several new capabilities that will broaden the utility of the communication networks. These capabilities will both enhance the performance of traditional services as well as enable paradigm-shifting new services. For this expanded set of capabilities there should be clear definitions and targets both in terms of intrinsic performance of the capabilities as well as the enabling effect to other features. These performances will be developed further during the progress of the project to capture the improved understanding and align it across technical work packages.

Integrated sensing

The intrinsic properties of localization and sensing rely on traditional sensing parameters such as relative precision in position and velocity; angular resolution; accuracy in parameter estimation; and convergence time of estimation. However, the system co-design for both, communications and sensing purposes, allows for enhanced performance in terms of coverage and throughput, as well as service interruption during mobility.

Local compute integration

The intrinsic properties of local compute integration will be key parameters such as round-trip time (RTT) to compute and storage as well as TTM to introduce additional compute capabilities. However, the integration of local compute capabilities is done to enhance other features which could be measured with use-case specific KPIs, for example, Quality of Immersion.

Integrated intelligence

Integration of AI/ML encompasses both utilization of AI/ML for optimization of network operations in a pervasive way (for example, AI/ML-defined air interface framework), as well as optimization of network operations for optimal performance of AI/ML features. For the utilization of AI/ML to enhance network features, the relevant parameters will be, for example, convergence time; enhancements over existing analytical or heuristic features; fault rate; and added energy consumption. For the optimization of the network to facilitate AI/ML features, the relevant parameters will rather be flexibility to adjust parameters; TTM of new features.

Embedded devices

If a wireless device is to be embeddable anywhere, access to an external power source cannot be taken for granted. In addition, the placement of the devices may prevent or prohibit the usage of batteries as a power source. Therefore, these devices may rely on energy-harvesting of some form and to keep down cost, the devices may be produced using printable electronics.

Key aspects to consider for embeddable devices are: energy consumption; form factor; cost; time between maintenance occasions; total resource consumption and end-of-life handling.

Flexibility

With the overall move to cloud-native realization of 5G and beyond, and increasingly the RAN, new capabilities and requirements around flexibility for 6G emerge. This includes the ability of the system to be adapted and tailored to specific use cases and environments. Flexibility as a consequence of disaggregation, softwarization and automation/orchestration is also seen as an enabler for self-healing and for smoothening the transition from 5G to 6G. Quantifying the achieved level of flexibility should include not only the operation of the system, but also its design, deployment and integration into other systems that is required for targeted adaptation towards specific use cases.

5.3.4 Challenges when capturing societal needs with KVIs

There are key values and defining characteristics that will drive 6G, as outlined in the project vision in Section 3.2. These include sustainability (sustainable 6G and 6G for sustainability), inclusion and trustworthiness.

It is generally much harder to quantify values than technical capabilities. If it appears to be overwhelming to measure a certain value, it is always possible to resort to softer indicators in the value evaluation. This could mean, for example, weighing specific KPIs based on their significance from the application and use case point of view or recognizing emerging trends as an indicator for the relative weight of a KPI in quantifying a value and taking those into account while elaborating KVIs. In addition, the perceived performance is more or less universal; the perceived value is heavily rendered by background, culture and even ideology of individuals as well as operating locations, regulatory environment and stakeholder structure of enterprise. Consequently, an open and inclusive framework is required to be able to adapt to different perceptions and backgrounds when quantifying and weighing different values with KVIs. This is the reason why Hexa-X puts forward the UN SDGs which represents the most widely agreed framework for sustainable development that exists.

Being able to include individual perceived value also addresses ethical issues when it comes to the right of being included (and, equally important: the right not to be included) in certain new technical abilities of a system. This relates, for example, to localization and mapping, but also to utilization of data in AI-based algorithms.

Regarding the Hexa-X view on sustainability and the distinction into *6G for sustainability* and *sustainable 6G*, a detailed discussion is presented in Chapter 8, including aspects of measurability and relevant indicators for sustainability in the context of 6G.

5.3.5 Challenges with measurability and increasing complexity

The KPIs and KVIs (and their target values) may lead to conflicting requirements: providing a global coverage may require the deployment of additional infrastructure, for example, base stations, and then lead to an increase in power consumption and carbon footprint. So while respecting the values the 6G technology needs to provide built-in capabilities to (i) maximize the performance of each design dimension in a cost-efficient way (TCO) and (ii) allow network operators and involved parties to resolve the inherent trade-offs according to their needs and use cases.

In general, the quantification of values will be very challenging, as already discussed in the previous section and the use of KPIs as proxies is foreseen in line with Section 5.1. However, in some cases interpreting those quantified results in a meaningful way is even more challenging. For example, what does a higher value in trustworthiness mean? The system is more trustworthy, the vendor is more trustworthy or the service is trustworthy? One-dimensional KVI measures might, thus, not be suitable to address the problem; instead, multi-dimensional criteria need to be established to provide meaningful and comparable data regarding a specific value that is to be quantified, as outlined in Section 5.1.

In addition, the scope of a KVI needs to be carefully specified, as it is important contextual information required to interpret and compare solutions. For example, KVIs require a precise definition of E2E. Looking at 5G, E2E is about from one end of a network to the other end depending on use cases, which is totally reasonable for KPI definitions. For KVIs, such as sustainability and trustworthiness, we need to carefully define the criteria of what is to be included, as sketched above: do we want to also include the value chain and the use of material and energy resources in the production? There needs to be a balance between the complexity of measuring and quantifying a KVI and its ability to quantify the underlying societal value to provide a real benefit for enabling technologies and the 6G system. Consequently, we need to distinguish between quantitative and qualitative KVIs.

5.3.6 Methodology and way forward

This section contains the mission and rationale behind KVIs and KPIs in Hexa-X and an initial set of research challenges and planned contributions derived from the overall project mission and the core enabling technologies. It serves as a blueprint for the technical work packages with the bottom-up refinement of KPIs and KVIs. This includes, for example, the refinement of "integrated sensing" as a new capability and "location accuracy" as an associated KPI driven by WP3. It also puts forward an approach for establishing the SDGs as a main framework for KVIs together with other complementary targets, as illustrated in 6.1.

Work on KVIs and KPIs will further benefit from technical work packages refining and augmenting the use cases and scenarios during their initial gap analysis phase. The respective work in WP1 (Task 1.1 "Common Vision" and Task 1.2 "Services, use cases") contributes to the top-down view on KVIs and KPIs. In the following section, a more detailed discussion of selected use cases and their KVIs and KPIs is discussed, extending the work presented in this section and serving as an input to the technical work in Hexa-X.

6 Deployment scenarios and associated KVIs and KPIs

This section focuses on a representative subset of Hexa-X use cases and provides for each one a description of the deployment scenario and defines the corresponding sets of KPIs and KVIs, to be used for assessment of the technologies developed in the project.

A set of representative use cases have been selected from the complete set described in Chapter 4, in order to be further described in terms of deployment scenario and corresponding KPIs / KVIs in this chapter. One use case has been chosen for each use case family, according to the representativeness of this use cases of the characteristics of the use case family.

6.1 E-Health for all

6.1.1 Scenario

Using cost-efficient 6G connectivity it should be possible to reach a very high fraction of the world's population and provide advanced E-health services, resulting in an enormous public and personal health benefits.

6.1.1.1 Exemplary applications

This use case is about providing basic or advanced E-health services to all in a cost-efficient way, considering secure transmission and identification, complying with privacy and health regulatory frameworks. The services can span from, e.g., simple health data being gathered in a secure way, via in-home video-based doctors' appointments, to remotely located expertise supporting local health-workers, as well as more advanced remote examinations with tactile support (e.g., touch, feel) and user device sensor data analytics, including image and volumetric data. A complement could be connected intelligent machines, such as drone-based blood/tissue sample retrieval, supporting robots and medicine delivery.

Depending on region (urban, rural, remote, more or less privileged) the level of E-health that can be provided will vary, and will be in direct relation to, what the network securely can deliver and what the cost will be for network/coverage, its performance, for the use and for the service. Four examples that address the previously mentioned challenges are:

- Patients within more advanced health-care systems who could more easily get access to health care services in their homes, with or without access to medical personnel, for example self-monitored advanced treatment of chronic diseases or elderly.
- Health workers in rural areas and less privileged regions with access to only basic health care knowledge and equipment who could consult with specialized medical experts (human or AI based) over video-link to extend their diagnoses and treatment precision. This could e.g. include maternal care and support at deliveries, or support to wounded patients in conflict areas.
- Universal healthcare for everyone, including under-privileged groups in privileged areas, by using low cost/existing devices and AI to improve access to basic healthcare, and remittance to a stationary or mobile medical hub in case there is need.
- Public health monitoring & disease prevention on a large scale by combining sensor data from humans and earth monitoring systems (see use case Earth monitor) to identify health hazards, such as contaminated water, heat waves, outbreaks of disease et c. and give personalized advice on how to act to protect oneself.

It is expected that video connections would be relevant for many applications, but in a health care system of 2030 one could also foresee the relevance of enabling other technologies such as sensor-based monitoring, XR and drones to further enhance remote healthcare. In particular, it could be expected that there would be a broader future demand for state-of-the art healthcare in the 2030s for those that already have access to advanced health care today. In addition, there may also be a need for state-of-the-art healthcare in mobile hubs such as ambulances, etc. possibly even mobile mini-clinics, e.g., medi-hubs that can move to wherever needed.

6.1.1.2 System aspects

To cover the populated areas of the world in a cost-efficient and sustainable way a combination of wireless access types will likely be needed. For rural areas with a low population density, both long range terrestrial and NTN (satellite/drones) solutions, in combination with low-carbon energy supply will be of importance. For more populated areas, terrestrial deployments will be dominating and in intermediate areas a mix of solutions can be considered, such as long-range relay links, multi-hop solutions, and flexible architecture. Resilience can be addressed by allowing regional network portions to continue operation even when central functions may fail, which will be important for emergency health care.

6.1.1.3 Actors and interactions

The above cases are combinations of autonomous systems, guided by AI and remote access to medical expertise in case this is needed. Users access the more advanced and sickness-treatment service in their homes through personal devices or in local clinics/medi-hubs. For the public health monitoring the ubiquitous coverage and use of personal and embedded sensors together with an AI system identifies and alerts citizens and authorities.

In use cases in more prosperous settings, in home environments as well as in medic hubs, various connected devices (e.g. smartphones, XR headsets, in-body/on-body devices, etc.) or wearable sensors (pulse, temperature, ecg), or stand-alone sensors or analysis tools (e.g. simple lab-on-a-chip) could gather data in a local hub (e.g. a smartphone or similar device) which would complement a video consultation. High-resolution cameras enable for examination of eyes, skin, wounds and XR-systems and tactile support enable more advanced medical examination. Automatic analysis tools based on speech and visual input, for example volumetric analysis, can provide first-level examination and diagnosis.

The medi-hubs may be stationary or mobile (driverless) vehicles/minivans. In medi-hubs these devices can be complemented by simpler analysis devices for telemedicine, e.g. for blood pressure, stethoscope, or ultrasound examination.

The medi-hubs could be staffed by nurses/health care workers to complement the telemedicine services with basic care and testing. Autonomous transports of samples (e.g. with drones) can be triggered from the medi-hubs or even from the homes. If staffed, the connectivity to the medi-hubs would also enable availability of medical expertise with live connectivity to, e.g., any central/university hospital / expert.

In less privileged settings a sub-set of those capabilities might be more likely, but high connectivity and coverage of more advanced services would benefit also such use cases and prevent a digital healthcare divide.

6.1.1.4 Related enabling services

This use case can be served by the following "enabling services harnessing new capabilities": the "Energy-optimised services", "AI-as-a-service" and "Compute-as-a-service".

6.1.2 KPIs / KVIs

Enabling E-health for all is a key step towards digital inclusion and a sustainable development of society where trustworthiness is both a prerequisite for and products of improved health. From an UN SDG perspective E-health for all could contribute positively to several SDG targets, primarily:

- Target 3.8: Achieve universal health coverage (for inclusion and sustainability)
- Target 3C: Increase health financing and support health workforce in developing countries (for inclusion and sustainability)
- Target 5.6: Universal access to reproductive health and rights (for inclusion and sustainability)
- Target 16.6: Develop effective, accountable and transparent institutions at all levels (for trustworthiness, inclusion and sustainability).

This use case would potentially also enable a range of other SDGs.

The contribution to SDG's and its association to the project KVIs and KPI's follow what is outlined in Section 5.1, for, e.g., KVI-to-SDG-mapping and the importance of, e.g., for every use case, offer services in an energy-efficient and GHG-optimized way.

6.1.2.1 Population service coverage

A very high fraction of the world population should have affordable coverage that support sensor data gathering and internet connectivity for information exchange. This level also supports, e.g., disease alerts.

A high fraction of the world population should have a coverage of MBB-level services (few Mbps (data rates) at a sustainable cost level. This requires achievable data rates with extreme and affordable coverage with a high level of guaranteed service availability.

A medium fraction of the world population should have a coverage of ultra-reliable near-real-time (determinism / dependability) communication for tactile examinations.

6.1.2.2 Trustworthy communication

Any communication and storage of data relevant for this use must guarantee data confidentiality, integrity and privacy. Specifically, identification verification needs to be supported by the network. All connections must have a high level of network reliability, availability, and resilience (NRAR), surviving e.g., natural events, malfunction, and hostile attacks.

6.1.2.3 Integration of local compute and artificial intelligence

In order to provide advanced health monitoring and E-health care in remote areas only using simple low-cost devices, it will be necessary to migrate functionality and artificial intelligence to the network which should be located as close to the user as possible. In addition, with distributed and federated AI functionality, it will be possible to aggregate health indicators on a population level while ensuring patient privacy and integrity.

6.2 Immersive Smart City

6.2.1 Scenario

The real-time and accurate digital representation of the world of a city with the massive use of digital twins, can generate insights and predictions to enhance the liveability of our cities. These insights in conjunction with means that influence the physical world can manage city flows to many application areas such as city utilities, transportation, safety, environment, education, health and more.

6.2.1.1 Exemplary applications

Massive twinning will be in all facets of our lives. This will stress the networks and push for development and deployment of 6G. A huge target area is the improvement of the liveability of a city. City liveability is a concept that represents the living conditions in the city and is determined by large parameter sets, which are weighted. The sets correspond to wide application areas, relevant to:

- city infrastructure (e.g., roads, buildings, networks, transport, energy, water, gas, etc.)
- ambience/environment (e.g., climate, air quality, etc.),
- healthcare aspects,
- education/culture issues,
- stability/safety, and many others.

Several aspects of deploying massive twinning to these liveability factors are quoted subsequently. The quality of the air is an indicator for the environment state and is closely related to industry consumption and vehicle actuation in urban areas. Measuring and forecasting the air quality of the cities can induce the reduction of emissions trough electrification, digitalization and optimization which will subsequently boost sustainability. On the other hand, public transport can be enhanced by monitoring on real time and forecasting the actuation and flows of citizens as well as traffic congestion across the city. Additionally, the enhancement and materialization of the automated train operations for mass transit can boost the safety, minimize delays and as a result can improve mobility infrastructures. On the other hand, measuring and simulating the availability of drugs, health devices and vacancies of beds and doctors in hospitals can enhance health system. Moreover, the use of wearable devices to collect data, simulate and exchange this information virtually with doctors, can improve personal healthcare. This idea of wearable technology and self-tracking was introduced in quantified self movement and can be expanded within 6G vision.

In education sector, digital classes where teachers can be aware of student reaction and behavior as well as student can hear, feel and see their teacher and colleagues so that they can form groups for possible team work etc., are some potential aspects of twinning this sector (AR/VR powered classes). Additionally, there could be a mix of these liveability factors by using cross areas information like air quality for health purposes, transportation, traffic conditions and gas, water or energy utilities for environmental reasons and more.

In conjunction with real-time feedback from the physical world and its associated assets, the digital twin city model will be a powerful tool for future evolution and planning as well as enhanced and efficient operations of future smart cities. An interactive spatio-temporal 4D map can be used to plan utilities management such as public transport, garbage, piping, cabling, buildings, heating, etc., or to connect the many parts of a factory that can be inspected and steered in detail.

6.2.1.2 System aspects

Such a use case could be realized in an urban or industrial type of environments. The deployment of twinning will be in various spaces like hospitals, schools, universities, houses as well as highways, railways, metros, industries around the city. For this reason, the type of deployment varies. For instance, macro cells might be more appropriate for transportation twinning and micro cells for personal healthcare twinning. Moreover, there needs to be interaction between different segments and components such as end-user devices, small cells, edge cloud, core and cloud.

