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Hexa-X

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Abstract

This report presents the final Hexa-X vision for B5G/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.

Keywords

6G vision, Use cases, Services, Key performance indicators, Key value indicators, E2E architecture, Spectrum, Sustainability, Security and privacy

Disclaimer

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Executive summary

This report is the fourth and the last deliverable of Work Package 1 (WP1) — "Hexa-X architecture for B5G/6G networks – final release" — and focuses on updating the 6G Hexa-X vision, novel use cases, services, and Key Value Indicators (KVIs) as well as Key Performance Indicators (KPIs). This report also indicates the latest progress on the impact of sustainability, security, and spectrum evolution aspects for 6G. The final draft end-to-end (E2E) 6G architecture has also been presented.

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, the evolution of regulatory frameworks and technological as well as architectural 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 with transformational impact across industries and sectors; future alternative business scenarios; and telecommunication and vertical-specific regulations (such as medical regulations).

As for the **use cases**, a detailed mapping of Hexa-X requirements to 6G state of the art is included in this deliverable. The **KPI** definitions and the underlying methodology from earlier deliverables are summarized, providing a self-contained view. For **KVIs**, a more detailed discussion of the methodology for their assessment and quantification is provided. Each identified value area within Hexa-X (sustainability, inclusion, flexibility, and trustworthiness) is discussed in terms of suitable indicators and relation to technical enablers within Hexa-X.

To accommodate the envisioned 6G use cases as well as satisfy the main values of 6G namely sustainability, inclusivity and trustworthiness new architectural design principles needs to be in place. The **architecture of future 6G** network should be flexible and highly specialized to be used in large scale wide area networks as well as on very small on -premises and personal area networks. To this end, an **E2E system** view 6G architecture has been introduced. This design can satisfy a comprehensive and highly advance wireless ecosystem. It combines the technology enablers horizontally from extreme-edge to the central cloud and vertically from infrastructure layer to the application layer.

Concerning **spectrum**, aspects relevant to extending spectrum utilization in frequency ranges already in use (i.e., low, mid, and mm-wave) and in potential new frequency ranges (e.g., 7-15 GHz in the centimetric range and 92-275 GHz in the sub-THz range to address 6G service requirements are considered. Furthermore, linked with relevant studies carried out in the technical work packages, enhancements to further optimise spectrum utilization, such as distributed MIMO and advanced carrier aggregation for 3GPP technologies and 6G "**Networks in Network**" (NiN) concepts for interference-controlled operation in shared spectrum scenarios are also addressed, as well as the use of AI/ML in certain spectrum usage scenarios, for e.g., throughput and spectral efficiency improvement, AI-assisted spectrum sharing scenarios in non-wide area networks, spectrum (and computing) resources dynamic orchestration in edge cloud server offloading, Digital Twin-based human presence model for flexible and dynamic spectrum management at high frequencies (mm-wave, sub-THz, and above). Finally, an

overview on initiatives to enable new spectrum for mobile is also addressed, complemented by a set of high-level spectrum-related elements that have been deeply discussed at both Task and Project level.

6G technology holds considerable promise for enhancing **sustainability** in both ICT and non-ICT sectors. Infrastructure sharing, artificial intelligence, spectral efficiency, sleep modes, and adaptative architecture, among other levers, have the potential to reduce the energy consumed per transported data unit (Wh/bit) in the RAN perimeter by a factor of 10. This corresponds to **90% improvement in energy efficiency** compared to 5G. When considering only two technical enabler families out of four, the reduction of the total 6G network TCO is about 26.4% compared to the baseline, 5G new radio system. It is reasonable to expect that technological enablers have the potential to **reduce the 6G network TCO by almost 30%** compared to the baseline. 6G-powered ICT solutions have the potential to help other sectors **reduce GHG emissions by almost 30%.** Assessing enablement effects of 6G is based on comparing a scenario with a 6G-powered ICT solution, and a reference situation with an activity that is not powered with 6G.

The nature of security work in networking is always that of an activity required to work both horizontally, across different network segments and domains to address E2E properties, and vertical, addressing the different planes and layers and their interactions to detect threats and propose remediations. This document presents the final results of the Hexa-X **security analysis** for 6G, including:

- The architectural mapping of security components on the proposed E2E 6G network architecture.
- The impact of security and privacy on one of the key KVIs identified for 6G: network service trustworthiness.
- The proposal for assessing trustworthiness through measurable indicators and an evidence-based, AI-enabled process.
- The importance of data exchange trustworthiness in evidence-based network management, including the possibility of a dedicated evaluation mechanism to support context awareness.
- The requirements and technologies for a trustworthy application of AI techniques in network infrastructures and services, with a specific focus on explainability and privacy protection.
- Other considerations on 6G security, related to D-MIMO, location services and functional isolation.

We believe these considerations set the ground for further experimentation, development, and standardization of security procedures, as the general 6G technology evolves. Early experimentation will be required to follow the ***security-by-design*** principle, unanimously acknowledged as the correct method to follow in developing dependable ICT infrastructures. The first stages of this early experimentation will require the use of synthetic environments, like Network Digital Twins as proposed by Hexa-X-II, to provide an accurate assessment with respect to technologies that are still in a consolidation phase

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List of acronyms and abbreviations

3GPP	3rd Generation Partnership Project
4D	4-dimensional
5GC	5G Core
5GPPP	5G Infrastructure Public-Private Partnership
5GS	5G System
aaS	as-a-Service
AC	Autonomic Computing
ADC	Analog to Digital Convertor
AGV	Automated Guided Vehicle
AI	Artificial Intelligence
AIaaS	Artificial Intelligence as a Service
AM	Autonomic Manager
AMF	Access and Mobility management Function
AP	Access Point
API	Application Programming Interface
AR	Augmented Reality
ARoF	Analogue Radio over Fibre
ATIS	Alliance for Telecommunications Industry Solutions
B2B	Business to Business
B2G	Business to Government
B5G	Beyond 5G
B5GPC	Beyond 5G Promotion Consortium
BB	Buildings Blocks
BEREC	Body of European Regulators for Electronic Communications
BS	Base Station
CaaS	Compute as a Service
CAGR	Compound Annual Growth Rate
CapEx	Capital Expense
CAPIF	Common API Framework
CBRS	Citizens Broadband Radio Service
CD	Continuous Delivery
Cd	Continuous Deployment
CI	Continuous Integration
CI/CD	Continuous Integration/ Continuous Delivery
CIA Triad	Confidentiality, Integrity, and Availability Triad

CL	Control Loop
CM	Continuous Monitoring
CN	Core Network
CNF	Cloud-native Network Function
CoCoCoCo	Communication-Computation-Control-Codesign
CP	Control Plane
CT	Continuous Testing
CU	Centralized Unit
D2D	Device to Device
DC	Dual Connectivity
DCCF	Data Collection Coordination Function
DDoS	Distributed Denial of Service
DFP	Dynamic Function Placement
DL	Down Link
D-MIMO	Distributed MIMO
DSCP	Differentiated Services Code Point
DT	Digital Twin
DU	Distributed Unit
E2E	End-to-End
ECF	Exposure and Coordination Framework
ED/LC	Early Detect/ Late Commit
EE	Energy Efficiency
eMBB	enhanced Mobile Broadband
EMF	Electromagnetic Field
EMG	Electromyography
e-MTC	enhanced Machine-Type Communication
ETSI	European Telecommunications Standards Institute
FL	Federated Learning
FLaaS	Federated Learning as a Service
FLM	FL Local Manager
FLP	FL Service Provider
FPC	FL Process Controller
FPCE	FL Process Computation Engine
FR	Frequency Range
GaN	Gallium Nitride
GDP	Gross Domestic Product
GeSI	General European Strategic Investments

GHG	GreenHouse Gas
GPAI	Global Partnership on Artificial Intelligence
GPS	Global Positioning System
GPT	General-Purpose Technology
GSMA	Global System for Mobile Communications Association
HAPS	High Altitude Platform Systems
HMI	Human Machine Interface
HRPS	High Reduction Potential Scenario
HSM	Hardware Security Module
I4.0	Industry 4.0
IAB	Integrated Access and Backhaul
ICAS	Integrated Communication And Sensing
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ICT	Information and Communication Technology
IEA	International Energy Agency
IIoT	Industrial Internet of Thing
IMSI	International Mobile Subscriber Identity
IMT	International Mobile Telecommunications
INT	In-band Network Telemetry
Intra-X	Intra-subnetwork
IoT	Internet of Things
ISL	Inter-Satellite-Links
ITU	International Telecommunication Union
ITU-R	International Telecommunication Union – Radiocommunication Sector
ITU-T	International Telecommunication Union - Telecommunication Standardization Sector
KPI	Key performance Indicator
KVI	Key Value Indicator
LCM	Life-Cycle Management
LEO	Low Earth Orbit
LIDAR	LIght Detection And Ranging
LoS	Line of Sight
LoT	Level of Trust
LoTAF	Level of Trust Assessment Function
M&O	Management and Orchestration
MAC	Medium Access Control
MCS	Modulation and Coding Scheme

MEC	Mobile Edge Computing
MFAF	Messaging Framework Adapter Function
micro-DTX	micro-Discontinuous Transmission
MIMO	Massive Input Massive Output
ML	Machine Learning
mMTC	massive Machine Type Communication
mMTC+	evolution of massive machine type of communication
MNO	Mobile Network Operator
MR	Mixed Reality
MRPS	Medium Reduction Potential Scenario
MTBF	(Mean) Time Between Failures
MTTFF	(Mean) Time to First Failure
MTTR	Mean Time To Recovery
Multi-TRP	Multiple Transmission and Reception Points
MVNO	Mobile Virtual Network Operator
NB-IoT	Narrow-Band IoT
NCR	Network Controlled Repeater
NESAS	Network Equipment Security Assurance Scheme
NextG	Next-Generation
NF	Network Function
NFV	Network Function Virtualization
NGMN	Next Generation Mobile Networks
NG-RAN	Next Generation Radio Access Network
NIC	Network Interface Card
NiN	Networks in Network
NPN	Non-Public Network
NR	New RAN
NRF	Network Repository Function
NSA	Non-Standalone
NSF	National Science Foundation
NSM	Network Service Mesh
NTN	Non-Terrestrial Network
NWDAF	Network Data Analytics Function
OECD	Organisation for Economic Co-operation and Development
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
OpEx	Operating Expenses

O-RAN	Open-Radio Access Network
PA	Power Amplifier
PAPR	Peak to Average Power Ratio
PER	Packet Error Rate
PM	Programmability Manager
PMSE	Program Making and Special Events
PPDR	Public Protection and Disaster Relief
QoE	Quality of Experience
QoS	Quality of service
R&I	Research and Innovation
RAN	Radio Access Network
RAP	Radio Application Package
RE	Reconfigurable Equipment
RF	Radio Frequency
RINGS	Resilient and Intelligent Next-Generation Systems
RIS	Reconfigurable Intelligent Surfaces
RRM	Radio Resource Management
RTT	Round Trip Time
RU	Radio Unit
SA	Stand Alone
SBA	Service Based Architecture
SBI	Service Based Interfaces
SBMA	Service Based Management Architecture
SBTi	Science Based Targets initiative
SCITT	Supply Chain Integrity, Transparency, and Trust
SCP	Service Communication Proxy
SDG	Sustainable Development Goal
SDN	Software-Defined Networking
SIM	Subscriber Identity Module
SINR	Signal to Interference and Noise Ratio
SLA	Service Level Agreement
SLAM	Simultaneous Localization and Mapping
SNR	Signal Noise Ratio
SNS-JU	Currently Smart Networks and Services - joint undertaking
SNVC-SG	Societal Needs and Value Creation Sub-Group
SON	Self-Organizing Network
SS	Spread Spectrum

SSLA	Security Service Level Agreements
SUCI	Subscription Concealed Identifier
TaHil	Tactile Internet with Humans in the loop
TCO	Total Cost of Ownership
TDMA	Time Division Multiple Access
TEE	Trusted Execution Environment
TN	Terrestrial Network
TSDSI	Telecommunications Standards Development Society, India
UAP	Universal Adversarial Perturbation
UAV	Unmanned Aerial Vehicles
UC	Use Case
UE	User Equipment
UHD	Ultra-High Definition
UL	Up Link
UN	United Nation
UN SDG	United Nation Sustainable Development Goal
UNFCCC	United Nations Framework Convention on Climate Change
UPF	User Plane Function
URA	Unified Radio Application
URLLC	Ultra-Reliable and Low Latency Communications
UWB	Ultra-Wideband
VNF	Virtual Network Function
VR	Virtual Reality
vRAN	Virtual RAN
WP	Working Party
WRI	World Resource Institute
X2I	Subnetwork-to-wide-area network
X2X	Inter-subnetwork
XR	Extended Reality
ZSM	Zero-Touch Service Management

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 6G vision and an intelligent fabric of technology enablers connecting human, physical and digital worlds.

This report is the fourth and the final deliverable of Work Package 1 (WP1) — "Hexa-X architecture for B5G/6G networks". It starts with an updated analysis of current trends in societal, economic, regulatory and technology and moves to a summary of most significant 6G global activity. It also presents the updated Hexa-X vision on 6G based on technical developments inside and outside the project. Identifying aspects of 6G business are also included.

This deliverable provides a summary of all Hexa-X use cases and their requirements, including final refinements of the Telepresence use case. The use cases and requirements are mapped to state of the art from other ICT-52 projects, the research community in general, and company whitepapers. The final set of Key Performance Indicator (KPI) definitions and the underlying methodology is briefly presented, including a discussion of the relation between resiliency and dependability. Finally, the Key Value Indicator (KVI) methodology is detailed and the four KVI areas sustainability, inclusion, flexibility, and trustworthiness are characterizes. Technical enablers, measurements and ideas for quantification are also discussed.

An updated version of End-to-End (E2E) architecture is provided. This is continuation of previous architecture version from Deliverable D1.3. The main objective of the presented architecture is to map the enablers developed in the technical WPs of Hexa-X project to the E2E architecture and show the relationship between those enablers. The architectural aspects of Radio Access Network (RAN) technologies, localization and sensing as well as enablers of intelligent, flexible and efficient are discussed. Various aspects of Management and Orchestration (M&O) are also presented.

Concerning spectrum, aspects relevant to extending spectrum utilization in frequency ranges already in use (i.e., low, mid, and mm-wave) and in new potential frequency ranges (e.g., 7-15 GHz in the centimetric range and 92-275 GHz in the sub-THz range) to address 6G service requirements are considered. Furthermore, linked with relevant studies carried out in the technical work packages, spectrum related aspects concerning innovative concepts of flexible spectrum usage and management are also addressed in this deliverable. Finally, an overview on initiatives to enable new spectrum for mobile is also addressed, complemented by a set of high-level spectrum-related elements that have been deeply discussed at both Task and Project level.

Conclusive outcomes regarding the sustainability assessment of Information and Communication Technology (ICT) solutions are presented. A comprehensive analysis of the enablement potential evaluation methods and applicability to 6G use cases is provided. For environmental sustainability, the analysis reveals a tenfold (x10) enhancement in Energy Efficiency (EE) corresponding to 90% improvement compared to 5G New Radio (NR) system. The assessment methodology of the Total Cost of Ownership (TCO) for financial sustainability shows that 6G networks will achieve almost 30% reduction of TCO compared to 5G.

Once the 6G *security delta* was established and discussed in D1.3, along with an identification of the building blocks to incorporate security and privacy concerns in the proposed 6G architecture, this document focuses on three main aspects related to these concerns. First, as a conclusion of the identification of the security building blocks, an architectural approach to security is proposed, mapping these building blocks on the general Hexa-X architecture. Second, a deep analysis of the connection of security and privacy techniques and the key trustworthiness KVI is provided, with a proof-of-concept tooling to support trustworthiness assessment. Finally, an analysis of the most relevant security considerations, both motivated by the direct reflections within the security team and by the interaction with other project WPs, is provided.

1.1 Hexa-X objective on "Foundations for an End-to-End system towards 6G"

This section gives an overview of the work in Hexa-X towards the objective of providing a foundation for an E2E system towards 6G. Work package 1 developed a cross-WP visions and roadmaps of the Hexa-X fabric with relevant use cases, architecture blueprints, security support, new spectrum design as well as addressed the 6G sustainability aspects, key value indicators (KVIs) and performance targets (KPIs). The main goal of this objective is to connect intelligence, sustainability, trustworthiness, inclusion, and extreme experience. Work package 1 guided the work in the whole project and provided requirements for all other work packages.

1.1.1 Hexa-X outputs towards "Foundation for an End-to-End system toward 6G"

The outputs towards the objective are reported in the four work package 1 deliverables:

[HEX21-D11]	Hexa-X, "Deliverable D1.1: 6G Vision, use cases and key societal values" February 2021.
[HEX21-D12]	Hexa-X, "Deliverable D1.2: Expanded 6G vision, use cases and societal values – including aspects of sustainability, security and spectrum" April 2021.
[HEX22-D13]	Hexa-X, "Deliverable D1.3: Targets and requirements for 6G – initial E2E architecture" March 2022.
[HEX23-D14]	Hexa-X, "Deliverable D1.4: Hexa-X architecture for B5G/6G networks – final release" July 2023. (this document)

1.1.2 Hexa-X measurable results towards "Foundation for an End-to-End system towards 6G"

The following measurable results for the objective are completed in the work package 1 deliverables.

A 6G vision report describing four main use cases driving the 6G development; key values and requirements, including United Nation Sustainable Development Goals (SDGs); key technical enablers; E2E system vision.

In order to design the 6G system, which would realize the Hexa-X 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 are not only a simple extension of the 5G use cases, but they are outline new usages, based on a more inclusive (along the geographical as well as the societal axis) and more sustainable use of the technology. Hexa-X has defined in *Deliverable D1.1* and *D1.2* initial use case families and use cases which associated to the six research challenges. Hexa-X has successfully identified 27 use cases (instead of 4) grouped in 6 use case families. The use cases have been reviewed based on the work conducted in the technical work packages and the updated version published in *Deliverable D1.3*. The current document (Deliverable D1.4) contains a analysis of Hexa-X use cases in compare with the 6G eco system.

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 sustainability, trustworthiness, and inclusion. 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, etc. *Deliverable D1.2* presented a qualitative analysis of KPI and KVI areas for a selection of use cases and formulated functional requirements for the respective use cases. Based on this analysis, technical work packages identified and refined KPIs related to the service offered by the work package (e.g., communication, AI, localisation, sensing, ...) in their gap analysis during the first phase of the project. These individual inputs on KPIs have been aligned in work package 1 and, consequently, updated KPI definitions are presented in *Deliverable D1.3.* This document (*Deliverable 1.4*) focuses on deepen the analysis of the technical enablers proposed in other Hexa-X work packages regarding their potential to contribute to the key values sustainability, trustworthiness, inclusiveness, and flexibility. This includes the impact of the architectural concepts on performance indicators and limitations in potential deployments.

Deliverable D1.3 summarised the technical enablers which are required for the 6G architecture envisioned by Hexa-X. The technical enablers are the important components for the transformation to the new architecture and they are essential for supporting the requirements of 6G use cases presented in the previous deliverables of work package 1 as well as in *D1.2*. To this end, in *Deliverable D1.3* the most impacting architectural enablers such as enablers for RAN technologies, Localization and sensing, enablers for intelligent, flexible and efficient network and service management and orchestration are thoroughly reviewed and their requirements from the new architecture are also characterised. *Deliverable D1.4* (current document) conducted a comprehensive study on the architectural technical enablers in order to be able to provide a concrete conclusion on the design of the 6G E2E architecture. In particular, deepened the knowledge on each technical enabler and collaborated closely with technical work packages to identify the details of each building block of future mobile network generation.
Deliverable D1.3 also has the first description of a Hexa-X 6G E2E architecture. The gap analysis is performed based on use cases defined in *Deliverable D1.2* as well as a set of requirements introduced by each technical enabler. Furthermore, a system view figure (figure 3-2 Deliverable D1.3) of 6G E2E architecture is presented. A parallel study in collaboration with the security task is also conducted in order to present the security architecture components aligned with E2E architecture.

Network solutions contributing in significant ways to the UN SDGs 8, 9, 11, 12, and 13.

Technical works done in Hexa-X contributed to the following UN SDGs:

UN SDG #8: Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.

Network solutions aiming for coverage extensions, e.g., Non-Terrestrial Network (NTN), would provide coverage towards remote areas and provide e-commerce opportunities for these areas and contribute to inclusive and sustainable economic growth. Taking advantage of the technical advantages in telepresence area e.g., Augmented Reality (AR), Virtual Reality (VR) and Extended Reality (XR) make the digital education and employment training a possibility for all and hence would contribute to full and productive employment for all. More details on the work on these areas can be found in work package 5 deliverables.

UN SDG #9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

Network solutions proposed by Hexa-X would enable mobile networks to provide Compute as a Service (CaaS) and Artificial Intelligence as a Service (AIaaS) which would reduce the capital investment for compute infrastructure for small/medium size innovative companies in the least developed countries and hence would promote inclusive industrialisation and would foster innovation in these regions. More details on the work on these areas can be found in work package 5 deliverables. Additionally, the progress of Hexa-X on the security, privacy and trust aspects of the future mobile network laid the foundation for building a resilient infrastructure. More details on the work on the security can be found in *Deliverable 1.2, 1.3 and 1.4*.

UN SDG #11: Make cities and human settlements inclusive, safe, resilient, and sustainable.

Hexa-X has been contributed to this goal from different aspects. As part of developing the various use cases, immersive smart city had a particular importance due to the necessity of providing a safe and sustainable environment for the society. Additionally various works has been done in work package 5 for instance on the topic of sub networks and integration of micro-networks for a smarter city.

UN SDG #12: Ensure sustainable consumption and production patterns.

Possible solutions related to eco-design of products (extended lifetime, life cycle analysis, choice of materials, enabling enhanced circularity), and end-of-life management (reuse and recycling strategies to reduce electronics waste) as well as network solutions towards integrating zero-energy devices would reduce the need for batteries and hence slow down the growth of material footprint for producing electronic communication devices. are namely few of the analysis that has been done by sustainability task of work package 1 and reflected in Deliverable D1.2. It is also important to mention that the solutions towards enabling new services beyond communications, e.g., localisation, sensing, AIaaS, and CaaS, make it possible for the network infrastructures to provide services beyond communication and hence the material footprint would be reduced compared. These techniques can be found in detail in work package 3 deliverables.

UN SDG #13: Take urgent action to combat climate change and its impacts

Sustainability task of work package 1 has been done exclusive work on the sustainability environmental aspect e.g., enabling reduction of emission of more than 30% of CO2 equivalent in 6G-powered non-ICT sectors. So far investigation has been done on the baseline (5G NR SA) for the calculation as well as method of choosing.

Technical enablers for digital inclusion of a high fraction of the world population.

In *Deliverable D1.3* as well as *D1.4* particular study conducted on the impact and requirements of the enablers for flexible network which is continuation of the work done in work package 5. Flexible networks intend to enable extreme performance and global service coverage. The network functionality and architecture must then be flexible enough so that it can adapt to different topologies. To this end enablers such as NTN as a new solution for mobility and coverage as well as campus networks to providing extreme performance has been introduced and studied.

Spectrum solutions supporting high flexibility, bandwidth, and coverage.

In *Deliverable D1.3* technical enhancements to further optimise spectrum utilisation have been studied. Also, it was highlighted that conditions for spectrum sharing between International Mobile Telecommunications (IMT) systems and systems of other services could improve and prove to be possible if more realistic technical characteristics and deployment scenarios are applied. Additionally, some techniques had been introduced both for spectrum utilisation and sharing enhancement, e.g., improving the usage of available spectrum in the different IMT frequency bands, new coordination mechanisms and techniques for local spectrum use, 6G Networks in Network (NiN) as prospective solutions that can allow interference-controlled operation. In Deliverable D1.4, the above- mentioned topics have been updated and further elaborated, considering e.g., the evolution on the international stage of the discussion around new spectrum allocations to IMT systems with respect to the extending spectrum utilization aspects, and the work carried out in technical work packages with respect to the flexible spectrum usage and management innovative concept.

1.1.3 Hexa-X quantified results towards “Foundation for an End-to-End system towards 6G”

The quantified targets of work package 1 are 3-folds:

1. **Enabling reductions of emissions of CO_2 equivalent by more than 30% in 6G-powered sectors of society**
   Hexa-X has committed to meet requirements related to multiple domains like performance, social value, and sustainability. In *Deliverable D1.3 (page 91)* a dedicated study conducted to the enablement effect, that is, the opportunity for 6G to support society and stakeholders across all sectors of the economy in becoming more sustainable (“6G for sustainability” trend in Hexa-X). Today, both the baseline and agreed detailed methods and harmonised standards that describe a clear methodology for evaluating the “enablement” impact of ICT on other sectors are lacking. It is also concluded that the overall effect of 6G (the aggregated effect of all potential, future use cases is beyond reach as the total use of 6G) cannot be foreseen. Consequently, the evaluation of 6G can only be scenario based, and refer to specific use cases, mainly those defined by Hexa-X. In *Deliverable D1.4*, conclusive outcomes regarding the sustainability assessment of ICT solutions, and a comprehensive analysis of the enablement potential evaluation methods are highlighted. The enablement potential of ICT solutions in 6G-powered industries is estimated around 30% GHG emissions reductions compared to 5G. An educated reading of the ITU-T L1480 assessment method analyses its applicability to 6G use-cases as well as challenges and uncertainties resulting from the lack of data.
2. **Total Cost of Ownership (TCO) reduction by almost 30%**
   The TCO allows for quantifying the economic effort of an operator prior to deploying a new generation of mobile networks, encompassing both Capital Expenses (one-time costs) and Operating Expenses (recurring costs) – i.e., CapEx and OpEx. In Deliverable D1.3 some research has been done in the perspective based on MNO legacy networks. E.g., 30% of Capex in the emerging market vs. 10 % in the developed market when including the energy supply and backup systems as well as the site technical environment (batteries, cooling system, AC/DC converters, etc.). The estimated energy OPEX is about 20% in the emerging markets vs. 10 %in developed markets of the total OPEX per site. In *Deliverable D1.4*, an in-depth study of the TCO reduction potential of different technological enablers is provided. The potential weight of each cost item when applying only two out of four technical enabler families, results in 26.4% reduction of the total 6G network TCO compared to 5G NR SA. Thus, the 30% TCO reduction target is expected to be attainable given that the remaining families will bring further reductions, and is potentially provable by future research.
3. **Reducing energy consumption per bit in networks by more than 90%**
   It relates to the sustainability of 6G (“Sustainable 6G” trend in Hexa-X) in terms of performance and efficient transmission by linking the energy consumption to the delivered data to users. Energy efficiency is defined as the energy consumption per transported data unit (Wh/bit) in the RAN perimeter. In *Deliverable D1.4,* the energy efficiency of 6G is approached from an agility perspective which considers a deployment from local to global scale while implementing consumption agility regarding the other classic KPIs (datarate, latency...) for each given use case. Several 6G technology levers, including RF power amplifier technology, electronic components, artificial intelligence systems, adaptive air interface, sleep modes, infrastructure sharing, etc. have been assessed for their potential to enhance energy efficiency compared to 5G NR SA.

1.2 Objective of the document

The objective of this document is to provide a conclusion on all the E2E topics in work package 1. This includes the final update on the Hexa-X 6G vision which achieved based on the progress inside and outside the project. An analysis has been conducted on the introduced use cases, services, and KPIs/KVIs to map them in compare of other ICT-52 projects, research and industry ecosystem.

Sustainability targets as well as spectrum studies is concluded. This document also provides the final draft of the Hexa-X E2E 6G architecture including a security architecture.

1.3 Project and Work Package 1 set-up

The Hexa-X project is structured in nine work packages (see Figure 1-1) 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 E2E view. The technical work packages are focused on the 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.

This report is Deliverable D1.4 of WP1. WP1 has the main objective to define an overall vision, use cases, and 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 1-1) to achieve its main goal.

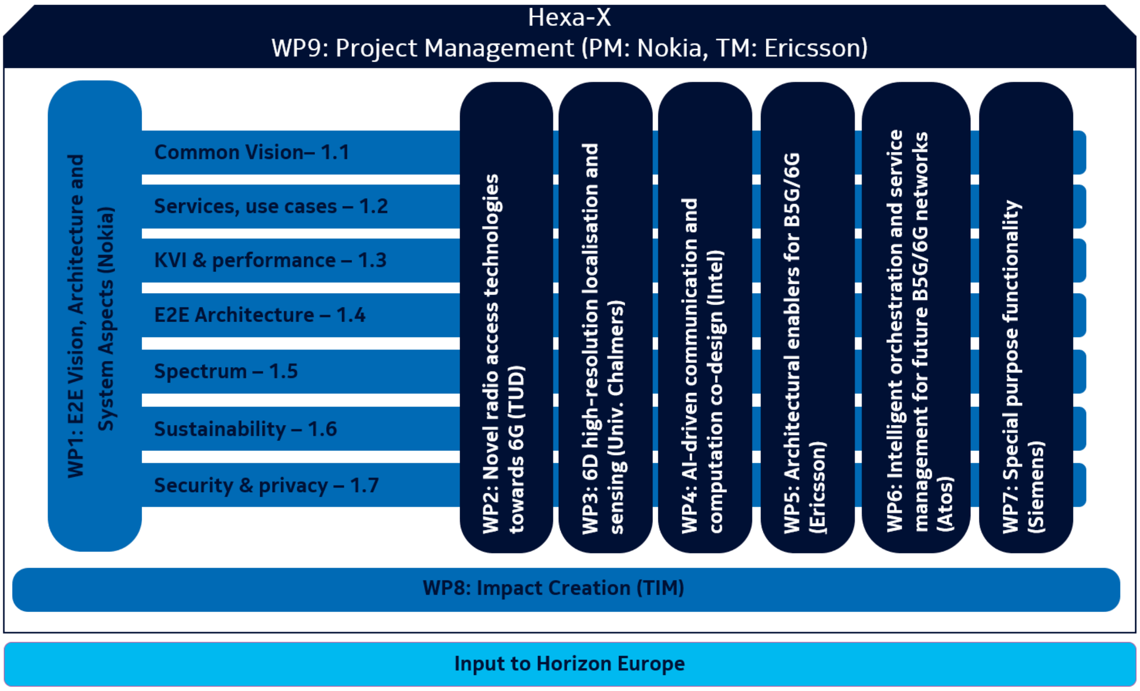


Figure 1-1: Hexa-X project structure

1.3.1 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), E2E architecture (Task 1.4), 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 provided the following deliverables:

- D1.1: 6G vision, use cases and key societal values (delivered: M02). This report describes 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 (delivered: M04). This report describes 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. Initial consideration of sustainability targets, spectrum, and security aspects will also be included.
- D1.3: Target and requirements for 6G – initial E2E architecture (delivered: M14). This report includes 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 is delivered, including a draft security architecture and an update on security considerations.
- D1.4: Hexa-X architecture for 6G networks – final release (delivery date: M30). This current report presents 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.

1.4 Structure of the document

The document is structured in the following way: Chapter 2 introduces provides an updated view on the Hexa-X 6G vision. Chapter 3 gives a view on the 6G ecosystem on the use cases and their requirements and performance targets. Chapter 3.1 describes the final version of the E2E 6G architecture. Chapter 4.1 presents the final recommendations on the security and trustworthiness topics. Chapter 5.1 focuses on spectrum evolution aspects and Chapter 0 describes the Hexa-X sustainability targets and the proposed methodologies. The document concludes with the outlook and way forward on the 6G development in Chapter 7.1. Annex A position Hexa-X use cases in the 6G eco system. Annex B is the extended version on the assessment of enablement effect. The Hexa-X project technical terms can be found in Annex C.

2 Common Vision

This is an update on the common vision Task 1.1 provided at the beginning on the Hexa-X project. This update is based on the progress inside and outside of the Hexa-X.

1.1 Analysis of current trends in society and technology towards 6G

1.1.1 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 affects 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 a key enabler for such a transformation. The evolutionary 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 high economic and societal impact.

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 and perspective in all steps of the design [LUM12], while also factoring in the ecological and economical aspects. The design of future networks is expected to strike a balance between technological innovation, economical and environmental sustainability, and human-centric values. The goals are to not only promote economic prosperity and sustainable growth but to also act responsibly and to serve the individual and collective needs, interests, and values of European and global society.

In this context, Hexa-X analyzed major societal and economic trends towards 2030 and beyond for guiding the design of human-centric future networks. This analysis is presented in the following sections in addition to the evolution of regulatory regime and technological as well as architectural trends that are critical for the design and deployment of future networks. The text has been updated for D1.4 from D1.2 [HEX21-D12]. The vision and the research work developed by Hexa-X encompasses all the essential elements of these trends and has led to a future network design that is deeply rooted in reality and profoundly benefits humanity in the mid-to-long term.

1.1.2 Societal trends towards 2030 and beyond

1.1.2.1 6G for sustainability: Connectivity for a better and more sustainable world

In 2015, 17 interlinked Sustainable Development Goals (SDGs), as depicted in Figure 2-1: United Nation's sustainable development goals, 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], [ITU19]. Global System for Mobile Communications Association (GSMA) also estimates that mobile and digital technology can help achieve 40% of the 2030 emission reduction targets for the four industries that make up 80% of global emissions, namely, power and energy, transport, buildings, and manufacturing [GSM22].

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 communications 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], [NGA22], [Ora22]. 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]. This thinking has also been a part of [URB21] and Hexa-X (c.f. D1.2).

Figure 2-1: United Nation’s sustainable development goals

The Hexa-X contribution will mainly focus on SDG #8, #9, #11, #12, and #13. SDG #13 is an issue that poses profound long-term threat to world population and will continue to 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]. The UN has also announced an action plan to invest US$ 3.1 billion in creating a global early warning system to detect hazards and communicate warnings [WMO22] which will benefit from a global coverage. Future networks are expected to have a significant impact in reducing carbon emissions on many more public and private sectors (e.g., automotive, industrial, transportation, agriculture, education) by means of complementary innovation, unleashed by 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. It is also worth noting that the SDG framework is intended for states and applications to a technology sector such as ICT requires some adaptation.

1.1.2.2 Sustainable 6G

The European green deal [EC19] also 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-emissions and supporting companies’ net-zero ambitions [MAA+20], i.e., having as net no emissions caused by the activity of the company. 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 continue supporting the exponential growth in data consumption, it is critical to minimize the increase of energy usage in networks, striving for zero power consumption at zero load [ML18]. Such reduction must 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 of equipment and terminals will be counted for improving sustainability of networks and devices [Eri20], [ER20].

1.1.2.3 Built-in trustworthiness in an open society

Trustworthiness, in general, is a human-centric value that is closely related to several of the SDGs, especially #16 and #9. As communication networks are servicing and intertwined with all aspects of everyday life, the need for trustworthiness is apparent. In the context of communication networks, trustworthiness has a wide scope and can span anything from security and privacy (as discussed in detail in [ZSV+21], [HEX22-D13]) to aspects that also sort under the dependability framework, as described in [HEX21-D71], for example, availability and reliability of a network. The broader characteristics of trustworthiness — security, privacy, as well as availability, resilience, compliance with ethical frameworks — are foreseen to become new fundamental requirements for network design towards 2030 [Eri20], [Dem20]. Future networks must 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 End-to-End (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, which will make delivering trustworthy services paramount [Nok20].

With future networks, incorporating beyond communication-enabled services, there will likely be a massive deployment of wireless cameras, radar, lidar, and radio access with integrated sensing, and other sensing modalities 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] [ZSV+21]. 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].

1.1.2.4 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. According to [ITU22], it was estimated that around a third of the world population, i.e., around 2.7 billion, had no internet access at all as of 2022 (among them 75 million in Europe), where roughly 54% of individuals in rural or remote areas and 18% of households in urban or metropolitan areas have no internet access at home. In Africa, the situation is even more dire with no internet access at 36% of individuals in urban areas and 77% households in rural areas. However, the urban/rural divide has decreased in the last three years, from 2.3 to 1.8 as rural areas gradually catch up.

Meanwhile, global coverage is very important to address the climate transformation of energy and transport infrastructure as well as to improve the operational efficiency of 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].

The GDP impact of such global coverage is significant. According to [ITU20], an increase of 10% in mobile broadband penetration would result in a 1.5% increase in global GDP, with impact most pronounced in Africa and middle/low-income countries in the Asia-Pacific region. Most of the countries in these regions would see a GDP increase of approximately 2.4%.

Moreover, new technologies are typically expensive when initially introduced and cost goes down over time with wider adoption and due to economy of scale effects. This trend will also hold with 6G. Consequently, 5G, which would have become mature when 6G rolls out would be one option to satisfy global coverage. Alternatively, 6G can be envisioned to have multiple gears – where different performance targets can seamlessly be traded off for one another. For instance, the network may be put on a high-performance gear to aggressively meet performance targets such as throughput and latency, or an energy efficiency gear that minimizes energy consumption at low/medium loads. Likewise, 6G could be envisioned to have a cost efficiency gear that could either offer 5G features at lower deployment and/or operational cost or introduce new 6G features that are designed with affordability in mind.

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], [Ora22].

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 have faced 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 spread 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].

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

AI has started being 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 anywhere.

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. 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. According to [EC19a], an AI system is deemed trustworthy when it has three components, namely, lawfulness - complying with laws and regulations, ethics - ensuring adherence to ethical principles and values, and robustness from a technical and social perspective.

Several pieces of legislation and policy initiatives have been introduced both globally and in the EU since 2020 with regards to the legality, ethics, and utility of AI in society and technic fields. For example, the EU AI act [EC21a], introduced by the EU in April 2021, aims to establish a common European framework for AI, which would cover the development, deployment, and use of AI systems. The act includes provisions that prohibit certain AI applications that are deemed high-risk, such as social scoring and facial recognition in public places, unless they meet strict conditions. It also requires transparency and accountability for AI systems and introduces mandatory testing and certification for certain high-risk AI applications. The US national artificial intelligence initiative act [US20], passed in January 2021, aims to accelerate the development and adoption of AI technologies in the US. The act provides funding for research and development of AI, as well as for workforce training in AI-related fields. In addition, the Global Partnership on Artificial Intelligence (GPAI) [GPA20] was launched in June 2020 by the G7 countries along with Australia, India, Mexico, New Zealand, South Korea, and Singapore. The initiative aims to promote responsible and human-centric AI through international cooperation and collaboration. GPAI focuses on four key areas: responsible AI, data governance, AI innovation, and the future of work. Additional regulations and frameworks include the Organisation for Economic Co-operation and Development (OECD) AI principles [OEC19] introduced in 2019 that have value-based principles such as inclusive growth, sustainable development and well-being, human-centered values and fairness, transparency and explainability, robustness, security, safety, and accountability, as well as recommendations for policy makers.

Furthermore, 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 [Eri22b].

1.1.2.6 Metaverse as a driver for 6G

The metaverse has come a long way since being coined by Neal Stephenson in a science fiction novel almost 30 years ago [Ste92]. Virtual and Augmented reality (VR/AR) have been under discussion for quite some time before the beginning of the Hexa-X project [EPB+18], with VR platforms such as Second life (launched in 2003) [Lin13] and VRChat (launched in 2014) [Vrc14] being one of the initial pushes towards a consumer metaverse. However, limited computing power, resulting in mediocre graphics, a niche and nascent display technology, and a cumbersome human-machine interface have limited its adoption to gamers and enthusiasts.

The recent buzz around the metaverse began in early 2021 (after Hexa-X started) when Facebook rebranded itself to Meta and bet its future on the success of its metaverse, Horizon Worlds [Met21]. This brought the idea of the metaverse into the limelight and piqued the interest of the public and companies. Indicative of this is that brands such as Adidas, Burberry, Gucci, Tommy Hilfiger, Nike, Samsung, Louis Vuitton, and even the banks HSBC and JP Morgan have set up stores in the Meta's metaverse [BBC22]. The metaverses – for consumer, enterprise, and industry - are a part of Nokia's Technology Vision 2030 and is built on the merging the physical, digital, and human worlds [Nok21]. Ericsson believes that 5G is paving the way for the metaverse [Eri22] and that 6G will make it possible to seamlessly move in a cyber-physical continuum [Eri22a]. Chipmakers Nvidia and Intel also see potential in this concept [Nvi21], [Int21].

However, the metaverse has a much broader scope than what is currently being portrayed in the media. The metaverse is considered to be an evolution of the internet [Mit22] and promises to change the way we communicate, consume media, and work. For example, Nokia's Technology Vision 2030 for the metaverse is based on the idea of human augmentation (extensions that enable people to interact with and within the digital world) and/or digital-physical fusion (dynamic connected representations of real-world things in the digital world) [Nok21]. In addition, this metaverse (or these metaverses) are built on highly detailed digital twins of the physical and human worlds like connected sensors, actuators, and interfaces. The metaverse and its key enablers are shown in Figure 2-2.