6.2.1.3 Actors and interactions

Depending on the case of deployment, the main involved actors interacting with each other as well as with the environment, will be humans, varied sensors and machines. In the case of twinning the air quality of cities, multiple sensors placed all over the city will exchange information and data with the intention to stabilize the good air condition and prevent a possible hazard. In a similar manner, in the case of controlling and simulating the public transport and citizens flows, cameras and other IoT sensors will interact to materialize the digital twin in this sector. Additionally, in the case of twinning in education, humans will interact with each other and with the environment by using wearable devices and so on. Finally, concerning healthcare, humans and machines will be the main actors and will interact so as to succeed the enhancement of health care services.

The effective management of all these factors, on various time scales, opens technical challenges, potential from a societal perspective, and business opportunities. Technical challenges are associated with aspects related to the volume of traffic that needs to be transferred, the associated time scales and reliability, etc. Societal value lies in the potential of perceiving, predicting and managing hazards or other less critical situations. Business opportunities occur for operators and other ICT players, by assisting cities in the accomplishment of their goals. A city in the 2030s will be a dynamic system of systems with many constituting elements such as people, infrastructure and events.

6.2.1.4 Related enabling services

This use case can be served by all the “enabling services harnessing new capabilities”: “AI-as-a-service", “Compute-as-a-service". “Flexible device type changed”, “Energy-optimised services”, “Internet-of-Tags", “AI-assisted V2X” and “Security-as-a-service".

6.2.2 KPIs / KVIs

Digital twins can be built for each of the liveability factors that were described above and form a general digital twin city model. Human and AI operators can explore the rich data and simultaneously modify to manage and schedule activities, effectuating changes and tasks through actuators and controllers in the network. This model can be materialized by monitoring multiple sensors (IoT), collecting data (data ingestion), analyzing data (data management and analysis), visualizing, making decision and then simulating.

Some challenges that need to be addressed for materializing digital twinning for liveability are the pressure of the network for supporting twinning functions, the possible low latency and high reliability in conjunction with the high capacity, more volume, the trustworthiness and sustainability and more.

This use case requires the transfer of vast amounts of data within certain time limits (from ultra-low latency to vehicles or health, to “near” real-time). In parallel, the highest possible levels of sustainability are called for, while trustworthiness is most important and will be demanded by citizens.

6.2.2.1 Sustainable urban development

As it is implied in the title, this use case of managing city flows to optimize liveability will boost sustainability from all perspectives. The management of air quality, garbage flows, traffic (emissions), etc. will cover the environmental perspective, the management of industrial flows, transportation, utilities will cover economic perspective and the twining in education sector, ect. will cover the social perspective.

6.2.2.2 Trustworthiness and dependability

Massive twining needs a vast amount of data to be transferred and analyzed so it is crucial the network to be trustworthy. The data that will be collected are either personal or public. The protection and privacy of data should be guaranteed so that citizens will trust the wireless networks and feel secure. Dependability on the other hand, which is related to the coverage of the network, the latency of data transmissions and probability of error, is an important quality for managing city flows.

6.2.2.3 High capacity and data rates

In order to twin the city flows, high traffic capacity and data rate transmission, will be needed. The total traffic capacity will increase to support the massive twining of all the application areas of a city with a great number of users.

6.3 Fully-merged cyber-physical worlds

Here there would be seamless and synchronous interaction of humans and objects, independent of their location and of whether being physical or fully digital. This would be realized via mixed reality combined with telepresence. MR telepresence allows interaction with both physical and digital objects, them being near or far in physical reality. Users want to communicate with distant persons with a quality of interaction very close to reality.

6.3.1 Scenario

Fully-merged cyber-physical worlds need to be deployed anywhere and anytime. Initially the deployments could be in dedicated spaces at work or home – or perhaps in the city, like telephone booths used to be. In more limited way one would need to deploy this anywhere with the wearable and handheld devices one happens to have with.

6.3.1.1 Exemplary applications

This use case is about providing experience of interacting with other humans and machines as well as real and digital objects independent of location. Hence the services that can be provided include:

- Meeting other people in a very realistic way without being physically present
- Efficient remote work and interaction
- Virtual traveling
- Take part in real and digital events in an immersive way
    - Select the best place at a concert
    - Join a sports event in the middle of the players and action

- Interact remotely with real or virtual objects and machines, if needed together with other humans
    - mixed reality co-design

6.3.1.2 System aspects

Initially the deployments could be in dedicated spaces at work or home – or perhaps in the city, like telephone booths used to be. In more limited way one would need to deploy this anywhere with the wearable and handheld devices one happens to have with.

At one extreme, high proportion of people in dense cities could be needing this use case simultaneously. For this dense set of small cells would be needed.

Another extreme is when a person would need this in rural or remote location with limited infrastructure to support. Here the density of devices would be low, but requirements for each device high despite remote location.

This experience and use case will be enabled by wearable devices, such as earbuds and devices embedded in our clothing and other novel user interfaces. Humans will carry multiple wearables, working seamlessly with each other, providing natural, intuitive interfaces.

Touchscreen typing will likely become outdated. Gesturing and talking to whatever devices are used to get things done will become the norm. The devices we use will be fully context-aware, and the network will become increasingly sophisticated at predicting our needs. This context awareness combined with new human–machine interfaces will make our telepresence interaction intuitive and efficient.

6.3.1.3 Actors and interactions

The involved actors would be human or a group of humans together with any amount of physical and digital devices being part of the interaction. All humans would have the physical or digital representation of the other human(s) and object(s) available for interaction and to be sensed via various senses. Wearable devices would be needed as well as human-to-human and human-to-machine interfaces.

6.3.1.4 Related enabling services

This use case can be served by the following “enabling services harnessing new capabilities”: “AI-as-a-Service (AIaaS)” concept to facilitate and enhance device context awareness and holistic (i.e., both environmental and human body) perception by utilizing inferencing methods applied to a collection of sensor and wearable data. Similarly, it can be served by the “Compute-as-a-service".

This use can also be served via energy optimized services as users want to pay an additional attention to the energy consumption.

6.3.2 KPIs / KVIs

Fully-merged cyber-physical worlds require quite a lot in different ways. There is wide set of requirements from extreme evolution of capabilities point of view via high data rates and traffic capacity as all participating humans and machines need high amount of data to create the experience. Such connections could also be needed densely in urban or industrial areas. For the proper creation of the experience location accuracy is needed.

Despite strong performance needs, the experience needs to be provided in a sustainable way. This could also even further reduce need to travel and thus help in sustainability. Due to the authentic way of sharing a lot of information, trustworthiness is important.

Several new capabilities are needed. Integrated sensing helps in re-creating the experience remotely. Embedded devices enhance the experience and could enable it outside of dedicated spaces for providing this experience. Integrated intelligence has potential to improve the experience.

Via service availability one could join this experience with more freedom from the location. One would also often have the need to depend on the availability of the service.

6.4 Interacting and cooperating mobile robots

This use case focuses on future industrial environments, especially in the automation domain. In these environments, there is a move from fixed and static production lines to a flexible, modular production of goods with high degrees of customization and individualization of the manufactured product. This is enabled by an increased share of Autonomous Guided Vehicles (AGVs), mobile robots, and potentially drones that cooperate and blur the border between logistics and production processes within modular flexible production cells.

6.4.1 Scenario

Within the industrial environment, a multitude of private managed networks (fixed and wireless) are used for connectivity within a single machine, among machines in a production cell and among different production cells. When interacting with a production cell or moving in-between different production cells, seamless connectivity of mobile robots with these networks ensures a dependable production. Additionally, when collaborating on a common task (e.g., multiple robots carrying a good), dependable and deterministic, low latency connectivity among the collaborating entities is the basis to ensure synchronization of actions and reactions.

6.4.1.1 Exemplary applications

In addition to interacting robots, humans are involved in different roles within the deployment and consume respective services: they might assist at certain tasks and thereby directly collaborate with robots and machinery, or they perform observation and assist in optimization of processes. Mobile robots always need to adapt their behaviour accordingly to ensure worker safety – this includes adapting movement speed, potentially halting or delaying operations, or choosing different movement trajectories. Humans thereby interact with the system both directly (e.g., through mobile or mounted HMIs) and indirectly (e.g., through their actions or presence being sensed by the system).

To ensure dependable operation of the production process, close monitoring of the network and detection of potential disturbances (e.g., caused by moving obstacles or external factors, such as jammers) is required. To detect such unforeseen situations, local AI capabilities are utilized at the edge and respective mitigation strategies can operate on a local level (e.g., within a modular production cell) by flexibly re-assigning resources based on the digital twins of the network and the applications. Mitigation involves signalling conditions to the application (e.g., automation process) to enable application-level adaptation and potentially other networks in the factory. Tracing the respective decisions and underlying measurements and sensor data for later audit is a key requirement.

6.4.1.2 System aspects

Focus are private indoor deployments in (multiple) production halls on a confined area, integrated with brownfield networks and devices. The network can span limited outdoor areas as well (e.g., used for storage of goods). Data exchanged over the network and insights into production processes used for network optimization are sensitive information that is to be kept either on premise or within an infrastructure managed by the factory operator. The environment exhibits unique factors that affect signal propagation and coverage characteristics: while antennas can be mounted on ceilings or walls/pillars, the density of static and mobile metal objects is high (e.g., storage racks, machinery, robots). The density of (mobile) devices requiring low latency and dependable, deterministic communication is high, some having increased throughput requirements, e.g., for camera-based sensors.

Usually, the 6G system is part of a diverse setup of networks and existing management and security frameworks (brownfield), requiring interoperability and integration especially in terms of local management and orchestration of compute, AI capabilities and additional resources (e.g., frequency).

6.4.1.3 Actors and interactions

As outlined above, collaboration among robots and machinery (mobile and static) and interaction of humans with these collaborating robots is at the core of this use case. Collaboration among robots (e.g., several mobile robots carrying goods, placing goods in static machinery, or operating tools) exhibits local communication patterns with stringent latency and dependability requirements, potentially involving multicasting reference signals and expected behavior from a single leader to multiple affected parties. Humans can either directly be involved in the collaborative task at hand (e.g., performing certain actions assisted by robots) or monitor and potentially repair or optimize/train the respective part of the production process. As mentioned, this interaction can be intentional and direct via HMIs (mounted to machinery or mobile, carried by the human operator) or indirect, e.g., caused by mobility of humans affecting certain decisions by the collaborating robots such as trajectories or movement speed. It is expected that airborne actors (e.g., drones) introduce additional layers of mobility and interaction in future factories. Consequently, the coordination of moving entities will need to consider all three dimensions.

For management and operation of a factory network, local IT/OT operators require insights into operating conditions of the network. AI-assisted failure detection and mitigation is expected to lower the complexity for human operators to ensure manageability of the network and ease of commissioning.

6.4.1.4 Related enabling services

This use case can be served by the following “enabling services harnessing new capabilities”: “Compute-as-a-Service for resource-constrained devices” to enable distributed decision making also on less-powerful or constrained devices, “AI-as-a-Service” to benefit from AI for the intelligent optimization of cooperative tasks, and “Flexible device type change service” to ensure changing communication requirements are met when humans and machines dynamically form collaborating groups.

6.4.2 KPIs / KVIs

KVIs and KPIs in the focus of this use case are further discussed in the following.

6.4.2.1 Extreme evolution of required location accuracy

When location information is utilized to ensure safe interaction among humans and machines, the accuracy in terms of maximum location error and the maximum latency (or age) of the location information has a direct impact on the set of realizable use cases. Further, the required frequency and accuracy of location updates for a given use case depends on the mobility characteristics of the entities involved (e.g., their maximum movement speed or their axes of freedom). Here, localization information can include the vertical axis, especially if Unmanned Aerial Vehicles (UAVs) are to be utilized, e.g., to carry lighter goods or for remote maintenance and observation tasks. In addition to focusing more on the corner cases (e.g., worst case analysis and guaranteed location accuracy and age) as foundation for safety-critical applications, scalability becomes an issue: the characteristics need to be achieved not only for a single device or human, but for a potentially large number of devices in a confined area.

An increased density of connections in a rather confined area also affects other KPIs: low latency and high throughput (e.g., for video as control input) is to be achieved at the same time for many devices within that local area, leading to a rather diverse set of KPIs for different areas of a factory floor.

6.4.2.2 New E2E measures for dependability and availability

Dependability needs to cover multiple dimensions in an industrial context: reliability and availability of the communication channel and all services offered by the network, but also resilience to disturbances and, as a consequence, achievable service continuity. New E2E measures for dependability need to take the potential for adaptation and mitigation into account, as well as the consequences of failures both in the network and within the application for the specific use case. In the use case discussed above, dependability is to be achieved at scale (i.e., for a high number of devices and applications) and in a flexible environment.

6.4.2.3 Focus on trustworthiness

6G can act as an enabler for more sustainable production, e.g., by allowing more flexible utilization of machines and closely intertwined logistics and production. Moving to flexible and highly customizable production capabilities enables a more efficient and sustainable production of highly customized and individualized products (down to lot-size one, i.e., manufacturing of fully unique single products) and enables new production capabilities by intelligently combining existing machinery to fulfil more complex tasks. The 6G system itself needs to be sustainable in that components are typically deployed and used with a long lifetime expectation in industrial use cases. Maintainability and clear update paths are required.

While 6G can act as an enabler for more sustainable production processes and a better interlinking between logistics and production, the focus is on trustworthiness of the network and its services. If production processes are coordinated in a distributed fashion utilizing AI and compute capabilities (e.g., for digital twins) offered by the network as a service, these services need to be trustworthy. The structure of a production process and data utilized in the process (e.g., utilization of machines and algorithms for efficient control) are key assets for the respective plant operator. With the 6G system acting as a sensor for localization information, as outlined above, trustworthiness becomes even more important.

6.4.2.4 New capabilities: local compute and integrated sensing/intelligence

For local and flexible collaboration among robots and humans, the assignment of resources (both, in the network and in the production process) relies on AI for continuous optimization. As mentioned above, the respective service needs to ensure trustworthy execution of the AI models, and ensure that training data and derived models remain private and (potentially) on-site. This also motivates the need for local (trusted) compute capabilities as part of a 6G system. In addition, as outlined earlier, safe collaboration of humans and machines and new HMI concepts depend on integrated sensing capabilities for accurate location information.

6.5 Dynamic and trusted local connectivity

This use case aggregates the characteristics of three use cases described in Chapter 4, in the "Local trust zone" use case family: 6G IoT micro-networks for smart cities", "Infrastructure-less network extensions and embedded networks" and "Small coverage, low power micro-network in networks for production & manufacturing").

6.5.1 Scenario

Body area networks supporting personalized health applications, machines and vehicles collaborating in a harvesting campaign, cameras and mics being connected during Program Making and Special Events (PMSE): all these examples have in common that highly reliable, trusted and partly high performance connectivity is required temporarily and often only in small local areas. For MNOs, it is usually economically not feasible to provide connectivity for these scenarios by their wide-area cellular networks. Thus, alternative dynamic and trusted local connectivity solutions are needed.

6.5.1.1 Exemplary applications

PPDR and PMSE, roadwork and harvesting campaigns typically need massive video transmissions that often require temporary local networking coverage fulfilling high and application-specific requirements. PPDR, for example, has high requirements on the deployment time (related to the *flexibility* KVI and capability) and problems with non-calibrated equipment. For PMSE, many parallel video streams are often transmitted with low compression to allow lower application latencies. Transmission is latency critical with relaxed target latencies around 50ms, however, synchronization requirements are high (below 10 ms) for parallel streams. In general, these scenarios are very dynamic and the deployment and environment can only partially be controlled.

Collaborating machines or coordinated AGVs often need local short-range connectivity built-in in order to support super-agile V2V links.

Mobile machines and any kind of vehicles need on-board communication networks or networks connecting vehicle platoons that as moving network within the wide-area networks provide high performance connectivity, seamless integration in the wide-area networks but often separate trust and security solutions. The portfolio of supported applications will comprise safety-relevant applications (e.g., emergency halt, alerts), sensitive proprietary data processing (automation control data), as well as privacy related services (e.g., on on-board humans).

6.5.1.2 System aspects

At the edge of network coverage, a temporary network coverage extension is required, for example, for providing connectivity between several agriculture vehicles during harvesting campaigns. The connectivity should remain even when the vehicle platoon is leaving the network coverage completely while still in the harvesting campaign. Here, the basic coverage is provided by wide area cellular networks. Dynamic extensions of coverage can be provided by D2D options including multi-hop, multicasting, new potentially local radio resource management evolutions of today`s solutions.

In other scenarios, temporary potentially mobile embedded networks in networks provide local zones of higher trust and higher performance based on dedicated networking nodes. Examples are trains moving in cellular wide-area networks, vehicles with their on-board networks, body area networks for body area networks and medical applications or new HMIs.

6.5.1.3 Actors and interactions

Actors are classical MNOs operating the wide-area cellular network and third parties requiring dynamic and trusted local connectivity. Note that this does not exclude the option that the MNO can take the role of the third party in some use cases as well.

In the production and manufacturing-related use case, a third party operates a group of machines or vehicles that should be mutually connected using their mounted equipment. Protecting the processed proprietary information and guaranteeing the availability of the connectivity independent of the MNO network is of great concern for this third party.

In a scenario where body area networks are used for personal health application, the third party can be a single human operating its body area network consisting of a set of sensors and their built-in connectivity equipment. Again, protecting personal and sensitive information and guaranteeing availability is a key concern.

The capability to allow exchange of information (push and pull) by interconnecting the third party network and the MNO network is crucial. It might not always be possible in both directions, if coverage of the local network is very limited, however, it has to be supported.Security regimes in the third party network and the MNO network are separate but should be compatible (e.g., via a gateway being part of both security domains). When licensed spectrum is to be used by the third party (e.g., in case of underlay networks), access to the respective spectrum bands typically have to be granted by the MNO or by a national regulator (on a temporary basis). This interaction between third party, MNO and national regulator can be automated.

6.5.1.4 Related enabling services

As this use case in based on local dynamic networking solutions in networks supporting trust and local often AI-based applications, enabling services as “AI-as-a-service", “Compute-as-a-service", and “Security-as-a-service" will define the design space.

6.5.2 KPIs / KVIs

Underlay networks and island networks in networks will reduce the capacity of the wide-area cellular MNO network (and thus requires the approval of the MNO, in case it is not operated directly by the MNO). This capacity degradation compared to the local capacity provided by the embedded network measures the quality of the network integration. More specific KPIs depend on the respective use case that is to be realized with the underlay network or the island network and are, thus, not discussed here. In general, being able to dynamically extend coverage for the respective use case is the primary goal.

The general targeted KVIs include trustworthiness and flexibility. The scenarios covered by this use case are new and are today typically addressed by specialized solutions that have to meet very high and application specific requirements (e.g., for medical devices). Supporting these applications in mobile networks will allow to improve performance and availability of these services, and it will allow to introduce innovations and add functionality, however, it will also result in an extended set of new requirements on security, privacy, availability, and safety for which metrics are not yet defined.

6.6 Deployment scenarios and associated KVIs and KPI: Summary

This section has provided information on deployment scenarios and associated KPIs/ KVIs for a subset of representative use cases, one for each use case family. The relation with the use-case enabling services has also been highlighted. Figure 6-1 summarizes these relationships.

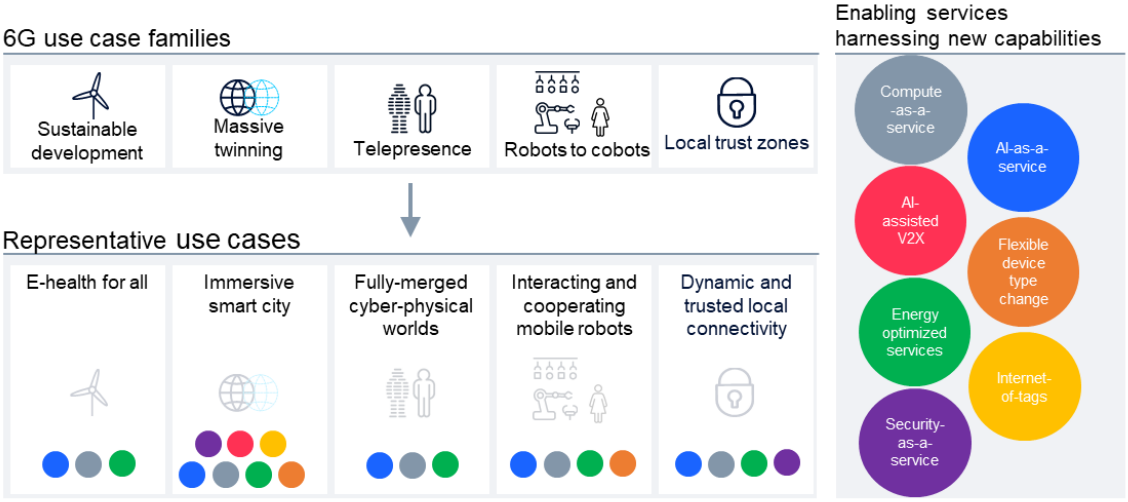

Figure 6-1: ***Reference use cases and relationship with enabling services harnessing new capabilities***

In addition, key values and KPIs identified in Chapter 5 were mapped to the selected use cases. The resulting coverage of KVIs/KPIs is summarized in Figure 6-2, indicating the core focus of each use case.

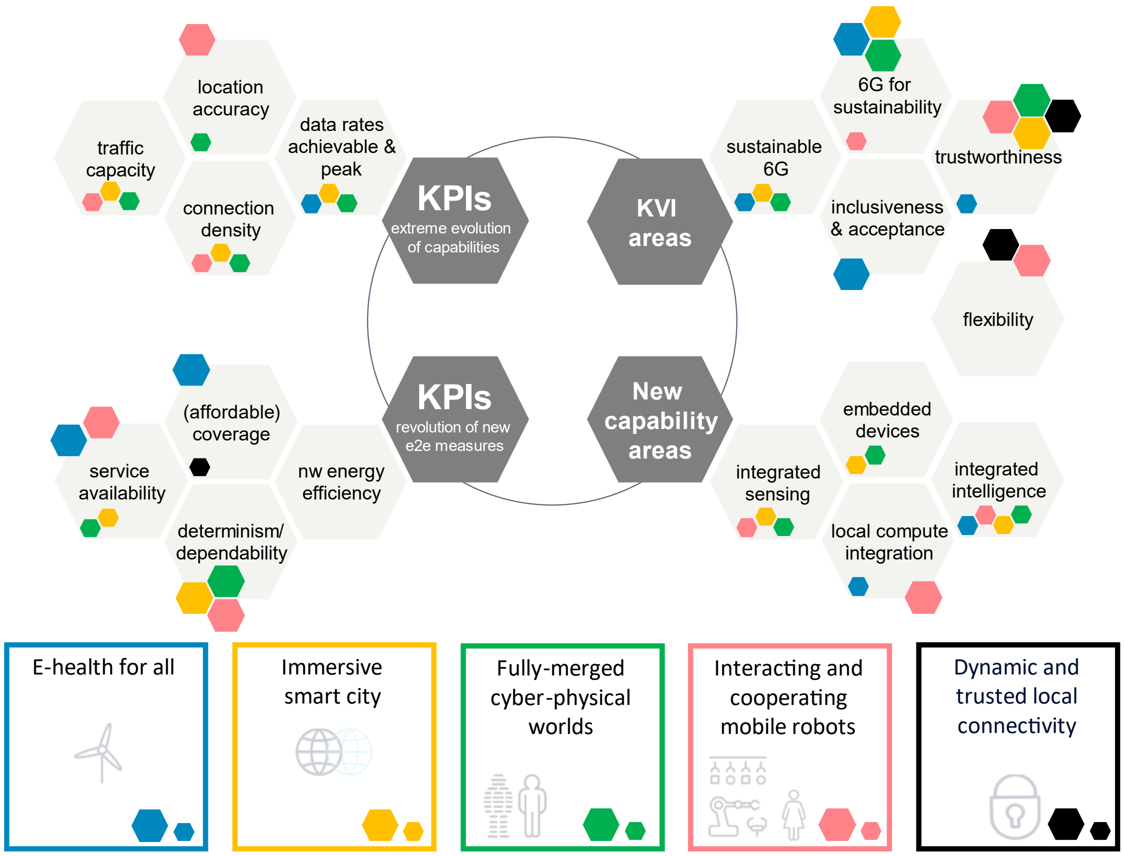

Figure 6-2: ***Mapping of selected use cases to KVIs/KPIs and new capabilities. Large hexagons indicate the core focus KVIs/KPIs for the respective use case.***

Sustainability and trustworthiness are core values for most use cases, with integrated sensing and integrated intelligence acting as an enabler. New end-to-end KPIs for determinism/dependability and service availability are required for the selected set of use cases. Network energy efficiency is not mentioned as core target of the use case, even though sustainable 6G is targeted to some extent. This does not come as a surprise, as network energy efficiency is more related to the targets of technical workpackages in Hexa-X and not a specific focus of a top-down use case description.

7 Spectrum evolution aspects

7.1 Improving spectrum utilization

Bands in the low, mid, and millimeter wave (mmw) ranges or combinations thereof will be utilized with THz spectrum to provide various types of wireless links with different bandwidths and beam-propagation characteristics that satisfy the wide range of service requirements of future wireless systems.
Spectrum resources under 6 GHz will continue to be pivotal to support wide radio coverage. Developing further intelligent spectrum access systems, in particular for newly available spectrum resources in higher bands, will be highly beneficial to improve spectrum utilization by dynamically assigning frequency resources to the various authorised subsystems on both a time and geographical basis while preventing interference issues.
The spectrum range currently not available for mobile communications in 6-24 GHz can also be utilised for 6G provided that methods are developed for sharing with the current users. As an example, Figure 7-1 below shows the allocations in Europe [EFI20] indicating that numerous frequency bands could be investigated for efficient shared usage.

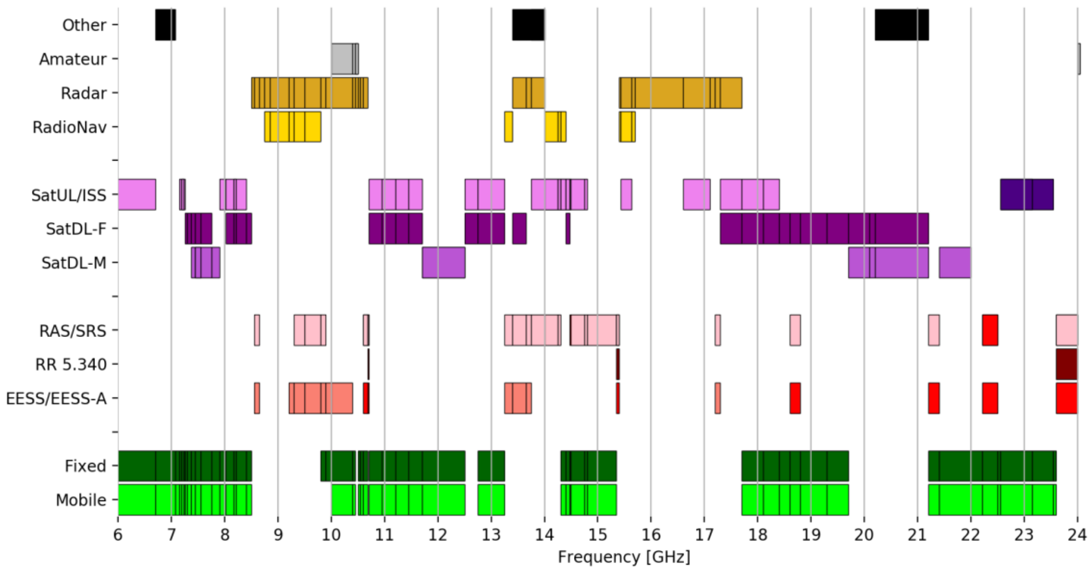

Figure 7-1: ***Overview of spectrum allocations in Europe between 6-24 GHz.***

Implementing AI engines distributed throughout the whole network (devices, radio access network, and core network) capable of avoiding spectrum usage collisions among different users will be a key component for the expected full success of dynamic spectrum management systems. Additionally, new regulation and licensing strategies suitable for dynamic spectrum sharing are also required.
In particular, access to appropriate spectrum resources is in Hexa-X an inevitable prerequisite for many of the use cases considered. Although many of the scenarios will be supported with the classical cellular network structures using spectrum licensed to mobile network operators, while some use cases, deployment concepts, and new radio links will also benefit from the possibility to access spectrum resources under other conditions. In addition, the demand for more mobile services and applications drives the demand for spectrum and results in a need to increase the spectrum usage efficiency.

On the other hand, Hexa-X will develop solutions to support more intelligent systems and spectrum usage modes.

For instance, the further development of technical enablers such as AI network functions will help to make the networks smarter providing the means for more efficient handling of interference and coexistence problems. In addition, the introduction of distributed ledger technologies such as Blockchains will provide a possible enabler flexible spectrum management and supporting regulatory requirements in an automated mode.

A number of challenging spectrum usage scenarios are envisaged to be studied in more detail in Hexa-X requiring intelligent spectrum usage and interference management schemes, e.g.:

- Nomadic, mobile, or temporary spectrum usage: various use cases require dynamic reconfigurations (on-off switching of base stations or frequent dynamic re-deployments). For instance, road construction work, harvesting campaigns, sport events, PMSE often require local and only temporary connectivity, while others, such as drones, vehicles, trains, and ships using on-board connectivity solutions or providing coverage to others, require support of nomadic cells.
- Spectrum access for local low power networking: very low power underlay networks might be solutions in various industrial connectivity scenarios, where, e.g., manufacturers of large machines (up to several hundred meters in length) and vehicles want to integrate these solutions inside their machines using spectrum in controlled interference conditions. Body area networks and “other networks in networks” also represent scenarios where local low power networking is suitable as well.
- Exploitation of predictable properties of radio transmissions for AI-based interference avoidance: exploiting such properties would facilitate interference avoidance even between transmissions of independent systems. For example, predictable properties of radio transmissions are peculiar in industrial and IoT scenarios, where radio usage often shows periodic and poly-cyclic transmission patterns.

7.2 Extending spectrum boundaries

In 5G NR (New Radio), current 3GPP core specification supports operation up to 52.6 GHz and the first step towards the extension of operating spectrum beyond 52.6 GHz is under development for 3GPP Release 17, with target finalization in September 2022.

Extending the usage of frequency bands will provide a promising opportunity for addressing 6G service requirements and achieving both enhanced and novel applications, e.g., precision positioning and sensing applications and wireless power supply technology for e.g., for energy harvesting.

As an initial effort to enable and optimize 3GPP NR system for operation in spectrum above 52.6 GHz, 3GPP RAN has studied requirements for NR beyond 52.6 GHz up to 114.25 GHz in various potential use cases spanning over several deployment scenarios. As part of 3GPP Release 17, spectrum support will be extended to up to 71 GHz [38.808], as frequencies between 52.6 GHz and 71 GHz are especially interesting in the short term because of their proximity to sub-52.6 GHz for which the current NR system is optimized and the imminent commercial opportunities. The extension will include the introduction of one or more new numerologies (i.e., larger subcarrier spacings to reduce the device complexity) and procedures for operation in licensed spectrum and unlicensed bands between 52.6 GHz and 71 GHz.

In addition, both industry and academia have already expressed interest in pushing technological boundaries in wireless communications even further to develop new equipment and applications that could operate in higher frequency bands.

The emerging interest in opportunities for innovation in the spectrum above 95 GHz, especially for data-intensive high-bandwidth applications as well as imaging and sensing operations, has been, for example, recognized and initially accommodated by FCC by establishing rules ("Spectrum Horizons Licenses") for authorizing communications above 95 GHz to encourage new opportunities for innovators and experimenters to develop new equipment and applications for spectrum between 95 GHz and 3 THz [FCC18]. In addition, a total of 21.2 GHz of spectrum has been made available for use by unlicensed devices in four frequency bands (i.e., 116-123 GHz, 174.8-182 GHz, 185-190 GHz, and 244-246 GHz) with suitable propagation characteristics that would allow large unlicensed use, while limiting the potential for interference to existing governmental and scientific operations in the above-95 GHz bands, such as space research and atmospheric sensing.

In Europe, for example, the EC Horizon 2020 ICT-Call-09-2017 on Networking Research beyond 5G launched a research and innovation action [EC16] to bring little explored technologies and system concepts closer to exploitation, including "perspectives for the full exploitation of the spectrum potential, notably above 90 GHz, with new waves of technologies and knowledge, bringing wireless systems to the speed of optical technologies, and for new applications".

Studies to identify the most suitable frequency ranges for e.g., what application, use case, and deployment scenario and overcome the related technical challenges are at their initial steps in a process that at a proper stage will properly involve spectrum regulation. The frequency ranges under consideration include the frequencies in the W-band (above 91 GHz), D-band (120 GHz to 170 GHz), bands between 275 GHz and 300 GHz, and in THz range (0.3-10 THz).

Today, allocation of the bands above 71 GHz to 5G systems is not done yet and it is important to start, as early as possible, the identification of candidate bands which will be optimal from a technological point of view, while at the same time answering to the needs in the most promising and highly desirable verticals applications and use cases.