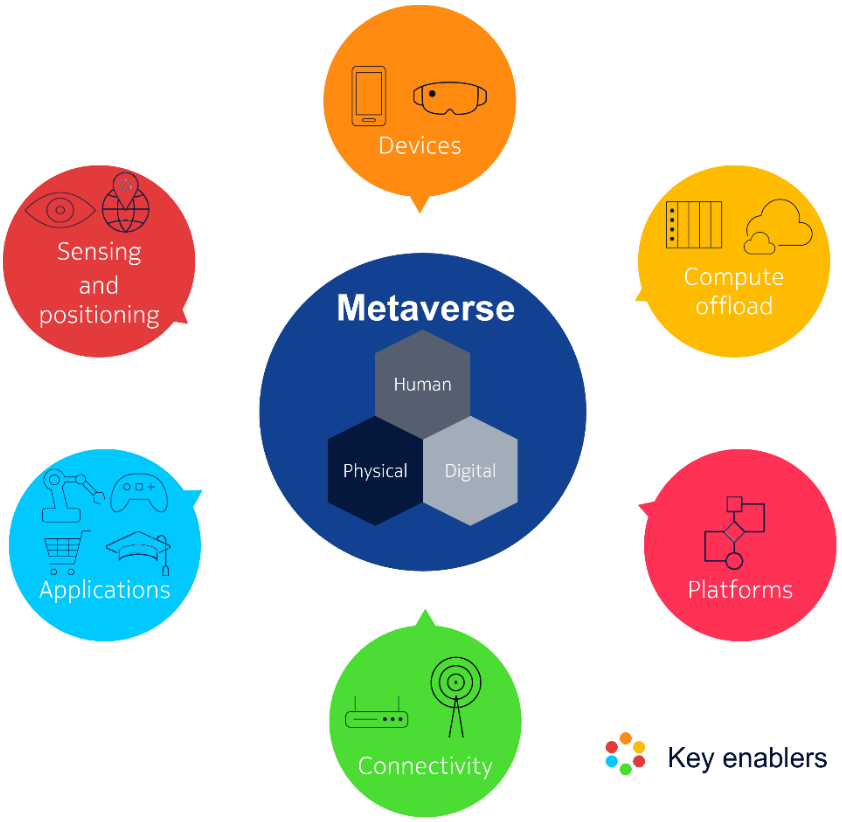


Figure 2-2: The metaverse with key enablers

As can be seen in Figure 2-2, the metaverse enables seamless interaction between the physical, digital, and human worlds and is built with six key enablers – connectivity that enables real-time exchange of information between the three worlds, platforms for building metaverse experiences, compute offload to enable low-power low-cost devices/sensors by offloading computations to the edge cloud, devices to help humans interface with the digital world, sensing and positioning to enable a digital representation of the physical world, and lastly, applications that can utilize the metaverse to generate value.

The metaverse is poised to offer significant opportunities for industries, enterprises, and consumers [Nok22a]. Industries could have an Extended Reality (XR)-enabled workforce, provide remote control and support for industrial exoskeletons, improve efficiency with predictive maintenance, and develop and support new specialist industry 4.0/5.0 use cases. Meanwhile, enterprises would benefit from immersive team collaboration, digital co-design, XR training and simulations, remote office/infinite workplace, and enhanced customer engagement. With video calls already having become common in the last decade, the metaverse has the potential to take telepresence to the next level by enabling an immersive experience where one could envision immersive gaming, on-demand entertainment, AI-optimized social interactions, and new shopping and travel models becoming more engaging and lifelike than their present counterparts. Holographic communication will be an important enabler for consumer metaverse applications [Eri22c].

The key enablers for both the consumer and industrial metaverses include a strong communication and sensing/localization backbone capable of meeting strict Key Performance Indicator (KPI) targets while being sustainable and energy efficient [Nok22a]. A communication backbone would enable offloading computation, for example, to render the virtual environment or to render virtual objects for augmented reality. A next generation standard, 6G, would provide this backbone [Eri22]. For consumer applications, 6G would enable AR and VR in outdoor environments, whereas, for industrial applications, it would mean improvements in efficiency through better data visualization and control.

1.1.2.7 Mobile communications as a global ecosystem and success story

Since its second generation, mobile communication and its research have become a true global success story driven by a worldwide joint effort and open collaboration by researchers, developers, standardization organizations, and companies. 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 [3GP]. The 5G Infrastructure Public-Private Partnership (5GPPP) under Horizon2020 framework programme 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]. Currently Smart Networks and Services and its joint undertaking (SNS-JU) together with European commission is on its way to continue the heritage of 5GPPP in the new funding framework Horizon Europe [SNS22]. To address the sustainability aspects of networks, standardization has started to take increasingly into account energy efficiency in the communication systems. Efficiency in material usage is taken into account in recent work in Telecommunication Standardization Sector (ITU-T) and European Telecommunications Standards Institute (ETSI) via assessment criteria [ETS18].

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. These geopolitical factors and the push for digital sovereignty and supply chain security have resulted in economically significant rulemaking, such as the CHIPs and science act ($280 billion) [Mck22] and inflation reduction act ($370 billion) [US22] in the US, the chips act (€43 billion) in the EU [EC22a], government export financing ($130 billion) in China, and the chips act ($53 billion) in Korea.

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 [ORN23]. Since 6G will target a wide variety of different applications, a risk of fragmentation and duplication of effort can arise.

Hexa-X has begun guiding the 6G design in line with the best practice of Research and Innovation (R&I) principles in Europe, advocating the European position of fair and open collaboration, standardization, and precompetitive joint research, with the publication of technical reports and organization of workshops with global attendance [Hex23].

1.1.3 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. According to [Pwc21], 5G could add US$1.3tn to global GDP by 2030 in healthcare, smart utilities, consumer and media, industrial manufacturing, and financial services. Estimates of the economic impact of 5G in Europe in time period 2021-2025 in [Acc21] expect 5G to drive up to €2.0 trillion in new economic gross output (sales), translating up to nearly €1 trillion in GDP over the time period. Future networks will be a key enabler for such a revolution with advanced technology capability and human-centric design.

1.1.3.1 Digital technologies as foundations of recovery and sustainable growth of global economy

Rattled by the COVID-19 pandemic, global economy was pulled into a 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]. The economic recovery from COVID-19 has also been impacted by the war in Ukraine and the energy crisis that followed it. 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.

On the other hand, the digital economy saw rapid growth during COVID-19 [UN21] with digitalization and wireless technology playing a critical role in softening the economic impact of lockdowns. Some of these economic benefits were through enabling certain sectors of the economy to continue functioning normally through remote work, education, healthcare, and e-commerce. Digitalization also helped slow the spread of COVID-19 through better contact tracing [WB20] and by allowing non-essential personnel maintain social distancing till the development and distribution of vaccines, thereby keeping people healthy and productive.

According to the econometric analysis in [ITU21b], countries with less than 10% fixed broadband penetration experienced a GDP per-capita contraction of -0.024 percent for every 1 percent increase in deaths per 100 population. However, countries with more than 90% fixed broadband penetration experienced a 21% smaller GDP per capita contraction when compared with countries with less than 30% fixed broadband penetration. Similarly, countries with more than 75% mobile broadband penetration experienced a 19% smaller contraction in the GPD per capita when compared with countries that have less than 50% mobile broadband penetration. However, it is important to note that such studies have a fundamental limitation – the resilience of an economy to COVID-19 can be attributed to a variety of factors such as the quality of healthcare, the underlying health of the population, and the effectiveness of social distancing measures. Consequently, it is difficult to isolate the impact of digitalization on the economy during the COVID-19 pandemic.

Given the current economic environment, digital transformation is expected by global governments and industry to be one of the pillars for economic recovery, resilience, and growth while building and maintaining a sustainable future in next decades [EC22], [ITU20]. 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. Further, the digital decade policy programme 2030 is formally established in [EC22b].

1.1.3.2 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 and sensing, providing ultra-high data rates and capacity, which opens a new door for use case and new business innovations, 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].

1.1.3.3 Network as a powerhouse for sustainability 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 ("there is no green without digital") 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.

1.1.3.4 Disruptive transformation of global education, skill, and labour markets

As shown in the pandemic starting in 2020, many economic activities could 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 era in terms of both contents and formats of education. Internet of skills, meaning connected world enabling any human to teach, be taught and execute actions remotely, 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 current jobs by AI and machines, it is of paramount importance to educate and promote skills aiming at future jobs to help all population prospering in the digital age and data economy.

1.1.4 Regulatory trends towards 2030 and beyond

1.1.4.1 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. 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 relevant issue is Electromagnetic Field (EMF) exposure, which has already been a relevant aspect. 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 countries in Europe, such as Brussels, Paris, and Italy, have defined more stringent limits, impacting the deployment of networks [Sta18], [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 investigate climate issue [RSP21] and the benefits of access to spectrum from a perspective of 6G as a potential enabler of environmental, social, and economic sustainability.

1.1.4.2 Ethical aspects

Networks are expected to encompass certain technologies and use cases that are likely to stress current ethical boundaries. For instance, many people could have on-body health sensors and monitors, 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 1.1.5.1. 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].

1.1.4.3 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 [ABB+17] sets out the requirements for energy efficiency, and also following the EU's SDG, policy background has been studied to facilitate the common methodologies for product environmental footprint [EC12]. In Europe, the Body of European Regulators for Electronic Communications (BEREC) has taken environmental sustainability in its agenda and published its first report on the environmental sustainability of the digital sector [BER22]. 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].

1.1.5 Technological and architectural trends towards 2030 and beyond

1.1.5.1 Disruptive technologies that will shape future connectivity

Future technology trends of International Mobile Telecommunication (IMT) systems towards 2030 and beyond were identified at the global level at the ITU-R and collected into future technology trends report published in 2022 [ITU22a]. Key identified emerging technology trends and enablers include technologies for AI-native communication networks; integrated sensing and communications; in-network computing; device-to-device communications. Here, AI-native communication networks refer to leveraging AI to design communication systems E2E (from RAN to core network functions) so as to adapt to different radio environments and optimally serve the needs of the application.

Technologies identified at the ITU-R to enhance the radio interface include advanced modulation, coding, and multiple access; advanced antenna technologies; in-band full-duplex, multiple physical dimension transmission; THz and ultra-high accuracy positioning. Technology enablers to enhance the radio network include RAN slicing; support for resilient and soft networks for guaranteed Quality of service (QoS); new RAN architecture like a full softwarized RAN based on microservices and multi-agent systems; support for digital twin for network; interconnection with Non-Terrestrial Networks (NTNs); ultra-dense network deployments and techniques for RAN infrastructure sharing.

Some families of technological trends are described below.

Convergence of communications, localization, imaging, and sensing [HEX22-D32]: 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 [HSP+19]. The vision of the Tactile Internet has contributed to increasing the attention on the role of sensing and sensors in communications. With the full immersion of humans in virtual environments, sensing and communications will seamlessly converge to a unique paradigm. Next, localization was introduced in Release 9 of the 3GPPP specifications and is continuing to evolve. Utilizing the mmWave radio spectrum (>100 GHz) in 6G allows for wider sounding waveform bandwidth, which translates into superior ranging accuracy, thus enabling centimeter-level localization and sensing, especially imaging. The fusion of radio-based solutions with non-radio-based solutions (such as LIght Detection And Ranging (LIDAR), camera, acoustic, etc.) further increases the positioning performance and robustness. In addition, Simultaneous Localization and Mapping (SLAM) can benefit from the radio and visual landmarks to build a map of the environment which can be then used for localization and sensing. In order to fully benefit from the geographic information for communication, and vice versa, a joint co-design of the communications, localization and sensing is desirable. This requires the development of 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 such as immersive telepresence.

Use of AI/ML in network [HEX22-D42], [HEX22-D52], [HEX22-D62]: 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 of computing resources for achieving superior performance [Nok20], [Nok20b], [Dem20], [HEX22-D42]. It will become essential for the E2E network automation dealing with the complexity of orchestration across multiple network domains and layers [ZVF+20]. AI/ML will help in ensuring 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 [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 (c.f. Section 1.1.2.5). 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 least, the system must involve humans when needed [Eri20].

Network of computing [HEX22-D42], [HEX22-D52]: Future network platforms will bring most physical things into the realm of software and computing. It will act not only as a complement resource but also as a central element and controller of physical communication 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]. Here, network compute fabric refers to a fusion of connectivity and computing acting as a unified entity that enables seamless use of edge cloud and central cloud computing resources [SJO+21].

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 computing and storage into increasingly virtualized networks to provide applications with increased 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]. Multi-party network-compute fabric can also enhance security and trust [ZSV+21]

Network resilience and security [HEX21-D12]: 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 E2E communication, need to be supported. A distributed architecture may ensure that not all information (and 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, increasing the possibilities of security breaches [NLC+21]. New and efficient security and privacy schemes need to be developed [Nok20], [ZSV+21], [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 trustworthiness can only be fully realized when they are embedded in both the corresponding software and hardware implementations of the network [Fet20] [ZSV+21].

Digital twin for the network [HEX22-D72]: 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 or system throughout its life cycle. The creation and update of DTs relies on timely and reliable multi-sense wireless-wired 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.

1.1.5.2 Technology evolution towards cost reduction and improved efficiency

Flexible network architecture [HEX22-D52]: The increased flexibility of the 6G network architecture is addressed via the decomposition of the architecture into the platform, functions, orchestration, and specialization [ZVF+20]. Future network platforms will be associated with an accessible, scalable, elastic, and agnostic heterogeneous cloud, which is data-flow centric and will include hardware acceleration options. The heterogeneous cloud consists of different kinds of virtualization and computing technologies, which provide communication, computing, and storage resources to microservices and intelligent agents. These software entities consist of virtual chains that perform network functions. Functionally, the computing of the RAN will be virtualized and moved to the edge and core network to reduce architectural complexity [FGS20]. At the same time, options of flexible offload, extreme slicing and flexible instantiation of subnetworks will drive the increased level of specialization of the architecture. Of high relevance for the provision of services and the monetization of resources will be the transformation of orchestration architecture; cognitive closed loop and automation are likely to become pervasive [HEX22-D62]. All future deployment scenarios will rely on a heterogeneous 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 means and resources to enable all the AI operations in the network.

Deterministic latency and reliability: Future networks shall address the extreme performance requirements of more advanced industry applications on latency, reliability and potentially, age of information and age of task [NOK20a]. To achieve such extreme performances with reasonable costs a joint design of communications, control and even computing is required [Fet20], [HYJ+20]. A deterministic latency E2E 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. AI-AI communications refers to AI based algorithms exchanging information between each other. 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 very low cost and zero-energy devices where printable, energy harvesting devices can be deployed anywhere [Eri21].

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 be needed to address high performance required by AI and the real-time 6G physical layer. 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. For instance, power amplifiers contribute to most of power consumed in the RAN, which in itself is a big component of ICT power consumption. Advances in power amplifier design including waveform adaptation as well as AI/ML algorithms [FHS23], [PKH+23] could help bring about energy efficiency gains at all loads, whereas muting and sleep mechanisms are expected to lower power consumption at medium/low loads [Nok22].

Software: Application development for enabling functions and services will become easier than ever before. 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 Application Programming Interfaces (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 management technology [HEX21-D12]: Spectrum for 6G will continue to use a mix of different frequency bands but with potentially larger bandwidths and including higher operating frequencies [ITU22a]. Expected higher capacity demand drives to look for broader bandwidths, not only in the THz bands but also in lower frequency bands, where higher capacity needs to be combined with good coverage [ITU22a]. 6G is expected to involve various combinations of spectrum sharing through different techniques for interference mitigation [ITU22a]. More dynamic spectrum sharing methods are appearing (e.g., Citizens Broadband Radio Service (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 [HEX22-D52]: In order to capture local and specialized network and subnetwork 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 QoS and connectivity, employing edge processing for further automation. With DT, massive data harvesting from local sensors builds up capillary subnetworks 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 [HEX22-D52]: 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. In standardization, 3GPP included NTN in the 5G New Radio Release 17 [3GP20], which also included Narrow-Band IoT (NB-IoT)/enhanced Machine-Type Communication (e-MTC) over NTN in the specifications for IoT operation in remote areas with low/no terrestrial cellular connectivity [3GP20a]. Release 18 continues improvements in NTN, focusing on coverage enhancements, deployment in frequency bands above 10 GHz, mobility enhancements including mobility between NTN and Terrestrial Network (TN) and network verification of the User Equipment (UE) location, while also the work in the IoT part continues in Release 18 with performance, mobility improvements as well as improving the performance for discontinuous IoT networks. 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]. Virtual RAN (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 sub-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 a radical change on how knowing and learning, guessing and discovering is independently implemented today. This brings us to semantic and goal-oriented communication, which is a set of communication paradigms in which the semantic correlations among the concepts and the goal of the communication play a key role instead of the exact transmission of the information to the receiver. In other words, whenever communication occurs to convey meaning or to accomplish a goal, what really matters is the impact that the received symbols have on the interpretation of the meaning intended by the transmitter or on the accomplishment of a goal [SB21]. Taking this approach to communication may stimulate novel and innovative research directions that will tackle fundamental opportunity resulting from interacting AI functionalities embedded in 6G networks.

1.1.6 Most significant global activities on future connectivity

With significant impacts on society, economy, and politics towards 2030, the global race on the research and industrial leadership in 6G networks has already started. A map of the significant activities on 6G is shown in Figure 2-3. 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 framework work in 2021 regarding IMT for 2030 and beyond [ITU21a]. The future technology trends report was published in December 2022 [ITU22a] and the framework recommendation is expected in 2023. Additionally, the Next Generation Mobile Networks (NGMN) alliance announced the launch of a project on visions and drivers for 6G in October 2020 [NGM20] and released their first deliverable on this project in April 2021 [NGM21]. More recently, the alliance published a deliverable on 6G use cases and analysis [NGM22] and 6G requirements and design considerations [NGM23].

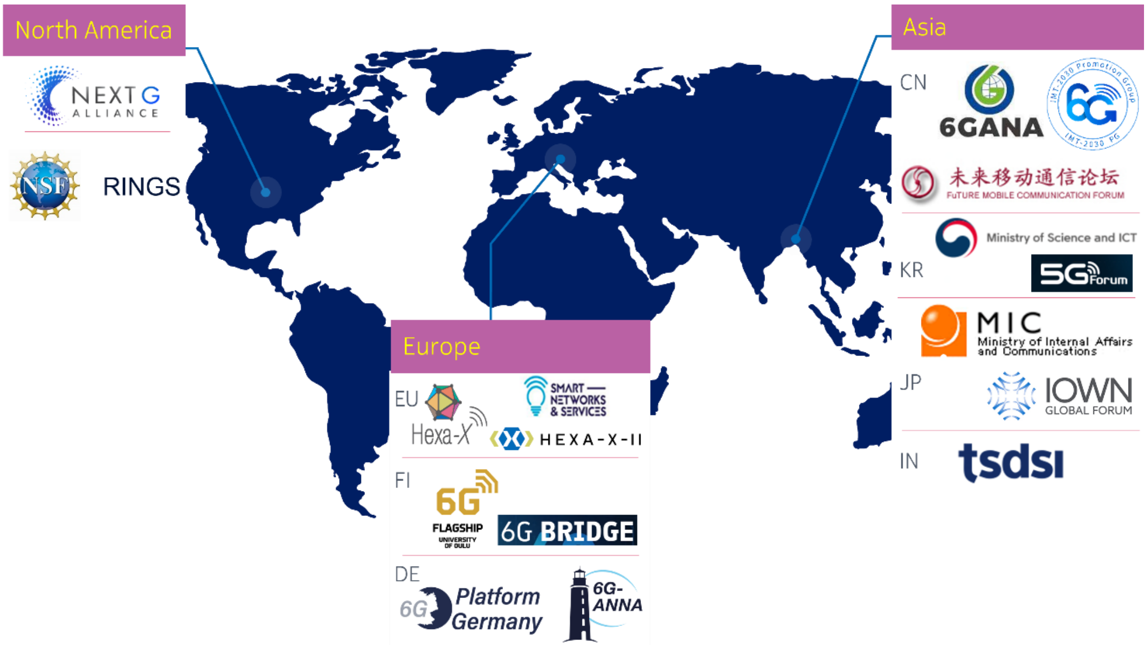


Figure 2-3: A map of the significant global activities on future connectivity.

In Europe, with support from the Academy of Finland, the world's first national 6G program, 6G Flagship, was established at the University of Oulu in 2018 [6GF18], [6GF19], showing strong international initiative in research in 6G. In January 2021, nine EU 6G projects (including Hexa-X as the flagship) kicked off under the last call of Horizon 2020 [5GPa]. These projects have been carrying out explorative research and paving the way towards 6G. Meanwhile, building on activities and results of 5G-PPP in Horizon 2020, a renewed European level private-public partnership on SNS joint undertaking was launched under the 2021–2027 European Research Frame Programme, i.e., Horizon Europe, targeting at R&I beyond 5G and towards 6G [SNS20]. SNS JU announced fall 2022 on 35 new projects to start 2023 [SNS22], with the next 6G Flagship Hexa-X-II among them. In different European countries there are significant activities around 6G, like lighthouse project 6G-ANNA [6GA] and other national projects in Germany. 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. COREnect [Cor20], a cross industry imitative which brought together European major players in microelectronics, was complete in June 2022 and resulted in an industry roadmap with detailed insights on strategic actions required to target the reduction of Europe's dependence on other continents for suppling electronic subsystems and components towards 6G [Cor20a].

Meanwhile, outside Europe, with "Secure 5G and Beyond Act" published in March 2020, the US administration officially announced its intention to work with the private sector to facilitate the evolution and security of 5G [Cor20b]. 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]. The U.S. National Science Foundation (NSF) with other federal agencies and private industry to formed RINGS, the Resilient and Intelligent Next-Generation Systems program, to accelerate research in areas with potentially significant impact on Next-Generation (NextG) networking and computing systems [NSF21].

In addition to many strong activities by vendors, operators and academia, these organizations are jointly present in the IMT-2030(6G) Promotion Group in China [IMT30]. A white paper on 6G vision and candidate technologies was released June 2021 [IMT21].

In Japan, Beyond 5G Promotion Consortium (B5GPC) was founded in 2020 [B5G20]. B5GPC is a forum for industry, academia and government to share information on the latest international trends related to specific initiatives and R&D, to discuss how to promote initiatives for the early realization of Beyond 5G, and to disseminate the status of Japan's initiatives related to beyond 5G internationally.

Korean government has announced 6G R&D strategy with the ambition to achieve "World's first 6G commercialization" and has started national R&D projects in August 2020 with plans for technology trials in 2026, and commercial service in 2028 [6GW20]. A long term network strategy called the K-Network 2030 strategy was announced in February 2023 by the Korean government with an objective to utilize next generation networks such as 6G, satellite, open LAN, and quantum communication and secure the world's best 6G technology [MSI23].

The Telecommunications Standards Development Society, India (TSDSI) started to establish a 6G initiative with focus on 6G use cases and requirements [Tsd20]. TSDSI has published a technical report [Tsd22] that lists the 6G use-cases and enabling technologies. It has also published a whitepaper on its 6G vision [Tsd22a] where it has adopted a two-pronged strategy for 6G – steer research in India to serve its 6G goals and continue engagement with global standard bodies for harmonization.

1.2 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 AR and VR will continue. Therefore, the need of services for connectivity is expected to keep growing exponentially [Eri22d] 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 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 future networks. As illustrated in Figure 2-4, 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, subnetworks and device technologies. Such a transformation can 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. Work on these technologies in addition to others have been a part of projects such as Hexa-X and will continue in projects such as Hexa-X-II. Results exist on targeted requirements and gap between that and currently achievable performance. 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 connectivity in the best way via local networks. One example of this is campus networks [HEX21-D51]. 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. The research into 6G is looking more closely at the cooperation between humans and machines by fully merging all senses as necessary.

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 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.

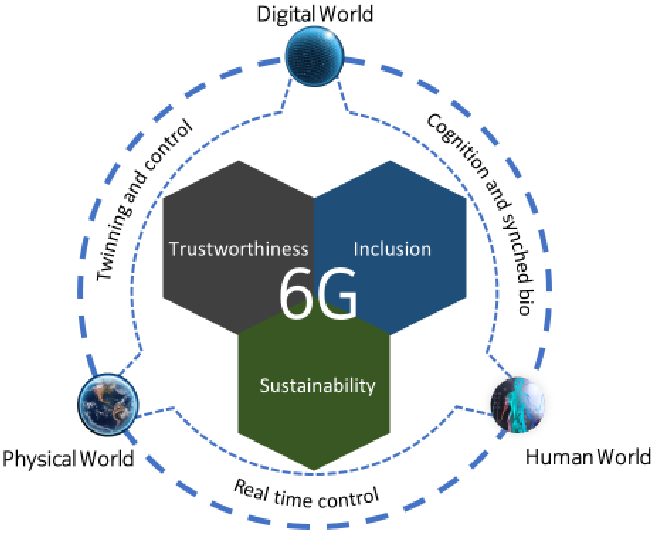


Figure 2-4: Hexa-X 6G vision

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 enable E-health applications such as preventive healthcare [FS19].

Importantly, the vision has three core values at its center, around which the three worlds revolve (see Figure 2-4), 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 have strongly influenced and guided the targeted 6G capabilities and requirements and together with the three world interactions guided the research in the project. Taken together, the vision points towards a set of research challenges for 6G, which have been initially addressed by the project, presented in the next section.

To fully embrace such a vision, Hexa-X recognized 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 has led to a new class of evaluation criteria, i.e., KVIs [ZY20], [6GIA22], [HEX21-D12], (see Section 3.3) 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. Therefore, there has been 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 [HEX21-D12]. An open, modular, and flexible framework — the x-enabler fabric — has been as a starting point and foundation idea for the work, 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 R&I globally towards 6G during this time, Hexa-X has begun to 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.

1.2.1 6G research challenges and how Hexa-X advanced these towards realising the 6G vision?

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 2-5. These challenges have guided the research in Hexa-X towards laying the technical foundation for the wireless systems of the 6G era:

Figure 2-5: 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. This will 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 moving us 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 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, 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 E2E 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.

1.3 Aspects of 6G business impact

1.3.1 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 for 6G must be done in a sustainable way. New business ecosystems will appear to bring together stakeholders to solve systemic sustainability problems together through different resource combinations 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 6G ecosystem. 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 (GPT), 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 [YAM22]. 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 following broad themes have been identified as influencing the business of 6G: convergence and platform-based ecosystems, new business ecosystem and stakeholders, sustainable ecosystemic platform business models, alternative future business scenarios, as well as telecommunication and vertical specific regulation. They are discussed in more detail in the following.

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 [MYA20], [AMY+21]. In addition to wide area networks based on distributed multi-stakeholder cloud architecture, millions of subnetworks designed for both autonomous operation as well as operation in co-ordination with wide area policies are expected to emerge. 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]. Future 6G business ecosystems will be formed around specific verticals and locations, such as ports and factories, where the vertical's own ecosystem meets the mobile communications ecosystem resulting in different 6G ecosystems. 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 opportunity 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 influencing the business of 6G continues to be regulation, which defines the rules and conditions for the telecommunication networks and services as well as the different verticals making use of 6G. 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], [AMY21]). 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.

1.3.2 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 device and 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 maximize 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, emphasizing 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 considered since the beginning, when developing new systems and services. 6G will need to natively support the requirement of environmental sustainability. Awareness of the environmental footprint of mobile communication devices and services consumed will become of interest to consumers and policy makers, who search for sustainable consumption models. Limiting the consumption of highly scarce/limited resources, 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 Business to Business (B2B) to explicitly include Business to Government (B2G) could be recognized as a business case for public expenditure savings including the serving of challenge areas.

Finally, business models will need to be economically sustainable 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.

3 Use cases and requirements

This chapter provides the final update on use cases and requirements from the Hexa-X project. It acts as a wrap-up of earlier iterations in [HEX21-D11], [HEX21-D12], and [HEX22-D13], while also presenting and discussing an updated view on related works on use cases, Key Performance Indicators (KPIs), and Key Value Indicators (KVIs) from whitepapers, project results, and research papers.

Section 3.1 summarizes the work on use cases and provides a refinement of the Telepresence use case and its requirements based on feedback from the technical work packages. Section 3.2 positions the Hexa-X work against recent related works, considering both, use cases and KPIs/KVIs. Section 3.3 summarizes the work on KPIs from earlier deliverables and includes final updates on their definitions and the methodology utilized in Hexa-X. Section 3.4 discusses KVIs and the underlying methodologies, characterizing the Hexa-X key values and deriving measures for those values (sustainability, inclusion, flexibility, trustworthiness).

3.1 Summary of use cases and requirements

3.1.1 Overview of Hexa-X use cases

An initial set of use cases has been introduced in Hexa-X deliverable with a first overview in D1.1 [HEX21-D11], a first deep dive in D1.2, and updates in D1.3 [HEX21-D12] and D1.3 [HEX22-D13]. Use cases have been selected and described considering the end user perspectives and gathered into six use cases families. Each use case family is centred onto a main usage, or a value served by the group of use cases. Figure 3-1: Hexa-X use cases and use case families [HEX22-D13]below summarizes the different use cases and families.

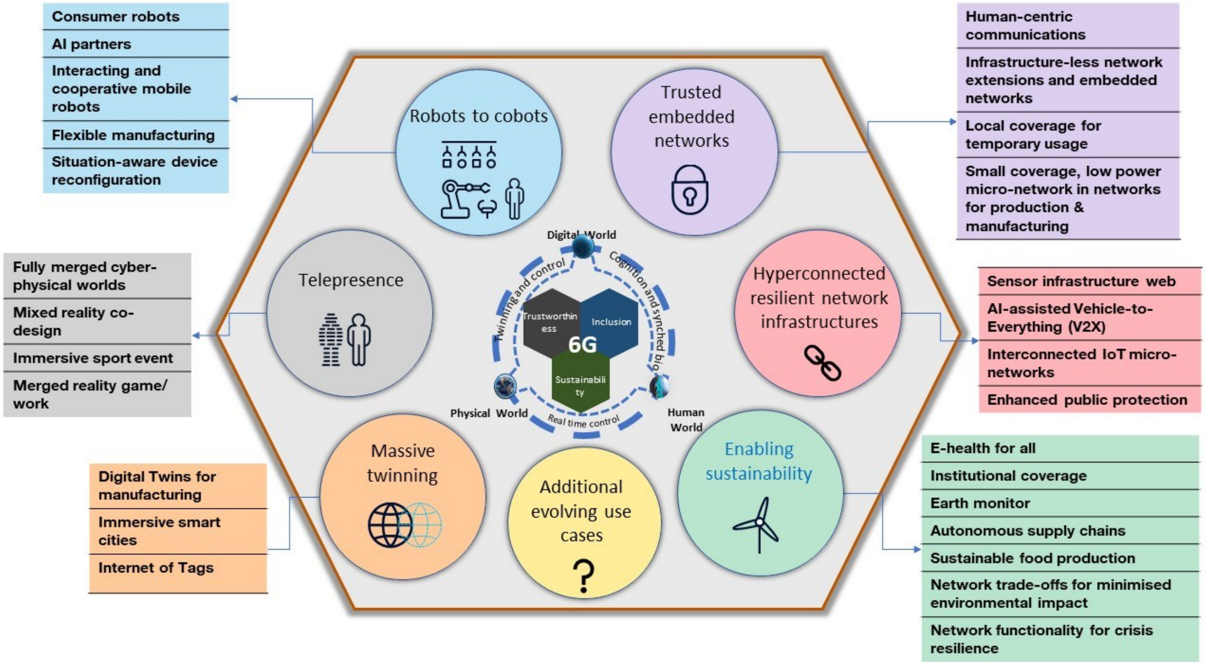


Figure 3-1: Hexa-X use cases and use case families [HEX22-D13]

This section provides a summary of the Hexa-X use cases (identified in italics) and use case families (identified in bold letters) as an overview. Deliverables D1.2 and D1.3 should be consulted for further details on the use cases descriptions [HEX21-D12] and deployment characteristics [HEX22-D13].

3.1.1.1 Telepresence

The focus of the use cases classified in the **Telepresence** use case family [HEX21-D12 - section 4.2.4] is the ability to be present anytime, anywhere. These use cases allow people to interact with each other as well as with the physical and digital things around them. Telepresence use cases such as *Fully merged cyber-physical worlds* [HEX21-D12 - section 4.2.4.1], [HEX22-D13 - section 2.3.3] involve interactions between humans and the cyber-physical world using sensory information addressing all human senses. Mixed Reality (MR) is used to make the holographic telepresence and allow interactions between physical and digital objects, close or distant. Telepresence will be feasible in the next generation of cellular networks with new network technologies and devices capable of perfectly enriching the physical, digital, and human worlds. *Mixed reality co-design* [HEX21-D12 - section 4.2.4.2] use case can make remote collaboration and "experience before prototyping" possible. 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. The network of the future is required to fulfil the strict requirements of such use cases, in particular the very high data rates required for an extreme experience as well as low latency and high reliability to ensure a good experience, without feelings of nausea. Such requirements will have to be met for example in the case of *Immersive sport event* [HEX21-D12 - section 4.2.4.3] or *Merged reality game/work* [HEX21-D12 - section 4.2.4.4] use cases. In the first use case (immersive sport event), the user will experience the sport event as if he/she was in the sport event, playing himself/herself. In the latter use case (merged reality game/work), participants to a meeting or players of a video game will interact as if they were physically present in the same room, even though they are remotely located. It will be possible to mix the physical and digital worlds and interactions will be enriched with sensory information. Various network architectural enablers are required for enabling the telepresence use cases. As an example, network of networks, building on the aggregation of multiple types of resources (HEX21-D12 – section 3.2.1] is the basis for the multi-connectivity which leads to performance improvements due to connected intelligence, and computational offloading will be required to enable lightweight untethered user devices with sufficient battery longevity. Global service coverage will also be needed for provisioning of telepresence everywhere.

3.1.1.2 Robots to cobots

6G is expected to witness the generalization of cobots, where cobots means collaborative robots, interacting and collaborating with humans in a shared area. Within the **Robots to cobots** use case family [HEX21-D12 - section 4.2.5] [HEX22-D13 - section 2.1.3], focus is on the increased utilization of Artificial Intelligence (AI) and the potential of dependable communication [HEX21-D71] and collaboration among robots (in both consumer and industrial use cases), either mobile or static and humans. The advances in AI and the respective support and capabilities being built-in into future 6G systems motivate the *AI partners* use case [HEX21-D12 - section 4.2.5.2], where agents such as robots or machines interact intelligently with each other and with human partners to support execution of challenging or risky tasks. This requires trustworthy cyber-physical systems and dependable communication to reliable devices. The *Consumer robots* [HEX21-D12 - section 4.2.5.1] use case further details this collaborative behaviour for the consumer market. In this use case, robots will extend their range of applications, beyond vacuum cleaners and lawn mowers, to facilitate everyday life at home. By accomplishing domestic chores, they could help maintaining at home of elderly persons or some persons with diseases affecting their autonomy. With the *Interacting and cooperating mobile robots* use case [HEX21-D12 - section 4.2.5.3] [HEX22-D13 - section 2.3.4], focus is on the interaction among mobile robots, both in consumer and industrial scenarios. The mobility of robots requires the coordination of their respective actions and avoid collisions. This requires meeting the underlying real-time and synchronization requirements to enable distributed execution of control tasks among robots [Hex21-D71]. The goal of the *Flexible manufacturing* use case [HEX21-D12 - section 4.2.5.4] is to enable personalization and modularization of production in highly dynamic factories, beyond industrial 5G functionality, calling for high flexibility and self-organization capabilities in dense industrial environments. The use case requires powerful wireless communication, localization, and sensing capabilities as well as flexible, dynamic configuration of (real-time) communication services in a network. In the S*ituation-aware device reconfiguration* [HEX21-D12 - section 4.2.7.4] [HEX22-D13 - section 2.1.3] use case, configuration of a device needs to be adapted as a consequence of collaboration among mobile entities, or to the variety of tasks assigned to a single device: if, for example, a human is planning to interact with robots on a factory floor, the mobile device needs to be reconfigured from, e.g., data and voice services to an industrial Internet of Things (IoT) device to ensure seamless service continuity.

3.1.1.3 Trusted embedded networks

Many use cases from the **Trusted embedded networks** use case family [HEX22-D13 - section 2.1.5] require local or private communication capabilities for very sensitive information that are tightly integrated into wide area networks. Trusted embedded networks can be dynamically reconfigured with autonomous and intelligent enabling of service capabilities, to adjust to the type of network coverage required for the services. In particular, the use case of *Human-centric communications* [HEX21-D12 - section 4.2.6.1], [HEX22-D13 - section 2.1.5], involving body area networks (both in-body and on-body networks,) requiring a high level of protection of the privacy of individual or machine-specific information to enable advanced medical diagnosis and therapy for example. In this case, very high privacy requirements including the need for anonymization and pseudonymization will require local protected signal processing capabilities. transparently integrated into wide area networks, or remain on-premises as private networks, as needed. Another example of this family of use cases is *Infrastructure-less network extensions and embedded networks* [HEX21-D12 - section 4.2.6.4] which can provide temporary network coverage at the edge of the network, 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. In *Local coverage for temporary usages* use case [HEX21-D12 - section 4.2.6.5], the Public Protection and Disaster Relief (PPDR) and Program Making and Special Events (PMSE), roadwork, and harvesting campaigns that benefit from applications such as massive video transmissions that often require local networking coverage fulfilling high requirements. 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 licensing, might help this option to become more widely used. Another example is the *small coverage, low power micro-network in networks for production & manufacturing* use case [HEX21-D12 - section 4.2.6.6], involving sensors in a factory setting to be interconnected locally, as an underlay network, sharing public or non-public spectrum.

3.1.1.4 Hyperconnected resilient network infrastructures

6G is expected to cover different scales of networks, physical and virtualized, with different ranges, from very wide area to local and very short-range networks. **Hyperconnected resilient networks infrastructure** use case family [HEX22-D13 - section 2.1.4] gathers different use cases building on this granularity, requiring a highly resilient infrastructure based on multiple networks, or networks of networks. An example use case is the *sensor infrastructure web* [HEX21-D12 - section 4.2.6.2], where a device can collect and exploit the data retrieved from external sensors. The network will aggregate and share the data collected from various sensors, even third parties, with utmost confidence in the reliability and timeliness of the data. Devices with limited or no sensing capabilities will therefore benefit from the aggregation of data, collected from various sensors, even external to the network. A possible application area is the automotive sector e.g., for a vehicle collecting information on traffic and roads status from devices. It can also be extended to another use case, *AI-assisted Vehicle-to-Everything (V2X)* [HEX21-D12 - section 4.2.7.3], [HEX22-D13 - section 2.1.4], where AI algorithms will exploit and process large amounts of data, shared with the sensors, but also with the base stations, in order to provide recommendations to assist connected vehicles, for various purposes: management of traffic in dense urban environment, improved security. *Interconnected IoT networks* [HEX21-D12 - section 4.2.6.3] [HEX22-D13 - section 2.1.4], builds upon the possibility to leverage multiple types of IoT networks, with different ownerships, to collect information and share part of the infrastructure. Possible application is a smart city, to manage the flow of information among the communicating objects massively deployed. *Enhanced public protection* [HEX21-D12 - section 4.2.6.7], [HEX22-D13 - section 2.1.4], is a use case related to public safety. This use case will exploit the sensing capabilities, increasingly present in various categories of devices, and on AI capabilities to perform security screening in public areas.

3.1.1.5 Enabling sustainability

6G can be an asset for various sectors to reduce their environmental impacts or to provide value for society. Here some illustrative use cases are described in the **Enabling sustainability** use case family [HEX21-D12 - section 4.2.2] [HEX22-D13 - section 2.1.1]. *Earth monitor* use cases [HEX21-D12 - section 4.2.2.1] target improved environmental sustainability, through the deployment of bio-friendly energy-harvesting connected sensors to monitor crops and cultures on various parameters (weather, nature of soil, …), prevent possible risks (e.g., plant diseases) or disasters (e.g., flooding) and make early adjustments or take preventive actions or early adjustments once the event has been detected. This use case requires the development of zero-energy and very low-cost sensors, biodegradable, able to communicate with wide area networks and Non-Terrestrial Networks (NTNs) with very low power. Such use case is in line with decisions taken during the recent United Nations Climate Change Conference (COP27) to build early warning systems by 2027 [UN22]. Securing food production is the main motivation for *Sustainable food production* use case [HEX21-D12 - section 4.2.3.3] [HEX22-D13 - section 2.1.1], building on digital twins to monitor in real time the conditions for agriculture (temperature, soil conditions…) in micro locations, forecast threats and take preventive actions (e.g., targeted plant treatments in case of diseases). Both use cases will require 6G coverage even in remote locations, scarcely populated or uninhabited, where the lack of human presence demands for alternatives to monitor and control. Digital inclusion is the focus of *Institutional coverage* use case [HEX21-D12 - section 4.2.2.2], where 6G will be deployed even in remote rural or isolated areas to make sure that institutions such as hospitals or schools can benefit from new services. *E-health for all* [HEX21-D12 - section 4.2.2.3] [HEX22-D13 - section 2.3.1] is a use case related to coverage, offering basic E-health services everywhere. In areas lacking medical infrastructure, local medical E-health hubs can be an alternative, providing a first medical contact and check before deciding to move to a distant medical struct. This use case requires trustable connectivity in underserved area in a cost-efficient way. Connectivity can also be complemented by local analysis of samples, with dedicated devices. Environmental sustainability is the target of other use cases such as *Network trade-offs for minimised environmental impact* [HEX21-D12 - section 4.2.7.5] [HEX22-D13 - section 2.1.1], where network management and reconfiguration will be driven towards a trade-off between environmental impact of the service delivered, and the quality of experience for this service (e.g., changing the video resolution to still satisfying quality of service, but with a reduced energy consumption). Reducing energy consumption even in situations of crisis, where networks are operating on back-up power due to power shortage, is the target of *Network functionality for crisis resilience* use case [HEX21-D12 - section 4.2.7.5] [HEX22-D13 - section 2.1.1]. Finally, 6G can be an enabler for sustainability of other sectors, such as *Autonomous supply chain* [HEX21-D12 - section 4.2.2.4], building on deployment of tags and sensors, as well as AI capabilities, to optimize supply chain and reduce resource consumption.