7.2.1 Spectrum allocations above 52.6 GHz

Hexa-X will also study scenarios where the 6G spectrum usage is extended to new frequency bands, particularly in the range from 52.6 GHz to about 300 GHz.

There are a few previous studies done to investigate the status of the bands above 52.6 GHz. The most relevant studies have been carried out by 3GPP in preparation for upcoming standardization: [38.807] and [38.808].

In Europe, allocations of frequency bands above 52.6 GHz [EFI20] are depicted in the following figures, noting that such allocations are nearly identical in the other areas of the world thus providing good opportunities for harmonization. For clarity, some of the services are grouped under the same heading to make the figures easier to read. The exact grouping is outlined in Table 7-1 below.

Table 7-1: ***Different services and corresponding grouping***

Heading	**Services**
Mobile	Mobile, Mobile except aeronautical mobile
Fixed	Fixed

EESS	Earth Exploration-Satellite (passive)
EESS-A	Earth Exploration-Satellite (active)
RAS	Radio Astronomy
SRS	Space Research (passive), Space Research, Space Research (active)
SatDL-M	Mobile-Satellite (space-to-Earth), Broadcasting-Satellite, Broadcasting, Mobile-Satellite
SatDL-F	Fixed-Satellite (space-to-Earth), Space Research (space-to-Earth), Earth exploration-satellite (earth-to-space)
SatUL	Fixed-Satellite (Earth-to-space), Mobile-Satellite (Earth-to-space)
ISS	Inter-Satellite
RadioNav	Radio Navigation, Radio Navigation-Satellite
Radar	Radio Location
Amateur	Amateur, Amateur-Satellite

The range between 50 and 90 GHz [EFI20], depicted in the Figure 7-2 below, contains the fixed service E-Band (71-76/81-86 GHz), the license-exempt spectrum from 59 to 66/71 GHz (depending on geographic area regulation) as well as the automotive radars in the 77-81 GHz band.

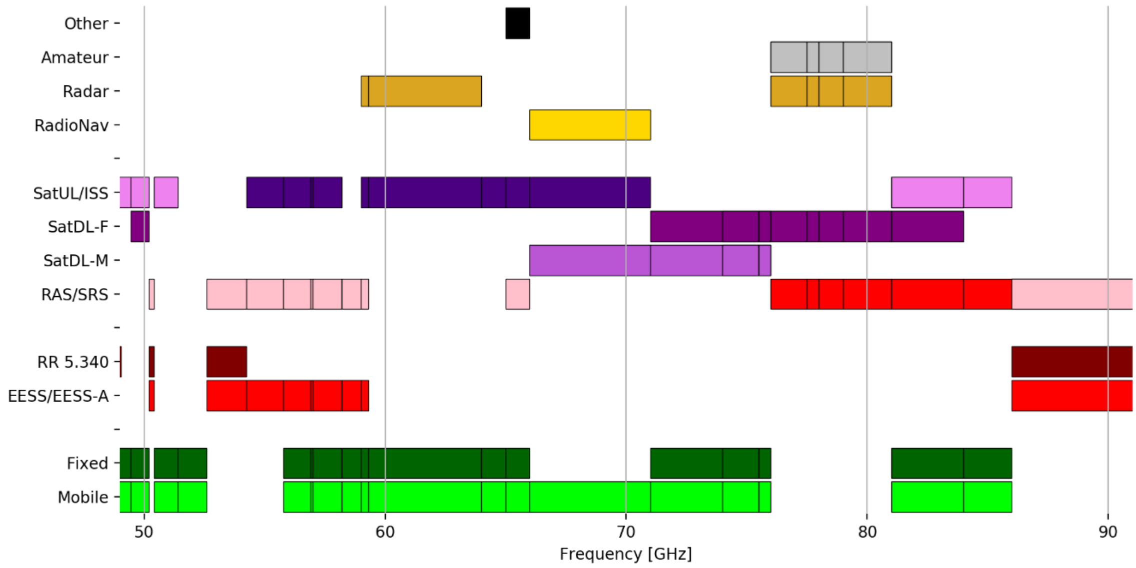

Figure 7-2: ***Frequency allocations' overview in the 50 – 90 GHz frequency range***

The allocations for the range 80-180 GHz [EFI20] are outlined in the Figure 7-3 below. The main thing to note is the segmentation of the Earth Exploration Satellite Service (EESS) allocations which limit the amount of continuous spectrum possibly available. Additionally, spectrum has been allocated to fixed service and regulatory studies on channel arrangements are ongoing where two future fixed service bands can be found, the W-band (90-115 GHz) and the D-band (130-175 GHz).

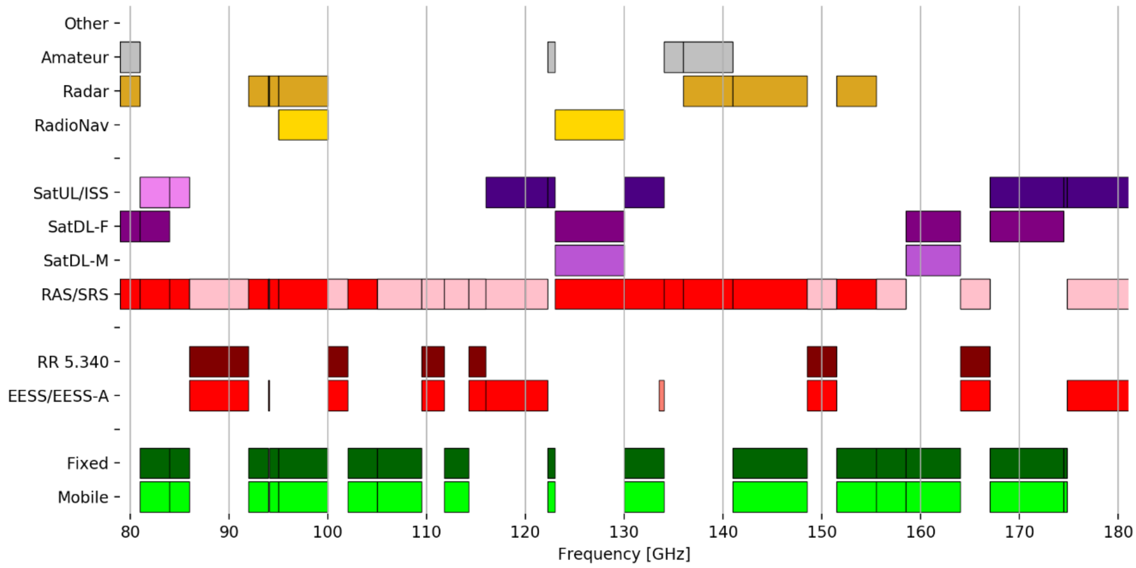

Figure 7-3: ***Frequency allocations' overview in the 80 – 180 GHz frequency range***

The allocations for the range 140-275 GHz [EFI20] are outlined in the Figure 7-4 below. The situation is similar to the previous range with several allocations for EESS (passive) and radio astronomy.

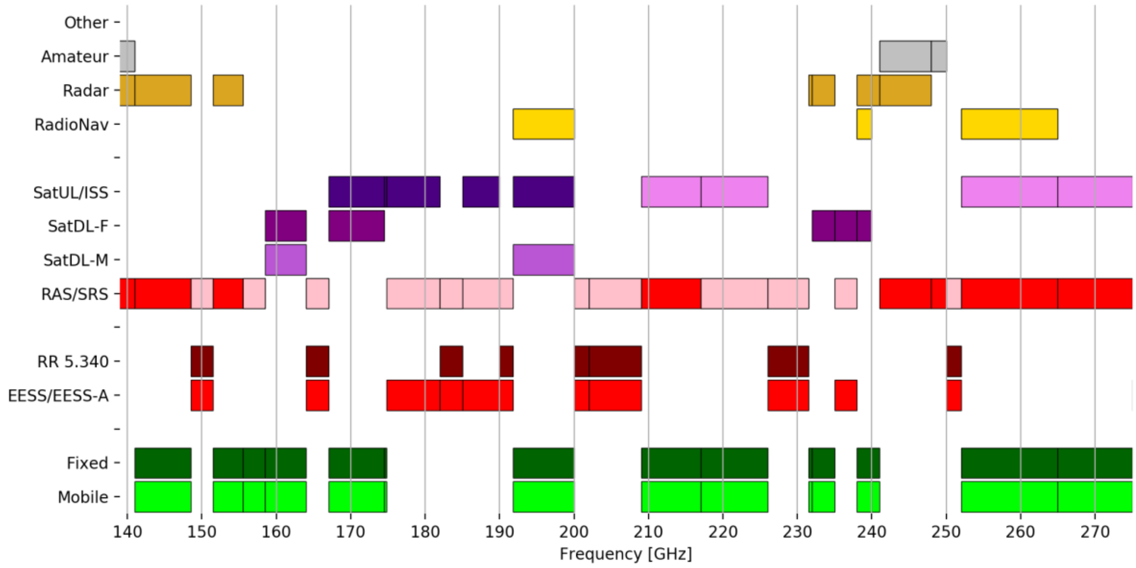

Figure 7-4: ***Frequency allocations' overview in the 140 – 275 GHz frequency range***

Currently, spectrum allocations generally stop at 275 GHz worldwide, however frequency bands have been identified in the range 275-450 GHz for the implementation of land mobile and fixed service applications and for radio astronomy and Earth exploration-satellite service and for space research service in the range 275-1,000 GHz. The frequency bands allocated in these new frequency ranges are illustrated in the Figure 7-5 below [ITU20d].

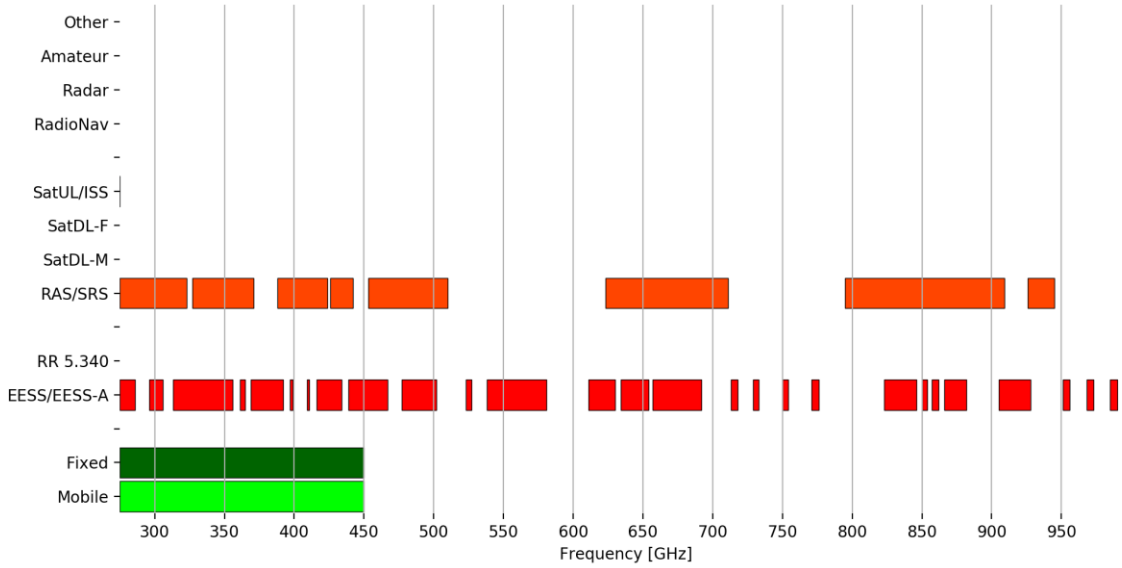

Figure 7-5: ***Frequency allocations' overview in the 275 – 1,000 GHz frequency range***

8 Sustainability Targets

8.1 Sustainability from a 6G perspective

As mentioned in the section on Hexa-X vision, today´s society faces major challenges, including in particular the pandemic, distrust and global warming, which all need to be addressed while creating innovation-led opportunities for economic prosperity and job creation in a circular, green and digital economy.

Sustainability, both a main research challenge and a core value of Hexa-X, is a holistic concept covering environmental, social and economic aspects, and it is built around meeting the needs of the present without compromising the ability of future generations to meet their own needs. From a 6G perspective, as outlined in Figure 8-1, this refers both to the sustainability of 6G itself (Sustainable 6G), and the opportunity for 6G to support society and stakeholders across all sectors of the economy in getting more sustainable (6G for sustainability). For Hexa-X this means that the project needs to apply a double lens when looking at sustainability: first the project needs to understand and minimize the direct impact of 6G during its life cycle, second it needs to consider 6G as a key enabler for sustainability and enlarge opportunities – and suppress risks – related to the use of 6G.

Focusing first on the direct impact it encompasses environmental impacts connected to the use of energy and materials, but also social impacts associated with e.g., transparency, traceability and respect for human rights. From 6G for sustainability perspective, Hexa-X need to consider a wide range of environmental, social and economic aspects as outlined by the UN SDGs – the main recognized framework for sustainable develop - which is further addressed in Section 8.2.

Regarding sustainability, even if the current contribution of the ICT sector to the total carbon footprint of the society is limited (estimated to 1.4% [ITU20a], [ML18] of overall global emissions), the increased use of digital solutions will likely require densification of network capacity and manufacturing of more devices (including IoT devices) which could lead to an increase of overall emissions unless energy efficiency continues to be addressed together with behaviors and the transition to renewable electricity supply. Supporting this, ITU, GSMA, GESI and SBTi have jointly developed trajectories which establish that the ICT sector should reduce its environmental footprint by 50% between 2015 and 2030 to decarbonize in line with a 1.5 °C trajectory in support of the Paris Agreement [ITU20a].

Referring to the same sources, It is interesting to note that in 2015 globally, the energy consumption from using devices represented more than 40% of the ICT power consumption while networks and data center shared the remaining consumption roughly equally between them. From a carbon emission and life cycle perspective, devices again dominate and represent more than half of the overall emissions, while networks represent around 25%. Overall, the majority of networks and datacenter emissions are associated with the use stage, while for devices use stage and embodied emissions require as much attention. However, this balance looks different for other impact categories so it is important to consider environmental impacts of the full life cycle also for networks and datacenter (including aspects such as life time, recyclability, materials efficiency etc).

The ICT sector in general, and the mobile sector in particular, has spent more than a decade improving its efficiency through hardware optimization, material novelties and sleep modes innovations. This helped maintaining the ICT sector energy consumption stable while the traffic increased by +40 to 100% per year in the same period. Despite stable energy consumption it is possible to reduce the carbon footprint via selecting the source of electricity. Trends in Europe and all over the world are now moving towards an ecological transition of all the sectors (agriculture, education, transport, industry, etc.) and ICT as a carbon lean sector has a crucial role to play to address this challenge. However, there is a wish to educate consumers to make them aware of the environmental impact of different activities including that of digital services. To move in this direction the French regulator ARCEP is developing a Green Barometer [Arc20]. Once this barometer and its parameters are known (end of 2020), Hexa-X should evaluate the applicability for Hexa-X and 6G and the opportunity to build on top of it to derive recommendations to end-users to reduce the life cycle impact associated with digital services running on the 6G system.

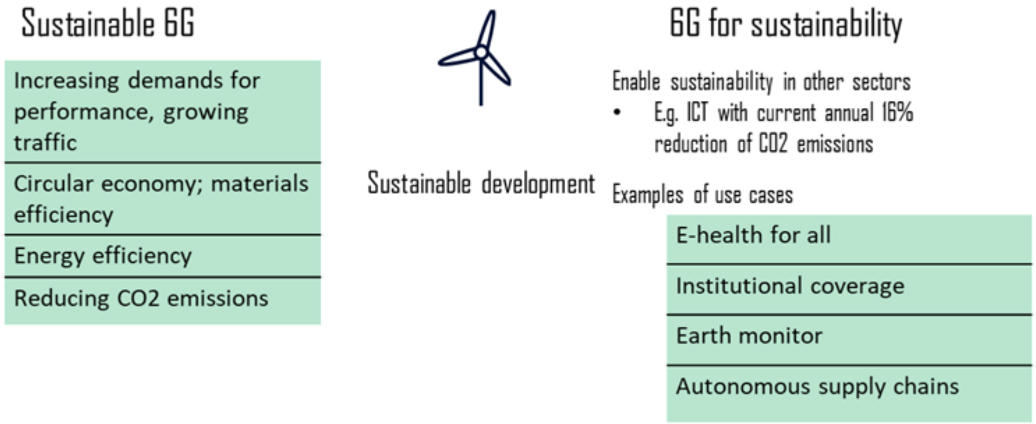

Figure 8-1: ***Sustainable 6G and 6G for sustainability***

8.2 United Nations Sustainable Development Goals (UN SDG)

The United Nations have agreed on 17 sustainable development goals “as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. The UN SDGs were introduced in 2015 to address key global challenges, such as climate change, poverty, inequality, environmental degradation, peace and justice [UN15]. There are 17 goals included in the Agenda 2030, which together with the related 165 targets and 231 individual indicators form an action plan for achieving the goals. Moreover, within its COVID-19 response, the UN state that: “The crisis has accelerated the digitalization of many businesses and services, including teleworking and video conferencing systems in and out of the workplace, as well as access to healthcare, education and essential goods and services. […] It has never been more important to bridge the digital divide for the 3.6 billion people who remain offline”.

Prior work on the connection between ICT and the UN SDGs has concluded that there is a linkage to all 17 SDGs [GSM18]. Although the UN SDG indicator framework only identifies seven of the indicators that directly measures the prevalence of, the role of ICT in the achievement of the SDGs is more significant. Mobile communication industry’s contribution to the achievement of the UN SDGs is usually considered at three levels: 1) the deployment of infrastructure and networks forming the foundation for the digital economy, 2) providing access and connectivity allowing people to use mobile communications, and 3) by enabling life-enhancing services and relevant content for people [GSM18]. Most recently, the connection between 6G and the UN SDGs was studied in [MAA+20], stressing that the developed 6G technology itself should be sustainable and used in a sustainable way. This is in line with addressing Sustainable 6G as well as 6G for Sustainability. Although the SDGs are defined for 2030 which will be early days for

6G, the framework as such and the different areas it encompasses will remain relevant also in the 2030s.

There are many examples of how the mobile communications could contribute to the achievement of the UN SDGs. In SDG #3 “Good health and well-being”, the UN aim at “ensuring healthy lives and promoting well-being at all ages […]”. This can be partly addressed by deploying sensors that are permanently monitoring several biometric parameters, such as blood pressure or heartbeat, to optimize the efficiency of emergency services whenever a threshold is crossed, for example. Autonomous cars facilitate the mobility of people who cannot drive, thereby reducing inequalities (SDG #10) and improving transportation conditions (e.g., by minimizing the risk of car accidents). ICT solutions could limit the energy consumption of the automotive industry. In SDG #12, the UN address the responsible consumption and production. For the ICT sector, this represents a real opportunity to turn digital into a tool to support sustainability for other sectors. Indeed, future 6G networks can help reduce the carbon footprint of multiple areas, including industry and transportation, thanks to increased dematerialization with new digital business models, such as sharing economy, smart working opportunities as well as applications to improve production efficiency and supply chains.

The availability of affordable and clean energy (SDG #7) is a goal underpinning most of UN SDGs. According to the data published by the UN [UN20], as of 2018, 789 million people lack electricity while the share of renewable energy in the total energy consumption was only 17% in 2017, a small percentage with respect to the use of fossil fuels. The ICT sector can contribute to this goal by increasing both the energy efficiency of ICT-related operations and the share of energy from renewable sources, as well as contributing to the deployment of advanced and more efficient energy infrastructure.

SDG #13 calls for urgent actions to combat the climate change and its impacts also beyond renewables. Climate change is responsible for increasingly more frequent and more severe natural disasters that affected more than 39 million people in 2018 [UN20a], not to mention the associated economic losses. 6G can enable both the global monitoring of the climate change as well as strengthen resilience through forecasting and early warning systems [ITU21b]. In addition, 6G can contribute to the reduction of greenhouse gas emissions (that are the main responsible for the climate change) by enabling other sectors to reduce their own greenhouse gas emissions, thanks to applications such as smart traffic, smart cities management, smart working, and precision agriculture [MAA+20], but it needs also to be mindful about its own impact. It is noted that goal 13 on Climate Action is not particularly elaborated. This is due to the Paris agreement being the main UN process to drive decarbonization. Specifically, for the decarbonization of the ICT sector, ITU [ITU18a], GSMA, GESI and SBTi have developed trajectories which shows that the sector needs to roughly halve its emissions by 2030, and continue to decarbonize in the same rate towards net-zero latest 2050 in the existing processes [ITU20a], [SBT18].

Mobile networks must be considered an essential infrastructure due to its capacity to empower industry and innovation [ITU21c]. 6G must therefore contribute to SDG #9 on “Industry, Innovation, and Infrastructure”: more than four billion people still do not have access to the internet, and 90% are from developing countries. Bridging this digital divide is therefore crucial to ensure an equal access to information and knowledge, as well as to foster innovation and entrepreneurship [UNP20].

An increasing number of people live in cities, and the number of mega-cities is raising, as well as the share of population living in slums. SDG #11 calls to actions to make cities and human settlements inclusive, safe, resilient and sustainable, and ICT sector can play a unique role to achieve this goal by enabling innovative approaches to cities management via applications such as smart water and waste management, and intelligent transport system [ITU21d]. Also, ICT can

encourage workers to stay in rural areas by exploiting smart working and improved collaborative systems [MAA+20].
However, the attention should not be restricted only to a subset of the UN SDGs, since it is possible to positively contribute to the achievement of the specific targets within all 17 goals.
In fact, the UN Global Sustainable Development Report [UN19] has identified six cross-cutting factors relevant to all SDGs, which are critical to successfully achieving the Agenda 2030 including obstacles to human well-being and capabilities, sustainable and just economies, food systems and nutrition patterns, energy decarbonization with universal access, urban and peri-urban development and global environmental commons. These cross-cutting factors should be considered when addressing any of the goals, because the advancement of one goal may advance other goals but may also have adverse effects on others.

8.3 Sustainable 6G

8.3.1 An operator point of view

Hexa-X project presents 6G as the technology to connect three worlds and revolves around their interactions: a human world of our senses, bodies, intelligence, and values; a digital world of information, communication and computing; and a physical world of objects and organisms. To reach its ambitious objectives, 6G needs to be a sustainable technology in itself to become the key tool for making other sectors more sustainable.
Moreover, 6G will have to meet all the expectations on sustainability that end-users will have on new technologies, based on 5G experience. From previous generations, we have seen that energy efficiency is not enough and that other sustainability requirements are gaining in importance. Consequently, some of the following items are of paramount interest for network operators in the design of future networks and in the conception of 6G:

- **Overall energy consumption reduction**: 6G should be designed to reduce absolute network energy consumption and the associated carbon emissions, as well as to reduce the energy consumption per transported bit. The continuous traffic growth delivered by telecommunication networks could lead to an increased need for energy. It is thus necessary to counter this development by adopting advanced technologies that are intrinsically more energy efficient, and by optimizing the energy performance of the overall network.
- **Embedded energy monitoring systems and sites management in order to optimize and adapt energy consumption to traffic flows and system activities**: This would allow to optimize the end-to-end energy efficiency behavior. To do so, new techniques of energy efficiency should be included in all the network sections in order to have zero consumption at zero load. In addition, the ability to perform efficient management of sites needs to be considered when rolling out 6G, i.e., energy consumed for cooling needs to be substantially reduced, as well as use of efficient powering, use of AI for site energy optimization, decommissioning out of service equipment, etc.
- **Adaptive protocols:** The constant part of the energy consumption of network is mainly driven by the signaling part that is periodically transmitted to ensure the coverage and to maintain the service. Communication protocols are configured to meet the minimum requirements of the most stringent service in terms of latency and reliability. Hence, adaptive protocols appear as promising measures to allow more flexible and energy efficient transmission that avoid permanent and “always-on” infrastructures. This way the network would be able to answer to the demanding real time applications in an energy efficient way.
- **Increasing the share of renewable energy**: It is necessary to substantially increase the share of energy from renewable sources. This could be addressed through PPAs (power purchase agreements), but - technically more relevant - also through self-produced energy e.g. photovoltaic plants, trigeneration plants, and investigating possible new sources for self-production. Overall, more compact and efficient renewable energy supply solutions

are to be developed to power 6G sites. In particular, a higher degree of integrations between site power supply and the electrical grid is foreseen, as electricity storage becomes more critical,

- **Use of materials**: In addition to network energy savings initiatives, the 6G architecture should also consider eco-design principles in its design in order to reduce the environmental footprint linked to hardware manufacturing, its distribution around the globe and its end-of-life treatment. A first step toward this goal should be a more systemic assessment of the environmental impacts of the different materials or of the design choices at all levels in line with the principles established by ITU-T L.1410 [ITU14] and ETSI EE ES 203 199 [ETS15]. In addition to this assessment effort, that has to be carried out in the early stages of 6G development, the architecture should also be built based on the circular economy principles, in order to ensure that the material used is optimized and losses at end-of-life stage are minimized.
- **Equipment and consumer products**: The use of energy and materials associated with equipment, including products offered to cosumers, need to be carefully considered throughout the entire life cycle, from the design, through production, and up to the end-of-life management. Multiple facets have to be considered, such as having equipment that are easier to repair thanks to, for example, a design based on more removable and reusable fasteners instead of gluing or welding parts together; equipment with better capabilities to be upgraded through the use of standardized connectors derived from server's architecture or that include larger proportions of recycled materials, be it polymers or metals. For this aim several methods have been developed recently to measure these different factors, such as the Cenelec standards (EN 4555X series) with for example the EN 45554 [Cen20] on the assessment of the ability to repair, reuse and upgrade energy-related products or the ITU-T recommendation L.1023 [ITU20c] which proposes a synthetic method to assess the circularity score of any ICT equipment.
- **Waste**: The obsolescence of ICT-related products is quite rapid and calls for increased commercial life time, circular approaches and an effective management of technological waste. Devices for 6G products should be designed in a way that allows extensive life extension and for systematically applied refurbishment which should be offered by vendors together with a quality certificate in order to guarantee the possibility of reusing equipment as much as possible. In addition, products at the end of life or faulty need to be properly handled in order to guarantee recycling of components and raw material recycling.

Regarding the role that 6G will play in making other sectors more sustainable, Hexa-X project intends to develop many use cases and applications which will contribute to the UN SDGs. These use cases encompass several sectors which are relevant to operators: industry, agriculture, smart cities, etc. In this sense, 6G could affect in a direct way other SDGs such as the goal 11- Sustainable cities and communities and goal 9- Industry Innovation and infrastructure. Operators need thus equilibrate a complex equation where on the one hand they invest to build new infrastructures and provide new devices which will on the other hand induce an environmental impact. 6G will therefore have to compensate its direct life cycle impacts by generating gains that counterbalance these. The good news is that after a decade of racing towards high data rates and high-resolution video, the trend is now increasingly towards sustainability and how ICT industry will follow this societal transformation. The ICT usage overall (including also data center and user devices) represent around 3.8% [ML18], [ML18a], [FGB+20] of overall electricity usage and 1.4% of carbon emissions: while it is projected to allow to avoid about 15% GHG emissions for other sectors [FGB+20].

Finally, 6G and future networks should offer new techniques to evaluate and monitor energy consumption per service and not only per hardware system. This requirement would help operators for assessing energy efficiency per provided service to support other sectors and B2B customers. For this reason, operators are also seeking for solutions and application that allow detailed energy monitoring of services.

8.3.2 Almost zero watt @ zero load

In recent years the mobile industry has experienced a real change from the sustainability point of view. Indeed, a great effort has been accomplished during the last decade that brings benefits to actual devices and infrastructure [MKC+19], [HER+15]. It is also fair to say that this paradigm change, which is radically transforming the ICT industry, has not been initiated by a need to answer to the environmental challenge alone, but more basically due to two practical reasons: on one hand the growing demand for equipment autonomy and on the other hand the technological coverage expansion to developing countries with no or limited electrical infrastructure. Drivers also include TCO and the physical footprint. The 6G, embraces ambitious objectives and use cases. To achieve these targets, 6G should reduce latency, improve the communications reliability, have longer battery life for devices and higher user bit rates. All this with a drastic enhanced energy efficiency which will enable 6G systems to consume much lower energy than legacy mobile networks consume today. 6G needs to be designed right from start to consider sustainability and responding to UN SDGs United Nation sustainability goals.

In this section, we address the sustainability aspect in terms of energy requirements for hardware components of 6G networks. From a practical point of view, efforts should focus on access networks as they are responsible of 70% to 80% (e.g., celtic OperaNET project, FP7-Earth project) of the total mobile network energy bill. Recent research studies have shown that the base station power consumption is composed of two parts: 1) fixed processes not scaling with load, such as control signaling, backhaul infrastructure, and the load-independent consumption of baseband processors and 2) transmission processes linearly varying with the traffic above a certain fixed consumption, such as transceiver chains, coding and decoding and channel estimation and precoding.

Figure 8-2: ***Zero watt @ Zero load principle***

As shown in Figure 8-2, power models for next generation networks should evolve in such a way that the integration of new techniques and more power proportional components (like Gallium Nitride [DDL15] material and envelope tracking [SMA+19] and sleep modes techniques [SOI19], etc.) should accelerate the green transition and achieving “almost zero watt at zero load” systems. The energy reduction at high loads should also benefit from “focusing” technics that allow to transmit only towards the end user during their usage time. This will substantially reduce the energy spread in space and in time.

Nowadays, research focuses on decreasing the power consumption at minimal load, which is the straightforward way to make mobile networks greener, as presented in Figure 8-2. Notably, advances in hardware during the last five years have allowed shifting this level from 80% of the total base station (BS) consumption to less than 50% for the newest technology. Thanks to that, current power models have 50% fixed consumption and 50% that scales with the load. Furthermore, software advances, i.e., sleep mode, allow to decrease an extra 10%.

Power demands of a BS change with the change of the cell traffic load. On one hand, as the cell traffic load increases, the power amplifier (PA) progressively becomes the most energy consuming BS component. On the other hand, in no traffic load scenarios, the radio base station power demands are mainly attributed to digital intermediate frequency modules. It is notable that in no traffic load scenarios and in between control signaling transmissions, BS parts consume energy even though there is no need for transmission. Thus, the opportunity arises to reduce unnecessary radio BS energy consumption by progressively deactivating components when they remain unused. .

The idea of shutting down components of a radio BS is already present in 4G/5G. Micro-discontinuous transmission (μDTX) was used in the LTE as an energy saving scheme on the radio BS side [FMM+11]. According to μDTX, the PA is shut down at symbol level, for at least the duration of a symbol and for multiple repetitions as long as there is no data to transmit to user. As the PA is an energy consuming BS component that has no utility during transmission inactivity, energy saving prospects on the BS side from this feature are important and with no impact on the user side. Nevertheless, important gains in energy savings could be achieved with the design of more sophisticated and comprehensive sleep modes, e.g., deep sleep mode, which would require a change in the air interface i.e., duty cycle, frame structure, etc. This could be possible with the new air interface design in 6G.

8.3.3 Software features for energy efficiency

Due to environmental, as well as economic, concerns the energy consumption in wireless networks has been the topic of a lot of research. The increasing complexity and requirements of the networks have made the development of energy reduction methods more urgent. Energy efficiency can be calculated as the energy consumption of a system per bit capacity, as introduced in [SCA+19] or other forms as given in [YTE+17]. Software features have been continuously developed during the last decade to reduce the energy consumption of radio systems while maintaining the same quality of service.

A series of features, going from 2G to 5G, have been developed by the mobile industry and have induced between 2 and 10% power consumption reduction in mobile networks per feature, depending on their activation time and the evaluation method (i.e., at the site level or at the base station level). Those features range from carriers fast sleep mode, to complete shutdown or MIMO muting in some situations. For example, Advanced Sleep Modes (ASM) enables to shut down components of the base station in gradual levels. Depending on the delay caused by the deactivation and reactivation of components as well as the gains in energy efficiency, the optimal sleep policy is determined [LAC+13] without triggering any considerable QoS implications. At periods of zero traffic load, Base Stations can be completely deactivated, substantially reducing consumption, but also inducing the latency overhead of reactivation. Today, such features are largely adopted by mobile carriers and future 6G should continue in the same direction.

Another approach is using AI/ML techniques to achieve network efficiency, tackling needless over-provision and avoiding unnecessary power consumption when the traffic load does not compel it. Hence, the application of machine learning techniques in the 5G network to enable energy efficiency at the access, edge and core network has gathered a lot of interest [EET20]. The allocation of the system radio resources aiming to maximize the energy efficiency rather than the throughput has been shown to provide substantial energy efficiency gains at the price of a moderate throughput reduction.

8.3.4 EMF aware networks

The radio access network optimization aims at mitigating interference, leading to lower RF emissions and/or higher capacity/quality. Optimization is a specific network design goal and several features have been developed to achieve this goal. Beamforming is one of these features since it confines the power in the direction of the UE, and it is one of the features in 5G networks. Therefore, the objectives for operational efficiency and sustainability also lead to lower EMF emissions.