3.1.1.6 Massive twinning

An important aspect of most 6G use cases is the support for – and utilization of – Digital Twins (DT), a trend that is expected to gain significance in various domains. DT will gain more and more importance, being used in growing set of use cases, and this generalization of the application of DT is labelled massive twinning. In the **Massive twinning** use case family [HEX21-D12 - section 4.2.3] [HEX22-D13 - section 2.1.2], different domains are considered, moving DTs from use in production/manufacturing towards a full digital representation of our environment. This comes with associated costs caused by the transfer of vast amounts of data and extreme performance requirements in terms of low latency and compute power depending on the planned utilization of the DT. Three use cases illustrate the variety of use cases involving DT and building on this representation of environments, at different scales (from a manufacturing unit to a city-wide representation). With *Digital twins for manufacturing* [HEX21-D12 - section 4.2.3.1] [HEX22-D13 - section 2.3.2], the cooperation among multiple DTs and the utilization of a DT in product design and development as well as infrastructure management are presented discussed. Within the *Immersive smart cities* use case [HEX21-D12 - section 4.2.3.2], the idea is to create and maintain a 4-dimensional (4D) spatiotemporal map to, e.g., plan utilities management. These 4D maps will allow planning of smart cities and forecasting of events and expected behaviours. This involves the transfer of heavy data loads on varying time scales according to the exact task at hand. On the *Internet of Tags* use case [HEX21-D12 - section 4.2.7.6] [HEX22-D13 - section 2.1.2], this is further extended to vast amounts of IoT devices that may rely on energy harvesting or have restricted compute or communication capabilities. Massive deployment of these tags will allow monitoring of the environment, tracking of goods, and optimization of the different flows, in application areas such as supply chain, or industrial factories. In all these use cases, the underlying challenge is to maintain a digital copy of the environment that meets the accuracy and timeliness requirements within the given use case.

3.1.2 Services harnessing new capabilities

Deliverable D1.1 [HEX21-D11] identified a different category, corresponding to **services harnessing new capabilities**, further refined in D1.2 [HEX21-D12 - section 4.2.7], and D1.3 [HEX22-D13 - section 2.1.6], These services build on new capabilities, offered to the network "as a service" to realize the use cases. These new capabilities mainly stem from the convergence of communications, computing, sensing and artificial intelligence. *Compute-as-a-service (CaaS)* [HEX21-D12 - section 4.2.7.1], allow for any device or equipment to delegate demanding processing tasks to another part of the network, allowing to balance the workload and distribute it appropriately between computing nodes with different processing capabilities. Similar principle is applied for *AI-as-a-Service (AIaaS)* [HEX21-D12 - section 4.2.7.2], delegating AI processing to another part of the network to benefit from larger availability of AI resources, or more powerful AI processing nodes. *Security-as-a-Service* [HEX22-D13 - section 2.1.6] enables any kind of device to benefit or perform certain security functions, such as establishing trusted local connections or assess the security of an E2E path. Last, *Sensing-as-a-Service* [HEX22-D13 - section 2.1.6] and *Positioning-as-a-Serv*ice [HEX22-D13 - section 2.1.6] will allow any device or equipment to benefit from sensing and/or positioning capabilities thanks to the sharing of these capabilities in deployed equipment and devices in the network.

3.1.3 Final Refinements of Telepresence use case and requirements

The *Fully merged cyber-physical worlds* use case, in the Telepresence use case family, has been introduced in D1.1 and D1.2, and further detailed in terms of deployment characteristics and KPI targets in D1.3. However, this use case can cover a wide range of usages. Some of them will be very demanding, such as holographic communications, providing a multi-sensory experience, and allowing to experience a different physical environment through a hologram. This kind of usage will require high-end devices and can set ambitious performance targets for the infrastructure. On the other hand, other usages related to MR experience, involving low-end devices (MR glasses,), will entail less constraints on the infrastructure. Different kinds of usages can range between these two extreme cases, between the demanding holographic communications and the more generic MR glasses experience case. To capture the requirements for this whole range of usages, these two extreme cases are considered as the two sub-use cases of the *Fully merged cyber-physical worlds* use case: *Holographic communications* and *Generic Mixed Reality experience* KPIs targets are defined for these two cases, setting the limits (low limits and high limits) for the range of usages. The KPI targets described in D1.3 correspond to the generic MR glasses, i.e., the utilization of many low- or mid-range terminals, potentially involving mobility in an urban scenario. The Table 3-1 and Table 3-2 provide deployment details and requirements for the holographic communications case with high-end, more stationary equipment to provide fully immersive experiences (e.g., online meetings, "Holodeck"), augmenting D1.3.

Table 3-1: Deployment characteristics for *Holographic communication* use case

Environment	Indoor, e.g., confined to a fixed installation in a room.
Type of deployment	Dedicated local infrastructure (e.g., small cells) providing high bandwidth especially in Line of Sight (LoS) configuration. Edge computing capabilities for rendering spatial mapping, adapted for low latency.
Users / devices	Number of devices usually determined by the equipment within the respective room, e.g., projectors or AR/XR-glasses plus additional Human Machine Interfaces (HMIs) such as (tactile gloves, Electromyography (EMG) wristbands, smart watches, smart fabrics, etc.).
Mobility	Stationary, within a confined space (e.g., a meeting room).
Frequency bands	Higher frequency bands in small cells with high bandwidth, mm Wave, and higher.
Environmental constraints	High cost of cell sites, requirements for power sources for the local infrastructure.
Any other constraints	Depending on the underlying use case, additional security/trustworthiness constraints might need to be met (e.g., for confidential meetings).

In terms of requirements, the demands on the communication service are higher compared to the mixed reality use case discussed in D1.3. The following table contains the resulting communication KPIs based on the discussion in D2.1 [HEX21-D21] and information available in [TSM+21]. For other services (AI and localisation/sensing), requirements remain unchanged, although generic compute requirements not related to AI utilization might vary – this is largely implementation specific and beyond the scope of the discussion in D2.1 and this deliverable. Note, that the upper target values for service latency (1 ms) and data rate (4 Tbit/s) stated in those references are potentially neither required nor realistic in real-world deployments of the holographic presence use case: with compression and limited requirements on (local) haptic control loop latencies, these become more relaxed.

Table 3-2: Target communication KPIs for *Generic Mixed Reality experience* use case

		KPI	Target value	Reasoning / References
Communication	Dependability Attributes	Availability [%]	99	Acceptable with some service gaps, depends on the robustness of utilised codecs (i.e., impact on user-perceived quality should be low to avoid nausea). Depending on (business) use case, higher reliability and availability targets could be required.
		Reliability [%]	99.9	When Quality of Service (QoS) must be met to avoid nausea and user distress. Depending on (business) use case, higher reliability and availability targets could be required.
		Safety		No specific requirements
		Integrity	High	For confidential business use cases, high trustworthiness required.
		Maintainability	Mid	Acceptable with some service downtime (i.e., maintenance slots can be scheduled and aligned based on the meeting schedules).

	QoS Attributes	Service latency [ms]	Up to 1 ms for haptic, 10 ms vision	To avoid motion sickness and depending on the type of interaction [Hexa-X D2.1]
		Data rate (minimum expected, desired, maximum) [Mbit/s]	Varying, see comments.	Hologram transmission requirements vary significantly depending on the desired quality level and available compression algorithms, c.f. discussion in the text above.
		Resource efficiency		*Refer to deployment description (e.g., frequency, energy consumption)*
		Scalability		*Refer to deployment description (e.g., number of users, mobility, ...)*

The final set of use cases is presented in Figure 3-2.

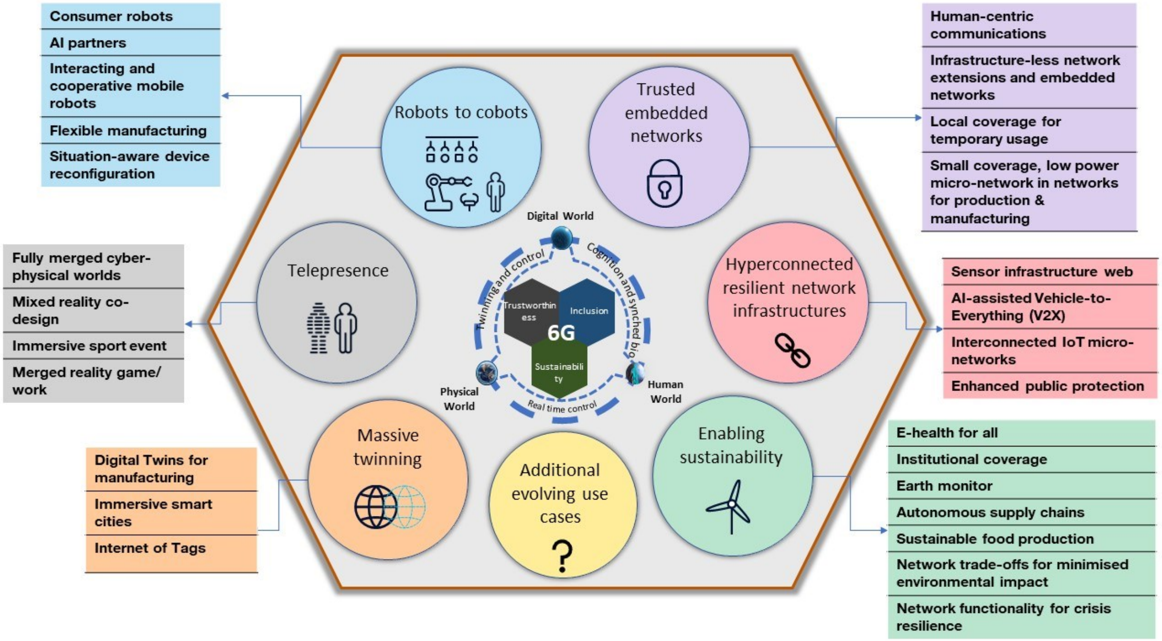


Figure 3-2: Hexa-X final set of use cases.

3.2 Mapping Hexa-X use cases and requirements in 6G state-of-art

3.2.1 Projects

This section presents a mapping between Use Cases (UCs), KPIs, and KVIs proposed by Hexa-X**, and those proposed by other ICT-52 projects** [ICT-52]. It should be noted that an overall one-to-one mapping is not possible, due to the different terminologies and, especially, commonalities and divergences among different use cases, which generally complement with one another, with several use cases covering one or more defined scenarios and services proposed by other projects, and vice versa. **Overall, the vision is mostly aligned, with the key cornerstones appearing in several contributions**, with more or less evident aspects, depending on the use case families. Nevertheless, **interesting complementing aspects (e.g., in terms of KPIs and KVIs) can be found.**

Starting from the *Enabling sustainability* use case family, it can be first noticed the positioning of Hexa-X, which is the only project (among the ICT-52 ecosystem) with a dedicated use case family on such topic. However, this does not prevent other projects to define different metrics of sustainability, mostly related (but not restricted) to energy saving/efficiency, which appears in several use cases. Similarities and complementarities can be identified between the Hexa-X *Sustainable food production* use case, and the **6G BRAINS "Animal Tracking in Indoor Farming Scenarios" use case [6GB21-D21], [6GB21-D22], whose scope is not directly and explicitly considered by Hexa-X**, and is to, e.g., allow farmers to track animals having issues, to monitor their health, etc. 6G BRAINS also provides requirements for this use case, which involves 1 mm to 1 cm location accuracy, and 1 degree orientation accuracy. Also, broadband access for mMTC from 10 to 20 thousand animals is required. Specific energy efficiency figures are not proposed.

However, other projects, as Hexa-X, address the issue of energy efficiency at different network components. **DAEMON proposes, as part of the "Network intelligence" use cases, two relevant use cases, both addressing energy** [DAE21-D21]: i) "**Reconfigurable Intelligent Surfaces Control**", aiming at keeping the energy consumption of Reconfigurable Intelligent Surfaces (RISs) control below 100 mW, and ii) "Energy-aware Virtual Network Function *(*VNF) control & orchestration", to achieve 50% energy savings thanks to network intelligence assisted VNF placement, and 40% reduction in needed computational resources at the edge. DAEMON also **explicitly mentions the United Nation Sustainable Development Goals (UN SDGs) when addressing the energy efficiency issue**. Although Hexa-X target proposals mostly addressing energy efficiency in terms of Joule per bit, proposed solutions address similar problems in technical work packages addressing AI/Machine Learning (ML) related workload management [HEX22-D42], [HEX23-D43], with energy reduction at both devices and network elements as main targets. For services including communication and computation (as in Hexa-X), DEDICAT 6G [DED22-D23], [DED22-D61] proposes a factor of 10 in energy consumption reduction in edge devices and potentially in the system overall, through dynamic intelligence distribution [5GP22], also addressed in Hexa-X by several technical enablers [HEX22-D42], [HEX23-D43], **to go beyond the energy efficiency improvement (i.e., a factor of 10 in terms of energy per bit)**. Finally, RISE-6G proposes comparisons between the energy efficiency with and without RISs, however not mentioning specific target values. This discussion is not carried out in Hexa-X, although a few technical solutions involving RISs have been proposed [HEX22-D32], [HEX23-D43]. At the same time, extended discussion is dedicated to **EMF exposure in RISE-6G**, which finds counterpart only in Hexa-X requirement specifications, as part of the sustainability targets, also reflected in technical solutions [HEX22-D72].

Going further, RISE-6G proposes dedicated use cases on "**EMF protection for workers or specific public and private area"**, under the "railway" station use case family, with more specific details on EMF definitions, including the concepts of intended and non-intended users, and boosted area of influence [RIS22-D23], [RIS22-D24].

Moving to the *massive twinning* use case family, one can find different counterparts. In the RISE-6G "factory plant" use cases [RIS22-D23], [RIS22-D24], several commonalities can be identified. Namely, the "**Kitting process monitoring**" aims at keeping an up-to-date map of a supermarket area, which requires precise positioning as the *Digital twins for manufacturing* Hexa-X use case. Similar description and requirements concern the RISE-6G use case component position in a container, where **precise positioning can reduce average picking time and failures**. Finally, in the different context of railway station use cases, the (anonymous) statistical behaviour of people and their geolocation are exploited also for security purposes, such as the alerting of isolated security agents at night, with precise location to enable a quick intervention in case of, e.g., aggression. Of course, all these services are enhanced by the use of RISs, whose investigation is less evident in Hexa-X, although **technical contributions can be found on localisation [HEX22-D32] and channel estimation [HEX22-D42]**. Another similar description of DTs' related use cases is provided by the AI@EDGE project [AI@21-D21], with the "*Virtual validation of vehicle cooperative perception*" use case, in which multiple vehicles exchange sensed data in real-time, to suggest drivers or self-driving vehicles, appropriate driving strategies. The collected information may be used to create a DT of, e.g., road intersections, roundabouts, etc. This requires low latency, but no specific target values to compare with Hexa-X are provided. Finally, one of the most closely related use cases is proposed by REINDEER [REI21-D11]. Indeed, the "**Real-time digital twins in manufacturing" is strongly relatable to the Hexa-X use case *Digital Twins for manufacturing***. Focusing on the proposed KPIs, one can notice a communication reliability greater than 99.999%, with Hexa-X proposing the range 99.9% − 99.999999%, i.e., covering the requirement but assuming possibly different services with more or less relaxed targets. The focus of REINDEER for E2E service latency (1-50 ms) is on real-time control services, while a range 0.1-100 ms is proposed by Hexa-X, with the stricter requirements referring to motion control (i.e., a slightly divergent target with respect to REINDEER). A comparison in terms of data rate is less straightforward. Indeed, REINDEER specifies the user experience data rate (1 Mbit/s, both for Up Link (UL) and Down Link (DL)) and 20 Mbit/s/m2 as traffic volume density, while Hexa-X specifies peak and average data rate (10-100 and 1-10 Gbit/s, respectively). However, considering connection density in specific scenarios [HEX21-D71], a rough comparison could be possible. From a localisation perspective, REINDEER identifies, as a challenge, a high accuracy positioning, while Hexa-X provides several target values [HEX22-D13].

The Hexa-X *Telepresence* use case family also presents convergent aspects with several REINDEER use cases, namely the "*Augmented reality for sports events*", "*Augmented reality for professional applications*", and "*Virtual reality home gaming*". For the first use case, differently from Hexa-X, REINDEER proposes **target values for user mobility, data rate, number of connections, and localisation accuracy, although the Hexa-X *fully merged cyber-physical worlds* use case provides connection density requirements**. For the virtual reality home gaming, REINDEER identifies, as main challenges, high sum and peak rate (i.e., 150 Mbit/s of Ultra High Definition (UHD) video streams), low latency (i.e., less than 1 ms for VR and less than 100 ms for other games), real-time processing, and high position accuracy (i.e., better than 0.1 m), all relatable to the *fully merged cyber-physical worlds* Hexa-X use case [HEX22-D13], [HEX21-D71]. Indeed, the problem of discomfort and sickness when losing video frames or receiving them with high latency and/or jitter, is recognized by both projects as an issue to be taken into account. As an additional aspect, user mobility under 2 ms is proposed by REINDEER. Finally, similar use cases have been defined by DEDICAT 6G, in particular as part of the "*Enhanced experience*" use case, defined for live public events with a dense number of local users, as well as remote users [DED22-D23], [DED22-D61]. Differently from Hexa-X and REINDEER, the use case is **Exclusively related to such public events**. Some KPI target values are also defined by DEDICAT 6G and they include E2E latency below 200 ms (against the 20 ms proposed by Hexa-X), per user bit rate higher than 5 Mbit/s (Hexa-X does not define per user bit rate), reliability above 99.999% in terms of packet loss rate (lower value is proposed by Hexa-X – 99.9%), and availability, identical to Hexa-X proposal (99%). Also, energy consumption measures are provided by DEDICAT 6G for the proposed use case. Finally, as a divergent definition, an edge offloading performance KPI is proposed, with more than 50% traffic offloaded to mobile access points.

The *Robots to cobots* use case family finds several common points across multiple projects, due to its strong relation with smart industry related use cases. In RISE-6G, within the factory plant use cases [RIS22-D23], [RIS22-D24], "Automated Guided Vehicle (AGV) localisation and navigation" relates to the Hexa-X *interactive and cooperative mobile robots & flexible manufacturing*, for rapid material delivery for production, and warehouse monitoring. This also relates to collaborative manufacturing, remote human robot interaction and control, proposed in RISE-6G. From a KPIs perspective, localisation accuracy at cm level is proposed in RISE-6G (1-10 cm), in line with Hexa-X (1-5 cm). No specific target values are proposed for service latency, reliability, and availability. The **collaboration between humans and robots is a well investigated use case**, and it also appears in REINDEER, with the "human and robot co-working" use case [REI21-D11], including challenges of **safety** (e.g., with robots moving at high speed or operating with dangerous tools) and high traffic volumes in some cases. Again, data rate is specified per user, along with high reliability (99.999%, against 99.9999% in Hexa-X *Interacting and Cooperative Mobile Robots*) and low latency (1 ms), in line with Hexa-X, which proposes 0.5-25 ms Round Trip Time (RTT), while 1-50 ms for collaborating robots. Also, in the "*smart home automation*" use case proposed by REINDEER, **sensor energy neutrality** is mentioned among other characteristics, which bonds together cobots related use cases with **sustainability challenges**. In such use case, high localisation accuracy is one of the main challenges, and is set to better than 0.1 m by REINDEER. 6GBRAIN proposes two use cases, mostly related to transportation involving robots and vehicles [6GB21-D21], [6GB21-D22]. The "*Airports Service and Baggage Handling Robots*" use case, where service robots answer passengers' questions and AGVs carry their baggage. This requires, among other targets, extremely accurate location (1 mm to 1 cm) every 20 ms. Also, the use case "*Smart*

Transportation Vehicles: Localization and Video Processing Offloading" proposes video processing of AGV cameras through computation offloading, a solution also explored in Hexa-X technical work packages [HEX22-D42], [HEX23-D43]. Again, high localisation accuracy at cm level is required, as well as high data rate up to 3 Gbit/s for video transmission, with the latter more relatable to the *Fully merged cyber-physical world* Hexa-X use case. Another use of guided vehicles is proposed by AI@EDGE [AI@21-D21], with the use case called "*Edge AI assisted monitoring of linear infrastructures using drones in BVLOS operation*". Finally, DEDICAT 6G devotes several use cases to smart warehousing, also involving AGVs. One of the objectives is to automate and remotely assist AGVs operation, using high-definition video and AR/VR functionalities, which also represents a link with the Hexa-X *Telepresence* use case family. This requires intelligence distribution and computation offloading with multi-access edge computing. For the general purpose of smart warehousing, low E2E latency and high energy efficiency are required. As additional KPIs with respect to Hexa-X, DEDICAT 6G proposes the time for completing product quality check is introduced, with a reduction of 15% [DED22-D61], as well as an enhanced safety of workers, with an expected ratio of accidents greater than 10%, without DEDICAT 6G solutions.

The Hexa-X use case family *Hyperconnected and resilient network infrastructures* includes characteristics building on different granularities of networks and a possibility to leverage on multiple more or less separate networks, e.g., for data collection or connectivity. In this framing, there are very few obvious use case families in other projects, although if comparing the actual use cases in the families, there are similarities. For example, DEDICAT 6G describes a "*Public Safety*" use case or disaster events when loss of infrastructure might occur and when means to get information and connectivity are needed [DED22-D61]. Connectivity is here achieved using drones and connected cars using a variety of communication technologies such as satellite, 5G etc. The AI@EDGE project describes a secure and resilient orchestration of large Industrial Internet of Thing (IIoT) networks carrying clear resemblance to one of the origin cases for the hyperconnected resilient network infrastructure, that of interconnected IoT micro-networks, however, the interconnectivity of different networks is not specified, even though different slices are defined and involved, the smart factory case comes somewhere in between the massive twinning and this case.

The closely related family in Hexa-X, that of *Trusted embedded networks*, (example is a body area network) includes use cases that resemble, e.g., the "*patient monitoring*" in REINDEER [REI21-D11], which is very similar to the Human-centric communication use case and describes continuous collection of data from sensors either worn or implanted. In Hexa-X, the trusted embedded network category is however wider than just healthcare and also span, e.g., low-power micro-networks in networks for production and manufacturing, as described in [HEX21-D12].

Figure 3-3 summarizes the matching between Hexa-X families of use cases and the use cases identified by other projects. A comparative analysis for each use case is detailed in the Annex A.

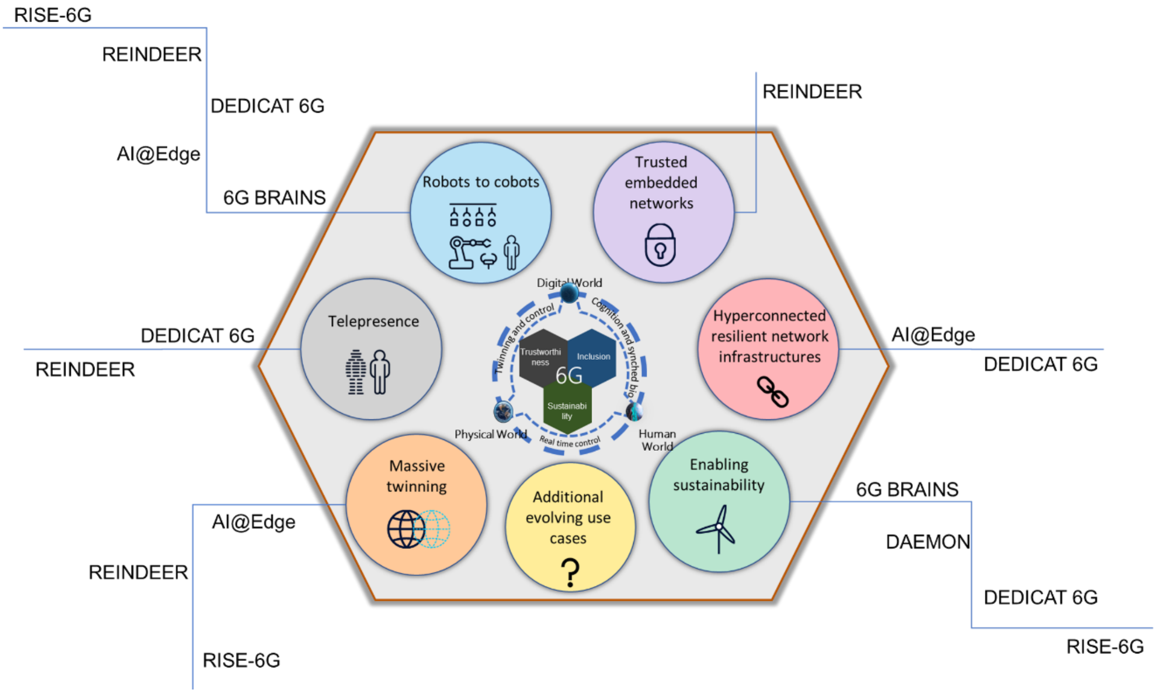


Figure 3-3: Mapping of the Hexa-X use case families [HEX22-D13] and use cases identified by other projects of ICT-52

3.2.2 Research Papers

Early research works defining the scope of 6G have appeared in 2020. While the works often share a common baseline with respect to use cases and requirements, there are interesting distinctions from each other. In the following, important research works are compared with the Hexa-X use case families and put into perspective.

Use cases fitting in **the Hexa-X *Enabling sustainability* use case family and discussions about key values have become an import topic in many research papers**. In [MLP+20] a *zero-energy IoT* use case family is proposed, for reduced and enlarged lifetime IoT devices similar to the vision of the Hexa-X *Earth monitor* use case. In this regard, 6G must also provide monitoring capabilities for a sustainable use of the ocean according to [MYA+21]. Fitting the Hexa-X *Sustainable food production* use case, IoT enabled agriculture is described in [MAA+20]. In terms of the Hexa-X *Institutional coverage* use case, [MAA+20] also suggest that 6G has to provide learning opportunities and compute power to remote areas. Similarly, [MYA+21] also emphasizes, that 6G must provide access to education and prevent poverty via new economic opportunities for the unconnected by enabling access for disadvantaged segments of society. [AKP+21] includes discussions in terms of *eHealth* in their *intelligent healthcare* use case family. Use cases on eHealth are also described in [VM20], where eHealth is expected to transform healthcare through wearable sensors that perform 24x7 monitoring of various health parameters. A very well cited publication on 6G use cases [GPM+20] includes discussions on *eHealth* use cases as well. However, for the authors eHealth is mainly a telepresence use case for the medical sector which also requires tactile feedback and thus makes it also a fit for the Hexa-X *Telepresence* use case family. Like the Hexa-X *Autonomous supply chain* use case, the authors of [MYA+21] describe, that 6G will be an enabler for a sustainable industry and sustainable consumption. Interesting additions to the Hexa-X use cases are found in [Pou20], which discusses **a sharing of infrastructure between operators** for the 6G era and **micro payment models which enable a sustainable shared use of products** or even **micro payments by machines to compensate environmental impact**. A big impact for sustainability according to [MAA+20] might also arise in the energy sector by 6G enabled devices that **make power grids more efficient and schedule domestic appliances with the availability of green energy**. Also, definitions and requirements in terms of KVIs are widely present in research papers, e.g., a **cell coverage up to 50 km** [Pou20] for inclusiveness or increased **energy efficiency of 10-100x compared to 5G** [GPM+20]. Examples for further KVIs are the **end-to-end resource consumption** [MYA+21] or the **mobile terminal price distribution** [MAA+20] amongst others.

Fitting in the Hexa-X *Massive twinning* use case family, the authors of [VM20] describe DT as an essential component for the future to augment human intelligence by bridging the physical and digital world. Furthermore, the authors also describe widespread deployment of cameras for visual sensing and radio/acoustic sensors for other sensing modalities. In [AKP+21], digital twins are not directly described, however the authors define an *Internet of everything* use case family about sensory monitoring for not only improving robots, but smart cities, healthcare systems and more. The anticipated monitoring and identification capabilities for taking decisions for a massive number of application areas is similar to the Hexa-X *Massive twinning* use case family. Requirements for the *Internet of everything* according to the authors are a **data rate up to 1 Gbit/s**, a **latency from milliseconds up to seconds**, but a trillion devices to be served with a **connection density of up to 1 million sensors per km^2**.

Telepresence use cases are widespread in available research works, fitting the Hexa-X *Telepresence* use case family. In [MLP+20] a similar use case family, called *Internet of senses*, is described. However, the definition in [MLP+20] uses interaction with machines and not between humans. Such a use case family requires ultra-reliability and low latency, as well as **ultra-broadband**, according to the authors. Targets for these extended 5G KPIs are a **latency requirement of 0.1 ms** and a higher **reliability of 99.99999% to 99.9999999%**. Similar values for latency, reliability is discussed in [Pou20]. In [GPM+20] AR and VR use cases are discussed. The authors also define the term T*elepresence;* however, it is defined separate from AR/VR, requiring 3D holographic content. While AR/VR pose requirements in terms of system capacity of 1 Tbit/s, the telepresence use case requires **data rates of more than 4 Tbit/s** and a **sub-millisecond latency**. Use cases on holography, extended reality and telemedicine combined in a *Holographic telepresence* use case family on par with the Hexa-X *Telepresence* use case family are discussed in [AKP+21]. These use cases require latency between 0.1 ms up to 1ms and a data rate of multiple Gbit/s as stated by the authors. In [VM20] the authors also consider industrial use cases driving 6G development, namely, holographic telepresence enabling remote work, as envisioned in the T*elepresence* use case family.

Matching parts of the Hexa-X use case family *Robots to cobots* the *Connected industries* family in [MLP+20] describes the factory of the future as more agile, adaptable and versatile, expanding on the 5G vision for future industrial applications. According to the authors, evolution of the KPIs latency, reliability and throughput is required as already discussed before, as well as new KPIs such as positioning accuracy and man-machine interface performance. However, no values are proposed for these novel KPIs. The use case family *Swarm networking* in [MLP+20] describing swarms of self-driving cars, automated guided vehicles and unmanned aerial vehicles, which fits the Hexa-X *Robots to cobots* use case family in terms of collaboration among mobile robots. In [GPM+20] no collaboration between robots is described, instead the authors vision for their *Industry 4.0 and robotics* use case family, is to realize and enhance on the 5G promises. New requirements compared to 5G are a microsecond delay jitter and **data rates in the range of Gbit/s.** Part of [Pou20] is cooperation between robots and humans, but only in the industrial context. KPIs for 6G industrial use cases in general are a **latency of <0.1 ms**, **jitter of <1µs**, a **reliability of 99,9999999 %**, and low data rates of <5 Mbit/s, a **positioning accuracy <1 cm**, and **high RF imaging resolution** among others. Similarly, robots working alongside humans or collaborating with humans are described in [AKP+21] as part of the *Collaborative robots* use case family. Again, focus is laid on industrial production. Furthermore, [AKP+21] describes a separate use case family *Industry 5.0* with, e.g., a **massive number of devices** compared to currently installed devices. Domestic, as well as industrial robots, including robot swarms, are expected to assist humans with day-to-day tasks as described in [VM20].

Related to the Hexa-X use-case family *trusted embedded networks*, a *personalized body area network* family for clothing or even skin integrated devices are described in [MLP+20]. The authors of [VM20] envision secure methods for security and **privacy-sensitive handling of data** generated by widespread deployed sensors.

Moving to the Hexa-X *Hyperconnected resilient network infrastructures* use case family, the authors of [VM20] expect autonomous vehicles to become prevalent in the 6G timeframe exchanging data with other autonomous vehicles and the infrastructure matching the Hexa-X use case *AI-assisted Vehicle-to-Everything* use case. Also, [Pou20] describes vehicular use cases, which however, only assumes edge connectivity. **Data rates are specified as < 10 Gbit/s,** the **latency requirement is specified as < 0.1ms** and the **reliability is specified as 99.99999%**. Different KPIs according to the authors are high **supported vehicle speeds up to 1200 km/h**, a **positioning accuracy of < 10 cm** and a high Radio Frequency (RF) imaging resolution amongst others. Similarly, a use case family *unmanned mobility* depicted in [GPM+20], about connecting autonomous vehicles including flying drones. Again, no focus is laid on the multi network perspective compared to the comparable Hexa-X use case family. The requirements for this family are a 99.99999% reliability and a latency below 1ms, as well as a mobility requirement for up to 1000 km/h vehicle speeds according to the authors. Finally, a S*mart contract* use case family is described in [MLP+20] which based on distributed ledger technologies, e.g., via the blockchain, enables payments between IoT devices. While this technology requires a *Hyperconnected resilient network infrastructure*, especially if data is latency critical, **the financial aspect is missing from the Hexa-X use case families**. These use cases require low-latency, reliability, and massive Machine Type Communication (mMTC)-like scalability according to the authors. Networks of vehicles enabled by AI are also described in [AKP+21], however the authors do not focus on a multi network aspect as envisioned in the *Hyperconnected resilient network infrastructures* use case family. The authors state that such a use case requires extreme reliability, a low latency of 0.1 ms and extreme throughput. Also, a *Personalized body area networks* use case family is described, which matches the multi network idea of the Hexa-X *Hyperconnected resilient network infrastructures* family. Local processing of IoT data and sensors around the human body for medical and nonmedical applications and interaction with networking services, e.g., social networks and the internet, is discussed. Similarly, the use case family of *Hyper-intelligent IoT* assumes connections of IoT devices to the internet and with each other. Processing of data can take place via connection to the internet and when no connection to infrastructure is available. A *Smart grid 2.0* use case family is described for connecting electrical equipment to the internet and monitoring it.

Finally, **some use cases are described in available research papers which cannot be directly mapped to the Hexa-X use case families**. The authors of [GPM+20] describe **Pervasive connectivity** as a use case for 6G to feature connectivity every time and everywhere for personal devices, sensors, and vehicles – an unwritten necessity for the Hexa-X definition of use cases. In [AKP+21] some interesting use cases are described throughout the document which are not featured by any of the Hexa-X use case families, i.e., classical use cases such as **higher resolution video streaming**, as well as some exotic use cases such as **connectivity during space sightseeing** and **deep-sea tourism**. These use cases require long distance and high-mobility communications.

3.2.3 Whitepapers

In this section, a literature review of white papers is provided, to discuss the vision of the industry, involving vendors and operators and that of the main associations discussing the 6G vision as a whole, to compare it with the Hexa-X vision and proposals.

From the point of view of companies (Ericsson, Nokia, Huawei, Orange, Samsung, NTT Docomo) [Eri22a], [VM20], [Hua21], [Ora22], [Sam20], [NTT20], as it will be clarified, the **Hexa-X vision covers a wide range of the proposed use cases, KPIs and KVIs**, although with slightly different terminology and description, which makes a one-to-one mapping not fully feasible. Nevertheless, the **visions are, all in all, aligned on the description of the envisioned 6G use cases, their societal impact, requirement, and enablers,** also from players beyond European countries [Hua21], [Sam20], [NTT20]. At the same time, as it will be discussed, most of the Hexa-X proposed use cases, KPIs, and KVIs exhibit an **alignment with international association groups** [NGM22], [NGA22a], [6GIA22]. All in all, main divergences concern the clustering and classification of use cases under slightly different families and terminologies in some cases, while the use cases themselves appear consistent across all reviewed contributions. This also pertains to KPIs and KVIs.

The *Enabling sustainability* use case family in Hexa-X, presents several common aspects with other visions (e.g., from companies), ranging from **network energy efficiency** and **digital inclusion** through coverage extension (e.g., the *E-health for all* Hexa-X use case) [Hua21], [Eri22a], [VM20], [Sam20], [Ora22], [NTT20]. This is also shared by different international associations, including Next Generation Mobile Networks (NGMN) [NGM22] with the network evolution use case family (involving coverage expansion and autonomous system for energy efficiency), Next G Alliance [NGA22a], with the use case "*Eliminating the North American Digital Divide*", and 6G-IA [6GIA22], explicitly mentioning the Hexa-X *Sustainable food production* as a use case. Interestingly, as main divergence point, **E-health is not necessarily considered as an *enabling sustainability* use case by other parties**. For instance, in [NTT20], telemedicine is identified as part of the telepresence use case, addressed by Hexa-X with different focus. Smart healthcare is also a sub-use case of the usage scenario "mMTC+" (evolution of massive machine type of communication) proposed in [Hua21], with tele-diagnosis and tele-surgery as part of the overall description. In [NGM22a], it appears as part of the "*Enabling services*" use case class. However, despite the different classification of this use case, these visions are aligned with each other. From the KPIs perspective, [NGM22a] explicitly leaves targets definitions for future work, while [NTT20] proposes qualitative figures entailing **high data rate and ultra-low latency communications, in line with the Hexa-X proposed service latency**, in the range 0.1-100 ms for the *E-health for all* use case (depending on the specific service), but also with data rate requirements in certain conditions (e.g., to support 4K video transmission [HEX22-D13]). Nonetheless, Hexa-X also proposes low data rate conditions for sensor data (100 kbit/s), as well as specific values for reliability and availability, depending again on the considered service.

Overall, **the choice of Hexa-X to define a dedicated use case family for sustainability is shared by other players** [VM20], [Eri22a], [NGM22a], while other sources consider sustainability as an added value of future networks, e.g., as a pillar covering and driving different use case families (e.g., [Hua21]). Namely, energy frugality is a background concept taken into account in most of the Hexa-X use cases and the resulting proposed solutions, whose description can be found within the technical work packages. Furthermore, as discussed in [Ora22], **Electromagnetic Field (EMF) exposure is considered as a fundamental aspect, with the continuous monitoring recommendations, to propose new low exposure solutions**, in order to attain the recommended and imposed values, also in case they become stricter in the future. The latter has been also reflected in some of the proposed technical solutions in Hexa-X [HEX22-D72], while it does not appear in most of the reviewed contributions, except for [Ora22] and [B5G20], with the use of RISs. While the vision is aligned for the general definition of sustainability and its values, KPIs and KVIs present some divergences. Among the most evident ones, one can identify the energy efficiency improvement proposed in **[Hua21], i.e., a 100 times energy efficiency improvement with respect to 5G, to keep the energy consumed by 6G lower than 5G, a vision also shared by [B5G20]. However, this differs from the Hexa-X proposal in terms of energy efficiency, whose target is a 10 times improvement**, which is however higher than the one proposed in [Sam20], i.e., a 2 times improvement, for both network and devices. Instead, [Ora22] proposes, as Hexa-X, an energy efficiency gain at least equal to the capacity improvement, not to increase the network energy consumption with respect to 5G.

Moving to the *Massive twinning* use case family, common points with most of the reviewed contributions can be easily identified. In [NGM22a], the "*Interactive mapping*" use case aims at connecting a large number of DTs to build a virtualised model of the physical world. Immersive smart cities also find common points in [Ora22] and [6GIA22]. The *Digital replica* use case proposed in [Sam20] also fits this use case family, together with two usage scenarios from [Hua21]: "*Ultra Reliable and Low Latency Communications (URLLC+)*", **especially for manufacturing, and *Sensing*, to construct, among the others, maps of the environment enhancing localization capabilities**. Moving to KPIs/KVIs, a detailed description with target values is presented by Hexa-X [HEX22-D13] for the use case *Digital Twins for Manufacturing.* For instance, **localisation accuracy (precision positioning) at cm-level** is in line with white papers explicitly mentioning target values [B5G20], [NTT20], while other sources propose generic figures without numerical targets. In [Sam20], the "Digital replica" 6G service is investigated and proposed, and the challenges identified are predicated on the fact that, for example, duplicating a 1 m^2 area requires a tera-pixel, 0.8 Tbit/s throughput assuming periodic synchronization of 100 ms and a compression ratio of 1/300. Then, as target values, [Sam20] proposes 1 Gbit/s user experienced data rate (1-10 Gbit/s in Hexa-X for *Digital twins for manufacturing),* and 1000 Gbit/s peak data rate, slightly different from Hexa-X proposal (10-100 Gbit/s for *Digital twins for manufacturing*). More specific target values on localisation and sensing capabilities have been defined in Hexa-X [HEX22-D13], also thanks to the work carried out within the technical work packages [HEX21-D31], [HEX22-D32]. Therefore, also with respect to this use case family and its identified KPIs/KVIs, despite a slightly divergence of terminology and clustering of use cases, **Hexa-X shares a common vision with most of the 6G players towards fully integrated cyber, physical, and digital worlds**.

This integration would not be fully addressed without the possibility for humans to be present at anytime and anywhere, using all senses, a concept covered by the *Telepresence* Hexa-X use case family, which finds several common points and counterparts in the ecosystem. Among the others, the "*XR Immersive Holographic Telepresence Communication*" [NGM22a] proposes a **fully merged reality, also thanks to wearable devices**. Also, "*living and working everywhere*" [6GIA22] (referencing Hexa-X), and "*Immersive gaming*" [NGA22a], are aligned with the Hexa-X proposals and vision. [Hua21] clusters a similar use case family under the "eMBB+" class. From a KPIs' perspective, for this use case family, Hexa-X proposed, for the *Fully merged cyber physical worlds* use case, high data rate (1 Gbit/s in DL and 0.1 Gbit/s in UL), which explains, for instance, the clustering in [Hua21] of such services into the "eMBB+" usage scenario, for which it is required a 100-fold increase in the raw data rate for the "ultimate immersive cloud VR" sub-use case. Whereas, from the latency point of view, the 20 ms E2E (UL+DL) proposed by Hexa-X for the *Fully merged cyber physical worlds* use case has a stricter counterpart in [Hua21], which proposes 2 ms RTT transmission latency (still for the "*Ultimate immersive cloud VR*" sub-use case), **to take into account possible remote computing delays for rendering**. In accord with this issue of the computing time, in [Sam20], for the "*Truly Immersive XR*" use case, hardware is the identified obstacle for XR materialization. Wireless capacity is another identified challenge since XR media streaming is estimated to require 0.44 Gbit/s throughput to 16K UHD quality video (e.g., 16K VR requires 0.9 Gbit/s throughput with compression ratio of 1/400). For XR applications, [Sam20] proposes very stringent latency requirements (less than 1 ms including communication and computation time), relatable to the Hexa-X, although for other use cases such as *E-Health for all*, *Digital twins for manufacturing and Immersive smart cities,* with a range of 0.1-100 ms. Another relevant use case in [Sam20], which can be related to the Hexa-X *Fully merged cyber physical worlds* use case, is the high-fidelity mobile hologram service, **which is estimated in the paper to demand hundreds of times greater data rate transmission than current 5G system** (e.g., a hologram display over a mobile device of 11.1 gigapixel, form-factor requires at least 0.58 Tbit/s). For such use case, **AI is identified as a means for achieving efficient compression, extraction, and rendering of the hologram data**. Again, localisation and sensing requirements are part of the Hexa-X proposal for this use case, while they are not explicitly considered in the mentioned papers, for the respective use cases.

Going further in the use case families' analysis, **flexible and automated manufacturing is one of the 6G use cases appearing in all visions**, and implicates, besides in the *Massive twinning* use case family, the Hexa-X use case family ***Robots to cobots***. **This use case family is present under various names in several works**, spanning from "*Interacting cobots*" [NGM22a], to "*Connected intelligent machines*" [Eri22a] and "*Collaborative robots in groups/from intelligent cobots to cyborgs*" [Hua21]. All of them propose the concept of robots collaborating with each other to absolve complex cooperative tasks, thus with a massive exploitation of AI as an enabler (e.g., **AIaaS**). Interestingly, in [NTT20], this covers logistics and unmanned operations in agriculture, **an aspect that is not explicitly mentioned by Hexa-X for this use case family**, although having a strong link with the *Sustainable food production* use case proposed by Hexa-X. Challenging target values for the collaborative robots in groups can be found in [Hua21], with 1 cm localisation accuracy (1-5 cm, with other detailed metrics in Hexa-X [HEX22-D13]), 1 ms E2E latency (it is not specified if computing time is included), against 1-50 ms overall AI and computation E2E latency in Hexa-X, and reliability greater than 99.9999%. **The latter is defined in Hexa-X for communication and AI/computation**, and the proposed target value is 99.9999999% for both, in line with [Hua21] (although being explicitly more stringent), and consistent with [Sam20].

The *Trusted embedded networks* use case family also finds a number of convergent aspects in the reviewed literature. Namely, in [NGM22a], the "*Trusted composition of services*" use case aims to allow the support of dynamic and complex use cases. **The main common point with Hexa-X is the need for trustworthiness**, in order to prevent the exposure of data. A similar discussion, together with some requirements, can be found in [6GIA22], within the "*Personal health monitoring & actuation everywhere*" use case, with focus on **personal health and protection, privacy and confidentiality, societal sustainability and trust**, **thus also with a cross-implication with the *Enabling sustainability* use case family**. Going further, the "*High-Speed Wireless Connection in Aerial Vehicle for Entertainment Service*" in [NGA22] well fits this use case family, also with respect to the proposed requirements, including low E2E delay (1 ms *for the Infrastructure-less network extensions and Embedded networks* in Hexa-X), extremely high availability (defined as *critical* in Hexa-X), and high packet reliability (defined as *very high* in Hexa-X). Also, within the suggested study areas in [NGA22], the **goal-oriented and semantic communication paradigm** appears as a research topic of interest, a common point with Hexa-X from the point of view of technical enablers [HEX21-D41], [HEX22-D42], [HEX23-D43].

The *Hyperconnected resilient network infrastructures* use case family presents **less evident commonalities with the reviewed white papers**. Nevertheless, across the different contributions, one can identify the following. From [NGM22a], the automatic detection protection and inspection, with various sensing modalities to screen people and detect potential threats, fits the *Enhanced public protection* Hexa-X use case. Other fitting use case families are the *"Emergency response and warning systems*" in [6GIA22], and the "*Untethered wearables and implants*" use case in [NGA22], as part of the distributed sensing and communication family, which identifies, among the others, extreme mMTC support, eMBB, and extreme coverage as requirements. Finally, with a similar view, the usage scenario "mMTC+" in [Hua21] covers smart cities and buildings, as well as "*Wide-ranging IoT services*", with their extension to unconnected locations after natural disasters to better protect the world. From the point of view of target KPIs/KVIs, with respect to the Hexa-X proposal for the *Integrated micro-networks for smart cities,* an interesting point raised in [Hua21], and not explicitly tackled by Hexa-X is the battery lifetime of sensors, i.e., 20 years of sensing battery life. Namely, it is suggested, in similar scenarios, **to consider zero-power backscattering-based passive IoT devices to provide extremely low-cost connections**. This aspect is however considered and proposed by Hexa-X, especially in the *Enabling sustainability* family, for the *Earth monitor* use case. Again, many aspects are covered by Hexa-X and the reviewed sources, although with slightly different classification (i.e., use case clustering) and terminology.

Finally, other use cases or use case families do not directly match with Hexa-X proposals and/or go beyond, but some of them can be related with the Hexa-X vision. A straightforward example is the usage scenario *AI* proposed in [Hua21], which explicitly consider AI as a use case, thus including AIaaS for different purposes. The latter is part of the *Enabling services harnessing new capabilities* class, which is not categorised as a use case family by Hexa-X, but rather as a set of enablers able to realise several of the proposed use cases, i.e., almost appearing as a technical enabler in Hexa-X [HEX22-D13]. Of course, for this class, **native trustworthiness and local data privacy** are fundamental values [Hua21], as also shared by the Hexa-X view.

3.3 Updates on KPI definitions and methodology

Based on [HEX21-D11], [HEX21-D12], and [HEX22-D13], this section provides a final summary and categorization of KPIs identified in Hexa-X. Updates on the earlier KPI definitions that were discussed in the technical work packages within Hexa-X are also presented in this section.

Hexa-X identified the need for three types of KPIs in the context of 6G systems: (i) “traditional” KPIs being increased for 6G (e.g., a tenfold increase in data rates), (ii) novel E2E KPIs (e.g., dependability of services), and (iii) additional KPIs that capture novel capabilities within 6G systems (e.g., 6D localization and sensing, AI and compute capabilities), as illustrated in Figure 3-4.

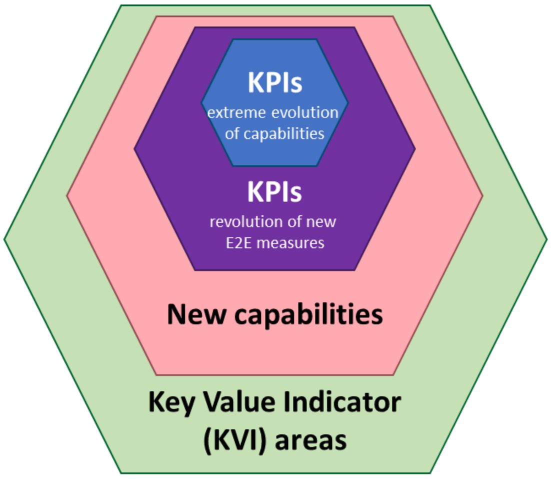


Figure 3-4: Three types of KPIs (topmost layers) extended by the novel KVI areas.

Based on the technical enablers studied in Hexa-X, capabilities identified for 6G are *communication*, *localization and sensing*, and *AI and computation*. For each of these capabilities, KPIs are split into *dependability* attributes and *QoS* attributes. The reasoning for this is to capture the need for E2E KPIs in the domain of dependability: if a capability is to be utilized in a use case and by an application, the respective dependability characteristics of the capability (and its realization in the form of a service) have a direct impact on the productivity of the application. To quantify dependability (or, more specifically, its availability attribute) one needs to specify additional QoS attributes that must be met by the respective service. This concept is illustrated in Figure 3-5. For each service, QoS attributes can further be distinguished: attributes such as service latency, round trip time, or scalability and resource constraints need to be specified for all capabilities. In addition, a varying number of domain specific QoS attributes exist for each service. For localization and sensing, for example, some domain-specific attributes are location and orientation accuracy or the resolvable range, as discussed later in this section.

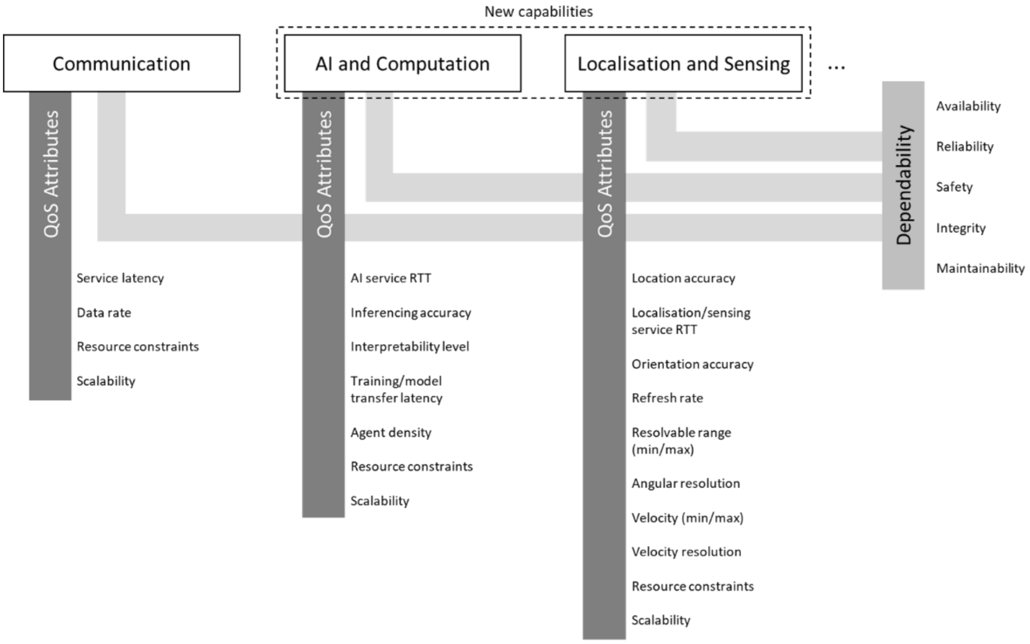


Figure 3-5: QoS Attributes for 6G capabilities.

The percentage of time during which the targeted QoS attributes as specified by the application or the constraints of the use case are met, and the service can be consumed is referred to as the availability of the service. The reliability of a service is the ability of the service to perform as required (i.e., being available) for a given time interval under given conditions [IEC61907], [22.104]. To quantify reliability, the (Mean) Time Between Failures (MTBF), the Failure Rate, or the (Mean) Time to First Failure (MTTFF), or the uptime can be utilized as generic KPIs. For a communication service, a service specific KPI for the reliability can be the percentage of the number of packets sent that are delivered within the respective QoS constraints required by the consumer (e.g., an application). For a more detailed discussion of the dependability attributes, please also refer to Hexa-X deliverable D7.1 [HEX21-D71].

Consequence of high dependability is a high productivity of the application relying on the dependable service (i.e., the application can function as expected). In addition to dependability, the term *resilience* is often used to describe the same target (maintaining application functionality) but focusing more on the impact of unexpected degradations of the system (e.g., faults, errors) and the way these impacts are handled by the system (e.g., learning and improving, “coming back stronger”). In [Lap08], a shorthand definition of resilience is given as “the persistence of dependability when facing changes”. In the scope of Hexa-X, the two aspects (dependability and resilience) are closely intertwined, as we assume that 6G relies on self-learning and self-healing capabilities in many aspects of the system to maintain the expected QoS. Therefore, whenever a previously unexpected situation is being handled (e.g., by self-learning and optimization mechanisms, or with the help of a human-in-the-loop [HEX22-D72]), it is reasonable that, this should lead to further strengthening of the system – the system becomes more resilient. These aspects are closely related to the Hexa-X values *trustworthiness* and *flexibility* and are being discussed in more detail in the following sections.

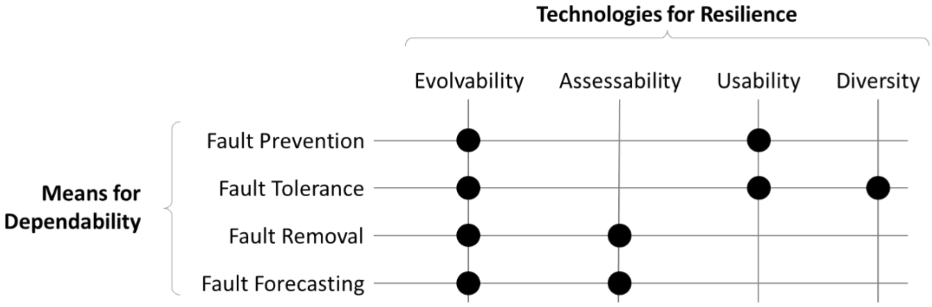


Figure 3-6: Means for dependability and technologies for resilience, adapted from [Lap08].

In [Lap08], four technologies for resilience are stated and their relation to means for dependability is discussed, as illustrated in Figure 3-6. Here, evolvability refers to the concept of "coming back stronger", or, in general, to our understanding of flexibility. Accessibility is tied to the concept of "justified confidence" in [Lap08]: by understanding the system and its interacting functions and components, a certain level of resilience is being implied. This is linked to our understanding of trustworthiness. While usability was mostly tied to cyber-physical systems by the author, the concept applies to communication systems as well: be it in maintenance or operation, or during fault detection and prevention. Diversity, as fourth aspect, refers to the heterogeneity of a system, seen here as a chance to reduce dependencies on potential single points of failure and the availability of multiple ways to achieve the same result. One example in the scope of Hexa-X is the "network of networks" concept discussed in D1.3 [HEX22-D13], allowing the 6G system to combine strengths of multiple heterogenous networks and their underlying communication technologies.

The initial list of KPIs for each capability and their definitions was provided in D1.3. In the following, we provide the final list of definitions in Table 3-3 based on the works done in the technical work packages dedicated to the respective capability.

Table 3-3: KPIs and their definitions [HEX22-D13].

		KPI	Definition / References
Communication	Dependability Attributes	Availability [%]	Percentage of time during which QoS targets are met and service is offered during operation [22.261]. Additional information on the resilience of the application, such as survival time [ms] as acceptable downtime of a service, should be included.
		Reliability [%]	Percentage of the amount of sent packets delivered within QoS constraints [22.261].
		Safety	Reference to applicable standards and regulations in the domain; functional requirements, if available.
		Integrity	Reference to applicable standards and regulations in the domain; functional requirements, if available.
		Maintainability	Functional requirements and regulations (e.g., time to recovery, auditability).
	QoS Attributes	Service latency [ms]	E2E latency for communication service (user plane) between two application endpoints from use case perspective with allowed variability/Jitter and/or expected upper bound. One should distinguish between UL and DL, and detail expected

			packet sizes and traffic characteristics in the deployment characteristics, if available.
		Data rate (minimum expected, desired, maximum) [Mbit/s]	Referring to a single UE. Minimum expected data rate ensures correct operation of the use case (with reduced Quality of Experience (QoE) or limited functionality). Desired data rate ensures desired QoE and full functionality of the use case. If an upper bound can be specified, this is the maximum data rate that can occur in the use case. [5GP21]
		Resource constraints	*Refer to deployment description (e.g., frequency, energy consumption)*
		Scalability	*Refer to deployment description (e.g., number of users, mobility, ...)*
AI and computation, c.f. [HEX22-D42]	Dependability Attributes	Agent availability [%]	Percentage of time during which the AI agent can receive and respond to an inferencing request (i.e., the agent can be utilised for decision making) meeting the agreed QoS targets.
		Agent reliability [%]	Percentage of requests that are fulfilled within the agreed QoS targets.
		Safety	Requirements or regulations related to the use of AI in the application domain.
		Integrity	Requirements or regulations related to guaranteeing that AI/compute operates as intended.
		Maintainability	Functional requirements or regulations as to how the system reacts to defects/faulty operation (e.g., how well and fast the AI agent recovers from attacks).
	QoS Attributes	AI service RTT [ms]	Maximum tolerable delay from the request being issued by the application until response available to the application by the AI service.
		Inferencing accuracy [%]	Domain-specific measures for the accuracy of the AI estimates, if available (i.e., quality functions).
		Interpretability level	Qualitative indicator for the interpretability of AI-based models and decisions, use case-specific.
		Training/model transfer latency [ms]	Tolerable time to train a new/evolved model relevant in the use case or transfer a model from one AI agent to another AI agent.
		Agent density	Density of AI agents supported by the network (depending on computation and communication demands), one aspect of scalability.

		Resource constraints	*Refer to deployment description (e.g., frequency, energy consumption)*
		Scalability	*Refer to deployment description (e.g., number of users, mobility, ...)*
Localisation and Sensing	Dependability Attributes	Service availability [%]	Percentage of time during which location or sensing service requests are answered and the given QoS targets are fulfilled.
		Service reliability [%]	Percentage of requests that are fulfilled within the agreed QoS targets.
		Safety	Requirements or regulations for localisation or sensing regarding safety in the respective use case.
		Integrity	Requirements or regulations for localisation or sensing integrity, e.g., robustness to potential disturbances or attacks.
		Maintainability	Functional requirements or regulations in the use case domain when it comes to utilisation of the service.
	QoS Attributes	Location accuracy [m]	Accuracy of the estimated location, reported in horizontal and vertical position accuracy [22.071].
		Localisation/Sensing service RTT [ms]	Maximum tolerable service latency from the request being issued by the consumer (application, service) until location/sensing response being provided. Not to be confused with RTT measurements as one method to measure the distance between user and base station.
		Orientation accuracy [°]	Accuracy of the estimated direction of UE: roll, pitch, yaw.
		Refresh rate [1/s]	The rate at which new location estimates need to be obtained by the application.
		Minimum and maximum resolvable range [m]	Required minimum and maximum distinguishable distance between two objects for the application/use case.
		Angular resolution [°]	Required minimum distinguishable angle between two objects (orientation).
		Minimum and maximum velocity [m/s]	Velocity range (minimum and maximum velocity) of the object that needs to be measured by the service.
		Velocity resolution [m/s]	Minimum measurable change in velocity of the object.
		Resource constraints	*Refer to deployment description (e.g., frequency, energy consumption)*
		Scalability	*Refer to deployment description (e.g., number of users, mobility, ...)*

Additional KPIs were identified for inherent parts of the 6G system, such as the management and orchestration capabilities. These KPIs serve as potential proxies for a quantification of *flexibility* KVIs and are discussed in more detail in the following section on KVIs and their methodology.

3.4 Updates on KVI definitions and methodology

In D1.2 [HEX21-D12], the Hexa-X value assessment methodology was outlined for connecting KVI's with use cases and where an intermediate step is to identify the value that a use case result in. The main value framework used for this purpose is the UN SDG, but other values are also mentioned (e.g., ease of life, entertainment), and in D1.3 [HEX22-D13], an assessment of the example use cases from each use case family were performed, from the perspective of contribution to the targets identified for the UN SDGs. Focus was on sustainability but as inclusion aspects are very much part of the SDG targets, this value is also well-covered. With respect to trustworthiness and flexibility, there is a need to look at suitable technical proxy KPI's to assess the value additions (making the identified KPIs potential candidates for KVIs for trustworthiness and flexibility) and for some aspects of trustworthiness related to security and privacy, a "Level of Trust" (LoT) KVI is introduced already in D1.3 [HEX22-D13]. Trustworthiness also has a close connection to dependability attributes, such as availability and reliability of a service, in the sense that many of them directly address aspects related to trust in the system and trust that the system delivers as requested and/or expected. These dependability primitives are mainly touched upon in D7.1 [HEX21-D71], with their relation to resilience being discussed in the previous section and further revisited when discussing trustworthiness and flexibility in the following subsections.

Among the four different key values, sustainability, inclusion, trustworthiness, and flexibility, it is in some aspect possible to make a distinction between two different value categories, indicated in Figure 3-7: Hexa-X key values and association to use cases. Sustainability and inclusion are key values that directly associate with humans, nature, climate or in general with a benefit potential of a connected society and these values often map well to the SDG framework.

Sustainability and inclusion are, consequently, values that are realized through use according to a set of use cases (e.g., realization of a telepresence use case might lead to increased inclusion and increased sustainability due to reducing barriers for participation to a meeting and, at the same time, reducing emissions that would be caused by business travel).

Flexibility and trustworthiness, in turn, are different in that they directly imply certain (additional) capabilities of the 6G system. These additional capabilities would allow the system to address additional, new use cases, as illustrated in the Figure 3-7: Hexa-X key values and association to use cases. – flexibility and trustworthiness act as enablers for these use cases. Consequently, the realization and utilization of these new use cases would again create value, as previously discussed. Therefore, KVIs associated to flexibility and trustworthiness are linked to sustainability and inclusion via the set of use cases that are either improved or enabled by the associated capabilities. As an example, certain use cases that would require handling and storing sensitive data can only materialize if the required degree of trustworthiness is realized in the system. Once realized, these use cases can then benefit sustainability and inclusion or any additional values.

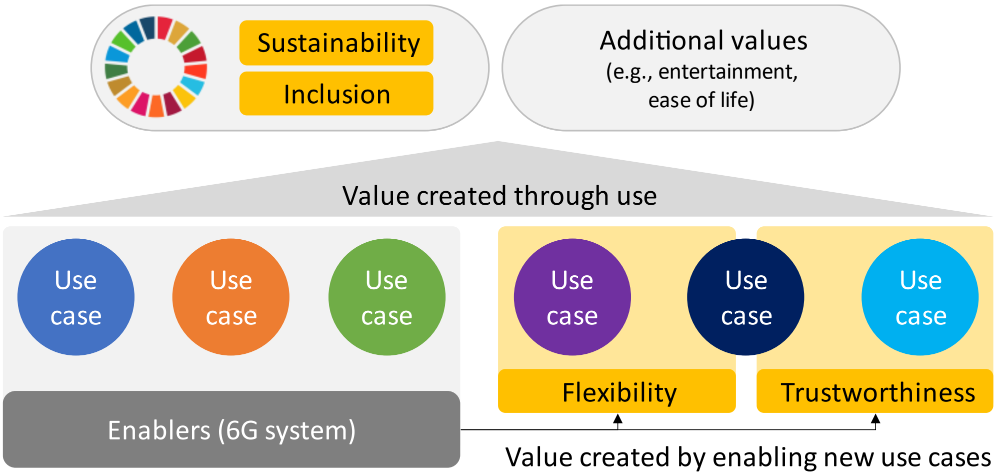


Figure 3-7: Hexa-X key values and association to use cases.

The Figure 3-7 illustrates that the flexibility and trustworthiness 6G are also enablers of more use cases than would have been the case without these values. The use cases in turn, deliver value in terms of sustainability, enabling values according to, e.g., SDGs, of inclusion or of some other desired value such as ease of life or entertainment.

The above reasoning suggests that KVI's directly associated to flexibility and trustworthiness are not always in the same way easily mapped to UN SDGs for example. In many situations these key values can be expressed as KPIs that in turn can be a prerequisite for sustainability or inclusion values.

The Societal Needs and Value Creation Sub-Group (SNVC-SG) within the vision and societal challenges working group in 6G-IA has recently published a paper on "What societal values will 6G address?" [6GIA22] outlining a set of key values that map well to the SDGs, adding a few that go beyond. The key value "Trust" is in this paper described as having a societal value of "*feeling of confidence, faith and explainability in the way that advanced systems may impact humans*". While this is indeed an important value, a system that is more trusted is more useful than a system that is less trusted, so while there is an inherent value as described in the 6G-IA paper, there can also be a translation to a larger value in terms of addressable use cases as described and illustrated above.

The 6G-IA paper is interesting in several aspects on assessment through key value indicators. It is noted that ideally, an assessment of value originates or is made by stakeholders or experts from the relevant segment (e.g., value of a health use cases should be determined by a health expert/someone from medical sciences) While this is an optimal principle, it is also recognized that assessments from experts in the ICT domain is a good starting point. The fundamentals are largely in line with the methodology outlined in D1.2 [HEX21-D12] and it adds a stepwise methodology that can work very well also for further assessment of the Hexa-X use cases, including for example that some KVIs may be approximated or represented by "proxies" in form of system KPI's that can be measurable. A simple example for such a KPI could be the *energy consumption per bit*, acting as a proxy for the quantification of certain aspects of the *sustainability* key value. The 6G-IA paper also highlights negative impacts of a use case and set forth the requirement-reward perspective with two simple questions: What does it cost? (In terms of system and technology capabilities or requirements) and what does it give? (In terms of key values and its indicators. In the following, inspired by the 6G-IA paper, we outline further details on how we would like to pursue the evaluation of the Hexa-X use cases, using the D1.2 methodology as a basis, but also adding a technical enabler aspect, as is done by 6G-IA.

One aspect of key values is that a key value comes from realizing a use case and in that sense can be illustrated as the qualified or quantified value from use cases as suggested in Figure 3-8 below, where e.g., the result of the realization of the blue use case is value 1. Along the same lines, and to differentiate KVIs and KPIs, the KPI is used to characterize requirements that the use case poses on the technical enablers required for the realization of the use case. This, in a sense, connects technical enablers and realized values via the use case: technical enablers 2 and 3 are fulfilling the requirements of the blue use cases and are therefore chosen for its realization, leading to achievement of value 1 and value 3 in our example. Naturally, technical enablers can be utilized for the realization of different use cases and their requirements, leading to additional such connections between technical enablers and associated KPIs and the realized values via the use cases, as indicated in the Figure 3-8.

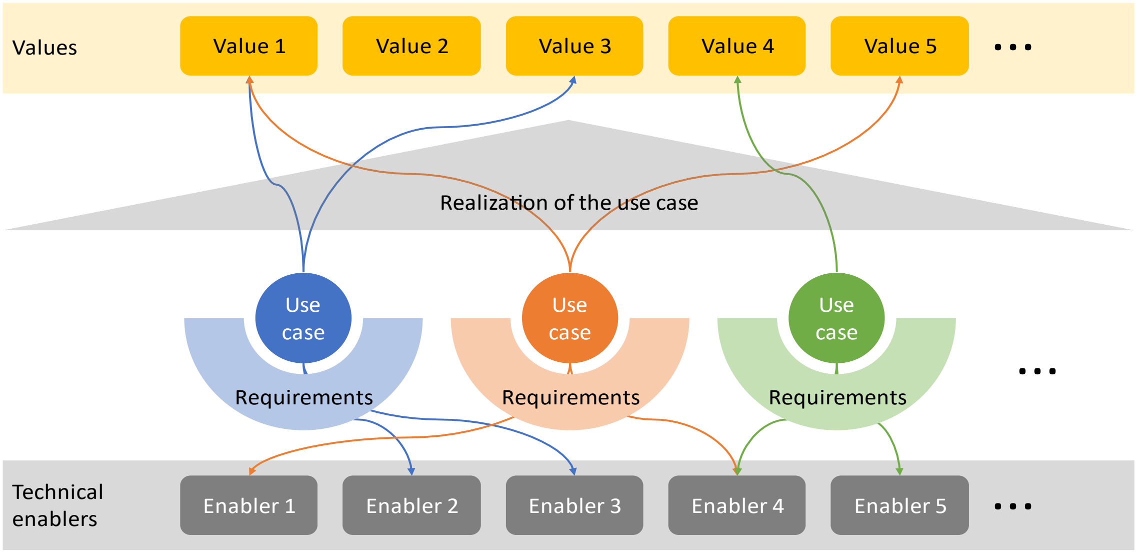


Figure 3-8: Additional values being enabled by realization of use cases, that rely on technical enablers fulfilling the respective requirements of one or more use cases.

While the above model holds well on a "per-use-case-level" it does not represent the values that associate with, e.g., improved energy performance, trustworthiness or flexibility and need to be complemented with key values and indicators that represent the more inherent values of the system.

The following sections characterize each Hexa-X key value and discuss related technical enablers that are proposed in the context of the other Hexa-X technical work packages, provide a list of identified KVIs or Proxies and discuss the potential scale of the effect by relating to the use case families discussed earlier in this chapter.

Regarding the evaluation of KVIs, Table 3-4 provides guidance as to what is to be expected for a given Technology Readiness Level (TRL) of the underlying technological development. Given the low TRL of 6G technical enablers discussed in the following, the evaluation of the impact of a technical enabler on a KVI is largely based on assessment by subject matter experts as highlighted in the table, with some results from early trials and experiments allowing an early subjective assessment. However, for a quantification within the proposed Hexa-X use cases, deployed networks, and input from users in the form of questionnaires and interviews are required for all key values discussed in the project.

Table 3-4: Methods for evaluating KVIs as proposed by 6G-IA [6GIA22].

Assessment type / phase	**Lower TRLs** (early in the technology development)	**Higher TRLs** (later in the technology development)
Subjective assessment	Trials, experiments, interviews	Questionnaires, interviews, focus groups
Objective assessment	Assessment by subject matter experts	Measurements on deployed networks

In the following subsections, the Hexa-X key values sustainability, inclusion, flexibility, and trustworthiness are discussed in more detail. Each key value is characterized, and technical enablers and potential KVIs for quantification and measurement are discussed.

3.4.1 Sustainability

3.4.1.1 Characterization

Sustainability is discussed from two viewpoints: sustainability of the 6G system itself (e.g., addressing the environmental footprint, emissions, and energy consumption of the system) and the enablement effect 6G systems can have on different sectors to become more sustainable or resource efficient. For a more detailed discussion, please refer to [HEX22-D13], Section 7. In the following, the key messages are summarized and relation to technical enablers and current concepts for measurements and quantification are outlined, serving as starting points for sustainability KVIs.

3.4.1.2 Technical enablers, measurements, and quantification

Technical enablers proposed in Hexa-X and listed in Table 3-5 focus on the sustainability of the 6G system itself. The enablement effect is addressed in the discussion of 6G use cases as motivator for specific technical contributions and their relation to the UN SDGs, but there are no dedicated technical enablers that are attributed to this group of sustainability KVIs. Instead, please refer to Section 6.5 in [HEX22-D13] and Section 7 in this deliverable for a detailed discussion of the enablement effect of 6G and the methodology for its quantification.

The target objective for more sustainable 6G is quantified along two proxies: a reduction of the total cost of ownership (TCO) by at least 30%, and a reduction in the energy consumption per bit in networks by at least 90%, as initially discussed in [HEX22-D13], Section 6.1. Table 7-1, Table 7-3 and Table 7-4 in Section 7.2.3provide an assessment of different technical enablers that contribute to this overall goal and the expected impact in terms of achieving the goal. An extensive discussion of technical enablers to increase energy efficiency is provided in [HEX22-D13], Section 6.3, and briefly summarized in the following table. Notably, increasing the overall energy efficiency requires an E2E optimization and cross-layer design taking all these enablers into account, especially if a wide range of use cases is to be addressed by the system (c.f. discussion on flexibility later in this section). AI-based solutions are seen as a key enabler for addressing the complexity of this optimization problem.

Table 3-5: KVIs for sustainable 6G systems and key enablers.

KVI / Proxies	Selected enablers	Targeted use case examples
Energy consumption during operation	Extending sleep modes to compute [HEX22-D42]	Earth monitor, smart cities
	Joint optimization / co-design of computation and communication [HEX22-D42], [HEX22-D72]	Interacting mobile robots, flexible production
Energy consumption at zero load	Advanced sleep modes, MIMO muting [HEX22-D22]	No specific use case
	Low/zero-energy devices [HEX22-D72]	Earth monitor, smart cities
	Complexity reduction in signalling [HEX22-D52]	No specific use cases
Signalling overhead, signalling complexity	AI-based orchestration [HEX22-D42], [HEX22-D62]	No specific use cases
	Functional decomposition, and reduced signalling [HEX22-D52]	No specific use cases
	Computation-Communication-Co-Design [HEX22-D42]	No specific use case

Energy consumption per bit (energy efficiency per bit)	Control-Computation-Communication-Co-Design [HEX22-D72]	Robots to cobots family, e.g., interacting mobile robots, flexible production

For a detailed discussion regarding the *quantification of the enablement effect* 6G can have on other sectors of society, please refer to Section 7 in this deliverable. In addition, [6GIA22] includes a list of KVI examples addressing the enablement effect for different use cases in [6GIA22], Section 5. Examples include the environmental footprint of urban transport in the case of a smart city, or the cost-efficiency of living and working in rural areas for the case of remote work and telepresence use cases.

To quantify the *sustainability of the 6G system itself*, several technical KPIs can serve as candidates for KVIs. The energy consumption of individual system components (e.g., UEs, base stations, compute, and networking infrastructure) needs to be quantified both in absolute terms (e.g., consumption at zero load, load-independent consumption) and relative to the load (e.g., consumption per transmitted data, “energy per bit”). Given that these metrics are highly dependent on the actual implementation and deployment of a system, we expect that they require measurements on deployed networks. However, early indicators for selected parts of a 6G system are available through trials or models (e.g., Section 3.5 in D2.2 [HEX22-D22]).

To quantify the signalling overhead and the complexity of signalling, one should quantify the number of network functions that need to be involved in a certain action (e.g., attachment of a new UE, handover) and potential dependencies between those involvements (i.e., iterative, or parallel invocation). In addition, the size of signalling messages (corresponding also to the need to transmit state between NFs) can be quantified and compared. These indicators can already be studied during the design phase of 6G, as done in [HEX22-D52]. To further quantify signalling overhead also in terms of induced delays, measurements in real-world deployments are required, as these indicators are highly dependent on the placement of Network Functions (NFs) and the realization of the underlying network.

When discussing energy consumption per bit in the context of sustainability of a 6G system, one might need to further distinguish between use cases and the associated “value” of the transmitted data from an applications’ perspective. By studying cross-layer dependencies between the application and the network, the amount, frequency or required QoS for a data transmission can be further optimized, resulting in less data being transmitted or in less demanding QoS for certain use cases, while still maintaining the required application productivity. This, in turn, can have a direct impact on the resources required and, consequently, on the energy consumption and energy efficiency of the 6G system. In Hexa-X, this cross-layer effect is studied in [HEX22-D72] and [HEX22-D42] for selected use cases (e.g., interacting mobile robots) under the term (Control-) Communication Computation Co-Design. Ensuring a high grade of efficiency (and flexibility, as discussed later) in the 6G system will enable this effect for a broader range of envisioned use cases.

The TCO of a 6G system is another important indicator for the sustainability of the system. This is discussed in Section 7 for selected technical enablers (i.e., how will the enabler contribute to a reduction in the TCO). Additionally, the flexibility of the system will have a direct impact on its sustainability, as a more flexible system allows to address a broader range of (potentially still unknown) use cases. Thereby, flexibility enables additional revenue streams and increased reuse and adaptability of the system, contributing to maintaining a high value of the system itself. This is later discussed in more detail in Section 3.4.3.

3.4.2 Inclusion

3.4.2.1 Characterization

In Hexa-X, the key value *inclusion* refers to the *capability* of a person or group to use a service, including the *ease of access* to the service. This understanding covers technical aspects such as coverage (i.e., spatial, and temporal availability of a network and service) and user-centric aspects such as availability and accessibility of the service for a specific group of people, e.g., through means of novel

Human Machine Interfaces (HMIs) or interaction with robots. Consequently, the term “inclusion” is used synonymously to “digital inclusion”.

3.4.2.2 Technical enablers, measurements, and quantification

KVI / Proxies	Selected enablers	Targeted use case examples
Increase in addressable workforce (additional workers being enabled to contribute)	Novel HMIs, DTs [HEX22-D72] and [HEX23-D73]	Telepresence (remote work)
Perceived quality of work (and related QoE for selected use cases)	Novel HMIs, DTs [HEX22-D72] and [HEX23-D73]	Telepresence (remote work)
Reduction in wait-time (use case specific)	n/a	E-Health for all
Ease of use (use case specific)	n/a	E-Health for all
Percentage of population reached	NTN, see [HEX22-D52] and [HEX23-D53]	E-Health for all, institutional coverage
Percentage of target area covered (use case specific)	NTN, see [HEX22-D52] and [HEX23-D53] Zero-Energy devices [HEX22-D72] and [HEX23-D73]	Earth Monitor
Spatial and/or temporal Resolution	NTN, see [HEX22-D52] and [HEX23-D53] Zero-Energy devices [HEX22-D72] and [HEX23-D73]	Earth Monitor

For the coverage-related aspects of inclusion, we propose to utilize KVIs that quantify spatial coverage related to the targeted use case. This would include coverage as percentage of the worlds’ surface, or coverage as percentage of the worlds’ population. The latter could be further divided into the (technical) network coverage of habited regions and availability of and access to required end devices or means for interaction (e.g., availability of smartphones) in the population. Depending on the use case, additional indicators for the achieved and achievable (upper bound) resolution might be required (e.g., spatial and temporal density of data points in case of the *Earth monitor* use case – desired target values for these specific use cases are discussed in [HEX21-D71]).

Additional KVIs include the reduction in time it takes until an interested party can consume a service (e.g., implying commute times) or the complexity associated with the consumption of the service (e.g., availability of certain devices, need for assistance in utilizing the service). These aspects are using case specific, as also noted in [6GIA22]. In case of *E-health for all*, for example, the corresponding indicators would be availability of access to a (remote) doctor or diagnosis, availability of the required devices (e.g., sensors, actuators), penetration of the service in terms of percentage of the population reached and their demographics (target vs. actual). A subjective indicator would be the ease of use, requiring an assessment via interviews or in focus groups for quantification – potentially leading to the definition of a QoE indicator for the specific use case.

In use cases related to *Remote work and telepresence*, suitable KVIs would be the increase in addressable workforce (e.g., trough remote work, home office, novel HMIs), and the perceived quality of work (e.g., via a mean opinion score, assessable trough questionnaires). In case of telepresence, additional QoE indicators known from video streaming can help in assessing the comfort and satisfaction of a user when consuming the service, e.g., related to the level of immersion or adverse effects such as motion sickness. These factors are further discussed in [HEX21-D71].

3.4.3 Flexibility

3.4.3.1 Characterization

Flexibility refers to the ability of the system to adapt to (or be adapted to) changes in its environment and utilization, considering costs that such changes would inflict. As discussed earlier, this property is closely intertwined with the dependability and resilience of a system. Flexibility also has an impact on the sustainability of the system, as it can allow the system to address additional (and potentially still unknown) use cases in a resource- and cost-efficient way through re-use and re-configuration of components. Flexibility also refers to being able to integrate different types of networks (e.g., mesh or Device to Device (D2D) networks) into the overall network topology. Achieving flexibility requires reducing and handling the inherent complexity of a system, with AI-based mechanisms for management and orchestration being promising enablers, as listed in the following.

3.4.3.2 Technical enablers, measurements, and quantification

The following table provides just an overview of technical enablers for flexibility for the discussion of potential KVIs in the following subsection. For more details, references to technical deliverables are provided.

KVI / Proxies	Selected enablers	Targeted use case examples
Convergence time	Flexible resource allocation [HEX22-D72]	Not limited to specific use case
Detection time	Handling unexpected situations, error detection [HEX22-D72]	Robots to cobots family
Re-configuration overhead (compute, communicate)	Hexa-X WP5 architectural enablers for flexible networks ([HEX22-D52], [HEX23-D53], also in [HEX22-D13]), network of networks	Use cases in trusted embedded networks family, hyperconnected resilient network infrastructure, and earth monitor
Re-configuration capability / related to scalability	Hexa-X WP6 enablers for flexible resource management, scalability ([HEX22-D62], also in [HEX22-D13])	No specific use cases
Re-use / sharing of spectrum	Flexible spectrum management (Section 5 in [HEX22-D13] and Section 7 in this deliverable)	No specific use cases

When discussing flexible network topologies and the need to adapt the network topology to changes in the environment or utilization of the network at vastly different time scales, the *convergence time* required to adapt to such changes is an important KVI for flexibility. The convergence time is further impacted by the *detection time*, referring to the time it takes to detect a change in the network or environment that would require the network to adapt accordingly. Early detection of events that require adaptation or accurate prediction-based action prior to the actual occurrence of the event further contribute to the resilience of the overall system.

The trend to utilize AI for management and orchestration necessitates the collection and exchange of additional data and leads to quantifiable *communication and computation overhead*. The trade-off between this overhead and the benefit of increased flexibility needs to be carefully balanced depending on the targeted use cases (e.g., weighted against the enablement effect associated to those use cases). This holds especially true if personalized or sensitive data is collected to be utilized in the respective models and algorithms (e.g., mobility of users).

Flexibility resulting from flexible topologies can be quantified by spatial and temporal coverage aspects as discussed for the inclusion key value in the previous section. Additionally, the dependability of the resulting network of networks needs to be captured, especially for use cases with stringent dependability or trustworthiness requirements. Suitable KPIs for this quantification are defined for the 6G capabilities in Section 3.3. Addition KPIs to quantify 6G architecture properties such as flexibility are also discussed in [HEX22-D52].