However, some public concern regarding EMF exposure remains within Europe, with specificities regarding countries [EC10] , and some countries, regions or cities have adopted EMF exposure limits or policies which are more stringent than the science-based ones recommended by international organizations (ICNIRP) and the European Commission (Council Recommendation 1999/519/EC). Even if no adverse health effects have been established based on decades of research on EMF exposure from mobile communication equipment, this concern may have an impact on users/citizens acceptability of new wireless technology. This is particularly the case during the roll out of a new generation of mobile network infrastructure, since the general public typically have limited knowledge about the new technology.

International standardization organizations (ITU and IEC) have developed methodology and published recommendations on how to accurately assess the EMF exposure from base stations (BS) and user equipment (UE) that use advanced antennas and new frequency bands [IEC17], [IEC19]. Academic organizations, equipment providers and governmental agencies have also evaluated the actual EMF exposure from such equipment [JGC+20], [CA1810].

In general, to effectively address the EMF aspects it is necessary to take them into account from the system design to the network planning, optimization and operation phases.

In order to obtain information for stakeholders (governmental agencies, scientific community) an EMF-aware network should be able to store relevant parameters that would make it possible to perform trustworthy assessments of the EMF exposure both for the downlink (exposure from BS) and uplink (exposure from UE). This kind of feature could be activated in order to analyze EMF impact of specific new usages or newly deployed technologies or simply to provide monitoring trends in order to report actual exposure levels to stakeholders.

8.3.5 AI for energy-efficient and resilient networks

There is a growing interest on machine learning for wireless networks, which can significantly contribute to the reduction of the overall cost of wireless networks related to energy consumption and, therefore, make them more sustainable. The main goal is to increase the efficiency of the operations, in a context that is more and more competitive, as well as complex, in terms of applications and resources. Wireless infrastructures need large investments, where a classic, “worst-case oriented planning” approach is no longer feasible for a financially viable operation. The complexity of the infrastructure and of the encompassed resources, and the multiplicity and heterogeneity of service requirements, amplify the difficulty of optimizing operation. Therefore, a way forward is to closely couple and blend AI/ML features in the wireless networks’ operations. This will enable the generation of insights and predictions regarding the situations encountered, and the reactive or proactive adaptation of the system to the requirements. This will lead to a more efficient utilization of resources, through the orientation/activation of resources where/when they are needed, with a parallel relaxation of the need for busy hour planning.
Another aspect that can be addressed by introducing AI to the network is its resilience. The prevention of potential disruptions in the network operation, as well as automated anomaly detection and response are key for a trustworthiness. Malicious attacks, for instance, can halt network operations for a significant amount of time, deteriorate customer experience and make network resource management very difficult and costly, leading to increased OPEX and risk for the operator. Therefore, in order to increase network resilience and ability to serve as and support critical infrastructure, the prevention of such threats, the immediate and reliable recognition of issues, as well as the prompt triggering of mitigation actions or alerting telecom providers to manage them is needed.

8.3.6 Virtualization and softwarization

There is a general trend towards more softwarization in the ICT world, with the goal to decouple functional implementation from underlying hardware and, consequently, being able to utilize Commercial off-the-shelf (COTS) hardware combined with powerful management and orchestration tools for better utilization of available compute resources and a high degree of automation. This concept is often referred to as “cloud native”, given its origin from IT cloud offerings. The need for hardware-accelerated functionality in the domains of AI/ML and 6G radio is, to some extend, being addressed by GPU- or FPGA-supported platforms or an extension of “general purpose” CPUs with the respective accelerators. This trend is expected to continue also during the 6G era.

At the same time, moving from specialized networking appliances towards general-purpose compute hardware (e.g., servers) or open hardware platforms (e.g., whitebox switches) combined with software to achieve a specific task is well known from software-defined networking (SDN) and the concept of Network Function Virtualization (NFV).

A third trend related to softwarization and cloud native approaches is towards decoupling and disaggregation, with a move towards edge offerings as an augmentation to large, centralized datacenters. While this is inevitable for certain use cases (e.g., very strict latency demands or potential privacy/trustworthiness aspects), it can even be more sustainable and affordable in the long run [SCP21].

Further refining these core concepts especially for the RAN leads to the following topics of interest regarding sustainable 6G:

- With regards to energy efficiency, the achievable benefits of better utilization of physical resources through means of virtualization on the broader scale need to be compared to the potential losses in energy efficiency when compared to ASICs or other highly optimized hardware platforms for specific purposes (e.g., especially DU, RU in the RAN) [SOI19].
- In addition to energy efficiency, use of material and the lifetime of a hardware component is an important aspect to consider when discussing required levels of disaggregation and openness in terms of standardized interfaces and HW/SW separation.
- Softwarization enables shorter development cycles, potentially enabling continuous delivery of functionality (i.e., CI/CD and DevOps), especially when coupled with powerful management and automation approaches (c.f. cloud native design). This can act as an enabler for optimization and innovation as well as fitting of 6G systems to specific use cases or different environments. To avoid frequent hardware exchanges as consequence of shorter software cycles and, consequently, a negative sustainability impact, the cycles of underlying hardware need to be decoupled and ideally increased. At the same time more integrated solutions might enable more resource optimized solutions. Thus, overall sustainability impacts of different approaches need detailed life cycle assessment studies to provide an understanding of the environmental impacts, impacts hot spots and issues to be addressed.
- Disaggregation and decoupling of hardware and software can lower market entry barriers for new businesses by offering tailored solutions for very specific use cases or environments, thereby opening additional potential for innovation and new partnering opportunities according to the UN SDGs.

It is important to discuss these topics also considering the architectural changes most likely to occur for a deeper integration of AI and general compute capabilities (e.g., “edge”) within the 6G system and as part of the offering of a 6G system. Adhering to the core concepts of softwarization could increase the potential for 6G in being a sustainable platform for currently envisioned and future use cases.

8.3.7 Hardware levers for energy efficiency

Moore´s Law which has driven the microelectronics performance and transistor power efficiency improvement pace during 60 years, is about to cease during the 2020 decade. However even if

the transistor technological node miniaturization slows down, the R&D institutes and industry roadmaps are now focused on more function specialized chips like AI (with neural engine or Machine Learning with ultra-low power [CCC+17]), audio or vision recognition [Gre19], GPU chip (heavy processing), memories/processing hybridization, etc. This trend is also important in the telecom domain where RF functions play a major role in impacting energy consumption. In each case, a dedicated architecture and technology node aim to optimize the component power efficiency. Taking the AI-chip example where high-end AI processors for edge servers and datacenters are shifting from 14-16 nm towards 7 nm technological nodes, whereas extremely low power IoT applications are moving 'only' from 40 nm to 20-28 nm lower cost digital node. For edge computing application, 22 nm FD SOI technology platform and FINFET for advanced technology nodes (7 nm) reduce more than ten times the energy consumption at same speed clock compared to classical bulk silicon techniques [Syn19].
These per transistor efficiency gains should not hide that the overall energy consumption at the system level could still increase compared to previous telecom generations, due to the increasing amount of data to process and also new introduced functionalities. This paradox can be explained by the fact that each component is dimensioned and design to support its maximal load and so the consumption is not optimal for the rest of the time. This topic is addressed by the reconfigurable hardware where the sub-system (small cell sleep-mode, fast switching PA), the component (reconfigurable multimode RF power amplifier) or even at the transistor level (low voltage biasing electronics) are able to reconfigure itself depending on its loading activity (i.e. the amount of data to process) in order to be always at its optimal energy efficiency in each working domain. This promising lever will require a feedback loop to master the optimality of the hardware matching regarding the required performance/consumption trade-off, which edge IA should provide.

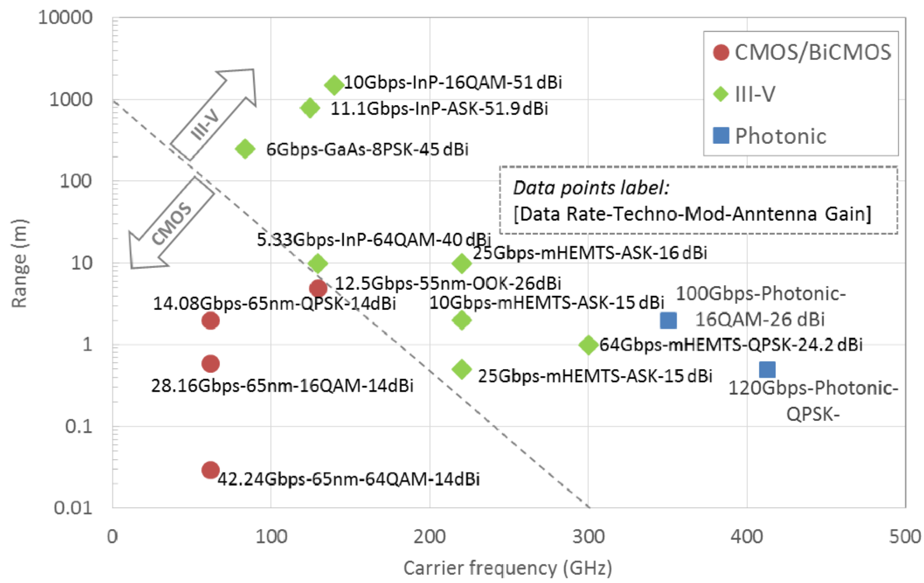

Figure 8-3: ***Sub terahertz hardware integrated circuit technologies.***

Indeed, exploring the opportunity offered by communication at higher frequency (sub-THz bands above 90 GHz), imposes a substantial evolution in the design of transceiver and antenna technologies. The available hardware to operate at such frequencies still presents severe limitations due to their energy consumption. This creates strong practical limitations to the exploitation of such frequencies to battery-powered terminals. In this context, it is critical to select the appropriate transceiver technology. CMOS-based transceivers are power-consumption bounded. Innovation is required today to explore the trade-off the complexity/power consumption of transceivers and antennas for high spectral efficiency communications, and the large amounts of bandwidth to be supported by very simple transceiver architectures operating at lower spectral efficiencies but with larger amounts of bandwidth [MLM+17]. Main sub-THz hardware integrated circuits technologies under consideration for energy efficient 6G communications are presented in Figure 8-3.

8.3.8 Recycling materials and electronics

New material might be required both for semiconductors (SiGe, InP, GaN, etc.) and for meta-material (e.g. graphene) [HE21][EC20a]. Materials such as Si, Ge, In, Ga and natural graphite were listed as critical raw materials by the EU Commission in the fourth version of list published in September 2020 [EC20a], due to the concentration of the supply or the very low recycling rates. If these materials are indeed used in the future 6G system their recycling, recovery has to be planned ahead, and their impacts needs to be understood

One of the key factors regarding the environmental footprint of electronic equipment is the semiconductor material of the components. Since current baseband chips are large size components (several hundred of mm²), there is significant material waste when these components are sliced from the semiconductor wafers. This is both related to the limited packing factor due to difference in geometry of the square components and the circular wafers as well as the defect density (D_0) on the wafers. Thus,it is important to develop components with smaller semiconductor surface in any given equipment. Adopting alternative architectures at die level, for example by using chiplet based design instead of monolithic large die can drastically reduce the material waste at the slicing stage by increasing the packing factor as well as reduce the defect rate of the components as the defect density remains constant while the component density increases.

Furthermore, adopting circular economy principles (i.e. reuse, repair, refurbish, recycled) in the design of the 6G electronics would help to make the equipment last longer or at least some of their part last longer. In the 2018 Care Electronics conference a paper explained how a modular design allows, if the right conditions are set up (ease of disassembly, spare parts available, overall electronic design fit for upgrade), to reduce the environmental footprint [VP18]. For 6G, designs involving interposer could for instance be used in order to regroup the main ICs on one board, which could be easier to reuse/refurbish on a next equipment

8.3.9 KVIs and KPIs for Sustainable 6G

From a sustainability perspective KVIs are mainly reflecting the UN SDGs and Section 8.4.2 describes how SDGs at a target level are used to frame the different use cases. In the same way SDG targets provide a starting point for the assessment of aspects relevant to Sustainable 6G, unless established standards and methodologies exists.

Sustainable 6G refers, inter alia, to the environmental impacts of 6G. To evaluate these, the well-established life cycle assessment standard for ICT goods, networks and services and including such as their GHG emission could be used [ITU14], [ETS15]. There is also an established trajectory for the decarbonization of the sector which different parts of the sector should follow to respect the overall ICT industry contributions and an associated methodology to derive the carbon footprint at a sector level [ITU20a], [ITU18b]. The ICT industry have since long addressed the above aspects and there are no immediate reasons to establish other frameworks and methodology than the ones already existing. However, a key challenge is that these methods are based on and evaluating physical properties of the final system, so they need to be adapted to be useful for assessing the implications of future systems. Also, in assessing sustainable 6G and to be able to demonstrate improvements, it is necessary to define a baseline and this baseline needs to be evaluated using the same methodology as will be used when assessing any sustainable 6G target. In addition, one would also need to evaluate overall energy consumption on a network level, starting from established standards when possible.

For other aspects of the Sustainable 6G area, including social aspects, qualitative targets and indicators may be needed when quantitative estimates are either hard to capture or associated with too high uncertainty. In any case, reuse of established standards frameworks is preferred. However, if these are missing, the SDG targets provides a starting point for deriving indicators and methods for evaluation, following the framework for KVI and KPI's that is outlined in Chapter 5.

8.4 How 6G could be a sustainability enabler

8.4.1 The role of 6G

Both the achievement of the UN SDGs and the commercial launch of 6G target the year 2030. Thus, 6G needs to be fully aligned with the UN SDG framework. Although 2030 will be early days for 6G, the framework as such and the different areas it encompasses will remain relevant also in the 2030s.

A three-fold role of 6G was identified in [MAA+20] where 6G is seen as:

- a provider of services to support activities towards UN SDGs
- a measuring tool for reporting of indicators;
- a reinforce of developing 6G in line with UN SDGs.

6G networks will become an infrastructure that supports a multitude of services to help the achievement of the individual targets in the UN SDG framework through the indicators defined in the framework. Currently, countries face significant challenges in reporting of the UN SDG indicator data as it is difficult to collect. 6G with its capabilities to e.g. sense the environment, can become a tool to help authorities and other stakeholders to collect various data at different levels of locality. The use of 6G technology as a measurement tool can help in providing evidence of the indicators as well as enable the monitoring of totally new indicators that will become relevant. The 6G technology itself needs to be developed and deployed in line with the UN SDGs, taking into account the potential sustainability criteria that the ICT sector needs to fulfil in the 2030s.

8.4.2 Hexa-X use cases and sustainability

In the Hexa-X vision, we believe that ICT powered by 6G has the potential to play an important role in addressing most aspects of the UN SDGs. To demonstrate the value associated with 6G for Sustainability, the use cases and the UN SDG targets will be key components. Following the relation/mapping between key values, challenges, target areas and KVI/KPIs as outlined in Chapter 5, several of the use cases can find its direct relation to one or several UN SDG targets. This association to an SDG target, will clearly illustrate the connection to the key value of sustainability, and it will also support in defining a relevant KVI, an indicator that can be used to illustrate or measure impact, either directly or as a bridge to relevant KPI's that can be measured. The SDG targets are already associated with indicators which forms part of the UN SDG framework, but to demonstrate the role of 6G to reach the targets, there is a need to define indicators that are more relevant from a 6G perspective as existing SDG indicators are developed for countries.

As an example, the E-health for all use case can be associated to target 3.8 *"Achieve universal health coverage, including financial risk protection, access to quality essential health-care services and access to safe, effective, quality and affordable essential medicines and vaccines for all"*, but the indicators, *3.8.1 Coverage of essential health services*, or *3.8.2 Proportion of population with large household expenditures on health as a share of total household expenditure or income*, may, although sometimes relevant for 6G too, need to be complemented by, additional indicators such as, *3.8.6G-n Availability of health data gathering (secure upload)/video/tactile examinations*, as further described in Chapter 6. Such KVI's can then be related to KPIs (e.g., service coverage) and/or capabilities that would become key to addressing the use case or use case enabling service. The example above is model for what will be pursued for all relevant use cases that associate to any of the UN SDG targets.

8.5 Conclusion on sustainability

Sustainability is a very wide area built around environmental, social and economic development. Consequently, it's spanning sustainable growth and development, societal aspects such as health, education, trust, and environmental considerations in terms of e.g., energy consumption, use of materials and greenhouse gas emissions. Much of the above is excellently framed by the UN SDGs as the main recognized global framework for sustainability, and both from a ***Sustainable 6G*** – and a ***6G for Sustainability*** perspective, it will be the framework that defines the project sustainability targets. The width of the SDG targets not only encompass the width of the sustainability scope, it also supports awareness of target interactions, like improvements in one area meaning cost in another.