To quantify the complexity of the overall system and, consequently, the expected complexity to adapt the system to new or additional use cases (as one indicator of flexibility), measures for the separation of concerns and the ease of adding new features (capabilities or network functions) should be utilized. Potential KVIs are the number of network functions a new/additional network service would invoke or depend on and the number of functions (concerns) the network function takes care of. Here, measures from software engineering and distributed computing could be utilized, e.g., based on the control graph of the software. In addition, distributing dependent network functions across the system induces further communication overhead and potential delays, constituting an additional trade-off to be made.

When discussing trade-offs, an important aspect for flexibility is the trade-off between performance required in certain use cases (e.g., low latency, high throughput) and sustainability of the 6G system (e.g., energy consumption, but also TCO) via mechanisms such as longer sleep times as discussed in Section 7. The achievable ratio between these two aspects or the ability to control this ratio constitutes an important KVI for flexibility of a 6G system – however, quantification is challenging given the need to quantify sustainability of the 6G system and the enablement effect as discussed earlier.

3.4.4 Trustworthiness

3.4.4.1 Characterization

Trustworthiness has a wide scope and can span anything from security and privacy (as discussed in detail in [HEX22-D13]) to aspects that also sort under the dependability framework, as described in [HEX21-D71], for example, availability and reliability of a network. All the above contributes to creating a trustworthiness level that allows for a larger set of use cases that wouldn't be possible with lower privacy or lower network availability levels for example. This means that when assessing trustworthiness, it is important to take into consideration also these aspects.

For dependability, [HEX22-D13] describes how dependability attributes and levels need to be specified per network service. Just because there is a certain need for availability of communication, it is not necessarily the same need for availability of other services such as localization, or sensing. Situations can occur, when there is excellent communication availability, but no sensing information can be obtained. By extension, it is reasonable to talk about trustworthiness (and flexibility) also for the different services. It is perfectly possible to have a high trustworthiness level for a communication service, but a lower trustworthiness level for, e.g., AI or sensing services. While the following talks about services on a general level, it is sometimes relevant to make this distinction based on the requirements and expectations within a certain use case.

Trustworthiness also has subjective aspects that relate to an understanding of a system. It is far easier to trust if system complexity and functionality is understood and concerns are well separated. To this end, [NGA22b] defines further impact factors that would increase confidence in a network to perform as expected in the face of disturbances. These factors include the organization of business processes and economic value chains spanning all actors associated to the offered network services, such that there is high confidence in equipment and involved parties. The importance of open standards that allow testing and certification against well-defined requirements is also seen as a strong driver for trust in the system. To be trusted, the system needs to be dependable and resilient (referring again to its capability of performing as expected, even in the face of – unexpected – disturbances, e.g., caused by natural disasters or man-made actions). The report further mentions interoperability across the ecosystem and fulfilment of the expectations of users (i.e., the realization of use cases as outlined in the previous sections).

3.4.4.2 Technical enablers, measurements, and quantification

Enablers for trustworthiness, with a focus on security and privacy, are discussed in detail in Section 4 of D1.3 and Section 5 in this deliverable. For a discussion of technical enablers for increased dependability, please also refer to [HEX22-D72, Section 4] and updated discussions in [HEX23-D73].

As discussed earlier, trustworthiness covers a wide range of aspects. The LoT as defined and discussed in detail in [HEX22-D13] focuses on security as the basis and privacy on top of security as a key aspect of trustworthiness. In this sense, the LoT KVI indicates, whether and to what extent security and privacy are being protected in a system.

Additional aspects of trustworthiness include availability and dependability, resilience, and compliance with ethical frameworks [HEX21-D12]. Focusing on technical aspects, [NIST17] lists safety, reliability, and resilience in addition to security and privacy. Security and privacy are discussed in more detail in [HEX-D13] and Section 5 in this deliverable. Safety and reliability are already covered under the umbrella of dependability. Resilience and its relation to dependability is discussed in Section 3.3.

When it comes to compliance with ethical frameworks, focus on Hexa-X is on the impact of the technical enablers AI and localization/sensing and related KVIs, based on discussions in [HEX23-D33], [HEX22-D42], and [HEX22-D72].

KVI / Proxies	Selected enablers	Targeted use case examples
AI privacy	Privacy-preserving clustering, differentially private Federated Learning (FL) [HEX22-D42]	No specific use cases
AI agent availability + reliability	Prediction of mobility, workload movement optimization; prediction of impairments in connectivity [HEX22-D42]	No specific use case, mobile users

With 6G systems becoming reality in the coming years, it is expected that the methods for evaluating KVIs will be extended with measurements and insight from real-world systems and deployments, as well as the realization of novel use cases and corresponding assessment of the real impact of the technology by its users.

4 End-to-End architecture

This chapter presents the final release of the Hexa-X End-to-End (E2E) architecture. The main objective of the presented architecture is to map the enablers developed in the technical work packages of Hexa-X project to the E2E architecture and show the relationship between those enablers. The technical enablers are the important components for the transformation to the new architecture and they are essential for supporting the requirements of the 6G vision and 6G use cases presented in the previous chapters as well as in previous deliverables [HEX21-D12] [HEX22-D13]. The following chapter starts with an overview of the proposed final version of the Hexa-X E2E architecture as well as its security aspects (for more details, please refer to Section 5). The following sub- sections (Section 4.2 - 4.7) present enablers from Hexa-X technical work packages for E2E architecture. Section 4.8 maps the technical enablers to subset of use cases from Hexa-X use case families in order to show the ability of designed architecture to support the chosen use cases.

In [HEX21-D51] as well as in [HEX22-D13], eight different architectural principles have been identified which are needed to fulfil the new design of 6G architecture. Those principles were the foundation of the work toward the first draft of Hexa-X E2E architecture which presented in [HEX22-D13]. In the following the updated version of the Hexa-X E2E architecture is presented. The aim is to show the latest design and structure of the communication system which includes the devices, network infrastructure, cloud services and applications that work together to provide a seamless experience. This requires a highly integrated system that can handle massive amounts of data, minimize latency, and ensure reliable connectivity.

Following the same approach as the Hexa-X E2E architecture ([HEX22-D13]), the following architecture presents the technical enablers in a layered structure composed of *infrastructure and cloud layer*, *network service layer* and *application layer*.

The *infrastructure and cloud layer* of the Hexa-X E2E architecture plays a crucial role in enabling the seamless communication experience that 6G promises to deliver. This layer comprises a set of technical enablers that work together to support the ultra-high speed, reliable, and secure communication network. At its core, the *infrastructure and cloud layer* comprise a network of interconnected devices, including Internet of Things (IoT) and User equipment (UE) devices, base stations, small and macro cells, access points, cloud infrastructure, etc. This complex network of various entities forms the backbone of the 6G network and is responsible for facilitating the flow of data throughout the network. Additionally, this layer provides physical resources to host the network services, cloud applications and application layer elements.

D-MIMO is a key technology in the design of the 6G architecture. It enables the use of multiple antennas at both the transmitter and receiver, leading to improved data transfer rates, increased spectral efficiency, coverage extension, and enhanced communication reliability. Section 4.2.1 draws more details on architectural aspects of D-MIMO.

One of the key components of this layer is the use of terahertz (THz) frequencies. THz frequencies are expected to provide significantly higher data rates than the microwave frequencies used in current wireless communication systems. However, THz frequencies also present significant challenges, such as signal attenuation and dispersion, that need to be overcome through innovative antenna designs and signal processing techniques. Section 4.2.2 presents three scenarios with different ranges in terms of distance which can satisfy the requirements of the applications envisioned for 6G network.

Localization and Sensing is one of the important services that 6G is envisioned to offer. The architecture of the future network must be able to support the requirements as well as provide means to seamlessly engage and interact various components. In Section 4.3 the localization and sensing ecosystem is presented.

The Hexa-X E2E architecture also includes the integration of extreme edge, which is part of a network with high heterogeneity of devices, characterized by a wide variety of technologies, in terms of both hardware and software. These devices could be personal devices (smartphones, laptops…) and a huge variety of IoT devices (wearables, sensor networks, connected cars, industrial devices, connected home appliances, etc.). Having extreme-edge as part of the E2E network cloudification can lead to the full integration of cloud-native technologies, such as distributed computing and virtualization. More details on this can be found in Section 4.7.

The future 6G architecture is envisioned to comprise several ad hoc and subnetworks that work together to provide a unified system. These subnetworks are designed to meet the diverse communication requirements of different use cases, ranging from high-speed data transfer for data demanding applications to low-latency communication for mission-critical applications. To be able to provide global coverage and enabling communication in remote and underserved areas, benefiting from the Non-Terrestrial Network (NTN) is one of the important aspects of the 6G architecture. More details can be found in Section 4.6.

The *network service layer* of the Hexa-X E2E architecture is responsible for providing various services to end-users. The layer also depicts Network Functions (NFs) and their services that are used within the network and are not exposed to the end-users. In the 6G network, this layer will play a crucial role in ensuring that users have access to high-quality, reliable, and secure services. In addition to the more common services such as communication services, the 6G architecture requires all sorts of new services from AI and compute to analytics and data collection as well as localization and sensing. By having all network functions, operations, and services implemented as cloud-native microservices, the 6G architecture can evolve towards a more softwarised, intelligent, and efficient architecture.

Considering the envisioned use cases, it is crucial that 6G networks are secure, preserve the privacy of their users, and can be trusted. To lay the foundations for this, Hexa-X has investigated the relevant security and privacy technologies and mapped them to the Hexa-X E2E architecture, resulting in the Hexa-X security architecture, which is described in Section 5.1.

The Management and Orchestration (M&O) of the future network is moving toward full automation and closed-loop control. This is supported by the parallel adoption of advancements in Artificial Intelligence (AI) and Machine Learning (ML) technologies. Section 4.7 introduced the architecture that can support such demands as well as details on its different components.

The topmost layer of Hexa-X E2E architecture is *application layer* which interacts directly with end-user applications, facilitating the exchange of data and information. The detail of this layer is out of scope of this document.

Overall, the Hexa-X 6G E2E architecture is a highly complex system that requires the integration of multiple technologies and disciplines. However, with its potential to provide unprecedented levels of connectivity and enable new and innovative applications, the development of a robust and efficient 6G E2E architecture is critical to the success of the next generation of wireless communication. Following Sections are dedicated to more details on the various architectural technical enablers which are illustrated in Figure 4-1.

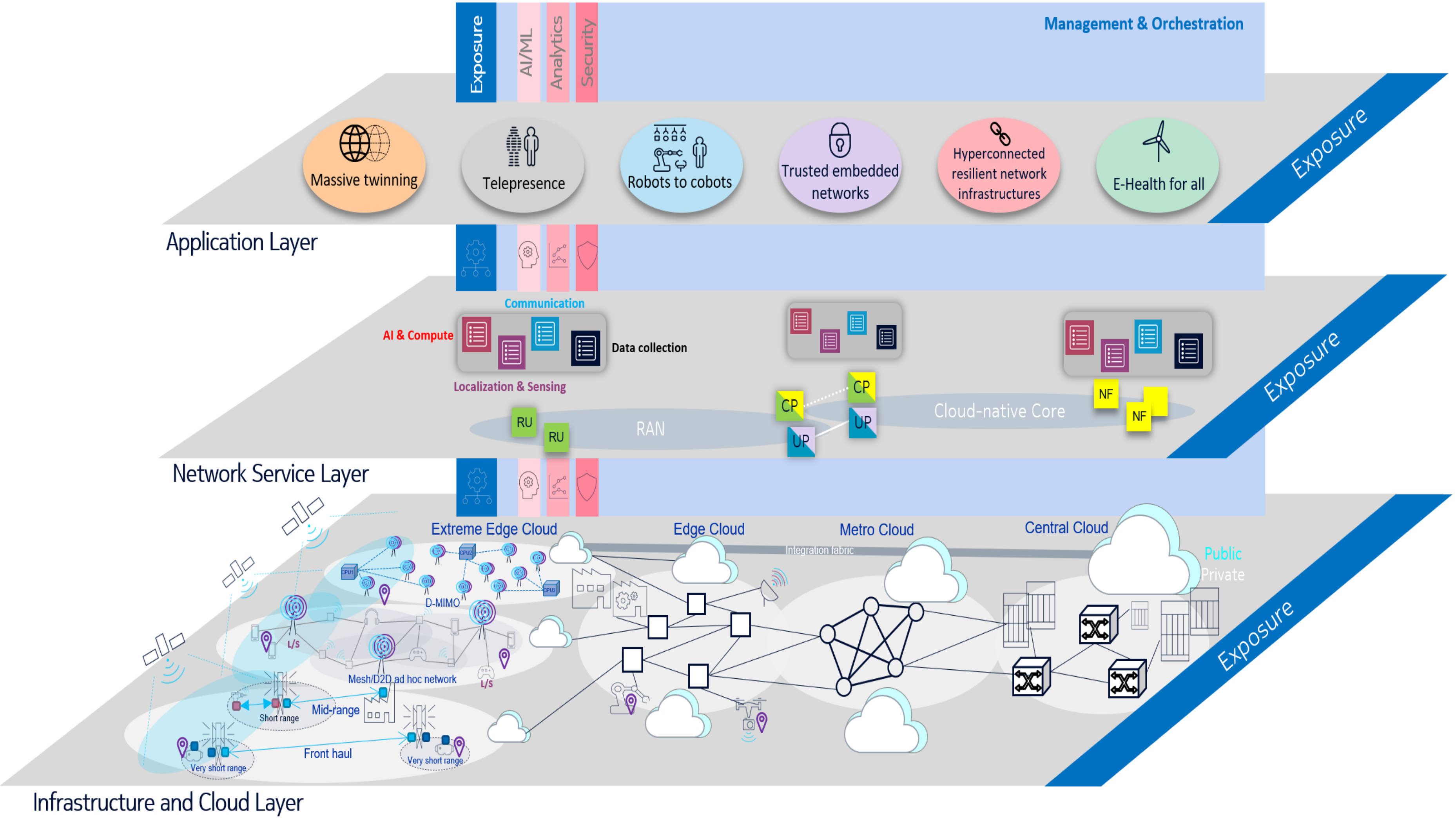


Figure 4-1: Hexa-X E2E architecture.

4.1 Exposure Coordination Framework

In [HEX22-D13] and [HEX22-D52], several different enablers and enabler frameworks, such as, AI as a Service (AIaaS), Federated Learning as a Service (FLaaS), analytics, programmability, Compute as a Service (CaaS) and mesh networks management frameworks have been introduced. These frameworks in many ways need similar functionalities e.g., the need to store models (repository), access data (analytics), use and train AI models, etc. To avoid duplication of functionalities and to enable interaction between the functions and frameworks mechanisms for cross framework exposure (to share e.g., training data, AI-models, network status, etc.) are needed. Moreover, since one of the main targets of the Hexa-X architecture is to be flexible, these frameworks are designed so that they can be implemented and deployed independently in a self-contained manner, however, if over corresponding services are available from the other frameworks they should not be instantiated by the orchestrator. Such services are marked as "optional" in [HEX23-D53]. This allows us to have a flexible sequential development and deployment procedure (Continuous Integration/ Continuous Delivery**,** CI/CD). To integrate the services of the various frameworks into a given coherent deployment cross-framework interaction, we propose a framework here referred to as "Exposure and Coordination Framework" (ECF). The ECF should meet the following requirements:

- Provide a frameworks discovery mechanism of the given deployment of the Hexa-X architecture that consists of multiple frameworks (principles #3 and 7 [HEX21-D51]),
- Manage the cross-framework connections and interactions according to given policies,
- Share data and information between the different frameworks of Hexa-X architecture,
- Manage potential conflicts and provide closed-loop control across the frameworks (principle #2 [HEX21-D51])
- Be extensible to include new and yet unspecified frameworks (principle #4 [HEX-D51]).

The interactions between functions of different frameworks can be achieved by tight integration of the functions of the frameworks or by integrating the exposed and consumed services of the various frameworks in a loose integration. Tight integration of individual functions of different frameworks can be achieved by leveraging a Service Based Architecture (SBA) approach where all service providing functions would be registered in a register similar to the Network Repository Function (NRF) that is used to discover the 3GPP core network functions and their services. This approach means that all the functions must be under the same trust domain based on SBA internal mechanisms as all functions can interact with others. This approach is suitable for deployments that are under the same administrative operator. As an alternative to the tight integration, the "loosely-coupled" approach keeps frameworks logically separated and isolated, even at the level where they could be operated by different service providers. Loose integration of the frameworks means that the frameworks need to offer exposure Application Programming Interfaces (APIs) by applying the cross-layer API manager approach introduced in [HEX22-D62] and can be implemented through the Common API Framework (CAPIF) of 3GPP [23.222], see Figure 4-2. For data sharing (e.g., keeping the various data bases of the frameworks in sync) a data mesh is proposed; a data mesh [Deh20] that takes care of streaming and synchronizing data authorized for sharing. The proposed ECF, Figure 4-2, consists of CAPIF API management functions, cross-framework conflict management functions, closed loop governance in addition to data mesh management that are needed to enable and manage the cross-framework interactions.

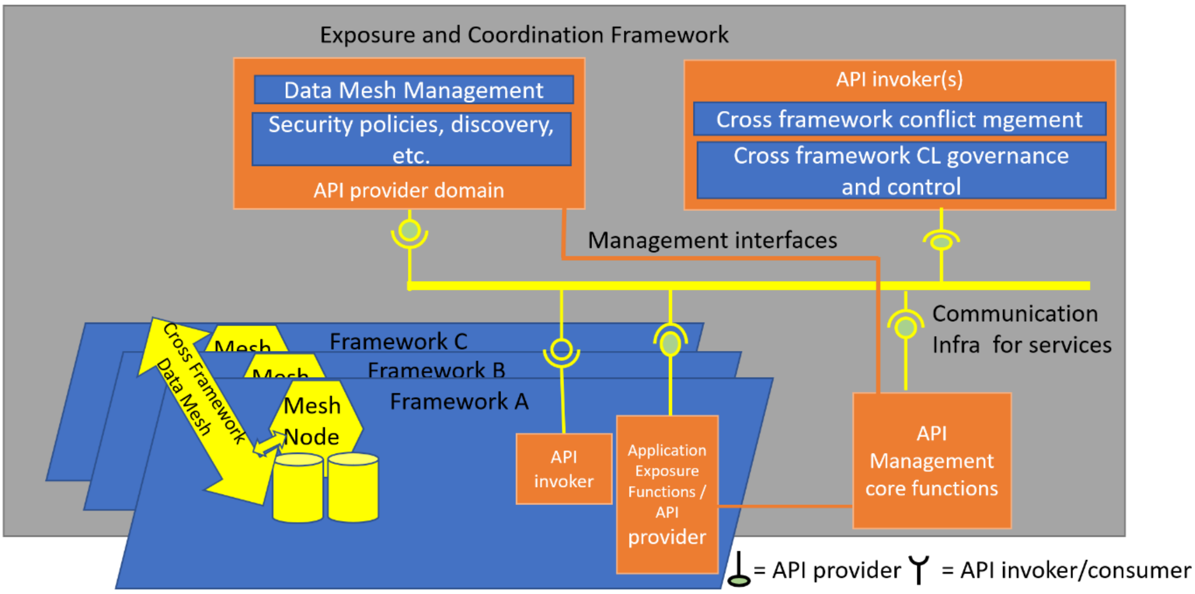


Figure 4-2: Proposed Exposure and Coordination Framework based data mesh and API manager of [HEX22-D62] applying CAPIF central mode.

4.2 Radio Access Network technology enablers

To meet the requirements on 6G networks, new radio components need to offer exceptional performance, such as ultra-high data rates. Other performance metrics like energy efficiency, coverage, reliability, transport efficiency, robustness, latency, mobility, security, deployment flexibility, and footprint must also be considered in the radio design and during network planning and deployment. One way to achieve these metrics is through the use of Distributed MIMO (D-MIMO), which can provide a high degree of macro diversity and ensure predictable service quality across the entire service area. Another 6G key enabler in achieving ultra-high data rates is the use of sub-THz spectrum, which provides large bandwidth and can be exploited in specific scenarios.

4.2.1 Distributed MIMO

6G technology components should be capable of providing significantly improved network performance as mentioned above and deployment flexibility compared to legacy networks, where D-MIMO systems can elevate these values due to the possibility of providing new functional benefits with macro diversity and enhanced capacity-based features, reliability, and resilience. Introducing coordinated techniques among distributed transmission points within a D-MIMO network affects the E2E system in the contexts of deployment scenarios, signal processing techniques, scheduling, and user and control plane security. Therefore, it is important to investigate inclusive and joint approaches to ensure better trade-offs between easy and cost-efficient deployment with performance and complexity, also trustworthiness and resilience to security attacks, malfunctioning, instability, etc.

D-MIMO systems can be tailored to address various optimization goals due to their inherent versatility in deployment. This versatility is enhanced by the distributed deployment which allows the serving antenna to be located in closer proximity to the UE overcoming path loss and ensuring a reliable access link thanks to a high degree of macro diversity. Achieving high spectral efficiency can be the main objective in sub-6 GHz, while it is more important to establish reliable communication links with UEs at higher frequency bands with challenging radio channel characteristics.

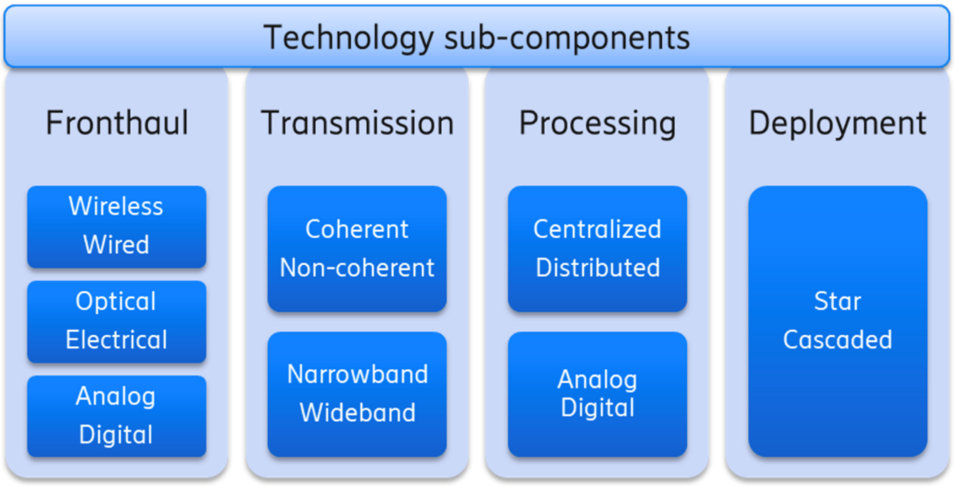


Figure 4-3: D-MIMO architectural options.

Figure 4-3 depicts a D-MIMO architecture in terms of transport media, transmission schemes, processing, and deployment. Due to the versatility in D-MIMO, the fronthaul needs to support different types of deployment, e.g., cascaded, star and combined topologies, where the media can be wired/wireless. Both digitally encoded signals and analog signals modulated over a carrier are considered. Moreover, the processing techniques can either be centralized or distributed, and in other terms can also be performed both in analogue and digital. In cases where a UE is served jointly by multiple antennas, the transmission can be either coherent or non-coherent.

In order to enable D-MIMO networks, it is important to understand how much distribution of Radio Units (RUs, a.k.a. Access Points, APs) is needed while considering the practical issues associated with distributed RUs, e.g., operating at higher frequency bands. In addition, understanding the transport solution needs and devising strategies to satisfy them is crucial. The optimum solution is to implement phase-coherent joint transmission with centralized processing. Although it is difficult to realize and may not meet the feasibility requirements, such implementations, bring about several benefits including, better spectral efficiency, signal quality and interference management. Alternatively, phase non-coherent transmission with duplicating data in each RU, is a technically viable technique, but it is inefficient in terms of spectral efficiency. Evaluating the synergies between D-MIMO and repeaters brings about an intriguing research direction towards D-MIMO systems, since repeaters have the potential to extend coverage in blind spots at a lower cost. The potential analogue and digital approaches that can be combined with D-MIMO are:

- Analogue Radio over Fibre (ARoF) based Fronthaul

  Due to the limited spectral efficiency and flexibility, existing digital fronthaul interfaces encounter various challenges especially in deployment scenarios needing extensive bandwidth signals or low-complexity RUs for cost-efficient deployments. These challenges can potentially be met with ARoF.

- Network Controlled Repeaters (NCR)

  NCRs are advanced beamforming and power amplification capable repeaters. Driven by the network densification, NCRs have also been recently considered as a study-item in 3GPP Release 18 (finished in August 2022),

- Reconfigurable Intelligent Surfaces (RIS)

  RIS is an interesting enabler as it can control the electromagnetic properties of Radio Frequency (RF) waves by adjusting the phase shift to the intended direction intelligently, such that the capacity, coverage and energy efficiency can be improved.

- Integrated Access and Backhaul (IAB)

> Motivated by coverage enhancements and flexible network densification, IAB has been considered in the 3GPP since 2017 to provide an alternative to fiber backhaul by extending New RAN (NR) to support wireless backhaul, where the IAB architecture is based on the Centralized Unit/Distributed Unit (CU/ DU) split in the gNB, has two types under consideration, namely, hierarchical (mainly) and mesh, based on its configuration. IAB approach can also be applied similarly in the fronthaul between RUs and DU in the context of D-MIMO.

D-MIMO systems can enhance network performance at varying frequency bands, addressing the needs for various optimization goals. Better understanding of the trade-offs between distributed and centralized processing, wired and wireless fronthaul solutions to cater the deployment scenarios is crucial for the successful implementation of such systems in the architecture of next-generation networks.

4.2.2 Architectural components for sub-THz RAN

Sub-THz RAN operating in the upper millimetre-wave range (100-300 GHz) with ultrawide bandwidth has the potential to support use cases with extreme performance requirements in terms of data rate and latency (e.g., fully merged cyber-physical word, digital twins for manufacturing, and holographic communication) [HEX23-D23], in addition to the opportunity to use sub-THz links for fixed access and fronthaul as alternatives to optical fibres [HEX21-D21]. However, a single radio hardware will not necessarily be an ideal solution to serve all the above-mentioned use cases, considering the implementation complexity and operation efficiency. For instance, a radio designed for mid-range communication may not be efficient in terms of cost and energy consumption for short-range communication scenarios. As discussed in the Hexa-X work package 2 deliverables [HEX21-D21], [HEX21-D22], a feasible radio architecture is sub-array-based, where each sub-array consists of a radio chain connected to multiple antennas with phase and amplitude control to steer its beams. The concrete parameters (e.g., number of antennas per sub-array, number of sub-arrays, etc.) are determined by analysing the link data rate, communication range, device mobility/time variability of the channel, expected number of users to be served, and the number of independent spatial directions provided by the propagation environment. Thereby, the relevant use cases are mapped according to their ranges to three scenarios [HEX23-D23]:

- Mid-range (100- 200 m): it focuses on fixed assess and backhauling with no mobility and can be realized by means of high-gain antenna arrays.
- Short-range (10-100 m): this scenario is for use cases with a data rate up-to 10 Gbit/s, with mid-speed vehicular mobility up to 15 m/s in indoor or outdoor environments.
- Very short range (less than 10 m): it can provide a link data rate up to 100 Gbit/s at walking speed mobility.

For each scenario, there are multiple radio options designed according to the carrier frequency and type of device (UE or Base Station (BS)), in addition to the maximum range and data rate. All these options achieve the highest data rate at the maximum range, and provide sufficient adaptability for dynamic link adaptation, such as adjusting the transmitted power with the actual range. With such adaptability, a radio design that covers the mid-range scenario can serve shorter-range scenarios as well. However, considering the maximum range in the design process allows to select more efficient solutions in terms of feasible implementation (e.g., cost and size) and sustainability impacts (e.g., power consumption and material life cycle assessment).

The radio options mentioned above, each with distinct specifications regarding range, data rate, and other metrics such as cost and energy consumption, provide flexibility for network vendors and operators to decide how to implement and deploy a RAN that fulfils the use cases' E2E requirements while improving other metrics such as sustainability. For instance, Figure 4-4 illustrates a deployment example using three radio options. Radio 2 is used in a cell with short range, radio 3 in a smaller cell with very short range, and radio 1 is deployed to provide a fronthaul link.

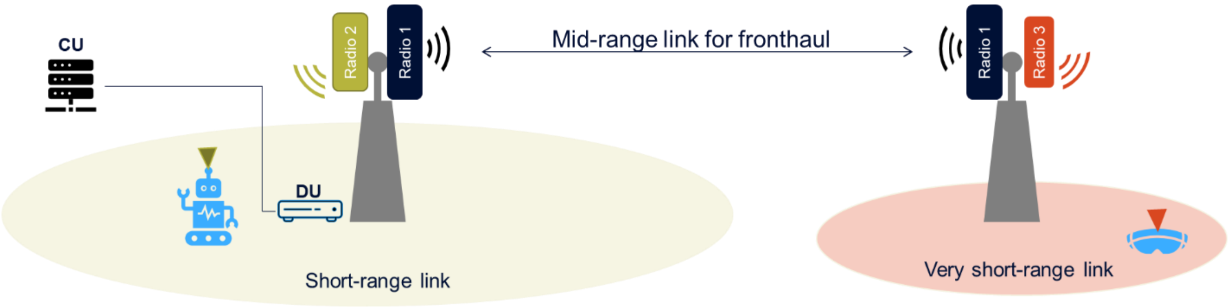


Figure 4-4: Deployment example of different radio options in different cell size.

4.3 Localisation and sensing

Localisation refers to the ability to accurately determine the physical location of a UE. Sensing, instead, refers to the ability of the network to detect and interpret physical parameters of the environment. Examples of sensing are radar-based localisation of objects (without UEs) or distinguishing between human movement patterns (walking, running) or environmental features (urban versus rural environment). As sensing is a very generic term it includes localisation. Both localisation and sensing are expected to be key enablers for a range of new emerging use cases in many fields and domains, for example within the domain of factories, by optimising routes and behaviour of robots and cobots (collaborative robots) based on their current position. The ability to locate with high accuracy and sense objects in the environment will unlock new applications and services that were not possible with earlier generations of mobile networks.

4.3.1 Localisation and sensing ecosystem

The process of generating and using information in the sensing (which includes localisation) domain is shown based on an example in Figure 4-5. The ecosystem for localisation and sensing consists of services, functions and applications within three functional layers: The generation and collection of sensing data, such as angles, timestamps, etc., within *Sensing Functions and Services Layer,* the usage and transformation of such sensing data (e.g., the measurement of angles between base stations and a UE and subsequently the calculation of the position based on the geometric approach of angulation of a UE) within the *Sensing Data Processing Functions and Services Layer.* And finally, the *Emerging Applications and Services Layer* in which localisation and sensing results are used to generate added value for a certain domain. The services, functions and applications in these layers may come from different (software and hardware) providers and need to work well together. This ecosystem unleashes all its potential when integration, management and operation is easy and fast.

An example of such a new application could be the optimisation of the communication based on the previously calculated positions of UEs. In the factory domain such calculated positions of Automated Guided Vehicles (AGVs) in combination with their planned trajectories (which is additional context and domain information fed into the application) can help to optimise the communication quality by beam optimisation or prioritisation of certain AGVs (depending on their current position and quality of service requirements).

Such kind of location-based services can handle network internal optimisation problems as mentioned before (when optimising communication parameters based on the position) or can take care of external optimisation tasks, such as optimising asset flows within a factory (e.g., through bottleneck detection or detection of unexpected delays within the factory processes) or managing human crowds during festivals.

Functions in this context are rather small tasks, whereas services bundle functions and often expose their functionality via APIs. Although the figure suggests no deployment scenario; naturally, sensing functions will be handled close to the hardware infrastructure, whereas both sensing data processing and emerging applications can be deployed in the network service and/or application layer from Figure 4-1.

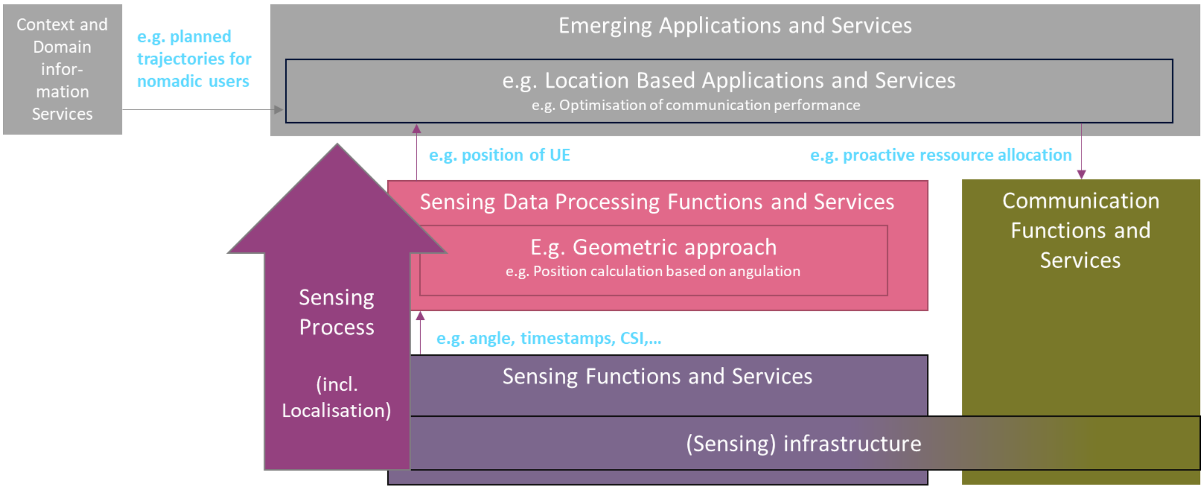


Figure 4-5: Example of localisation process and usage of position information to optimise the communication service.

4.3.2 Localisation and sensing challenges

In the past, the focus within mobile communication networks was on optimising the network regarding communication service enhancements. With localisation gaining in accuracy and sensing being introduced, more applications will make use of those functions and challenges arise to manage these in an efficient and sophisticated way. It could be imagined that localisation and sensing is used in a standalone manner (i.e., independent of the communication service) like Global Positioning System (GPS) outdoors or Ultra-Wideband (UWB) localisation systems indoors. However, such a scenario is not the core focus of 5G and next generation future mobile networks as the strength will be to offer communication and sensing in an integrated fashion.

If both services (sensing as well as communication) are used in applications at the same time (Integrated Communication And Sensing (ICAS)), the M&O of both services becomes crucial. Depending on the requirements from emerging applications and services, the M&O must balance mutual influences if the same infrastructure is used for both communication and sensing (compare Figure 4-6). The blue arrows indicate where M&O might need to be active. As soon as mutual influences arise decisions will be required to balance between certain requirements coming from either functions and services themselves or from applications. An application may require high accurate localisation and high throughput communication at the same time, which may in certain scenarios depending on the overall network structure not be possible.

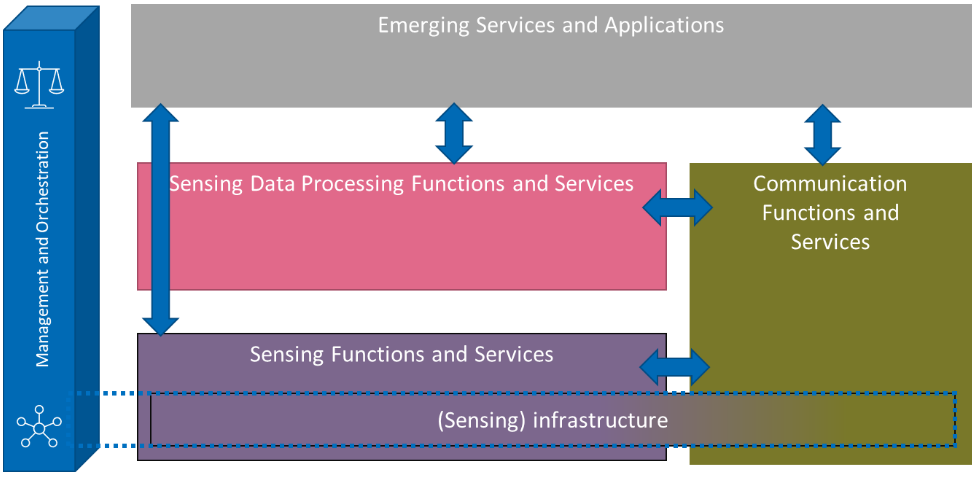


Figure 4-6: M&O must handle requirements coming from Emerging Services and Application layer and manage the interplay and parametrisation between all functions. The blue arrows indicate where M&O must be active.

Careful design during planning and deployment as well as sophisticated management during operations is essential to enable localisation and sensing with high Quality of Service (QoS). One example is the synchronisation of clocks of hardware components within the system. If time-based measurements are used for localisation and sensing, devices involved in the measurement process need a much better clock synchronisation as it would be necessary just for communication purposes (as one nanosecond time difference between two transceivers may result in ~30 cm deviation for a one-dimensional measurement). Many use cases for localisation and sensing require sub-ns synchronization to be able to meet accuracy requirements of (sub) cm. The localisation and sensing use case overview including a gap analysis between localisation capabilities nowadays and requirements for the future can be found in [HEX21-D31].

Latency requirements also affect decisions in deployment and operations phase. Subcarrier spacing, bandwidth, and transmission duration should be carefully designed to meet the localisation and sensing Key Performance Indicators (KPIs). For example, trying to reduce the latency by sending fewer symbols will affect the Doppler resolution and integrated Signal-to-Noise Ratio (SNR) which impacts the accuracy.

Another important aspect for localisation and sensing is the availability of sufficient spectrum to provide sufficient delay (distance) resolution, and complementation angle resolution using large arrays. Bandwidth requirements vary from less than 400 MHz up to 10 GHz depending on the specific use case requirements in regard to accuracy.

From an ecosystem perspective, another localisation and sensing-specific challenge is the data integrity. As the network infrastructure generates data and information that are (after being processed) used in emerging services and applications, such offered data must be trustworthy and protected. Falsification of data can happen during the generation of the data and the transmission of the data through the network. While securing the transmission of data is considered as a basic security feature for the communication network, securing the process of generation of sensing data is special. One example in the security domain are Early Detect/ Late Commit (ED/LC) attacks [SLC17]. Attackers fool signal receivers about the signal arrival time. The timestamp of the signal arrival time at receiver side is used for determining the distance between UE and the base station. Such attacks may lead to predated timestamps which result in a shorter distance between base station and UE and consequently to an arbitrary wrong final position. Physical layer protection mechanisms are important both for safety and security means to ensure a trustworthy sensing process. Safety considerations ensure that systems do not harm humans by malfunction and security considerations ensure that systems are robust against attackers. Even though the focus may differ, depending on the scenario both aspects are important and may influence each other. If systems are not well secured against attackers, they may malfunction and harm humans.

Details of all challenges from a localisation and sensing perspective can be found in [HEX23-D33] Chapter 3.

4.4 AI enablers for intelligent networks

As AI and ML applications are identified as key drivers for 6G networks, the adoption of intelligent components in the application layer and network functions are expected to increase. This motivates the need to develop not only the intelligent functionalities for the 6G network but also move further and design the future network AI-native, capable of supporting AI functions for both network and external/3rd applications. A variety of frameworks have been developed as a result of defining and integrating AI/ML capability as a crucial component of the Hexa-X E2E architecture, known as Hexa-X "*Intelligent Networks*" [HEX22-D52]. These frameworks (e.g., AIaaS, FLaaS, programmability and, analytics frameworks, etc.) can be deployed independently, even though they benefit from the services they provide to each other. The services enabled by each framework are described in this section, along with how they interact with each other. As an example, for the purpose of creating analytics, the analytics framework is responsible for collecting, preserving, and storing data from network operations across distributed multi-cloud environments. The framework proposed the 5G Network Data Analytics Function (NWDAF) capabilities, as well as ML model capabilities and related NFs such as Data Collection Coordination Function (DCCF), Messaging Framework Adapter Function (MFAF) used for data collection and messaging coordination [29.520]. On the other hand, automation based on AI manages technological complexity and service complexity to meet a variety of requirements, including quality, security, and resilience requirements. The AIaaS framework offers services to facilitate automated closed-loop networks and services and full machinery for controlling and maintaining AI agents along the cloud continuum. Depending on the particular customer and automation goal request, it offers AI services with specialized inference capabilities as well as other AI capabilities.

4.4.1 Analytics framework

The analytics framework [HEX22-D52] envisioned for the next generation of mobile networks (6G) should be self-contained to provide basic analytics services of mobile networks and to interact with legacy 5G systems that support enablers for network automation (including NWDAF, DCCF, etc.) [23.288], [29.520]. Additionally, following the architecture design principle #7 [HEX22-D13] (separation of concerns of network functions), the analytics framework, based on a particular deployment and needed configuration, can use the services provided by the other frameworks, e.g., AI/ML functionalities from the AIaaS framework [HEX21-D51], [HEX22-D52].

Currently due to the limited interactions between RAN and Core Network (CN) of a 5G system, data collection and the exchange of analytics and ML models are almost not existed. The analytics framework can be useful not only for seamless transfer of analytics across domains/planes but can also pave the way to a new AI-enabled architecture that supports distributed AI agents which are providing services such as analytics, prediction, classification, etc. This means, with the help of AI agents, the analytics services envisioned for 6G can analyse data and uncover hidden trends, patterns, and insights in a more automated fashion. In order to implement the analytics framework, the following entities are required either locally placed in the analytics framework or can be accessed from another framework e.g., AIaaS framework through CAPIF:

- Entities providing analytics services, e.g., analytics function, analytics repository, etc.
- Entities responsible for providing necessary AI/ML functionality for analytics service e.g., ML model training function, ML model repository, etc.

As explained above, the 6G analytics framework can be designed based on implementation requirements in two ways: The analytics framework hosts and provides the AI/ML related services locally (local to the analytics framework) and independently from other frameworks in the system (as shown in the Figure 4-7) or the analytics framework can delegate the AI/ML related services to other frameworks, e.g., AIaaS, and access them through CAPIF. In case of delegation, additional inter-framework communication is required. Figure 4-7 shows the entities envisioned for the analytics framework. In the following the services and functionality of each entity will be explained:

- *Analytics function* is the entity which provides the analytics, inference, and prediction services. In order for the analytics function to perform the abovementioned services, it has to collect data and, in some cases also, trained AI/ML models. Same as the AI/ML model training function, data collection can be facilitated by a data mesh either from the local repository of the analytics framework or through the data mesh node(s) of other frameworks. In case of trained AI/ML model collection, the analytics function can invoke the discovery service from the dedicated repository in the analytics framework for the trained models or use the CAPIF API [23.222] to invoke the training service for AI/ML model in AI framework. The analytics function registers the list of analytics services in the repository for other network functions (local to the analytics framework or from other frameworks) to discover and invoke them, see Figure 4-7.
- The *ML model training function* is responsible for AI/ML models; it is able to train the AI/ML models based on the designated data set. The AI/ML model training function can produce new ML models or retrain AI/ML models found in the AI/ML model repository with a different data set. This function can fetch the required data set by using the data mesh either from the local (local to the analytics framework) repository or from repositories from the other frameworks, e.g., AI framework. All the trained models will be stored in databases equipped with version controlling features.
- *Analytics service repository* is a dedicated repository for the analytics function to register the provided analytics services (for providing statistics and predictions).
- *ML model repository* is a repository for the trained AI/ML models. This repository needs to support version control features. This is due to the fact that AI/ML models can be trained and retrained by different data set for various purposes. Having a repository with the version control can help on getting access to any version of the models if required.

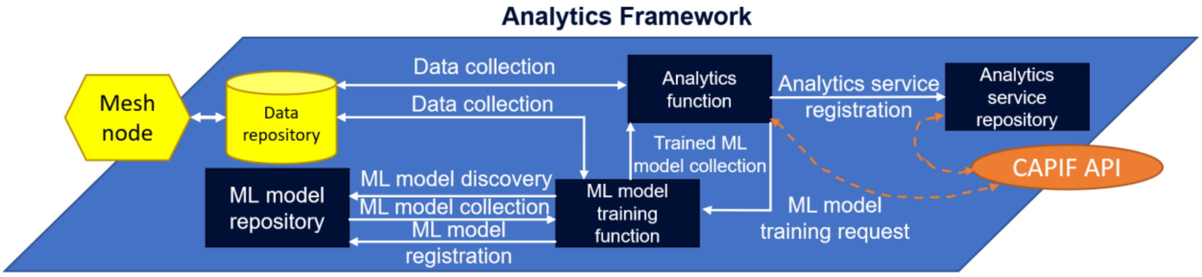


Figure 4-7: Analytics framework and how it connects to other frameworks.

4.4.2 AI and AI as a service

One important area for AIaaS is to automate 6G networks targeting to replace tasks performed by human operators with processes performed by machines or software. Improvements in application technology are increasing the requirements for automation leaving human interaction to supervise the training of suitable AI and ML models and the management of unforeseen error scenarios. In addition, being critical facilitators of full automation in 6G networks, AI may help 6G network and service orchestration platforms with Life-Cycle Management (LCM) services and slices and runtime operations at many stages, such as planning, deployment, functioning, scaling, and resource sharing. For this purpose, a comprehensive approach is required to achieve the level of automation and flexibility required by 6G networks and services, in which custom sets of specialized AI functions can be deployed and reconfigured on demand to support the various network optimization decisions to be made at the M&O platforms layers. Such approach should enable agile AI-driven orchestration of 6G networks and services, with concurrent and potentially cooperating AI functions addressing the complexity of different optimization aspects with data, models, and algorithms tailored to the various objectives and constraints of specific network domains, slices, slice subnets, or services. The first stage is to identify the necessary AI functions needed to deliver such a complete and seamless AI-driven 6G orchestration solution, as well as make them easy to manage and reconfigure in a cloud-native environment. The goal is to define a set of AI functions that can be virtualized, packaged, and thus orchestrated as AIaaS functions that can be deployed, activated, and re-configured on-demand to assist and complement regular network and service orchestration logic with additional AI, ML, and automation capabilities.

4.4.2.1 AI as a Service framework

The AIaaS concept proposed by Hexa-X is built by the combination of several functions which realize an entire framework offering a set of AI services and tailored inference capabilities depending on the specific consumer and automation request to the AI service itself [HEX22-D52]. Beyond the pure prediction, classification, etc., ML capabilities (which can per-se be consumed in support of full automation at the 6G network and service layers), the AIaaS framework provides additional AI capabilities and services (including training, monitoring, evaluation) to support closed loop network and service automation, targeting their implementation and deployment as cloud-native in-network virtualized functions. Similar to the analytics framework described in the previous section, the AIaaS framework is designed as an independent set of functions implementing and exposing specific AI services, but still capable to consume services from other frameworks. In particular, for some specific use cases and AI/ML model implementation requirements, the analytics services (and related data produced) offered by the analytics framework may be consumed by the AIaaS framework. In such a case, the EPF approach is leveraged to discover the required analytics capabilities, while the cross-framework data mesh is used to actually access and consume the analytics data.

As described in [HEX22-D52] and [HEX23-D53], four main AI functions are building the AIaaS framework: AI model repository function, AI training function, AI monitoring function and AI agent as demonstrated in Figure 4-8. The *AI model repository function*, the *AI training function*, the *AI monitoring function*, and the *AI agent*. The AI model repository function provides a catalogue of AI and ML trained models that are either already deployed or ready to be deployed into new or current AI agent instances. The AI training function trains ML models and generates executable models that may be incorporated into AI agents and is initiated either automatically by the AI monitoring function when a performance decrease is observed or by the M&O layer whenever a new model is required. The AI monitoring function is in charge of evaluating the performance of ML models and, as a result, serves as the trigger for training and retraining operations in the AI training function. Finally, the AI agent does inference using trained ML models including any required data pre-processing functionality. Figure 4-8 shows this AIaaS framework functional decomposition, specifically mapped to the ECF approach described in Section 4.1 Figure 4-2 aims at highlighting the high-level operational interactions among the functions, including the exposure of the related AI services and functions. As shown in the picture, the AIaaS framework includes other critical assets, and specifically two logically centralized data stores to collect and expose (either internally to the framework, but also externally to other frameworks) inference data to feed the runtime operation of ML models, and training data to feed the AI training functionalities. The presence of the two data stores aims at clearly separating the AI/ML model training and runtime operation/inference phases, including the possibility to use different data sets (e.g., either coming from different sources, or from the same source but with different data pre-processing).

The 6G network may take advantage of intelligent services by exploiting AI models that are built in a collaborative fashion (e.g., by UEs) according to the Federated Learning (FL) approach, which prevents disclosing private data. According to the FLaaS paradigm envisioned in [HEX22-D52], a UE is represented by an FL Local Manager (FLM), which can contact an FL service provider and ask to join the FL process specific for a given service/application (e.g., forecasting of Quality of Experience (QoE) in automotive scenarios). This can be done to i) obtain the global AI model available for that service/application, or ii) participate in the training process exploiting its private data to build and share a local AI model. Each FL process - instantiated on-demand by the FL Service Provider (FSP) - is handled within the network by an FL Process Controller (FPC) and an FL Process Computation Engine (FPCE), which take care of exchanging control plane information (such as authorization grants) and AI model updates with the FLM, respectively. While the FSP, FPC and FPCE reside in the CN (in the cloud or at the edge), the FLM can be hosted at either the UE or at the edge of the network (e.g., in Mobile Edge computing (MEC) hosts), in order to allow also low capability devices to enjoy AI-based services. An evaluation of the above two options is reported in [HEX23-D53].

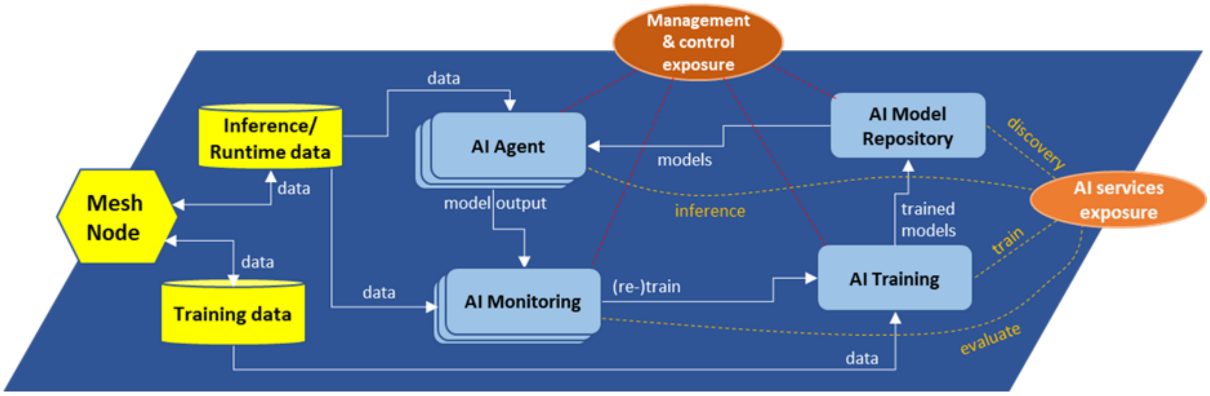


Figure 4-8: AIaaS framework functional decomposition and main interactions.

4.4.3 6G as an efficient AI platform – seamless exploitation of network knowledge

The challenges of the wireless environment, energy efficiency, device capabilities and data handling constraints require 6G networks to provide *efficient platform support* for distributed AI learning (e.g., FL) and inference functions. Efficient execution of demanding AI applications can be enabled by *flexible and real-time exposure of network knowledge* via APIs and services (e.g., service quality prediction for a planned trajectory), while the network can also utilize enhanced information shared by the AI applications to take timely and resource-aware actions, e.g., as part of flexible service quality contracts.

The above requirement calls for a joint communication and computation co-design, leading to network services and APIs with *seamless exploitation of network knowledge* for both network operation and end-user applications, as exemplified by the technical enablers from [HEX23-D43] described below. These functions can be executed as part of the analytics or AIaaS frameworks.

AI agent availability and reliability should be supported in high-mobility environments involving safety-critical communications. Network services should be provided for AI applications to enhance system robustness to mobility events, including (i) increased availability by improved mobility solutions, (ii) increased reliability by accounting for low quality connections, (iii) mitigating latency due to handovers. AI models can rely on a substantial information pool, including knowledge and states from the entire network, which can be exploited through providing AI models to the UE without exposing the actual underlying information.

Functional entities for managing / governing AI mechanisms are also envisaged in the 6G context. The specific requirements of AI applications should be considered during *workload placement*, with metrics including not only energy, E2E delay (including communication and computation), and learning/inference accuracy, but also *data availability and trust levels*.

There is a trend of having more and more intelligence deployed at the edge of wireless networks, where a major challenge is to overcome the constraints of limited computing capabilities of edge devices and take the special communication patterns of distributed intelligence into account (e.g., [ZCL+19a], [DZF+20], [PSB+19]). Flexible allocation of wireless and computing resources is fundamental to explore the typical edge inference trade-off between energy, delay, and accuracy. The resource allocation problem and further challenges of variable communication and edge compute resources are addressed by several technical enablers in [HEX23-D43], including resilient deployment of AI in distributed sensing and communications scenarios, cooperative edge inference via radio aware optimal multilayer neural network splitting and goal-oriented communications for edge inference. The above concepts require the network service layer to be *extended to the extreme/far edge*, with real-time exposure capabilities about the radio network conditions and a flexible low latency traffic control from the application layer.

4.5 Enablers for flexible network

The enablers of the flexible networks intend to enable extreme performance and global service coverage, and at the same time achieve scalability to avoid overprovisioning when and where it is not needed. Two main enablers are described here: the *NTN* and the *ad hoc mesh network*. NTN-enabled 6G networks aim towards provisioning of network resources anytime anywhere, thus contributing to targeting the theoretical limit of 100% network availability at a reasonable cost, overcoming the problems in complex and rural areas, where terrestrial networks are not a viable solution. The mesh networks aim for better flexibility when it comes to extreme capacity and coverage on demand basis.

4.5.1 Non-Terrestrial Network architecture

NTN subnetwork can provide coverage to exceptionally large and isolated rural areas at a relatively low cost. This means that in complex and rural areas, where terrestrial networks are not the main viable solution, NTN play a pivotal role. All non-terrestrial systems need to have some sort of connection to the terrestrial network, typically via a so-called ground station. This takes the architecture of 6G towards this so-called three-dimensional networking, where satellites, High Altitude Platform Systems (HAPS), or Unmanned Aerial Vehicles (UAVs) are seamlessly integrated in the network with the terrestrial network.

Here we investigate two scenarios, see Figure 4-9. The first scenario is when the terrestrial devices (UEs) directly connect to the satellite platforms. The second scenario is when the terrestrial devices connect to the NTN network via an Unmanned Aerial Vehicle (UAV).

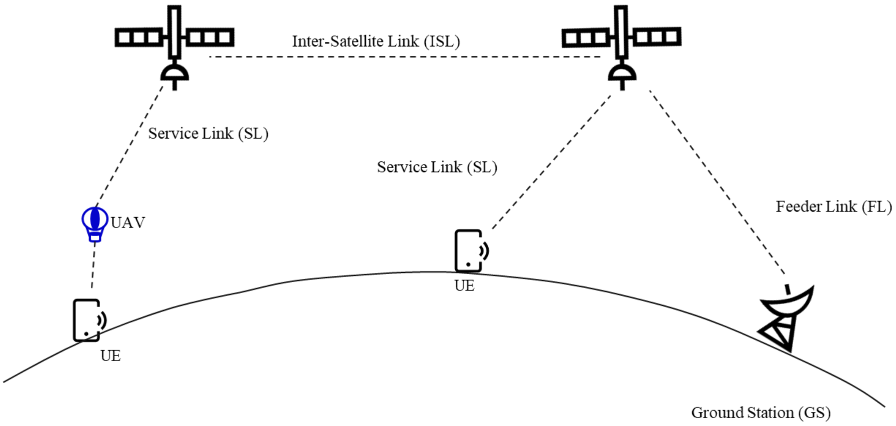


Figure 4-9: Links and nodes involved in the NTN architecture.

For the first scenario investigated, we assume an NTN architecture where the gNB is onboard the satellite. We further assume the Inter-Satellite-Links (ISLs) are part of the 6G standard using techniques similar to Integrated Access Backhaul (IAB) or Device to Device (D2D) to communicate between satellites. The reason ISL is needed is to achieve coverage over oceans and very rural areas. The investigations [HEX23-D53] found out that to achieve 100% availability, more than 600 satellites (with ISL) in Low Earth Orbit (LEO) are needed. For a very low population density, the 600 satellites are able to serve roughly 95% of the users with more than 1 Mbit/s [HEX23-D53]. With more available satellites per UE there is also an increase in available resources per UE [HEX23-D53].

The second scenario deals with the scenario where the devices (UEs) connect to a UAV which in turn connects to the satellites. This may provide a more robust mobility solution since devices can connect via almost stationary UAV units from the UEs point of view. To reduce the computational complexity, different functional splits are considered and evaluated. The radio unit, i.e., the physical layer (or part of the physical layer) is located in the RU. The remainder of the RAN protocol stack is realised in the satellite. This means that there is a backhaul connection between the UAV and the satellite. Several different split-options are considered, see e.g., 7-1, 7-2, 7-2x and 7-3 (see [HEX23-D53] for details).

It was found that split option 7-2x is the most optimal on multi-layered NTN in terms of energy consumption, reliable backhaul throughput, and to balance the amount of computing at the UAV [HEX23-D53].

4.5.2 Ad hoc networks architecture

In order to overcome challenges imposed by static infrastructure solutions, a flexible D2D mesh ad hoc topology of access nodes with the aid of UAVs are developed and analysed, see Figure 4-10 for an example of a scenario with UAVs forming a mesh network. The ad hoc network controller selects access nodes for maximization of the mesh network's trust, throughput, energy, and the minimization of the deployment cost (see [HEX23-D53] for more details). The ad hoc network is created and controlled by a management network that gives a detailed control of the mesh network.

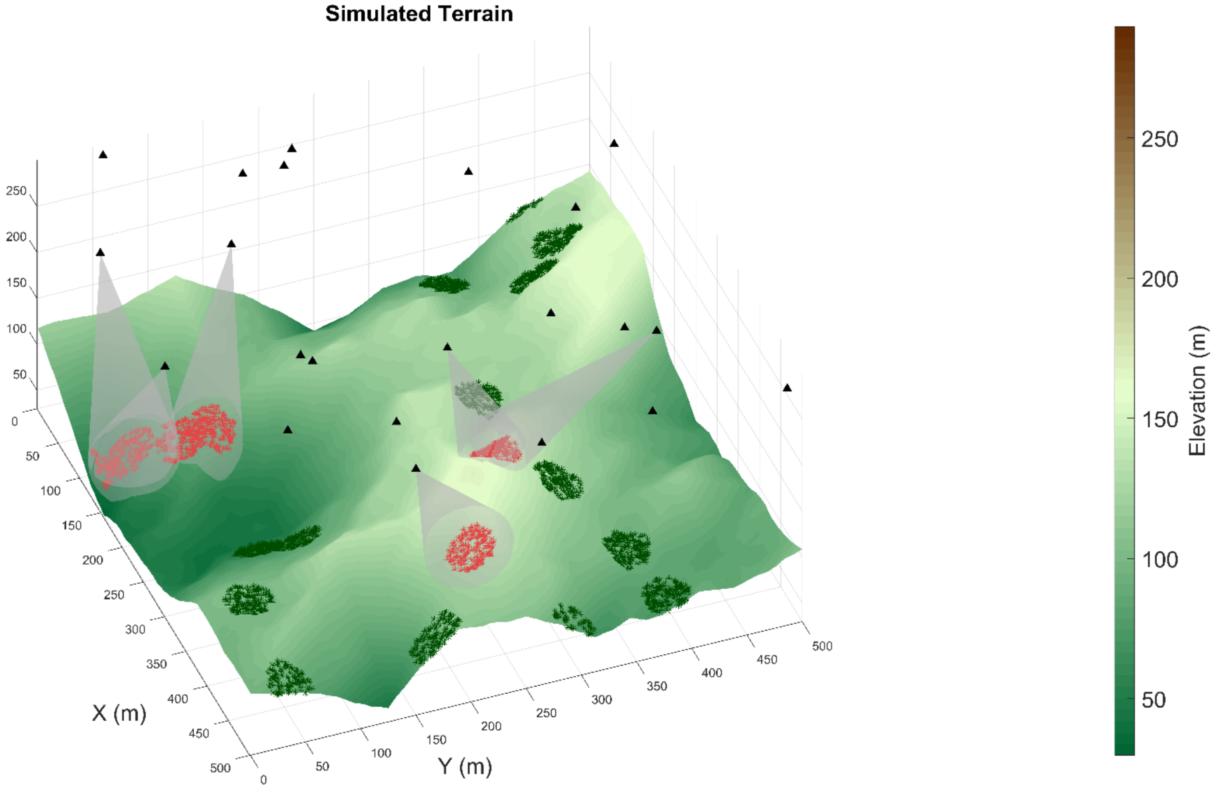


Figure 4-10: The ad hoc mesh network scenario with UAV access nodes.

Figure 4-11 depicts a full mapping between the D2D mesh ad hoc network solution and the M&O layer. This figure aims at giving a detailed vision, at every layer, of how the ad hoc network (D2D) might be allocated within the Hexa-X M&O architecture described in Section 4.7.

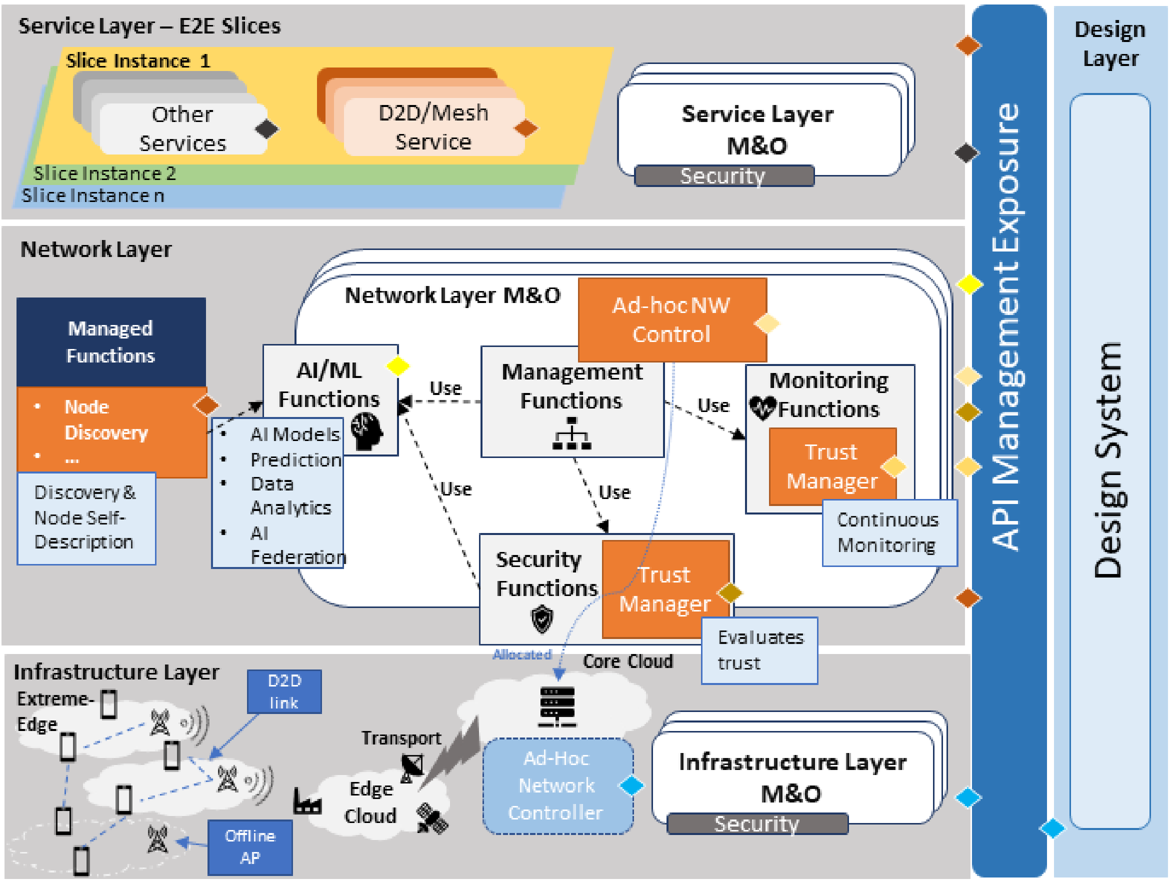


Figure 4-11: D2D mesh ad hoc architecture components allocation within the M&O architecture.

To enable the D2D mesh ad hoc network there are several enhancements on the original M&O described in Section 4.7. The layers and the enhancements are as follows:

1. Every layer in Figure 4-11 is composed of *Managing Objects* (i.e., those within the white "M&O" modules of each layer) and *Managed Objects* (i.e., those Buildings Blocks (BBs) of the D2D architecture outside of the M&O white module). This division clarifies the role of each BB and if it is part of the M&O system or if it is managed by it.
2. The *Service Layer* in Figure 4-11 has been added to reflect that the proposed D2D network architecture is able to face and deploy several types of services. Besides, it also demonstrates its capacity to work with independent slice instances and, thereupon, the proposed D2D architecture is capable to create the ad hoc network topologies based on the traffic load, computation, and communication needs. After the service is finished, it releases the allocated resources for the given slice.
3. The *Network Layer* has been modified accordingly to follow the *Managing vs. Managed Object* fashion of the other layers. Directional arrows have been included to clarify the relation between the D2D BBs that comprise the *Network Layer Managing Functions.* As it can be seen, the only D2D BB that has been mapped outside of the M&O is the "*Node Discovery*" as it was presented as a potential 3rd party *Managed Function* in the previous deliverable [HEX22-D52]. Moreover, two additional relationships have been established: *(i) AI/ML Function and Security Functions,* the "*Trust Manager*" functions related to security may use *AI/ML* to evaluate trust; *(ii) AI/ML Functions and Node Discovery*, in order to generate node self-descriptions and discover available modules with optimized discovery algorithms. The "*Node Discovery*" D2D BB may use *AI/ML* techniques to optimize its processes.
4. The *Infrastructure Layer* has been depicted in such a way that there is a clear view of the different infrastructure domains that might be involved as a compute continuum in future D2D ad hoc networks (i.e., extreme-edge, edge, and cloud). Furthermore, a D2D physical network

has been exemplified with different APs and D2D links in the extreme-edge domain/field domain. Finally, the *ad hoc Network Controller* server has been highlighted.

5. The *API Management Exposure Layer* has been represented as in the original Hexa-X M&O architecture [HX22-D62].
6. The small, coloured diamonds within each layer represent the endpoints or APIs associated to individual M&O or *Managed* resources and how the *API Management Exposure* functional block could act as a common and unified framework that regulates the exposure and management of the various APIs provided by each BB on each layer and, even more, in different domains i.e., multi domain federated D2D scenario.
7. The *Design Layer* is one of the main innovations introduced by the Hexa-X M&O architecture. It has been included as it has the capabilities to design, define, model, and distribute software components that may be used to create and run the 6G infrastructure. It exemplifies the implementation of cloud-native concepts in terms of bringing together development and operational teams through the use of DevOps approaches, facilitating how services are delivered and updated with a very high degree of automation.

4.6 Enablers for efficient network

The studies in previous deliverables ([HEX21-D51], [HEX22-D52], [HEX22-D62]) have set the stage for the studies presented here with a clear objective to investigate how a 6G architecture can be as efficient as possible from a set of perspectives. As a start, in D5.1 [HEX21-D51] a set of design principles were described. Three of them are addressed with the work on efficient networks namely:

- *Exposed interfaces are service based* (principle #6), where network interfaces should be designed for cloud use (i.e., cloud native) with care taken to design proper service separation enabling service reuse, and ease of adding new services to the network.
- *Separation of concerns of network functions* (principle #7), which means that interaction among services, through their APIs, ensures minimal dependency with other network functions, so that network functions can be developed and replaced independently from each other.
- *Network simplification in comparison to previous generations* (principle #8), which would be orchestrated by utilising cloud-native RAN and CN functions with fewer (well-motivated) parameters to configure and fewer external interfaces.

During the project these design principles have helped steer the work.

4.6.1 Architecture transformation with cloud and SBA

From the inception of Hexa-X [Hex23] it is assumed that the 6G architecture is service-based, however, the reasons why the architecture is assumed to be service-based and benefits thereof, may need to be reiterated. SBAs have been in use in the software industry to improve the modularity of products. This really means that a software product can be broken down into communicating services so that the developers can mix and match services from different vendors into a single product.

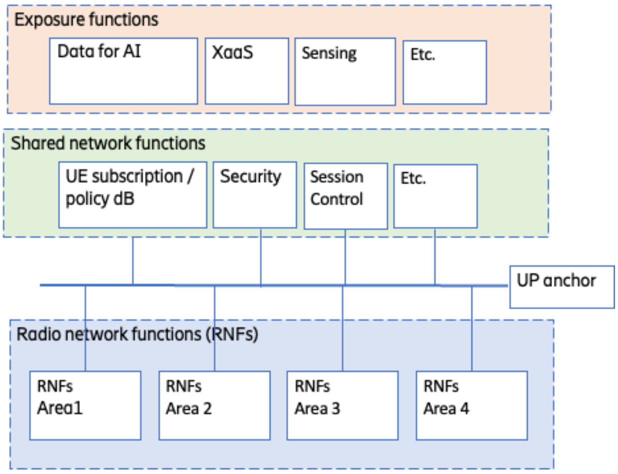


Figure 4-12: Components of 6G SBA architecture.

Also, in telecommunications networks the ability to develop new functions easily and the use of off-the-shelf technology, where applicable, drive changes in the NFs themselves. With this in mind, there is a push to migrate from telecom-style protocol interfaces to web-based APIs. In recent releases of the 5G core network this has been made possible and the network is based on what is called an SBA centred around NFs that can register themselves and subscribe to other services. This is believed to enable a more flexible development of new services, as it becomes possible to connect to other components without introducing specific new interfaces. The new system architecture is specified in 3GPP technical specification TS 23.501 [23.501].

In a future 6G architecture, the SBA can be also extended to applicable parts of the RAN. This was an assumption from the beginning of Hexa-X [Hex23]. Once again, the assumption is that this makes it easier to develop new functions that manage parts of the RAN functionality. With such an evolution, the rather clear distinction between CN and RAN in previous generations of cellular networks becomes less distinct. Instead, it might make more sense to group NFs as radio-near or not. Some advantages over the current architecture that can be anticipated are: less duplicated functionality, improved cross-layer AI/ML with full knowledge of UEs and resources in the radio near functions.

Further, there are principles that should be applied when designing procedures, e.g., a procedure for connection setup or mobility, using the abovementioned NFs. Procedures should be independent. In this way procedures can be updated separately, i.e., without notifying other procedures. Also, combinations of different procedures can be used to achieve different outcomes. Finally, procedures can rely on each other, i.e., they need to be executed in a particular order, but procedures should not be nested. The gain from applying these principles does not come from having smaller functions but the overall principle.

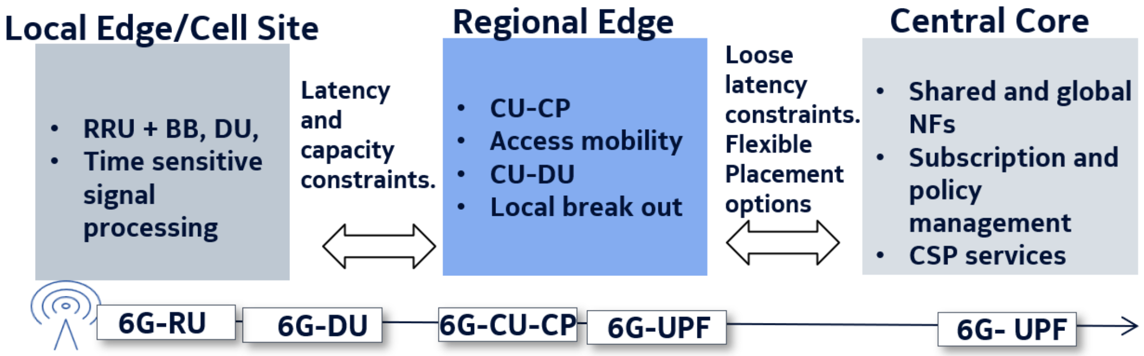


Figure 4-13: Functionality distribution between RAN and CN clouds [HEX22-D52]

In this SBA including both RAN and CN, it would not be RAN accessing CN functions but the UE that communicates with individual NFs. Proposals that make this possible comprise function elasticity [HEX22-D52] and in particular 6G-RAN-CN function elasticity and Service Based Interfaces (SBIs) replacing 3GPP N2 interface between RAN and the Access and Mobility management Function (AMF) to enable signalling directly between NFs (from different domains). The first proposal is achieved by co-locating some of the common 6G-CN NFs with the 6G RAN-CP (Control Plane) in the cloud environment, which allows placement of signalling procedures, such as mobility and session management, in the regional edge cloud, see Figure 4-13. As a result of placing critical signalling processing together with 6G-RAN-CP in the regional edge cloud, signalling performance is improved thus reducing latency. This approach can be applied for 6G-UE associated services since the 6G-UE context handling would remain within the control of the 6G mobility management without creating new or additional dependencies. The second proposal, introducing SBI, enhances the possibilities for signalling directly between NFs from different domains. The reason is that many services, such as remote interference management information transfer and configuration transfer procedure for Self-Organizing Network (SON), today require information transfer from one Next Generation RAN (NG-RAN) node to another NG-RAN node via the 5G Core (5GC). In 5GC the information is relayed transparently via the AMF [HEX22-D52]. With the SBI replacing N2 there is no need to pass through the AMF. Note that there may be cases when proxying is useful, e.g., to help with discovery of the correct NF.

When evaluating whether the proposed architecture and necessary signalling are efficient, a set of KPIs need to be considered, such as:

- *Latency (processing time)* to execute a procedure is an important KPI. To be a bit more precise latency is the time to complete a certain procedure.
- *The number of functional dependencies* indicates how many times a certain entity depends on another entity to complete a task. This measure impacts latency and, e.g., error handling as a result from failure to signal between NFs. The KPI is discussed in [HEX22-D52], as “good separation of concerns”. By separating the concerns of a function, the function can scale. Allowing the NF to accommodate a lager set of capabilities may be a reasonable assumption. This should be understood as if the NF becomes more capable and thus less external signalling will be needed. However, in some cases, having too good separation may affect the context handling poorly, i.e., rather than reducing the number of signalled messages they need to be increased.
- *The number of functional processing* occasions or points indicates how many times a functional entity must process messages received from another entity. Once again latency is affected by the individual processing times.
- *The number of failure point*s indicates how many times a functional entity would require a re-start of a procedure resulting from a failure to send/receive a message. Note that the number of failure points is not only an indication of the number of dependencies between NFs but also an indication of the likelihood that a process is interrupted.

4.6.2 Compute as a Service

CaaS allows delegating/offloading a generic application’s workload (besides radio signal processing ones) from devices to networked compute nodes based on different computing platforms.

ETSI TS 103.850 [103850] defines the so-called Radio Application Package (RAP) that is being used to provide a single or multiple radio application(s) and related information to networked compute nodes based on different computing platforms. At network setup time (e.g., using M&O) the RAPs will be installed in the Reconfigurable Equipment’s (REs). The existing overall structure of the RAP is outlined in Figure 4-14.

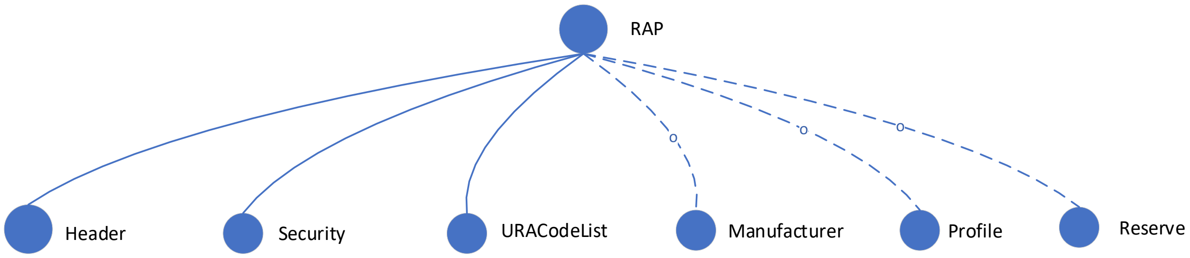


Figure 4-14: Top Level tree structure of the radio application information to a compute framework [103850].

The highest layer of the RAP graph consists of a RAP node which represents the whole RAP bit field as it is pointed out in Figure 4-14. The lower layer consists of the following nodes representing particular RAP sections as shown in Table 4-1:

Table 4-1: RAP node name definition.

Node name	**Bit field**
Header	The RAP header
Security	The Security section
URACodeList	Unified Radio Application (URA) codes
Manufacturer	The Manufacturer information section
Profile	The initial profile section
Reserve	Reserved for the future use

We propose an extension of the upper RAP structure to be applicable for delegating/offloading generic application related workloads (besides radio signal processing ones). It is proposed to transform the "*Reserve*" element into a structure with several attributes. The "*Reserve*" element is extended with the "**Regulation_Conformity**", i.e., descriptions on how requirements on regulations are being met, in particular related to the requirements of the draft AI Act [AIAct21]. The regulation requirements are summarized in Table 4-2:

Table 4-2: Requirements outlined by AI Act [AIAct21].

Requirements	Summary as defined by the AI Regulation [AIAct21]
Data and data governance	"High-risk AI systems … shall be developed on the basis of training, validation and testing data sets that meet the quality criteria ..."
Technical documentation	"The technical documentation shall be drawn up in such a way to demonstrate that the high-risk AI system complies with the requirements …"
Record keeping	"High-risk AI systems shall be designed and developed with capabilities enabling the automatic recording of events ('logs') …"
Transparency and information to users	"High-risk AI systems shall … ensure that their operation is sufficiently transparent to enable users to interpret the system's output and use it appropriately …"
Human oversight	"High-risk AI systems shall be designed and developed in such a way, including with appropriate human-machine interface tools, that they can be effectively overseen by natural persons during the period in which the AI system is in use …"
Accuracy robustness and cybersecurity	"High-risk AI systems shall … achieve, in the light of their intended purpose, an appropriate level of accuracy…"

Risk management system	"A risk management system shall be established, implemented, documented and maintained in relation to high-risk AI systems …"
Quality management system	"Providers of high-risk AI systems shall put a quality management system in place that ensures compliance with this Regulation …"

For each of the requirements, it is proposed to introduce sub-Elements as "*children*" of the proposed Regulation_Conformity attribute of the RAP "*Reserve*" attribute (or as additional attributes under the root of the RAP structure). Regulation_Conformity attribute provides information if the requirement is met, or the requirement is not met (likely no market access allowed in the European single market).

Since CaaS may be used by devices to offload heavy computational processes to the network, CaaS may also require a new type of mobility solutions in order to meet the requirements such as low latency and compute resources (e.g., floating-point operations per second). Therefore, we propose to modify the mobility procedure so that it incorporates the CaaS requirements and still maintain the adequate link quality. The main idea is to incorporate latency and compute requirements in the handover decision, making use of the so-called q-offset for each cell, which could be set to prioritize cells with low latency and down-prioritize cells with high latency.

The UE may be connected to a base station node which provides long E2E latencies to the compute resources, even if the throughput is acceptable (see Figure 4-15). If the UE is connected via an Integrated Access Backhaul (IAB) node (i.e., the base station node the UE is connected to, is itself connected wirelessly to another network node), the computational offloading resources may be located in the network which would require one or more hops between IAB nodes, where each hop would add to the latency.

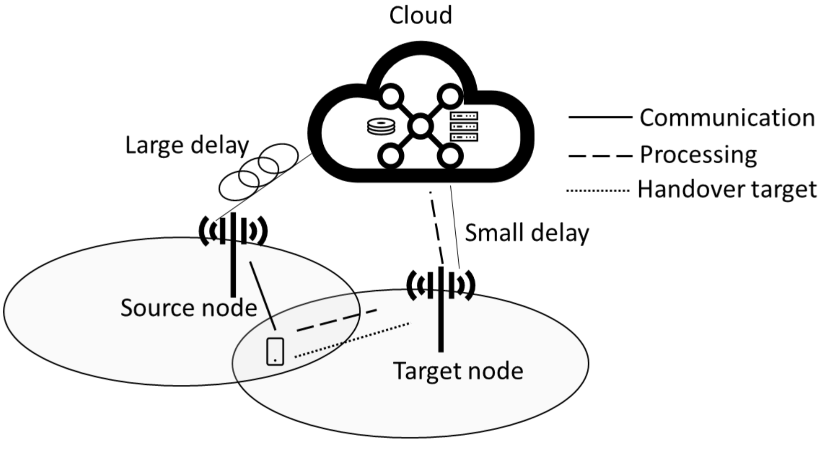


Figure 4-15: Overview of the CaaS handover solution.

If the UE is within coverage of another cell, with a different network path towards the computational resources, it could be beneficial for the UE to handover to that cell, even if the signal quality may be slightly worse (see Figure 4-15). To provide a compromise between the throughput and the computational offloading latency, the network would first determine which would be the suitable computational resources capable of serving the UE offloading and which computational latency each of these resources would provide for any cell in the vicinity (e.g., within the same and neighbouring tracking areas). Depending on the UEs latency requirements for offloading, the so-called q-offset for each cell could be set to prioritize cells with low latency and down-prioritize cells with high latency. The architectural implications of improving device compute offload and mobility are that there is a need for a modified mobility procedure. Also, there is a need for new signalling between the UE and the RAN and the function that handles the compute resources in the mobile network, using e.g., the RAP structure described above for generic offloading.

4.7 Management and Orchestration

The Hexa-X M&O architectural design was already provided in the Hexa-X Deliverable D6.2 [HEX22-D62], targeting the design of the service M&O functionalities. Figure 4-16 represents the structural view presented in abovementioned deliverable. This section describes the alignment between that M&O architectural design in D6.2, and the overall E2E Hexa-X architectural design in this document (Figure 4-1), focusing on the three main topics addressed in Hexa-X WP6: E2E seamless integration management (Section 4.7.1), automation, network, service programmability and Dynamic Function Placement (DFP) (in Section 4.7.5), and data-driven M&O (Section 4.7.6). But first, an overall introduction is provided right in this Section, summarizing what has been described in D6.2 and providing a general mapping between the M&O architectural design and the overall E2E architecture.