The coming decade will form the foundation of a more sustainable world and by the early 2030s, 6G will gradually become one of its fundamental infrastructures, contributing also to growth in a sustainable way. In defining 6G, it is not an option to miss out on any crucial sustainability aspect, whether it be in the architecture, in the access, in exploring the possibilities with AI, in sensing or in optimizations for its most important and vital future use. The 6G system must at the same time, for example, utilize and benefit to the renewable energy supply grid , have the most sustainable material selections from both a performance, lifetime, recycling and reuse perspective, optimize on-times and processing and minimize transmitted energy, always providing the performance necessary for its diverse use cases and the opportunity to enable sustainable solutions across society while suppressing any adverse effects.

Sustainability is everywhere in the Hexa-X project; part of the vision, as a research challenge and as a use case family, to secure that no stone is left unturned in addressing both dimensions: Sustainable 6G and 6G for Sustainability. The toolkit at hand, the SDG targets, the use cases, challenges, new capabilities and the overarching vision of sustainability, trustworthiness and inclusion paves the way for 6G to become the main sustainability platform (and in itself the most sustainable smart connectivity platform) in 2030.

9 Security Considerations

9.1 General Considerations

Trustworthiness is one of the six main research challenges the project is committed to address and security forms a basic foundation for all systematization of trust in connectivity. Security considerations must encompass all aspects of cyber-security: resilience against attacks, preservation of privacy, and ethical, safe application of automation to network operations and applications. Security also depends on active management of threat surfaces, including proactive measures such as threat prevention and protection as well as reactive measures such as attack discovery and mitigation. As network services consolidate as essential components in a growing number of application scenarios, their dependability and, equally important, the perception of such dependability as an achievable characteristic, becomes a key feature for network operators, service providers, application developers and, above all, end users.

A realistic approach to this trustworthiness challenge must acknowledge that complete security is not achievable, and that all security measures comes with a cost in other terms (such as usability, agility or swiftness). Therefore a balance is required in terms of this cost, the risks to be considered, and the impact of a security breach on the mission objectives being served. The Level of Trust (LoT) of a particular network service in a concrete application scenario is proposed as the essential KVI to be considered in this regard. The characterization of LoT will constitute one of the main goals of the security task.

Providing the necessary elements for the evaluation of such a LoT is the key goal for a security design and support task, identifying both the applicable technologies to domain experts, and respectively analyzing the solutions proposed by these experts in the framework of previous experience and feasible attack patterns. This becomes especially relevant for a project committed to propose next-generation network architectures, so those attacks related to network technology evolution and the increasing sophistication of tools available to malicious actors become especially worthy of attention.

Though it may seem obvious, it is worth recognizing the imperative to apply this security analysis at all levels: for each individual applicable technology (at any plane and layer in the communications stack and any segment in the network architecture) and from a holistic perspective (addressing network services as a whole, including the involved human roles). Therefore, the security task in Hexa-X is committed to analyze and drive the evolution of base security technologies, support the analysis of specific solutions at all levels, and assist the security evaluation of the different scenarios contemplated as reference within the project.

An initial assessment of these use cases has identified a set of security aspects to be considered:

- Improvement in implementation of general requirements: availability, confidentiality, integrity and personal data protection.
- Scaling implications related to massive, pervasive deployments of unattended and untrusted devices
- Data provenance and physical-to-logical mappings in digital twin applications
- Real-time data flow protection in new applications such as immersive media or haptic interfaces
- Establishment of trust mechanisms between networks protective of subscriber privacy
- Root-of-trust based approaches to provisioning network gear, including authorizations for virtual network functions that may be deployed on generic hardware.

- Active disruption of network resources to examine the resilience to attacks
- Extension of current network security practices to ad-hoc networking
- AI-specific threats, including threat surface and attack vectors
- Protecting AI data feeds of any nature: raw, pre-processing, normalization and knowledge sharing
- Address the use of AI by attackers
- Security impact of deployment on heterogenous cloud environments

9.2 6G Threat Landscape

This section gives a short summary of the 6G threat landscape – a more exhaustive threat and risk analysis is not in the scope of this document.

9.2.1 Residual Risks of Today's Networks

Today's ICT infrastructure is often perceived as poorly secured. Major security breaches are announced almost on a day-by-day basis. Such security breaches mostly affect IT systems, like web servers or data bases. In contrast, mobile networks, from the Third Generation onwards, have a sophisticated, standardized security architecture and have only rarely become victims of high-impact cyber-attacks. However, with the current trend to no longer deploy mobile networks on proprietary hardware, potentially on cloud platforms, and to adopt cloud-native software techniques for designing mobile network functions such as sets of microservices, mobile networks assume an aspect of mainstream IT systems, and are likely to increasingly become a target of the sorts of attacks carried out today against IT systems.

Many security weaknesses of today's ICT systems stem from vulnerable software. The reliance of future mobile networks on virtualized software deployed on cloud hardware brings tremendous advantages in terms of flexibility and scalability, and leverages essential new features such as network slicing. However, it significantly increases the amount of software that is required, in the form of a virtualization layer as well as a management and orchestration stack. Thus, the number of attack surfaces for software vulnerabilities grows in proportion. In addition, today's cloud-based systems often combine software from a variety of heterogenous resources. Custom software designed and implemented according to a vendor's secure software creation process may be combined with third party and free and open sourced software, making it harder to ensure a consistent, high level of software quality that is attentive to integrated operation and interoperability across large numbers of sourced components.

A second root cause for many devastating security breaches is the failure to stick to sound, secure operational practices. Partly, this may be due to the desire to reach a high efficiency in network management, foregoing tedious security procedures. Indeed, simple human negligence or human errors lead to vulnerable network configurations. As the complexity of networks rises, for example by supporting several network slices, e.g. several logical networks, all running in parallel on shared infrastructures, the potential of vulnerabilities in the network configuration also rises.

Deploying network functions in multi-tenanted clouds that are not dedicated to mobile networks, but host a variety of heterogenous applications from different sources, can make vulnerabilities in the virtualization software and in the configuration significantly even more dangerous, as a malicious or compromised application may attack network functions running on the same platform. While such mixed setups may partly be motivated by economic reasons, in other cases there may be a technical reason. In particular, when low latency applications need to be deployed in edge clouds, mixing mobile network functions and third party applications on the same hardware platforms would be unavoidable.

It cannot be denied that creating more secure software and operating networks in a highly secure manner is possible, but that incurs increased costs, without obvious return on investment.There is often a lack of economic incentive in implementing high security.

9.2.2 Increased Risks for Telecommunication Networks Towards 6G

While the overall architecture, features and deployment models for 6G networks are only starting to take shape, some trends influencing the security posture are already visible, like a huge expansion in the numbers and diversity of end-user devices. Other trends heraldhighly heterogenous, complex network structures, and potential divestment of responsibility in the variety of stakeholders involved in providing a communication service. All of this increases the potential for vulnerabilities, or in other words, the attack surface.

As the use cases described in Chapter 4 of this document clearly show, critical services will increase reliance on communication networks. Successful attacks against the network serving such applications could be devastating. In use cases such as “Precision healthcare” or “AI-assisted Vehicle-to-Everything (V2X)”, human safety is at stake, depending on the availability and integrity of the network. Many expected future use cases will also handle a wealth of highly sensitive data. The threat of leakage and abuse of such data poses a significant risk.

New technologies likely to be adopted in 6G networks can bring new security risks prominently the use of AI. In the past, striking examples have been given how AI methods, e.g. for image recognition, can be tricked into delivering erroneous inferences, endangering human lives in use cases such as AI assisted V2X. In the future, attackers very likely will figure out new attacks against new AI methods, and due to the complexity and sometimes unpredictability of the AI mechanisms, defenders may have a hard time to anticipate and mitigate such attacks.

9.2.3 Evolution of the Cyber-Attack Ecosystem

Malware, i.e. computer software designed by attackers to perform malicious activities on victim computers, began to spread in the late 1980s. At that time individual “hackers” started to search for vulnerabilities in widely used software, and create exploits. These exploits where quickly adopted by criminals to perform malicious attacks for profit.

At a later stage, attack tools became more diverse, trying out multiple exploits against a victim; and more automated, suitable to be applied to huge numbers of targets. This way, botnets (meaning potentially large group of computers owned by unsuspecting users, but compromised and controlled by an attacker) where created to perform hard-to-counter DDoS (Distributed Denial of Service) attacks. In parallel, a market emerged for attack tools, attack capacities and illegally retrieved information. New ways to monetize successful cyber-attacks were created, with ransomware as one of the most prominent examples, where a victim’s data is encrypted in order to extort a ransom for decrypting it again.

Cyber-attacks have also become part of the arsenal of the military and other governmental organizations, and are suitable to be applied on a large scale against countries and enterprises. Furthermore, valid concerns exist around cyber-terrorism, where huge disasters may be initiated by cyber-attacks.

Cyber-attackers have a track record of picking up and abusing new technologies quickly, often more quickly than the defenders, and there is no reason for AI being an exception to this trend. As a notable example,. AI-based attack methods could optimize the scanning for vulnerabilities, the analysis of huge, illegally acquired amounts of data, or maximize the success rate of spear phishing attacks.

9.3 Overview of security technologies applicable in 6G

9.3.1 Trust Foundations

9.3.1.1 Confidential computing

Today’s systems offer strong protection for data in transit, but data being processed and stored is comparably less protected. For protecting data while being processed and stored, i.e. at cloud platforms, confidential computing is becoming a strong paradigm. In such cloud environments, confidential computing provides hardware-based isolation for the processing of payloads, which a cloud provider cannot tamper with. It also allows remote cloud users to verify the isolated environments in which they want to place their payloads, and the verification and attestation procedures are carried out by the compute hardware itself, preventing a bypass by the cloud provider owning the hardware. Confidential computing is based on hardware-based roots of trust (RoT) that forms the basis for security assurance in cloud systems and allow retention of data ownership as well as protection of secrets and digital identities. The realization of confidential computing, such as software guard extensions (SGX) [CD16] and secure encrypted virtualization (SEV) [KPW16], relies on the use of secure enclaves within processor hardware, generally known as “trusted execution environments” (TEE) [GP20]. The TEE executes codes and stores sensitive data in attestable, dedicated, isolated, and protected areas of the processing system. It must be noted that the TEE technologies rely on vendor specific designs and threat models, what may lead to potential vulnerabilities like side-channels.

Confidential computing has the potential to enhance the security of network slices. Slices can be cryptographically isolated from each other by combining data in transit protection mechanisms and confidential computing technologies for protecting data being processed or stored. Another application of confidential computing is for AI, addressing proprietary concerns surrounding the protection of algorithms and underlying models along with privacy needs in multi-tenant environments. Confidential computing can be used to employ data for AI applications without exposing information by various means, including feeding encrypted data into an enclave, training an AI model without revealing cleartext, and showing only the final model.

9.3.1.2 Secure identities

Secure digital identities play a fundamental role in building trust. Identities are essential for secure communication in several layers and among several entities in mobile networks, including the connectivity layer and application layer. This includes the interaction between a mobile device and a network, intranetwork communication between network nodes, and internet communication between network nodes and external servers. Trust chains are a powerful tool for securing digital identities which allows an identity used in one layer to serve as an RoT for deriving identities in other layers.

While Subscriber Identity Modules (SIMs) are important identities for secured network access, there is a need for identities in various other parts of networks. There is an increasing interest in anchoring trust in the overall network from trusted hardware roots towards the entire chain of hardware, network software, and service-specific functions. The path to secure identities and protocols depends on establishing trusted identities for infrastructure, connectivity, devices, edge, and network slicing functions. This can be enabled by means of RoT mechanisms for identities that are established for every physical component, software function, and interface. The end goal is to create a system that offers privacy for all deployed software as well as the protection of data from unauthorized access.

9.3.1.3 Attestation technologies

Attestation is the process of validating the integrity of a system and, in the particular case of current network deployment practice, heavily based on virtualization technologies, it implies the integrity of the supporting platform, the software components implementing network functions, and the topology of these network functions to provide the intened service. The attestation steps may be specific to the level of assurance to be established, which, in turn, depends on the required level of trust (as defined above) and the different parties involved in providing and consuming the service. Generally speaking, attestation procedures imply the collection of measurements about the attestation target by tamper-resistance means and the verification of these values against a set of *golden measures*, via an attestation verifier.

The attestation procedures for the supporting platform (or at least its compute components) and the installed images are well understood and standardized. In the first case, through the use of Hardware-Based Roots of Trust (HBRT), such as Trusted Platform Module (TPM) [TCG19] or Trusted Execution Environment (TEE), and the composition of measurements through methods supporting assured boot procedures. While image verification prior to installation is a well-established practice, by verifiying signed hashes of the image to install, further research is required to support the lifecycle management of software images in a dynamic environment implying pervasive and ad-hoc deployments.

Topology attestation implies the ability to verify that a given network flow, at any given plane, is going to pass through the specific functions, optionally preserving a given order. To this purpose, the application of recent results regarding (Ordered) Proof of Transit (O-PoT) [ALP+20], in combination with inline operation and management and programmable packet forwarding devices, open a promising way for completing attestation mechanisms with one of its most relevant challenges.

Finally, while attestation verifiers have been typically a centralized service, the advent of disintermediation mechanisms provided by Distributed Ledger Technologies (DLTs) opens a wide range of possibilities for distributed solutions, including the incorporation of reputation mechanisms and dynamic trust assessment.

9.3.2 Privacy enhancing technologies

Privacy enhancing technologies refer to a set of building blocks that can be used to achieve privacy in communications and computations: data anonymization, differential privacy, homomorphic encryption, and secure multi party computations. Depending on the use case, privacy need, and the threat model they can be adapted alone or hybrid. Since each generation of mobile network technologies aim to improve privacy and with the increasing AI/ML integration in 6G use cases, it is foreseen that these technologies will be embraced to meet the privacy requirements arisen in 6G.

Data anonymization is a process of removing or abstracting the private data which prevents attackers from, directly or indirectly, linking between the data and the private party which owns the data. After the General Data Protection Regulation (GDPR), data anonymization has gained much more importance. As it is stated in the Recital 26 of GDPR [GDP16], anonymized data can be processed for statistical or research purposes freely and data protection processes are not required for the anonymized data. This makes anonymized data very valuable as it does not require these security procedures expected for the non-anonymized data. Most commonly, data anonymization can be achieved by removing attributes from the data or by adding noise to the original data. In both cases, the aim is to weaken the relation between the data and the data owner. However, this is neither easy nor a straightforward task. Because only removing the personal information features from the current evaluated data may not be enough if there are some auxiliary data which can be used to build a relation with the so-called de-identified data.

Differential privacy (DP) is a data anonymization technique that enables quantifiable privacy by bringing a bound on the probability that two datasets can be distinguished [DMN+06]. It is widely used to protect the privacy of the individuals whose information is in a dataset. In the ML context DP is rigorously addressing membership inference attacks (given a data record and block-box access to a model, determine if the record was in the model's training dataset). The random noise can be applied to input data (input perturbation), to output data (output perturbation or randomized response), or to the algorithm’s intermediate values. In the input perturbation, noise is added to the data itself, and noisy input is used for the desired computation which result in differentially-private output. In the output perturbation, first, the computation (e.g., training) is performed, and then noise is added to the resulting parameters. Algorithm perturbation [DTT+14] applied in adds noise to the intermediate values in iterative algorithms.

Homomorphic encryption (HE) refers to a form of encryption that enables the computation on ciphertext without accessing to secret key. The resulting computation persist in encrypted form until the keyholder decrypts the result. HE accomplishes this with operations such as addition and multiplication that can be used as basis for more complex arbitrary functions. However, enabling both addition and multiplication is hard to achieve efficiently. There are three type of widely known homomorphic encryption as partially homomorphic encryption (PHE) [Pai99], somewhat homomorphic encryption (SWHE) [Bra12], and fully Homomorphic encryption (FHE) [Gen09] where each can perform different classes of computations over encrypted data. PHE supports only one type of operations (i.e. addition or multiplication) with an unlimited number of times on the ciphertext. SWHE supports all sorts of arithmetic and logic operations but number of homomorphic operations is limited. FHE scheme supports arbitrary operations with an unlimited number of times over encrypted data.

Secure multiparty computation (SMC) is a cryptographic method that allows parties to jointly compute a function of their sensitive inputs without requiring to reveal their inputs. Some of the approaches used to realize SMC [Lin21] are Yao’s Garbled circuits, GMW (Goldreich, Micali and Wigderson) oblivious transfer approach, secret sharing, and homomorphic encryption.