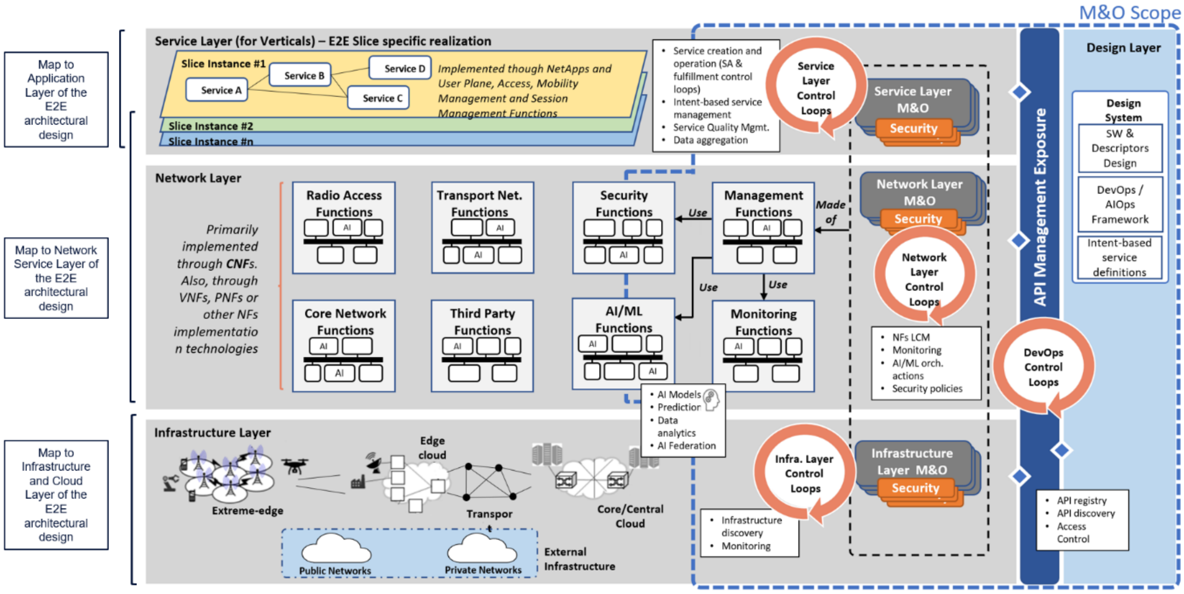


Figure 4-16: Hexa-X M&O architectural design - structural view [HEX22-D62]. There is an approximate mapping to the Hexa-X E2E architectural design is also presented.

In short, Figure 4-16 represents that network services (grouped within independent network slices at the *Service Layer* - top), which are executed on the network resources (physical or virtual) at the *Infrastructure Layer*, can be "made of" the different kind of network functions at the *Network Layer* (mapped to *Network and Service layer* of E2E figure architecture), being all those elements (network functions, services and slices) designed and provided from the *Design Layer* (following the DevOps practices), and communicating all of them through the API Management Exposure block, following the cloud-native principles (more details can be found in [HEX22-D62]).

Of course, some of the network functions at the *Network Layer* are specifically designed to perform M&O. To highlight this, Figure 4-16 distinguishes the M&O scope itself (the components within the blue dashed line on the right-hand side) from the managed objects (those blocks outside the blue dashed line, on the left). As represented in the Figure 4-16, specific instances of the M&O functions (grey blocks within the black dashed line) would be issued for managing the components in the different layers (service, network, and infrastructure). As it can be seen, network slices and service components at the *Service Layer* are purely managed objects, as well as certain specific network functions at the *Network Layer*, such as the radio access functions or the transport network functions, among others (see Figure 4-16). On the other hand, the "*pure*" M&O functions are the management functions and the monitoring functions, which can be supported also by specific M&O-oriented security functions and AI/ML functions. The functional blocks containing these functions (i.e., Security and AI/ML functions) are considered "*hybrid*", which is represented by the splitting dashed line through these blocks in the figure, meaning that some of the functions in them could be just managed objects (e.g., AIaaS functions or service-specific security functions, which would be outside the M&O Scope), or also managing objects (those functions supporting the specific M&O-related blocks).

On the other hand, the overall Hexa-X E2E architecture is the one in Figure 4-1. The M&O is represented by the blue block cutting through all layers of the architecture. This block represents the M&O scope delimited by the blue dashed line in Figure 4-16, while the other elements in Figure 4-1 would be managed objects (from the M&O perspective).

As it can be seen, the different architectural layers and their main abstractions in Figure 4-1 (*Application Layer*, *Network Service Layer*, and *Infrastructure and Cloud Layer*) correspond with the layers in Figure 4-16. The Design Layer in Figure 4-16 (providing the software artifacts to be deployed on the network), although not explicitly represented in Figure 4-1, would be part of the M&O block in this figure.

Since both architectural designs (the specific M&O design and the overall E2E architectural design) are built on the SBA principles, the interaction between managed and managing objects results quite straight forward relying on a Service Based Management Architecture (SBMA) approach. This approach, already introduced in [28.533] and [zsm-002], makes it possible to have a collection of management components (aka management services), each one representing a particular management capability (e.g., provisioning, performance assurance, trace control…) that would allow to manipulate a particular resource (e.g., a network slice, CN function, etc.). This SBMA still represents a paradigm shift on the telco stack design, based on moving from traditional network/service management systems (hard-to-evolve, and with siloed managers connected with point-to-point protocol interfaces) to a cloud-native management system.

In this regard, the exposure components associated to each layer of the architecture in Figure 4-1, would be an extension of the API Management Exposure in Figure 4-16. As described in [HEX22-D62], this API Management Exposure has been envisaged to enable the communication among the various network elements in the different layers, using an SBA approach. Beyond the communication among the M&O resources (i.e., within the M&O scope itself), this model can be applicable also to a wider scope to represent potential federation-based interactions, mimicking the behaviour of the Zero-Touch Service Management (ZSM) cross-domain integration fabric [zsm-002].

Beyond the structural approach described in this subsection (which shows the alignment between the M&O structural design and the E2E architecture described in this document), in the following subsections more details are given regarding the M&O associated processes (again, summarizing here what is already in [HEX22-D62] and focusing on the alignment with the overall E2E architecture in this document). The next subsection starts focusing on the so-called E2E integration management processes.

4.7.1 E2E seamless integration management

E2E seamless integration management refers those processes and management tools enabling the deployment and the operation of the E2E network services on all the available infrastructure resources in all network domains, e.g., cloud, edge, and even other resources beyond the Mobile Network Operator (MNO) own domain, such as the extreme-edge resources (personal devices, automotive devices, IoT devices or gateways, Augmented Reality (AR)/Virtual Reality (VR) and gaming devices, industry devices…) or other external networks, and considering the heterogeneity of those resources in terms of computational capabilities, storage capacity, underlying technology, or others. The term "seamless integration" stresses the challenge of orchestrating services on that variety of infrastructure as if it were a "unique" resources pool with no gaps, i.e., as if it were a *continuum*.

The work performed in Hexa-X WP6 in this regard focuses on providing efficient M&O processes through the so-called "device-edge-cloud" continuum, which targets to evolve the 5G E2E network slicing concept (focused on dynamically allocating network services components on the MNO core and edge infrastructure resources) expanding the network slices beyond the own MNO core and edge resources, and integrating also other network domains, from the extreme-edge (those end-user resources beyond the MNO edge) till to the central cloud, and considering all the network resources in between (like in a *continuum*), or even physical and/or virtual infrastructure beyond the MNO scope. In this regard, special focus is made on integrating the extreme-edge domain beyond the MNO access network. Regarding this, three main aspects are considered:

a) **The network slices orchestration**: Considering the “device-edge-cloud” continuum model, it is anticipated that 6G networks will require slice orchestration to achieve greater levels of automation and dynamicity compared to previous generations. This will involve customised provisioning of services based on their intended use and runtime operation, ensuring continuous service assurance. The objective of slice management strategies will be to optimize resource usage from an energy-efficient perspective while also ensuring compliance with Service Level Agreements (SLAs) for the running services. It is considered essential to have bi-directional cooperation between service and network layers to adjust network slices according to the changing needs of services. Furthermore, extending network slices to the extreme-edge will require increasing the awareness of the network infrastructure within the slice management logic.
b) **Integration with other networks**: To integrate external networks in the “device-edge-cloud” continuum it is envisaged also that, in the context of 6G networks, it will be necessary to accommodate diverse access and backbone networks to offer E2E solutions. This integration will usually involve combining different technological or administrative domains and may be quite dynamic in nature. The primary focus of this integration would be on the user plane, but in some cases, control plane services may also be required to facilitate E2E integration.
c) **Optimised placement**: The well-known optimised placement problem already mentioned in Section 4.7.5 gets more challenging in the “device-edge-cloud” continuum, considering the potentially huge number of devices on the extreme-edge, as well as the additional pool of infrastructure resources in external networks. When developing placement algorithms for deploying software components, it is important to consider up to date information on available infrastructure. This should include a focus on two key factors: 1) the integration of information on extreme-edge resources, and 2) the ability to handle the volatility and the volatile nature of some resources. These considerations are not limited only to extreme-edge resources, but also extend to 3rd infrastructure nodes. This real-time information should be integrated into the artifact management capabilities inventories/repositories so that placement engines can make informed decisions about orchestration actions. Certain infrastructure elements may not always be available or suitable for hosting certain software functions, especially given the high heterogeneity and limited capacity of some resources at the extreme-edge. As a result, it may be necessary to prioritize certain infrastructure resources, such as those powered with renewable sources, for running specific network functions.

4.7.2 Automation, network, and service programmability

Automation and programmability are two of the key enablers that will be used to facilitate the requirements of the future 6G networks and services. Automation, which is a natural consequence of programmability, is the building block on which algorithmically built processes will perform a multitude of operations with minimal to zero human intervention. On the other hand, programmability is the means to handle the diversity of the 6G infrastructure.

Programmability, in the context of 6G, is categorized in two types: service and network. Service programmability leverages on software virtualisation technologies and enables managing the network algorithmically. Network programmability, which includes UE programmability, abstracts the required network/service and resource configurations and also the creation and management of policy lifecycles.

The programmability framework provides dynamic control of the underlying infrastructure and user devices’ capabilities. This is controlled by the programmability management that can interact with other previously mentioned frameworks and other previously mentioned developed frameworks.

4.7.3 Programmability framework and application

Programmability allows the introduction of new features and functionalities into the system at a fast pace facilitating the agile evolution of the system. Adopting programmability in the 6G architecture enables dynamic control over the behaviour of the 6G network elements over time. This dynamicity allows changing the behaviour of the different nodes in the architecture, i.e., UEs and network nodes, to meet required KPIs/Key Value Indicators (KVIs) for the different served use cases.

Different technologies have been advancing to enable the building of programmable networks [BR18]. For example, Software-Defined Networking (SDN) separated the control plane of the network from the data plane and permitted programmability at the control plane. The P4 programming language complemented the SDN approach by enabling programmability at the data plane, where it introduced a new abstraction for programming the packet processing pipeline of devices. Network Function Virtualization (NFV) targets running network functions as programmable software instances on commodity servers instead of hardware appliances to facilitate leveraging the advantages of cloud-based deployments.

In cellular networks, programmability can be used to flexibly control the behaviour of elements in different domains: UE, access networks, transport networks, and core networks. Each of these network elements runs on different types of packet processing platforms (e.g., CPU, FPGA, ASIC, etc.) with different programming models and languages, compilers, drivers, etc. Therefore, to enable programmability in the 6G system, it is important to incorporate a programmability framework that abstracts the infrastructure details of the programmable elements and exposes services to other management functions in the 6G system to intelligently control the configurations and behaviour of the underlying system elements. For example, an AI management function can dynamically update the data to be collected from the network when a new inference task is assigned to it.

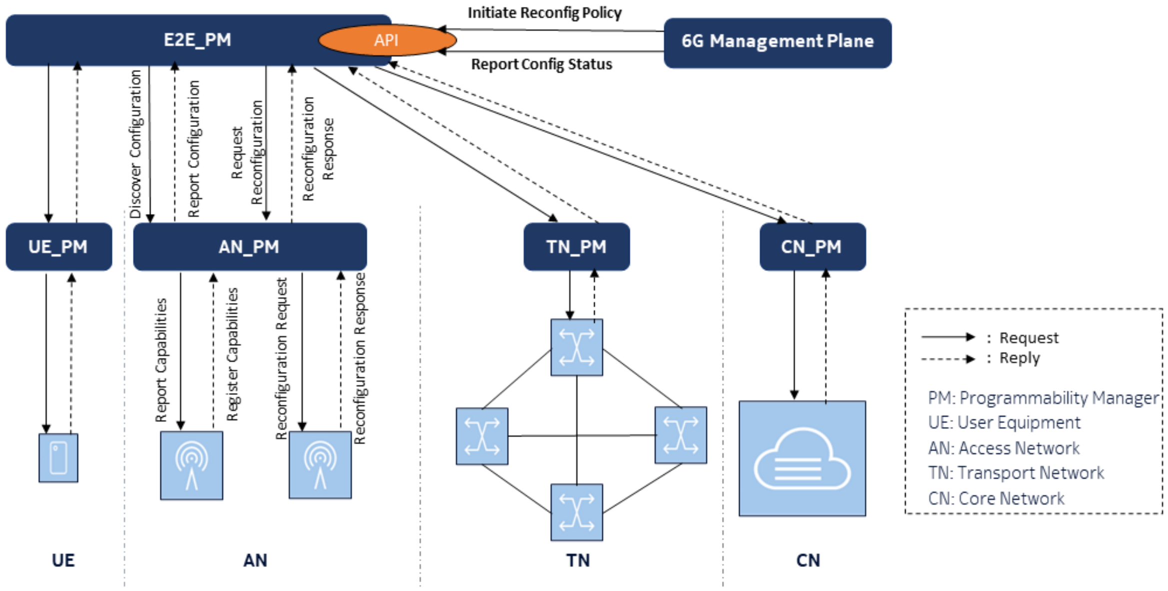


Figure 4-17: Programmability framework.

To this end, in [HEX23-D53], a hierarchical framework for E2E programmability management and orchestration is proposed as shown in Figure 4-17. This framework defines local Programmability Managers (PMs) for different domains to deal with the various infrastructure technologies adopted in these domains. The local programmability managers take care of the following tasks:

- Discovering the programming capabilities of the infrastructure such as the supported programming features and languages.
- Abstracting the device's runtime details such as the compilation process and driver's setup, etc.
- Defining APIs to specify the possible interactions with the devices.
- Establishing channels to enable the reconfiguration of the devices' behaviour.

Furthermore, in [HEX22-D52], a performance-aware orchestration mechanism is illustrated to manage the placement of NF workloads into heterogeneous cloud infrastructure. This task could be assigned to local programmability managers in transport, access, and core networks. The different local managers are connected to one centralized entity (E2E_PM) that takes care of the E2E programmability management of the system in a harmonized way as shown in Figure 4-17. On the southbound interface, this entity either commands the different local managers to enforce certain configurations into different domains' programmable elements or requests collecting information regarding the already running configurations. On the northbound interface, the E2E_PM interacts with the 6G management plane to report information related to the status of the running configurations in the system or to serve requests for initiating certain reconfiguration policies for the system's behaviour. For example, the management plane can dynamically change the metrics that should be collected and metered by the system based on the needs of the running analytics functions. More information on the correlation between the programmability framework and other frameworks introduced in previous sections (e.g., Section 4.4.1 and Section 4.4.2.1) can be found in Section 4.1 in which the exposure coordination framework can be found.

Adaptive packet processing implementation example

Programmable data planes are expected to enable the rapid development of new network functionality. Hexa-X deliverable D5.2 (see [HEX22-D52]) discusses how networks will become programmable by introducing Network Interface Card (NIC), routers, and switches supporting Network Programmability (e.g., based on the P4 programming language).

In today's 5G System (5GS) deployments, transport level packet marking on a per QoS Flow basis can be supported by the RAN and User Plane Function (UPF) on the N3 and N9 interfaces in case the underlying transport is using QoS differentiation. Typically, packet processing in the transport network uses the 6-bit Differentiated Services Code Point (DSCP) value in the GTP-U outer IP header for packet prioritization. However, limiting the packet processing priority handling of a specific packet of a specific QoS flow to a static value will result in a rigid forwarding performance not able to dynamically adjust to the varying network conditions. For example, the delay of a specific packet may accumulate (e.g., due to re-transmissions in RAN and network congestion) to a point where the packet is dropped at the receiver.

In 6G it is proposed to enhance In-band Network Telemetry (INT) [INTP4] with additional QoS related instructions derived from the associated QoS flow requirements and included in some or all packets (packet selection can be based on specific QoS requirements and/or network condition). In Figure 4-18 for uplink data, an INT header with QoS related instructions is inserted by the RAN (INT source) following the GTP-U outer TCP/UDP header and removed by the UPF-PSA (INT sink) before forwarding a packet over the N6 interface. Likewise, for downlink packets the UPF PSA (INT source) inserts an INT header with QoS related instructions following the GTP-U outer TCP/IP header and the access network removes the INT header with the QoS related instructions before forwarding a packet to the UE.

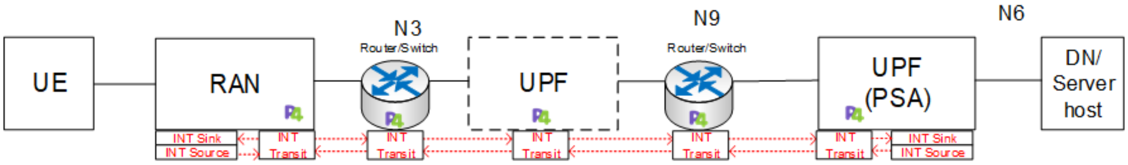


Figure 4-18: Adaptive packet processing implementation example.

The INT header can include a new instruction to enforce a packet latency deadline (maximum allowed E2E latency) to be used by the INT transit increasing priority when the deadline approaches. The latency deadline is derived from the associated QoS flow requirement and is included in the INT header or metadata by the access network (for uplink data) and the UPF (for downlink data). In the uplink and downlink path, the network devices are then programmed (e.g., by an SDN controller) to enforce prioritized packet processing based on the packet latency deadline (considering the latency of any previous hop) and to update the INT metadata with the observed hop latency. For example, in case the deadline approaches the processing is done with increasing priority, or in case the deadline has been exceeded the packet could be dropped. The INT sink decides whether to report the collected information (e.g., to the SDN controller). An example implementation of a queue management system on a P4 programmable network switch that works on a per-packet basis is specified in [TAZ+13]. The solution in [TAZ+13] demonstrates a significant improvement of network performance, especially for low-latency traffic, by significantly reducing the number of outdated packets without causing a drop in throughput.

4.7.3.1 Intent-based processes for expressing application/service requirements

The idea of "intent" is an innovative concept in the realm of autonomous and programmable networks because it allows for the declaration of requirements, constraints, objectives, and context of the desired connectivity in a technology-independent and abstract way. This approach shifts the focus from network operation and configuration to the expectations and requirements of the applications and services that utilize network connectivity. The concept of intent is simple to interpret and manage without requiring in-depth technical knowledge of networking aspects. Therefore, it is an appropriate way to describe the intentions of vertical users based on their own language and expertise, without needing to understand the underlying infrastructure's details or low-level management and operation resources. This straightforward and service-oriented language simplifies the verticals' approach to mobile networks and their interactions with the management and operation system when defining their requirements.

In general, intent can be defined at different levels of abstraction. For example, intents may describe expected infrastructure resource performance or identify mobile network connectivity characteristics, operating at the resource and network layers. Alternatively, intent can offer service or business-oriented indications, delegating the translation of these constraints into concrete policies and configuration actions to the lower layers of the architecture.

6G networks can enhance the functionalities available to process and translate vertical and customer intents to drive network configuration. For instance, an intent could declare the need to establish a secure tunnel between two networks to model a secure connection. Additionally, the operator could identify the classifiers for traffic using the tunnel and any other required parameters to configure the tunnel fully. Specific service requirements would also need to be defined, such as streaming high-resolution 1080p video or multiple streams of 4K video in future reconfigurations. Assurance checks would be enabled to reconfigure anything out of place to prevent service outages or infrastructure disruption.

Intent-based approaches are the first step in enabling full system automation and configuration of all software and hardware devices based on enhanced service description components in use. The initial system configuration would be generated by the intent-based mechanism, and ongoing assurance checks would utilize multiple data-driven processes to maintain the network's intended and operational state. The M&O system could provide enhanced support to automatically validate the users' defined intents and increase the efficiency of interpretation. AI/ML techniques would enable a "self-learning" approach to understand how to interpret and translate the customer's intents into concrete configuration and orchestration actions applied through specific management functions. Integration with network monitoring functions would enable the collection and processing of service and network KPIs to detect potential changes in the initially declared service intent and react accordingly during runtime.

Lastly, the current approach to translating intents into network configuration actions relies heavily on static criteria and policies configured manually by the network administrator. However, introducing AI/ML to enable continuous self-learning procedures would allow for the automatic updating and modification of translation criteria, rules, and policies dynamically, adapting them to the current network conditions to better match and guarantee the desired performance.

A possible workflow for the management of service intents in the context of 6G networks, highlighting the interaction with the M&O functions operating at the network layers and the applicability of AI/ML-based closed-loop logic to various phases of the intent management is the proposal from WP6 [HEX22-D62]. In particular, the management of the intent can be addressed introducing new functions at the design and service layers of the structural view.

4.7.3.2 Processes for enhanced service description models and profiling

The upcoming 6G networks are expected to bring significant improvements in terms of service characteristics and resource constraints. This includes the possibility of extending the target placement of application elements beyond the edge towards low-power computing resources in IoT gateways, industrial devices, or vehicles. Additionally, service-level metrics may be used to complement traditional network KPIs, and automated actions may be triggered if these metrics fall outside predefined ranges.

Service descriptors can also declare explicit service-level AI/ML components and their related requirements, which may include the kind of input data to be consumed, trained models to be applied, or AI/ML functions and engines to run. This definition of AI components can drive the joint management of resources, virtual functions, and monitoring sources to support data-driven service management.

To provide optimal services to verticals, an increase in programmability is necessary for both the network and service elements. The existing models used to describe these elements must be extended to accommodate new requirements, including information on profiling services and network slices. This increased programmability can lead to different operational conditions for a service or network slice, and the profiling process can help generate static profiles that estimate the expected performance under a set of known conditions. This information can be included in the service or slice profiles, providing a way to quantify the desired state of the service or network slice.

Increased flexibility in the utilization of available resources can lead to various operational conditions for a network slice or service. Adjusting the number of resources or changing the placement of elements can impact the performance, ranging from minimal to significant. The profiling process, proposed by WP6, facilitated by the monitoring functions components, and the diagnostic processes, part of the assurance functions components, can gather necessary information to create static profiles that estimate the performance of a service or slice under known conditions. This process can occur statically, based on pre-configured conditions, or dynamically, based on available options for modifying variables like network conditions and service traffic load. This information can be incorporated into the service or slice descriptions, utilizing formats like service profiles or slice profiles. This provides a way to quantify the desired state of the service or network slice.

With increased flexibility offered by the management functions and supported by the fulfilment control loops (part of the service layer control loops), services and slices can become more elastic. Their profiles can also be extended to become more elastic, considering resource reallocation, element placement, and energy consumption. During the profiling process, changes in the deployment of a service or slice, such as dynamic resource reallocation or element placement, can be tested and used to enhance these elastic profiles. This enables a more accurate estimation of performance based on resource usage trends and provides additional options for service quality assurance, in conjunction with performance diagnosis, by expanding the options of the fulfilment control loops to meet the service quality requirements.

4.7.3.3 Monitoring and diagnostic processes

6G networks require a system that can provide an overview of various components and services, and such a system is proposed from Hexa-X WP6 as part of the M&O workflows. The assurance subsystems, which are a part of the management functions, as shown in the structural view, play a critical role in ensuring service quality. Specifically implemented by the assurance subsystems, these diagnostic processes are supported by service quality management functions and AI/ML-driven orchestration actions that are part of the service and network layer M&O blocks. Serving as a link between service requirements and their assurance, these subsystems are designed to ensure that the services offered meet the specified requirements.

These stages are continuous operations running in parallel with components and services as part of a closed loop. To accomplish this, the diagnostic process interface with the appropriate mechanisms or components responsible for executing the actions decided by the process using a model of requests or notifications. These capabilities are provided by the fulfilment components within the management functions block. These requests are taken as suggestions for actions to alleviate any performance degradation and are not immediately executed since appropriate validity checks need to be done beforehand.

The need for detection of relations between the components and elements is handled effectively by the respective M&O systems in each of the various domains or by the management functions tasked with the overview of the system, which have access to the description of the services and functions. These relations are necessary to enable cross-domain correlation and the matching of events and performance, which opens the path to other innovative mechanisms and functionalities, like automated per-domain performance optimization, optimized resource allocation and management, and automated response to unexpected conditions.

4.7.3.4 Processes for reasoning

In the context of 6G networks, the ability to program networks allows for network intelligence to trigger various automated actions using data-driven and zero-touch patterns. However, to enable efficient reasoning, one of the challenges Hexa-X WP6 was called to address, is the creation of a representative knowledge base for 6G networks that can capture a wide variety of parameters that can impact performance and requirements at the service, network, and infrastructure layers. This knowledge base is considered when making decisions about network, slice, or service re-optimization. The network programmability allows for the generation and exposure of monitoring data to build such an extensive knowledge base as required by the reasoning entities that consume them.

Since in 6G networks, AI/ML agents where the reasoning engines run are expected to be provisioned and re-configured dynamically, the need for monitoring data to feed such agents may vary over time. Programmable interfaces at the infrastructure, network, and service layers enable provisioning new probes in different segments of the infrastructure and configuring heterogeneous monitoring data sources, as well as the retrieving efficiently collected data in a distributed, scalable, and secure manner.

There are several categories of parameters and monitoring data that are considered in reasoning procedures, including parameters related to service demands and requirements, network capabilities including resource availability and related constraints, and external factors not directly related to the network itself but impacting its performance or the service demands. To efficiently feed the intelligent decisions of the network, a scalable, secure, multi-domain, and distributed monitoring and data management system is proposed by Hexa-X WP6 [HEX22-D62] to collect, aggregate, filter, and elaborate data coming from different sources.

4.7.3.5 Software integration processes

Software integration processes involve DevOps practices such as CI/CD, which are widely used in cloud-native systems but not as extensively in the telco-grade industry. However, integrating development and operations, as done in the cloud-native industry, offers numerous benefits, such as improved software quality, fast and reliable problem-solving, and enhanced Mean Time To Recovery (MTTR).

Hexa-X WP6's proposed M&O architectural design includes a specific Design Layer to implement DevOps processes, which can trigger basic orchestration actions, including service instantiation actions, configuration actions, and scaling actions. The main DevOps processes that can be implemented through this Design Layer are Continuous Integration (CI), Continuous Testing (CT), Continuous Delivery (CD), Continuous Deployment (Cd), and Continuous Monitoring (CM).

CI involves automating the initial development stages and integrating different developers' contributions to the code development. CT executes multiple test batteries on the provided code to ensure it meets specifications. CD transfers changes validated in the developer's repository to a centralized artifacts repository in the operational environment, where all changes are continuously tested and verified in a production or production-like environment. Cd refers to the automatic deployment of changes generated during the CD stage without human intervention, and CM uses real production data to guide development and operational teams.

Implementing DevOps practices in a telco-grade environment is challenging because MNO and software providers are typically separate companies with different interests and cultures. Addressing technical challenges, such as enabling shared repositories and open interfaces, as well as cultural and procedural changes in the involved companies, will be necessary to implement this concept in such an environment. Although other processes could be considered, these five concepts showcase how the DevOps approach breaks down the barrier between development and operational scopes. While CI is still on the development side, CD, Cd, and CM enter the operations area.

The programmability enablers introduced in this section are split between the Design Layer and the Network Layer and utilise the API Management Exposure. The Design layer will provide the required inputs for the mechanisms in the Network Layer to operate or trigger actions. *Utilizing these programmability enablers unlocks the potential for automation across the 6G networks. Network based automation* utilizes AI to handle complex management operations to meet various requirements, such as quality, security, and resilience requirements. Finally, *dynamic function placement* is a management and orchestration solution proposed for multi-domain environments.

4.7.4 Network automation

The high degree of softwarisation and virtualisation of networks already happening with 5G enables networks and services to be more flexible and agile in their deployment and operation. On top of this, 6G is also expected to support more heterogenous network of networks and distributed functions and services across different network and infrastructure layers (see Figure 4-1). The increased flexibility calls for better network automation capabilities as a key requirement [HEX22-D52]. The expected benefits of network automation can be classified into four main areas: *(i)* reduced management complexity, *(ii)* OPEX savings, *(iii)* reduced time to market, and *(iv)* safe operations.

Network management automation practically impacts the network and service orchestration, which refers to the coordination of automated tasks to deploy and operate E2E network services and slices across the multiple domains. Due to the expected increase of heterogeneity and variety of 6G networks capabilities (i.e., brought by the network of networks concept, including heterogeneous types of services as well as virtualization and underlying cloud platforms), these coordination and orchestration tasks become, in turn, more and more complex. In this context, AI and ML are currently considered as the key enablers to achieve full automation [5GP-AIML], and in particular to assist lifecycle management and operation routines at different phases, such as planning, deployment (including resource sharing), and runtime operation (including scaling, migration, etc.). In addition, AI/ML based automation can handle the complexity in terms of technology and services to meet quality, security, and resilience requirements [HEX22-D52]. To achieve the level of automation and flexibility required by 6G networks and services, a more comprehensive approach is required to support the various network decision's logic to be taken at the M&O layer (in different phases and for different tasks) [MSD22]. This approach shall consider the integration of cooperative AI agents able to address the complexity of different optimisation aspects with data, models and algorithms specifically tailored to the constraints of specific network domains, slices and slice subnets, or services [HEX22-D62].

In practice, such AI agents have the capability to perform decision-making related actions individually or collaboratively, each specialized in targeting specific objectives and goals. In particular, AI agents can be tailored to automate the analysis of network and service-related (user and control) data through dedicated monitoring capabilities and platforms. Here, AI/ML provides the means for processing data and perform analysis and implement decision-logics related to network and service quality and performance, troubleshooting, security, etc. The AI functions can communicate, collaborate, cooperate, and coordinate to accomplish complex tasks, and can be also distributed across the compute continuum (i.e., extreme-edge, edge, cloud) to handle local analysis and decision-making.

With this approach, network automation can be based on distributed and cooperative closed loops, and thus provide immediate response to occurred or predicted events and behaviours based on AI/ML analysis and decision-making. Cooperative and distributed control loops require proper mechanisms for coordination and governance of decision logic. Indeed, control loops that insist and operate on top of shared services and resource may take conflicting, interfering or misaligned decisions. Also, prioritization of distributed and cooperative control loops decisions can be applied depending on the type of network and service event or behaviour targeted. Similarly, control loops can be isolated and separated to operate at different time scale (e.g., for long-term management operations and short-term or even real-time network control operations, e.g., at the radio level). Moreover, monitoring the impact of individual control loops' decisions is required to detect degradation of KPIs due to unstable system behaviour.

4.7.4.1 Zero-touch automation

The complexity of the technology behind network systems is increasing rapidly, making manual processes insufficient to manage them effectively. Automation, including machine learning, is essential to support orchestration and adapt to the constantly changing requirements of new services and networks, such as those in 5G and 6G systems. Zero touch automation is a new architecture design that eliminates human intervention in managing the lifecycle of networks and services across various domains, using closed loops and advanced machine learning to detect and remedy anomalies. The closed-loop automation framework consists of three main components: monitoring functions, AI/ML functions for data analytics and policy decisions, and an ML model marketplace for users to select and use appropriate models. This framework facilitates self-managing capabilities, reduces operational costs, and lowers the risk of human error by embedding intelligence with data-driven algorithms. The monitoring and analytics functions are independent, allowing for flexibility in their evolution without affecting the other, while the automation engine triggers the appropriate actions based on the input from the analytics component. The ML model marketplace stores models for users to use individually or in complex chains to optimize and re-configure systems for tasks such as auto-scaling, self-healing, anomaly detection, and automated troubleshooting.

4.7.4.2 Autonomic computing processes

Autonomic Computing (AC) is a concept that refers to the ability of a system to change its behaviour in response to changes in the environment, without human intervention. AC is based on the pillars of context awareness and self-awareness. Context awareness refers to the capability of the system to gather and consider the state variations of external entities, while self-awareness is composed of a set of "self-*" properties, including self-configuration, self-healing, self-optimization, and self-protection. The WP6 proposed architecture enforces these properties onto the services it manages through the M&O system, which acts as an Autonomic Manager (AM). However, there are still challenges to overcome to efficiently integrate AC in future 6G networks, including state-flapping avoidance mechanisms, evaluation of the performance and effectiveness of the AC instance, and creating trust conditions. AC is unlikely to operate in a centralized form and would be part of an overall multi-layer, multi-domain system containing several AMs that would need to work together, leading to issues of heterogeneity and scalability. The distributed AC system would also raise issues of isolation between domains. Within the Hexa-X M&O architectural framework, this decentralized paradigm would imply that AC systems located in the different M&O blocks should be connected. AC relies on context awareness and self-awareness to carry out feedback actions. The self-awareness properties are self-configuration, self-healing, self-optimization, and self-protection. In the proposed architecture, the M&O system enforces these properties onto the services it manages and acts as an AM. This M&O system relies on different functions in the Network Layer, such as monitoring functions to be aware of the state of the managed services and AI/ML dedicated functions to decide on the course of action and apply determined actions using the management functions.

Still, there are still challenges to overcome for efficiently integrating AC into future 6G networks. The system should move towards a stable state, and mechanisms should be proposed to prevent the system from oscillating between states as a result of an inability to determine the best state to align with the policy. It should also be possible to evaluate the performance and effectiveness of the AC instance without necessarily aiming for the optimal solution. Trust conditions should be created between the human operator and AC. AC is unlikely to operate in a centralized form, and rather, they would be part of an overall multi-layer, multi-domain system containing several AMs that would need to work together. The distributed AC system also raises another issue: the isolation between domains. The resolution of policy conflicts should lead to minimal loss in performance for all concerned domains. Within the Hexa-X WP6 proposed M&O architectural framework, this de-centralized paradigm implies that AC systems located in different M&O blocks should be connected, both between layers and within the same layer.

4.7.4.3 Closed-loop automation

The M&O architecture, proposed in Hexa-X WP6, consists of four sets of closed loops, each with its own operation timescale. These loops utilize the corresponding interfaces to perform monitoring and execution. The closed loops are implemented using Network Layer functions and may rely on AI/ML Functions for analysis and planning. While the monitoring and execution phases have their own set of challenges, the closed loops have been widely used in many networking scenarios.

However, there are several challenges associated with closed loops that need to be addressed for future 6G systems. Monitoring itself can be difficult, as data collection in a large and heterogeneous system is not easy to adapt to each data source and continuously report data monitored. Optimizing NFs may lead to the removal of a standard interface and the associated monitoring data, resulting in vendor-specific approaches. Additionally, while data may be available, it may be too abundant, resulting in a large data lake that is difficult to process and use effectively.

The execution stage needs an efficient mechanism to invoke relevant APIs and apply procedures sent by the planning stage. The use of AI/ML in closed loops typically involves long training periods and continuous exploration of the configuration space, which may be inadequate for URLLC scenarios imposing stringent delivery guarantees. Furthermore, the optional usage of AI/ML in the context of 6G by different functionalities of the closed loops brings its own set of challenges. To address these issues, monitoring should be an autonomous system that adapts its monitoring rate and the nature of the data being monitored to report only meaningful information.

4.7.4.4 Automation in multi-stakeholder scenarios

In complex systems, isolated closed loops provide limited benefits as they do not operate in isolation. This is particularly relevant for multi-stakeholder systems like the anticipated 6G system. Automation tools in 6G must be able to handle such scenarios where different stakeholders coexist.

In multi-stakeholder scenarios, closed loops need to communicate with each other to collect information and request services. However, this poses challenges for interoperability, especially as sensitive data must remain confidential. Therefore, the closed-loop's internal functions, such as the analysis and plan modules, must operate independently without relying on all the information available from other closed-loops.

Through the work done in Hexa-X WP6, and specifically as part of Task 6.3, the proposed structural view addresses multi-stakeholder scenarios through the API management exposure block, which enables connection between the MNO and other stakeholders. Each stakeholder can manage their resources using standardized interfaces to exchange monitoring, analysis, and action data. The implementation of this block may vary, depending on the context.

One way to expose services to an API in a public 6G network, involving multiple functions from different vendors, is through an API discovery system. This system includes a registry where service providers can register their APIs, and service consumers can discover them. Additional security services, such as access control and redundancy, can be added as required.

4.7.4.5 Dynamic self-optimization of network slices

6G networks are expected to handle numerous network slices with varying hardware, compute, and connectivity requirements. To minimize infrastructural costs and increase revenue, network operators need to incorporate mechanisms that facilitate dynamic optimization of network slice operations. This optimization should involve scaling resources according to current needs expressed through KPIs, with self-healing and self-configuration features supported by M&O processes. The Hexa-X WP6 approach assumes E2E and multi-domain optimization, requiring integration of multiple M&O systems that are organized in an E2E and multi-layer M&O distributed architecture. These can exchange vital information for E2E slice optimization using API management exposure.

A data-driven M&O approach allows for proactive operations that reduce KPI/SLA violations and efficiently allocate resources during a slice's lifetime. The optimization operations involve collecting and pre-processing slice-related data from all system layers, extracting relevant features for slice optimization from monitoring information, performing slice self-optimization algorithms, and carrying out slice self-healing and self-configuration actions. These actions should be fully automated to enable efficient scaling of the solution with an increasing number of concurrent network slices, eliminating the need for human intervention. The overall resource allocation scheme should keep slices isolated from each other to minimize the impact of congestion in one slice on other slices.

The automation enablers mentioned are mainly considered as part of the management functions block, in the Network Layer, and by definition mechanisms since other blocks of this layer as well as the Service Layer and Infrastructure Layer M&O mechanisms, since they are the backbone of the architecture-wide M&O system.

4.7.5 Dynamic function placement

In a SBA based multi-domain environment, each domain has its own internal SBA deployment covering critical functionalities like NRF and Service Communication Proxy (SCP) for service discovery and communication endpoint resolution. These are used together with a Network Service Mesh (NSM) that is inter-connecting multiple domains to build a uniform resourcing space where NFs are managed over domain boundaries in a congruent manner. This is the foundation on which DFP operates.

Besides the orchestration itself, also other supporting functionalities like management and monitoring need to support this hierarchical (layered) solution. Monitoring is something that is mainly done inside individual domains and the information is exposed externally (raw information or as (pre-processed) aggregate), but also some E2E type of monitoring over multiple domains might be needed, as depicted in Figure 4-19 where differently scoped control loops are shown. For NF scaling, a domain's internal scaling properties and the scaling over multiple domains should be considered separately as:

- Intra-domain: In internal scaling the deployed NF serving capacity are scaled up/down or in/out based on the local needs or based on the external triggers like a request from the top-level.
- Multi-domain: Overarching scaling needs the utilisation metrics and load predictions from each involved inter-operable domain to make decisions on requesting more serving capacity from domains or redirecting/refocusing service offerings from one domain to another.

Besides scaling, the other NF related operations are relocation and offloading. These operations should support distribution over domain boundaries and can be characterised as follows:

- *Scaling* is a "legacy" operation meaning scaling of existing service capacity needed to ensure the adequate service level of deployed NFs.
- *Relocation* is an operation used to change the location of NF instance(s) in the network topology. For example, either a new NF instance is created or resources from the existing one are taken into use proactively or reactively in the new location and context transfer is done, if needed.
- *Offloading* is used to distribute workload of an existing NF instance to the new location(s) in the network topology based on policies/KPIs/etc. Offloading does not involve the reduction of

existing service capacity, but instances in the new location and in the original location do co-exist.

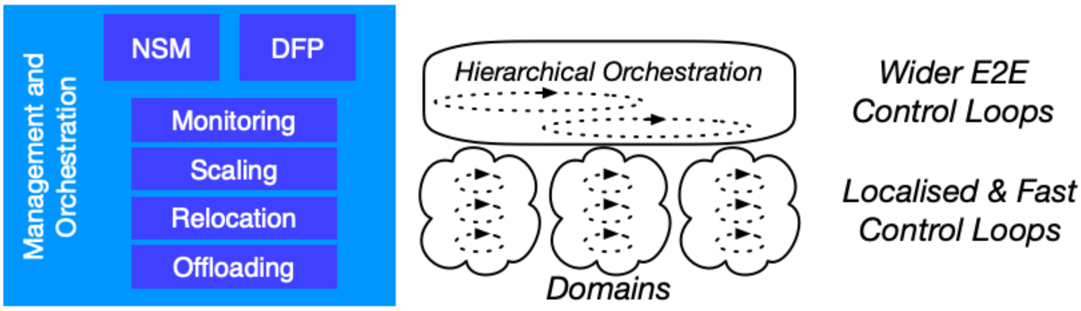


Figure 4-19: Overview of 2-layer orchestration including Dynamic Function Placement.

As shown also in Figure 4-19, the execution times of Control Loops (CLs) are impacted by their locations. For instance, domains have localized faster CLs compared to the top-level, where CLs are slower but with wider scope. These domains' internal CLs may contribute to the top-level CLs.