The efficiency of the protocols relies on the efficiency of representing the computation in arithmetic or boolean representations. More specifically, boolean circuits are not suitable for doing arithmetic operations such as integer multiplications but they perform well for comparisons. Most of the frameworks cannot support both operations, instead they use different tools like Garbled circuits, Homomorphic encryption or secret sharing for the unsupported one.

9.3.3 AI/ML as an enabler for security assurance and defense

With an ever-increasing digital transformation and inter-connection of several industries, we are also witnessing a growing dependency on the underlying network infrastructure. AI/ML raises as an ally for boosting security assurance and defence enabler solutions to defend against cyber-attacks. As an example of its paramount importance, we could consider a Vehicular Network, on which any misuse, anomaly or attack can compromise any services running therein (e.g., autonomous vehicles) and cause accidents. In this sense, AI/ML can aid on processing the amount, heterogeneous and unrelated data created by an enormous variety of end-devices and network entities, otherwise too complex to be handled by traditional methods. To this extent, service recognition, traffic and behaviour prediction, intrusion detection, or identification of malfunctions can be improved by AI/ML to boost security and defence mechanisms. Moreover, AI/ML is arising as an important piece to enhance the multi-radio access and radio configuration, and adaptive tracking and beamforming, which by becoming more reliable are assuring a higher degree of security.

9.3.3.1 Collaborative AI/ML as a Privacy Enabler

Despite the potential of AI/ML to boost and complement next-generation networks, its use also poses some challenges in terms of privacy of the sensitive data. The amount of data required to train accurate AI/ML models usually leverage on collecting data into a centralized storage. On one hand, traditional centralized approaches might compromise the privacy of data. On the other hand, training to be performed over a more realistic, heterogenous, and wider training dataset, which would result in more accurate AI/ML models and avoid overfitting issues. In order to address this privacy challenges and make use of distributed data, new techniques enable collaborative AI/ML without centralized training data. As such, accurate AI/ML models that reflect a wider dataset can be trained, while retaining the privacy and locality of private and sensitive data. Federated learning, split learning, and transfer learning methods are among the most widely used.

Federated learning decouples the ability to learn from the need to store the data in a centralized location [LST+20][YLC+19]. The learning process is performed in four steps: *(i)* the private node downloads the current shared model; *(ii)* the model is improved by training with local data; *(iii)* a summary of the changes is sent as an update to the centralized location; *(iv)* the shared model is improved by averaging the updates. This process is done for a set of distributed private nodes, allowing data to remain privately. Variations of this method were also proposed, among them is Distributed Federated Learning [HDJ+19] and Heterogeneous Federated Learning

Split learning [VGS+18] embraces the similar privacy perspective, training the distributed client data without sharing [YZQ+20] the data to any centralized server. Split learning achives this goal by dividing the neural network model into sub-networks, then training the some networks parts on clients and other parts on the server while federated learning adopts the approach of training whole network on the clients.

Transfer learning [PY10] consists of applying the knowledge acquired while learning on a specific dataset on a different but still related task. In this sense, models do not need to be trained from scratch, but instead can rely on previous knowledge. Additionally, the more related are the tasks, the easier is to cross-utilize the knowledge. With transfer learning, it would be possible to retain privacy of both the previous learning and the new data that is provided into the training.

In addition to collaborative AI/ML approaches which focuses architectural or algorithmic methodologies to handle privacy issues, privacy enhancing technologies pave the way for stronger privacy guarantees. Even though, collaborative AI/ML methods are a great advance in protecting privacy, there remains some risk to extract private information [MLD+20]. Privacy enhancing technologies such as differential privacy, homomorphic encryption, and secure multi-party computation as given in Section 9.3.2 can be used as a remedy for privacy attacks against collaborative AI/ML. Since differential privacy addresses privacy guarantees for algorithms on aggregate databases, characterized by several properties, it is suitable for AI/ML applications. This seminal paper [ACG+16] demonstrates the training of deep neural networks with differential privacy, incurring a modest total privacy loss, computed over entire models with many parameters. Homomorphic encryption would be a suitable tool for protecting privacy of updates as it allows federated aggregation over encrypted training parameters. The other privacy enhancing technology, secure multi-party computation, enables joint parameter aggregation without revealing any information about private training updates, hence it can play a role to handle collaborative AI/ML privacy issues.

9.3.3.2 Intelligent security monitoring based on virtual probes

One of the clear evolution paths for next-generation mobile networks is the use of elastic deployment patterns to address service demands. The use of cloud-based technologies at each network segment (RAN, edge and core) is a clear example of this evolution towards flexibility. Solutions for security monitoring should follow this dynamic approaches, with new concepts, such as software defined monitoring (SDM) [LOA+17], being proposed. NFV and SDN are already well-understood and widely-available technologies, allowing the on-demand deployment of virtualized probes in the network to detect and mitigate security problems.

On the other hand, the pervasive encryption mechanisms applied to protect privacy is limiting the visibility of the traffic in the network, complicating the application of the current practices used to addres attacks on the network. Machine Learning is already positioned as potential solution for traffic classification [RL19] and to address specific security threats, such as malware, spam, cryptomining, etc. [BCC+19][PMV+20]. The security solutions for next-generation networks will have to combine techniques that apply the on-demand deployment of network probes that take advantage of programmable dataplanes [EBP][PLC18] to collect specific data from network traffic flows at (close-to) line rates, combined with pretrained virtualized inference engines for quick threat detection. Once detection is performed, mitigation measures should follow the same dynamic, on-demand patterns relying on orchestration of programmable dataplane functionalities.

9.3.3.3 AI in software development

Today, many cyber-attacks are leveraging on vulnerable software, with buffer overflows continuing to belong to the most common, exploitable bugs. While there sometimes seems to be a consensus that bug-free software can never be achieved in an economically feasible way, AI methods in software development may help to come significantly closer to this goal.

As an example, a software versioning and revision control system may learn from the history of detected bugs in software that was earlier submitted to the system, whether a new piece of source code is likely to be buggy or vulnerable. The system may even learn which specific constructs in the code are (potentially) flawed, and flag such constructs, forcing the developer to revise the code. Other possible usages of AI methods may include code optimization or automated code generation, as well as test automation.

9.3.4 Distributed Ledger Technologies

Apart from the wide exploitations in financial applications, DLTs have recently gained a huge attention in the telecommunication industry as well. The key advantages of DLTs are identified as transparency, immutability, non-repudiation, proof of provenance, integrity and pseudonymity which are particularly important to enable different services in networking paradigms. Blockchain is the most popular DLT which has gained the highest attention for improvising the security, trust, and privacy features in future 6G networks [THD+20]. The members of the blockchain mutually collaborate in generation and persistence of replicated records of transactions, organized in blocks, that happen in real-time, or back in history up to until the creation of the blockchain network. Each blockchain network run different consensus algorithm that enables the members to decide and validate the next block added on the Blockchain. A smart contract is a set of binary code, very similar to a computer application, that runs on top of blockchain. Once a smart contract is deployed and run on the blockchain, it is immutable and operates independently (from its creator) with its own blockchain address.

DLT has the potential of protecting the integrity of AI data via immutable records and distributed trust between different stakeholders, by enabling the confidence in AI-driven systems in a multi-tenant/multi-domain environment. The smart contracts also open a range of opportunities for network applications that require trusty interactions omitting the need of a third-party authority for integrity verification. DLT based Smart contracts can be utilized to define Trust Level Agreement (TLA) and liability of each party or between components in case of TLA violations. Furthermore, DLT/blockchain can be used in 6G to support the enablement of the current 5G service models that need to be significantly evolved. NFV service providers may offer their services in open marketplaces which would allow customers to be able to browse a general catalog of NFV service offerings [KTK+19]. A deployed smart contract would be in charge of overviewing, validating and advertising new on-boarded NFV services. Additionally, customers directly interact with a smart contract to request a specific (set of) NFV services. The smart contract guarantees transparent, secure and private interaction between the service providers and the customers.

A solution with smart contracts has been envisioned by ETSI Permissioned Distributed Ledger (PDL) [ETS21], where smart contract should be used to provide users a NFV service with QoS monitoring. In addition to that, DLT can be also used in secure VNF management, secure network slice brokering, automated Security Service Level Agreement (SSLA) management, scalable IoT PKI management, and secure roaming and offloading handling. These DLT based solutions are possible to perform the federation of 5G services [AB20], even in a dynamic and rapidly changing environment [AGB+20].

9.3.5 Quantum Security

A significant part of data exchanges in today’s networks, wired or wireless, require protection mechanisms. These protection mechanisms are provided by different cryptographic methods and protocols, rooted at the computational complexity of solving certain mathematical problems. The advent of quantum computers, and their ability of exploring solution spaces by means of the superposition of states in the *qubits* used to represent information, is questioning this computational complexity and putting at risk the effectiveness of state-of-the-art cryptography.

Several solutions are in progress to address this issue. Post-quantum cryptography (PQC), or quantum-resistant cryptography, aims for secure cryptographic systems against both quantum and classical computers. NIST is leading a standardization effort [AAA+20] to make them interoperable with existing protocols and networks. PQC algorithms have been proposed for most cryptographic constructs like public-key encryption, key exchange, digital signatures, and certificates. PQC algorithms are designed to run in software on classical computers just like RSA and ECC and are in most cases just an algorithm replacement like the move from 3DES to AES. Lattice, code-based, and multivariate cryptography are as fast or even faster than ECC, but have larger public-keys and ciphertexts and equal or larger signatures. Current NIST activity in standardization will be considered for later 5G releases. These algorithms and their implications in network protocols and related security procedures, like key distribution, should be considered in the design of next-generation networks.

Quantum cryptography follows a complementary approach, where a Quantum Key Distribution (QKD) system [GRT+20] is nothing other than a source of synchronized random bits in two separated but connected locations (e.g. by a optical fiber or satellite link). These bit sequences can be used to derive a key at both peers. The main property of QKD systems is that, over public channels, they can leverage the laws of quantum physics to distil keys that cannot be eavesdropped. However QKD is focused on key distribution and requires other techniques to address full cryptographic functionality like authentication or signing. Multiple protocols and techniques exist (such as BB84 [BB14], E91 [Eke91] or continuous variable [WPG+12]), and standards are already in place, including the use of SDN-based APIs [ALL+19] to integrate different applications and dynamic delivery of key streams [ETS10]. Current applications of QKD are exclusively focused on physically secure a communication line [BSI21], and application beyond point-to-point relies on trusted intermediaries [NSA15]. Potential uses include direct application in crypto-enabled network protocols (optical layer encryptors, layer 2 encryption via MACSec, IP protection with IPsec, secure transport protocols like TLS, etc.) and applications (VPNs, secure storage, etc.). Next-generation networks could use this technology together with classical crypto to enforce higher security for specific needs such as the physical protection of point-to-point connections.

Quantum Random Number Generators (QRNG) is an additionally related technology able to generate random numbers from a source of entropy using unique properties of Quantum Physics. This property can provide secure high performance seeds in key derivation process, though it has been argued classical RNGs would continue to meet the need of critical infrastructure, government, and military applications for the immediate future [NCS20].

9.3.6 Physical Layer Security

5G network security is currently based on cryptographic mechanisms, using symmetric and asymmetric keys to secure communications, enforcing authentication, confidentiality and integrity of communications. These mechanisms offer many advantages: in absence of additional side channel information, there are no known successful attacks against them. Additionally, they have been tested and deployed extensively in the past generations of mobile communications. While cryptography will remain a key aspect of security in 6G, it still has some drawbacks that should be adressed. It consumes a lot of power, which is detrimental for IoT. Physical connections are assumed to be established, which leaves the system vulnerable to physical layer attacks, such as jamming. Finally, since they are based on computational complexity, some of them (the asymmetric ones) are considered potentially vulnerable to future attacks based on quantum computing.

To face these problems, PLS approaches can be applied in addition to current mechanisms. These techniques achieve security using unique physical properties of the channel, device or user, and not on computing complexity. Hence, they can be considered quantum-resistant, and do not require parallel key distribution mechanisms. Since PLS does not require to perform complex computations, and may only involve the PHY and MAC layers, it can also become a fast and energy-efficient solution, which favors IoT use cases. PLS is hence seen as a potential additional security protection for 6G systems [LL19], in conjunction with traditional systems.

For example, there are proposals for using PLS to provide node authentication, message integrity, message confidentiality and enforce availability, based on measurable physical properties [SCP21]. Among the different ways to achieve these goals, PLS can rely on the wiretap channel model that assumes attackers experience worse channel conditions than the legitimate endpoints. While this assumption has no reason to be true in general, specificities of 5G and beyond communication systems may favor this approach. Indeed, technologies such as beamforming, visible light communication (VLC), TeraHertz or molecular communications will focus the transmission power around the legitimate receiver, either through narrow beams or very small range emissions. Another example for a PLS method consists in using the characteristics of the radio channel that are only available to the legitimate communication peers to derive a common key, or to provide origin authentication for messages without the need to add a message authentication code to every message.

We should however note that PLS comes with its own drawbacks. Notably, PLS has not been widely tested in the field so far, so any theoretical advantage may be undermined by a poor implementation resulting from a lack of experience.

9.4 Hexa-X approach to security

The security task in the Hexa-X project is committed to consider the security issues already identified in the sections above, whether associated with requirements of the new business and use cases, or corresponding to altered or new surface threats induced by technology evolution. At the same time, the applicability of the relevant technologies introduced in the previous section to improve security in all aspects will be considered. The task will seek a proper definition of the Level of Trust as an essential KVI to be considered, in technical terms, and to establish the association of this KVI with the perceived, *psychological* trust stakeholders would be willing to put on the services provided by next-generation network.

To maximize this Level of Trust, the security team will work along three main lines:

- Directly cooperate with the different domain experts in all technical activities to understand and address the security implications of each technology evolution or breakthrough.
- Incorporate security considerations in the network architecture the project will produce, at all levels, covering different network segments, the elements in them, the protocols and data models to be used, and the infrastructure on which they will run.
- Supplement this security-by-design in the architecture with the necessary elements for the definition and management of security goals, from the expression and composition of policies to their actual enforcement at the infrastructure level. These elements will constitute the *security architecture* for next-generation networks.

The last of these lines will be an activity mainly internal to the security task, identifying how the current state of the art in security management must evolve to address the challenges identified within the former lines of action.

The second work line will imply a direct cooperation with the architectural activities within the project, coordinated by T1.4, while the first one would imply the realization of what we could call security assessments on the different technology choices. To address these two lines of action, each document related to such a technology choice or architectural decision shall include a section on security considerations, in the spirit of RFC 3552 [BK03], to be prepared in collaboration with the security team and considering at least these aspects:

- Requirements and/or implications on communication security: identity, confidentiality and integrity
- Needs on and/or capabilities for authentication, authorization and accounting
- Application and/or enforcement of non-repudiation and accountability
- Risks of inappropriate usage and denial of service
- Foreseeable passive and active attacks
- Personal data involved

WPs working in the different documents are expected to provide a first evaluation along the above lines (even when a “not applicable” assessment is made) and share it with the security team. The outcome of the dialog between the technical and security teams will eventually produce a comprehensive analysis of security implications and ways to address them, and provide first-hand material for the security team to improve security architecture.

10 Next Steps

As a next step the content of this report will be updated and extended in the following way:

In the coming months, the Hexa-X vision will be further discussed with external experts. Hexa-X will inform them on the Hexa-X view as well as seek for feedback. Near the end of the project, the trends and the vision are again analyzed to consider potential needs for changes. The set of use cases will be refined and consolidated, jointly with the work of specification of KPIs and KVIs. The technical work conducted into WP2 to WP7, as well as the development in the ecosystem, will be considered to strengthen further the set of use cases. The work on the architerural enablers and the E2E architecture has started recently. First gap analysis will be provided and based on the content of this deliverable an initial E2E architecture definition will be initiated. Regarding sustainability issue, the intention is to work further and elaborate propositions Hexa-X can use to influence our ecosystem including standardization and industry. Partners will be invited to share their experience in the sustainability domain and to explore new ideas like "low tech concept" or "sobriety" and to inspire from other sectors having introduced these challenging concepts in their industrial processes. In addition a list of specific requirements towards network manufacturer will be developed to be "green by design" for 6G. In the security area the plan is to work next towards a proper definition of the expected level of trust and its translation into an essential KVI and technical requirements, and to create the guidelines for producing the section on security considerations in the deliverables related to technology choices or architectural decisions. In parallel additional threats and applicable technologies will be analyzed.

The results of the described work will be reported in Deliverable D1.3 and published on the Hexa-X webpage.

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