Another important aspect on the CL execution time is its correlation with the ability to react to external changes like changes in networking between NFs or domains. This implies that the top-level decision making is better suited for predictions. Respectively, it is domains' internal scoped CLs that are faster and better suited for reacting to rapid changes inside the domain, or even inside a physical/logical node. This leads to the scheme where the top-level does predictive wider scope decisions with longer lifetime and then each underlying domain operates based on these decisions with ability to react fast on any issues. It is each domain's responsibility to fix any observed issue, maybe with a temporary solution, and communicate the local changes back to the top-level, where longer term optimal solutions could be found and required management transactions in underlying domains may be initiated.

4.7.6 Data-driven management and orchestration

6G networks are expected to be capable of autonomous operation, self-optimization, and prediction of the future network state. Data-driven orchestration is a mechanism that contributes to the features mentioned above. Considering the scope of the 6G expected capabilities, the Hexa-X M&O system will monitor and process monitoring data in the Service Layer, the Network Layer and the Infrastructure Layer. Each monitoring process has to be integrated using a cross-layer approach. Collecting and processing data as close to the source as possible, including filtering data at the source contributes to management efficiency and scalability. The monitoring data processes should be able to work in a multi-stakeholder environment. The multi-stakeholder poses new challenges as some stakeholders may be malicious and send false data to the orchestration system to gain an advantage or disrupt the network. Moreover, different stakeholders may be reluctant to provide their complete data, as some or all this data may be sensitive.

All the mentioned points call for a distributed and layered monitoring architecture. The exploitation of the monitoring data is essential for

- Proactive (anomaly-based) or reactive (alert-based) fault detection
- Discovery and self-configuration of functions, nodes, and services
- Collecting accounting-related information
- Monitoring of the performance, calculation of KPIs and their prediction
- Monitoring of thresholds’ crossing
- Security-related events detection
- Data-driven orchestration
- Training of AI/ML models

An efficient data management strategy becomes substantial to facilitate all data-driven processes conducted in the network. The Hexa-X data management strategy consist of:

- **Data architecture** – the formal structure of data flows management and processing.
- **Data collection strategy** – defining the scope of network components monitoring (NF metrics, user activity), monitoring data abstractions (performance and quality indicators), data pipelines, etc.
- **Data storage and provisioning** – a creation of data aggregation points (warehouses) and components collecting metadata (data catalogues) for easier processing and management.
- **Data governance** – creating data policies and procedures for data security (ownership, privacy, access), compliance and integrity maintenance.
- **Data security** – the processes to protect the collected monitoring data from corruption and limit access to privileged entities.

The data-driven management and orchestration provide multiple benefits due to the use of information coming from all the system layers. On the opposite, the classical orchestration processes are typically driven by the consumption of Infrastructure Layer resources. Such orchestration is typically reactive. The data-driven orchestration is more accurate as it takes information from different layers and enables proactive orchestration, giving more time for network or service reconfiguration. The proactive approach, due to the additional information, can change allocation of resources in advance and that way significantly reduces SLA violations. Data and KPI prediction can nicely support it. In general, data-driven orchestration should use multiple analytic engines, each of which has a predefined goal. Such approaches reduce the functional complexity of the orchestrator as well as the amount of data to be processed by the orchestrator and enable automated actions to be taken in real-time. Another mechanism that contributes to orchestration performance is using intents to reconfigure the orchestrated systems.

The data-driven orchestration may need AI/ML-driven processes implemented at different levels. The use of AI/ML in that context provides many benefits, including flexible adaptation and reducing the amount of data processed at each stage. The AI/ML processes may concern monitoring and data processing (including data analytics and predictions). The M&O framework described in [HEX22-D62] allows using AI/ML functions in a programmable way.

4.8 Relation of E2E architecture technical enablers to Hexa-X contributions

Table 4-3 summarizes the mapping of the aforementioned E2E architecture technical enablers to contributions addressing the use cases related to dependability in Industry 4.0 (I4.0) that are discussed also in more detail in [HEX21-D71] and [HEX23-D73]. There, solutions for special-purpose functionality are proposed that help in realizing the requirements of the use case by building on the enablers outlined in the previous section. The relation given in Table 4-3 provides insights into how the architecture technical enablers are applied within a given use case and how they are augmented with special-purpose functionality targeted to fulfil the requirements of the use case. For more details on the respective contributions, please refer to [HEX22-D72] and [HEX23-D73]. The overview is limited to the dependability-related use cases as the main focus of work in Hexa-X WP7.

Table 4-3: Mapping of architecture enablers to technical contributions, addressing use cases for dependability in I4.0.

Enabler	Details	Technical contributions
Distributed large MIMO (Section 4.2.1)	[HEX21-D22], [HEX23-D23]	Contributing with dependability in distributed massive MIMO ([HEX22-D72], Section 4.3).
Architectural component for sub-THz RAN (Section 4.2.2)	[HEX21-D22], [HEX23-D23]	Modelled for In2-X networks in factories ([HEX22-D72] Section 3.1), updates in Section 3.1 in [HEX23-D73].
Localization and sensing (Section 4.3)	[HEX21-D31], [HEX22-D32]	Formulate requirements and observe performance bounds and constraints, especially regarding

		utilization in the DT ([HEX22-D72] Sections 4.4., 5.3, 5.6). Considered for I4.0 / factory automation use case.
AI enablers for intelligent networks (Section 4.4)	[HEX21-D51], [HEX22-D52], [HEX23-D53], [HEX21-D41], [HEX22-D42]	Special-purpose case of federated learning in IoT ([HEX22-D72] Section 3.4; extended in Section 3.4 in [HEX23-D73]), AI and emergent intelligence in DT ([HEX22-D72] Section 5.7; updates in Section 5.5 in [HEX23-D73]).
Non-Terrestrial Network architecture (Section 4.5.1)	[HEX21-D51], [HEX22-D52], [HEX23-D53]	No direct NTN works. Utilization of drones for sustainable coverage extension in mMTC use cases ([HEX23-D73] Section 4.1.2.
Ad hoc networks architecture (Section 4.5.2)	[HEX21-D51], [HEX22-D52], [HEX23-D53]	In2-X networks in factories ([HEX22-D72] Section 3.1), updates in Section 3.1 in [HEX23-D73].
Architectural transformation with cloud and SBA (Section 4.6.1)	[HEX21-D51], [HEX22-D52], [HEX23-D53]	Reduced dependencies between network functions enables more flexible placement and, thereby, adaptation to latency requirements. Relevant for industrial scenarios with increased dependability requirements ([HEX22-D72] Section 5.6). Potential utilization in flexible functional split adaptation and joint trajectory optimization ([HEX23-D73] Section 3.3).
Compute-as-a-Service (Section 4.6.2)	[HEX21-D51], [HEX22-D52], [HEX23-D53], [HEX21-D41], [HEX22-D42]	Availability of (trustworthy) compute capabilities for the execution of digital twins ([HEX22-D72] Section 5). Can be enriched with allocation strategies, e.g., for federated learning in IoT scenarios ([HEX22-D72] Section 3.4). Further studies in relation to Communication-Computation-Control-Codesign (CoCoCoCo) in Section 4.2 of [HEX23-D73].
Management and orchestration (Section 4.7)	[DED22-D61], [HEX22-D62]	Exposure of local (domain-)knowledge through network-aware collaborating digital twins to aid in overall resource coordination and management ([HEX22-D72] Sections 4.4, 5.6). Formulation of an ecosystem of digital twins to allow cross-domain optimization and collaboration in a privacy-preserving fashion ([HEX22-D72] Section 5). Enabler for resource allocation, e.g., in In-X networks and networks-of-networks ([HEX22-D72] Section 3.1).

5 Security, privacy, and trust

Security and privacy as indispensable features of future 6G systems have been covered in the previous deliverables as follows: D1.2 [HEX21-D12] described the 6G threat landscape and introduced 6G security enabling technologies suitable to address these threats, as well as the concept of the "Level of Trust" (LoT), aiming to address the trustworthiness Key Value Indicator (KVI). D1.3 [HEX22-D13] further discussed the security technology enablers and how they should be applied in 6G systems in more detail and provided an initial view how these enablers can be mapped as security architectural components onto a preliminary 6G architecture. It also provided a more detailed version of the LoT concept, and a preliminary discussion of security management aspects.

As a final result of the work on security aspects performed in the project, this chapter provides an architectural mapping of the identified security components, concludes the analysis on network service trustworthiness and how it can be assessed for next-generation networks, and a discussion of relevant security, privacy and trust implications regarding base technology aspects for 6G.

5.1 Security architecture

The overall Hexa-X end-to-end architecture is visualized and described in Section 4. Based on the overall architecture figure (Figure 4-1), Figure 5-1 visualizes the security technologies to be applied in a 6G system according to this overall architecture, and to which architectural areas they map. This constitutes the Hexa-X security architecture, which intends to give a high-level view on how to secure future 6G systems.

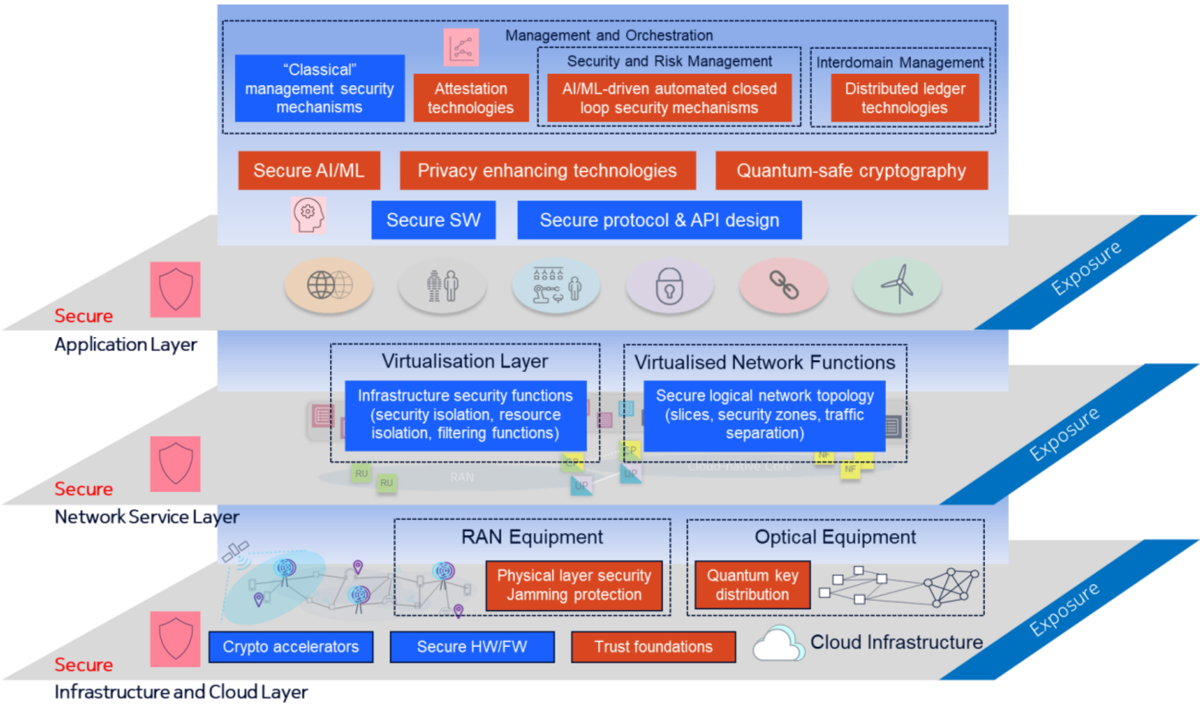


Figure 5-1: Hexa-X Security Architecture.

D1.3 [HEX22-D13] already introduced the essential 6G security architectural components and mapped them to the areas cloud infrastructure, non-virtualised equipment (including Radio Access Network (RAN) equipment and optical equipment) and cloud-based software, where the latter covers the virtualization layer, the virtualized network functions and the management and orchestration functions. We have sticked to these components and their mapping to areas but visualize them now in the context of the overall Hexa-X architecture. To preserve clarity, the figure only gives a rough overview where the different security technologies apply, leaving a more detailed description to the subsequent text. Like in D1.3 [HEX22-D13], the figure highlights (in red colour) the security technology enablers that are new, i.e., not yet pervasive in today's 5G networks. The figure also shows the essential security building blocks that are available today and will continue to be relevant in 6G (in blue colour). Note that we do not assume that a strict mapping of security technologies to 5G or 6G exists – rather, there will be a gradual adoption of the new mechanisms. So, the assignment to 5G or 6G shown in the figure is not meant to be absolute.

Secure software, and secure protocol & Application Programming Interface (API) design will continue to be a cornerstone of mobile network security. The pervasive use of Artificial Intelligence (AI), the growing capturing and processing of sensitive personal data, and the threat of quantum computers breaking today's crypto algorithms call for additional security building blocks: Secure AI/Machine Learning (ML) (see Section 5.3.1 below), privacy enhancing technologies (see [HEX22-D13], section 4.1.2), and quantum-safe cryptography (see [HEX22-D13], section 4.1.4). We consider these security technologies as crucial for future 6G systems. They apply pervasively throughout the system, not only in the network service layer and the management and orchestration area, but also in RAN and optical equipment.

To secure the Network Service Layer, well-known mechanisms such as security isolation, resource isolation, application of filtering functions as well as a secure logical network topology separating different traffic types, slices and security zones will continue to be essential.

A secure Infrastructure and Cloud Layer, including RAN equipment, optical equipment, and cloud infrastructure, builds on secure hardware and firmware, and may provide crypto accelerators to support high throughput and low latency requirements. Trust foundations (see [HEX22-D13], section 4.1.1), like trusted execution environments, will grow in importance, and a more pervasive deployment and use of them is expected in 6G. On the physical layer of the radio interface, physical layer security technologies (see [HEX22-D13], section 4.1.6) may become relevant to complement cryptographic protection. To secure communication between optical equipment, quantum key distribution (see [HEX22-D13], section 4.1.4) may complement current cryptographic key agreement schemes.

Several security technology enablers have been identified as specifically relevant for the Management and Orchestration (M&O) area. They include attestation technologies (building on trust foundations), AI/ML-driven automated closed loop security mechanisms, and distributed ledger technologies. Obviously, the "classical" management security mechanisms will continue to be the foundation of security for the M&O area. For more details, see [HEX22-D13], Section 4.3, and Section 5.3.2 below.

Some further explanations on the security building blocks available today can be found in [HEX22-D13], Section 4.1.

5.2 Trustworthiness in 6G networks

Hexa-X has defined **trustworthiness** as one of the crucial KVIs for 6G networks. Trustworthiness encompasses multiple facets, such as "security, privacy, availability, resilience, compliance with ethical frameworks" [HEX21-D12]. According to [NI-1500-201], focussing on technical aspects in the context of cyber-physical systems, trustworthiness comprises security, privacy, safety, reliability, and resilience. Other sources use similar descriptions, which have in common that security and privacy are considered as crucial properties of trustworthy systems. This section focusses on how to assess security and privacy of 6G systems, and on general principles to achieve a high degree of security and privacy, thus contributing to a high degree of trustworthiness. Further, it discusses the topic of trust-awareness in 6G multi-agent systems, which includes evaluating and maintaining reputation scores for the different agents, such as service providers and service users. Finally, it describes the context of a LoT assessment function, supporting service providers and service users to specify and monitor the security and privacy posture of services and give the user assurance on the trustworthiness of a service.

5.2.1 Trustworthiness based on security and privacy

5.2.1.1 Assessing the security posture of a 6G service

From the service consumer or network user perspective, security means that users' sensitive data, including the user traffic and all user-related data available in the network, such as the location, are protected against attacks that would break the confidentiality or integrity of the data. It must be noted that confidentiality violations, and to a certain extent also integrity violations may not be recognized by users, and there is no way for the service provider to prove that such violations do not happen. In contrast, availability as the third major security property, will be recognized by users. While attacks can for sure impact the availability of a service, protection against such attacks alone cannot ensure availability, because it depends on many other factors, in particular hardware or software failures unrelated to any attack.

Consequently, with respect to all three major security properties, users cannot easily measure the degree of security of a service they are using. Similarly, more specific attacks and exploits, like fraudulent (over)charging or a user device being compromised via the network may cause damage without the users noticing them or being able to attribute them to the usage of a specific service.

However, there are criteria that users, in particular enterprise-type users, may apply to assess (or at least get a notion of) the security posture of a service provider and its IT systems and communication networks. These include:

- Historical data on service availability and quality (this covers service degradations by successful cyber-attacks), and on successful attacks and security breaches affecting the confidentiality and integrity of user data (such as location) and traffic. Such data includes individual experience of the user itself, but more importantly information gathered by third parties, including crowd-sourced information, or by the service provider itself.
- Level of security certification of the network elements involved in providing the service (e.g., [GSM22a], [CC02], [NIST19]).
- Supply chain security measures taken by the service provider – this also implies a recursive assessment of service provider's suppliers and subcontractors. There are numerous recommendations available in this area, including the NIST Special Publication 800-161, ISO 20243 and the ISO 28000 series. More technical approaches include IETF recently started Supply Chain Integrity, Transparency, and Trust (SCITT) working group [SCITT].
- Insider attack protection measures and more generally, secure operational practices. It may however be difficult to obtain tangible information on that, and available certifications schemes, such as [ISO18], may not be suited to reveal hard facts about the actual security posture in this area.
- Available reactive network security measures (like ML-based anomaly/attack detection, closed loop security management automation etc.). An issue here is that the effectiveness of such measures may be hard to assess.
- Use of attestation mechanisms, Trusted Execution Environments (TEEs) and Hardware Security Modules (HSMs) for processing and storing the most sensitive information.
- Ciphersuites, protocol versions and other cryptographic mechanisms applied in the different planes and links constituting the services.

The above criteria are mostly independent of a specific technology, like a 6G network being used to provide the service. To address specifically the wireless technology, there is a relevant criterion to be added, i.e., the inherent security posture of the wireless network technology.

To illustrate the meaning of such inherent security posture, let us consider the fact that 5G provides strong protection of subscriber identity, while 4G does not due to the possibility of International Mobile Subscriber Identity (IMSI) catching. In this respect, 5G is inherently more secure than 4G. In contrast, both 5G and 4G use the same strong crypto algorithms to protect traffic over the air, so in this respect both are equally secure.

When narrowing down the field towards the notion of the inherent security posture of 6G technology, the security of standardized 6G features, protocols, procedures, and security mechanisms prevails over the other criteria. We expect 6G will have an excellent security posture. Still, a user cannot use the 6G technology per se, but rather needs to use a concrete service implemented using 6G technology. Therefore, deployment and operational security aspects for this concrete service implementation will still be the dominant criteria.

Based on these considerations, one might be tempted to conclude that specifying additional technical 6G security features (e.g., compared to 5G) may impact the security posture of concrete 6G-based services only to a moderate degree. However, a failure to develop and specify secure 6G technology, with the consequence that attackers will be able to exploit technology vulnerabilities, has the potential to completely undermine the trustworthiness of 6G networks. Therefore, despite all the other, 6G-technology-independent factors influencing the security posture and thus the trustworthiness of 6G networks, providing secure 6G technology are crucial for the trustworthiness KVI.

5.2.1.2 Potential 6G security KPIs

To overcome the difficulty to quantify KVIs such as trustworthiness, Hexa-X has adopted the approach to identify "*a set of KPIs serving as proxies for the respective KVI*" (see D1.2 [HEX21-D12], section 5.1). In case of security, the problem with this is that security KPIs do not readily exist. For concrete deployments, security KPIs like number of prevented intrusion attempts, number of successful attacks, meantime to detect attacks, meantime to recover from attacks, downtime due to cyber-attacks etc. may be applicable. But such KPIs do not measure the security of the technology itself.

However, some 6G-technology- or 6G-standard-related security aspects might be coverable by KPIs. Examples are:

- The strength of the crypto algorithms that are specified: There are estimations on how long it would take an attacker with (loosely) defined capabilities (e.g., "nation-state attacker") to break the crypto. A specific capability of the attacker may be quantum computing, and in this sense, it matters whether specified crypto algorithms are believed to be *quantum safe*. It must be noted that such strength assessments cannot be proved and might be overturned suddenly by someone coming up with a new, clever (quantum or classical) algorithm. As standards tend to allow legacy algorithms to ensure backwards compatibility, a further aspect is to which degree the specification prevents the usage of potentially weak legacy algorithms.
- The rigor and insistence of policies related to security such as authentication and key renewing frequencies and granularity of authorisation mechanisms.
- The degree to which interfaces and services are covered by specified security mechanisms in a future 6G standard. This implies the assumption that lack of security standards leads to less secure solutions, on average.
- The existence and coverage of security assurance specifications (as part of a 6G standard), describing means to evaluate the security posture of network function implementations. It is also important that a scheme to organize such evaluations exists and is commonly used. However, such a scheme need not be specific for a technology or mobile network generation. E.g., the Global System for Mobile Communications Association (GSMA) Network Equipment Security Assurance Scheme (NESAS) scheme used today for 4G and 5G network equipment is expected to be applicable also in 6G, when the respective 6G security assurance specifications have been created.
- The existence or potential impact of known attacks against the standardized procedures and protocols. As examples we can consider IMSI catching in 4G, linkage attacks via authentication challenge replay or Subscription Concealed Identifier (SUCI) replay in 5G, jamming attacks in all generations so far.
- The existence and coverage of an ML-related assurance framework, as considered by ETSI ISG SAI [ETSI21].

Obviously, such KPIs are much more vague than "classical" KPIs such as throughput or delay. Still, we consider them useful to get an impression of the security posture of future 6G standards on technologies and architectures, and this way they can contribute to assessing the trustworthiness of future 6G networks.

5.2.1.3 Ensuring trustworthiness by preserving privacy

Obviously, privacy can only be ensured when the network or service handling sensitive date is secure against cyber-attacks, i.e., it can prevent attackers to access the data. This aspect is covered by the security considerations above. However, privacy also comprises the protection of sensitive data against the service providers themselves. Such providers necessarily need to process sensitive data (e.g., mobile network providers need to know location data of the subscribers) and privacy in this context means that service providers do not abuse sensitive user data.

It is commonly observed that much higher amounts of sensitive data may become available to 6G network providers compared to previous network generations, e.g., by the sensing features expected in 6G networks. Also, more applications and more sensitive applications are expected to rely on 6G networks. This will raise the requirements in terms of trustworthiness.

Independently of the applied network technology, a provider may abuse any sensitive data gathered when executing the service. Privacy enhancing technologies, i.e., technical measures applied to better protect the privacy, typically cannot prevent this completely. Rather, their value lies in reducing the amount of data exposed to the service provider. For example, homomorphic encryption allows to use cloud-based computation resources without the need to trust the cloud provider to keep sensitive data confidential. Overall, privacy enhancing technologies can significantly contribute to protecting users' privacy and thus contribute to the trustworthiness of the service. This way, the pervasiveness of use of privacy enhancing techniques, and the existence of standards ensuring their use can be considered as a privacy KPI, contributing to the KVI trustworthiness.

The goal to expose less information to a cloud service provider may also be achieved by the use of Trusted Execution Environments (TEEs), where users can load code into and have it executed there, protected against access by the cloud service provider. It must be noted however, that here, users still need assurance that their data is indeed processed in such an environment and not secretly leaked to an external party. For this assurance users typically have to rely on the TEE manufacturer instead of the cloud service provider, so this may not in general increase the trustworthiness as perceived by a user.

With respect to trust in privacy (of any sensitive data that must be exposed) not to be violated by the service providers themselves, mostly non-technical aspects seem to be relevant, such as the perceived overall reputation of a service provider, the perceived accuracy and fairness of the service contract, the existence of a strong jurisdiction allowing to successfully sue a service provider violating a contract, the existence of service provider regulation and control, and data and consumer protection regulations and even citizen rights, that may protect users against illegal access to data by authorities. Further assessment and the possibility to quantify such criteria is clearly outside the scope of this chapter focussing on technical measures to ensure trustworthiness.

5.2.2 Level of trust assessment function

[HEX21-D12] and [HEX22-D13] introduced the concept of the LoT, aiming to address the trustworthiness KVI. The LoT results from the process to assess the security and privacy of a network service in a particular application environment. In order to enable the security evaluation of 6G network services, following the stages and actions set out in the LoT concept, Hexa-X has created the concept of a *LoT assessment function* aiming to ensure security [HEX22-D62] for network services by utilizing a set of applicable security technologies. The LoT assessment function can provide a LoT value for infrastructure and network functions by taking into account their security and privacy properties and technologies, and potential threats and attack patterns, and can thus ensure that user intents with respect to security and privacy can be met. Note that the LoT assessment function does not aim at measuring the actual level of trust a specific (human) user may have in a service, as this is influenced by a variety of factors such as emotions and predispositions that are not in the scope of this research. Instead, it focuses on the level of trust that can be derived from the technical methods applied to provide and secure the service.

The LoT assessment function (LoTAF*)* is conceived as a neutral and bidirectional service that may be utilised by both trustors, e.g., users who intend to leverage services and resources of telecom infrastructure(s), and trustees, e.g., infrastructure and network providers. From the trustor point of view, the LoT assessment function brings an intelligent service to check how much confidence may be attributed to network services before they are instantiated and used. From the trustee perspective, the LoT assessment function may ameliorate the QoS offered by providers since they might get insight into how well a service complies with certain security requirements, share it with a user and decide if additional security measures should be taken.

The deployment of AI-enabled intelligent architecture for 6G networks strives to support tasks such as smart resource management, automatic network adjustment and intelligent service provisioning [YAX+20]. In this vein, the LoT assessment function uses intelligent mechanisms to automatically perform an internal pre-processing to match the security and privacy features announced by infrastructure and network providers, e.g., through security policies or Security Service Level Agreements (SSLAs), and the user intents. With respect to security requirements, Confidentiality, Integrity, and Availability, also known as the CIA Triad, are three fundamental pillars to be considered in information security. Yet, the security requirements are not limited to the CIA Triad since the LoT assessment function should be designed from a holistic perspective and without being associated with a specific context. Therefore, appropriate data model formats may be considered to boost the adaptability and flexibility of the LoT assessment function as well as find out generic security property sets that allow users to define what is the minimum set of security properties that an infrastructure and network function should have to be considered as a candidate. In this regard, the LoT assessment function would support users to customise services and cater for higher interaction. Likewise, privacy requirements also play a pivotal role in assessing the trustworthiness of 6G networks; therefore, properties such as integrity of traffic, personal data protection (such as user location) or access control are just a few of the requirements that users may consider for network services.

Another pre-processing step entails identifying from SSLA or security policies what kind of technologies may be leveraged to guarantee security and privacy requirements. In this sense, the LoT assessment function should discover for each requirement how available technologies, settled by infrastructure and network providers, may ensure it as well as analyse acceptable risks of utilising such technologies. The LoT assessment function should investigate attack patterns that may be linked to the technologies so that the user may later determine what combination of security properties and technologies best meets their requirements. Regarding the analysis of attack patterns on network services, AI-driven threat detection mechanisms may support the identification of cybersecurity threats or attacks, where explainability capabilities are key to comprehend the logic behind AI predictions. Likewise, the LoT assessment function may also be supported by human experts so as to compile risk and attack patterns associated to specific technologies. Hence, the analysis of attack patterns on network services intends to cover those threats and risks that may be recognised from historical data and monitoring data provided by trustworthy data repositories.

As it was mentioned in [HEX21-D12] and [HEX22-D13], complete security is not achievable, so a balance is required in terms of cost, risk, and impact. To carry out a reasonable balance, the LoT assessment function may use ML-based intelligent optimisation algorithms which allow users to declare what criteria, i.e., usability, agility, swiftness, risk and impact, and maximization or minimization functions should be used to come up with the optimal configuration of the available network services. Once the LoT assessment function has gathered information related to the user's security requirements, security- and privacy-enhancing techniques, potential technology-related threats and optimisation criteria, the function finally assesses a set of thresholds so as to categorise the trustworthiness of 6G network services and to determine the affinity of the final LoT to each threshold (e.g., untrustworthy, little trustworthy, moderately trustworthy, trustworthy, full trustworthy), ranking network services from the most trustworthy to the lowest.

After finishing all actions related to the achievable LoT assessment, the LoT assessment function may begin a second phase that is related to the achieved LoT evaluation stage. Note that these phases are totally aligned with the principal actions declared in [HEX21-D12] and [HEX22-D13] with respect to LoT. Regarding the second phase, it is mainly focused on checking that security and privacy properties previously exposed to the user are being achieved during the lifecycle of an infrastructure and network service, since new threats might have appeared and compromised prior properties. To this end, the LoT assessment function contemplates a dynamic mechanism to guarantee a continuous update of LoT. Trust is a dynamic characteristic that changes over time, and in consequence, it is necessary to collect real-time events or triggers which enable its reassessment and adaptation. Thus, the LoT assessment function considers, for meeting the intrinsic characteristic of the trust concept, the following significant objectives:

- To aggregate relevant monitoring data provided by trustworthy data repositories, results of specific measurements executed on-demand, available infrastructure and functional features, and recorded events (such as incident records or user experiences).
- To adjust the initial LoT based on compliance or non-compliance with previously declared security properties.

By means of such an updating mechanism, the LoT assessment function may be endowed with a re-assessment-based learning process which might help to determine if AI-driven models under the LoT assessment function are producing a correct answer for users' requests. Ergo, the feedback of users may be primordial to analyse whether the LoT assessment function performed a mismatch during the selection process. Last but not least, it should be noted that not all attacks may be detected based on the information collected in the trustworthy data repositories in a short term, for instance, unnoticed leaking of confidential information., The LoT assessment function carries out a reassessment of the LoT based on the detected attacks during instantiation and use stages.

To summarize, the LoT assessment function strives to guarantee security and privacy properties in 6G network services taking into account the applicable technologies to support properties as well as possible attack patterns associated to specific technologies. Similarly, the LoT assessment function also intends to ameliorate both end users and providers experiences and support to automatic network adjustment and intelligent service provisioning.

5.2.3 Trust-awareness in 6G multi-agent systems and services

While expected to deliver pervasive AI to users, 6G itself is also an intelligent system. These intelligent services, both those that are enabled by 6G and exploited by the users, and those that are integrated by 6G itself, are fundamentally data driven. To achieve trustworthy AI and trustworthy networking, 6G must guarantee the trustworthiness of data that is exchanged among the involved agents and utilized by the AI algorithms. Such agents include but are not limited to users, service providers, and network functions. Generally, there are three main classes of trust relation in 6G systems and 6G-based services:

1. A user trusting a service or the network, sharing its confidential information with the service provider to be able to use the service. It is worth remarking that the provided service can be a data service (e.g., cloud storage), an intelligent application (e.g., cloud-based speech recognition), or even the networking service itself (e.g., radio access).
2. A service or the network trusting a user, providing certain services to the user, and exploiting feedback data from the user to adapt/optimize those services.
3. A user trusting another user, exchanging information with the latter, and exploiting data shared by the latter to support its own decision making.

Independent from the trust relation class, the trustworthiness can only be established on a solid base of availability, reliability, integrity, security, privacy, and authenticity. While the essential availability and reliability can be provided by dependable transmission technologies, the integrity, security, and privacy are also supposed to be ensured by the use of the appropriate technologies and standards in 6G, as discussed in the section above. However, the authenticity of data can still be compromised despite of these measures, for instance, when fake data is maliciously injected into the system by an agent inside, or in case of an unintentional malfunction of the agent. Such injection of unauthentic data can induce destructive impacts on the intelligent services by abusing the trust among involved agents, without violating the data privacy or integrity, which raises a new type of risk.

To encounter such risk, trust-awareness shall be introduced to in 6G and 6G-based intelligent services, where an agent shall only selectively exploit the data that it receives from other agents, with respect to the assessed trustworthiness of the latter. Especially, regarding the trust between users and network services, this refers to the LoT assessment, as discussed in Section 5.2.3 For other services where no generic framework is available for centralized trust evaluation by a third party, a hybrid approach of direct and indirect trust evaluation models must be applied. More specifically, with direct trust, an agent evaluates the trustworthiness of another based on its own observations in the past; with indirect trust, a.k.a. reputation-based trust, it evaluates the trustworthiness based on observations from other agents in the same environment [YSL+13]. For example, in [HKZ+23] and Section 5.5 of [HEX23-D73], the threat of data-injection attacks is assessed in the context of emergent intelligence such as swarm systems, and a trust-awareness based solution is proposed.

It shall be noted that, to enable indirect trust evaluation, the agent-assessed trust value of users or services must be sufficiently spread and shared among the agents. Therefore, a 3rd entity/platform must be involved to record, maintain, update, and distribute the reputation score. In the context of 6G mobile networks and its ecosystem, the 6G Mobile Network Operator/ Mobile Virtual Network Operator (MNO/MVNO) is the most appropriate stakeholder to implement and operate this function, for a two-folded reason. First, the detection of trust-abusing attacks is only possible at the communicating endpoints because it essentially requires a semantic understanding of the message to distinguish the malicious data from the benevolent data, which can only take place on the representation and application layers. Therefore, the reputation-context broker needs to be globally accessible for all users and all service providers regardless the service domain, which can be challenging for any stakeholder but the MNO/MVNO. Second, the reputation evaluation service itself, as the source of trust, requires the involved agents to trust the reputation data, which may create a dilemma unless the service is provided by the MNO/MVNO, which is always trustworthy to a certain degree for all users and service providers that are connected through the 6G network.

Moreover, for a universal assessment and maintenance of reputation for all agents in a 6G system across different applications and use cases, it requires a heavy load of data acquisition, fusion, analysis, exchange, and synchronization. To address this challenge, the Digital Twin (DT) technologies exhibit a good potential, as discussed in Section 5.5 of [HEX23-D73].

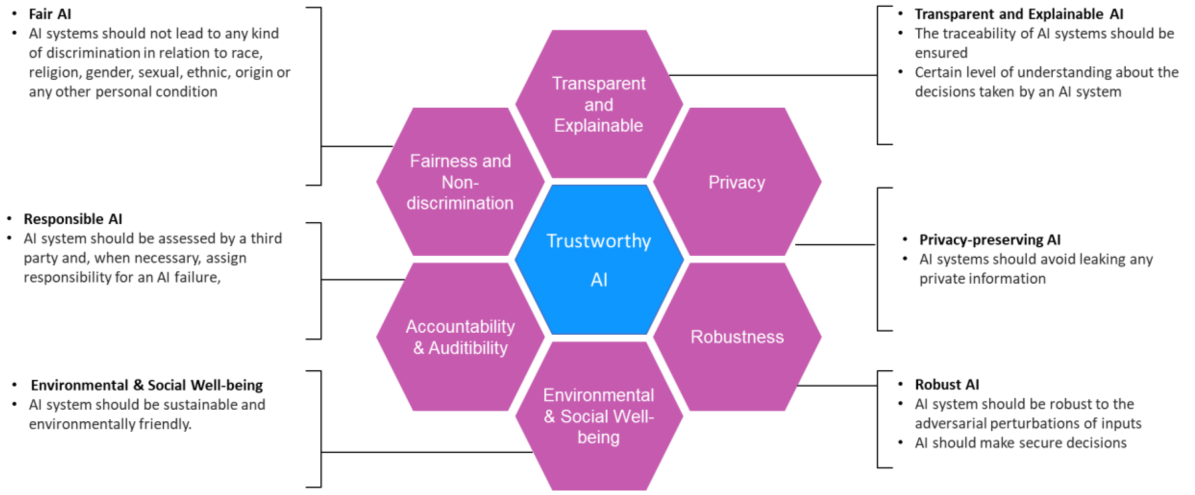
5.3 Security consideration for 6G technologies

When new technologies are taken into use, potential security and privacy issues must be considered, i.e., potential threats must be identified, and suitable protection concepts must be investigated. Among the most notable, we can consider the pervasive use of AI/ML and the implications for M&O functionalities, as covered by the work in Hexa-X WP4 and WP6, respectively. Other aspects, connected with the work in other project work packages, have been also considered and the results are briefly discussed in this section as well.

5.3.1 Trustworthy AI/ML for 6G

The development of AI strives to advance society and assist people by tackling challenging problems. Although AI plays an important role in diverse domains and use cases, it may inadvertently hurt people by, for instance, making judgements that are inaccurate in security-sensitive situations or leaking private information of the users. As a result, trustworthy AI has lately received wide attention from the research community due to the need to minimize the negative effects that AI may have on people [LWF+21].

The topic of trustworthy AI is broad and intricate, and studies related to trustworthy AI can be arranged into six categories as depicted in the figure below.



- **Fair AI**
- AI systems should not lead to any kind of discrimination in relation to race, religion, gender, sexual, ethnic, origin or any other personal condition

- **Responsible AI**
- AI system should be assessed by a third party and, when necessary, assign responsibility for an AI failure,

- **Environmental & Social Well-being**
- AI system should be sustainable and environmentally friendly.

- **Transparent and Explainable AI**
- The traceability of AI systems should be ensured
- Certain level of understanding about the decisions taken by an AI system

- **Privacy-preserving AI**
- AI systems should avoid leaking any private information

- **Robust AI**
- AI system should be robust to the adversarial perturbations of inputs
- AI should make secure decisions

Figure 5-2: Trustworthy AI main categories.

To begin with, trustworthy AI is anticipated to possess the qualities of robustness and explainability. In robustness terms, we should guarantee that the decisions of the AI model should not change in the presence of a malicious attempt where tiny modifications are introduced to the input data by an adversary. And from an explainability perspective, human-understandable explanation of decisions must be possible for trustworthy AI in order to reduce risks and possible damage. When used in critical applications such as communication and security services, the decisions of AI models cannot be taken for granted until the underlying mechanisms driving their predictions are fully explained. As a result, developing a trustworthy AI system requires an insight into how specific decisions are made.

In addition to robustness and explainability, trustworthy AI should have the properties of privacy, availability, and safety. In privacy terms, AI is expected to safeguard the privacy of all users and should not leak any private information. Besides privacy, it is expected that people should have access to AI systems whenever they need them, and these AI-driven systems should be simple to be used for diverse users. Furthermore, no AI system is ever intended to harm anyone, under any circumstances, and it is always expected that user safety is a top priority.

Finally, trustworthy AI should be fair, ethical, and environmentally sustainable. In particular, AI-driven systems should function in complete accordance with all applicable rules and regulations as well as ethical standards. Trustworthy AI should ensure fairness for all users and should not discriminate against certain groups. From a sustainability perspective, AI-driven systems should be environmentally friendly to ensure sustainable development. They should, for instance, consume less energy and produce less pollution.

We should expect future communication networks to comply with all the above requirements as AI is being expected to be one of the key enablers of 6G networks. Deep learning models are already emerging as a helpful tool for assisting with various communication tasks in different network layers. To give some examples, in mobile networks, AI/ML has been utilized to solve a variety of challenges such as encoding/decoding operations, power-allocation/Radio Unit (RU) selection/beamforming for Massive Input Massive Output (MIMO) systems, spectrum sensing, Radio Frequency (RF) signal classification, signal authentication, and anti-jamming. In the core network, AI/ML is used in Network Data Analytics Function (NWDAF) for network data analytics function. In the M&O stack, AI/ML is being used for resource management, fault management, and so on. Besides all these, we anticipate AI/ML to be a powerful catalyst for security-related functions in 6G networks.

To ensure the trustworthiness of future 6G networks, we should identify all possible AI-driven communication tasks and use cases. Then, we need to assess any potential weaknesses in these AI systems by taking into consideration the main pillars of trustworthy AI. And we should focus our efforts on ensuring the required degree of quality for each of the crucial dimensions of trustworthy AI by considering all the requirements.

Trying to cope with security threats in next generation telecommunication systems is becoming increasingly difficult due to the growing nature of cyber-security threat landscape and the increase in the complexity of these threats. The requirements from 6G, the immense volumes of data that will be resulted by the expected 6G use cases and new networking concepts will pave the wave for the usage of advanced deep learning-based AI architectures. And it is expected that these deep learning-based AI architectures will play a significant role for the security-related functions within 6G network as well. However, the applications of AI in the field of cyber security are also encountering difficulties as a result of the shortcomings of the AI-based methodologies [ZHD+22].

When incorporating AI models into the field of security, we should pay closer attention to one of these shortcomings, which is the black-box characteristics of these models. Due to the black-box nature of AI models, it is challenging for security professionals to comprehend how cybersecurity-related decisions are made by AI-based models because these conclusions lack justification and reason. It is expected that AI will be intensively used for advanced security analytics, incident/threat detection and prediction. If explainability capabilities are introduced to the AI-driven security mechanisms, then for example, zero-touch network management systems can have a chance to understand the underlying logic behind AI predictions which in turn can help them to provide accurate and adaptive responses to the security threats.

Another important drawback of AI-driven systems is adversarial attacks. AI/ML models have recently been discovered to be vulnerable to malicious attacks. In fact, very small and often undetectable changes in data samples are enough to fool state-of-the-art classifiers in inference time and lead to incorrect predictions. In the past few years, we have witnessed extensive research which shows the vulnerability of AI-driven systems in different domains like image, text, and audio. And despite the distributed nature of communication domain and the heterogeneity of the network, we still have the risk of adversarial attack in a telco environment. However, from the adversary perspective, there are several important constraints which limit the success of the adversarial attack in a mobile network. Firstly, the adversary mostly does not have access to the details (architecture and weights) of the original AI model, therefore cannot use it in a whitebox setting for crafting adversarial samples. Secondly, the adversary may not have complete knowledge of the input features of the AI model. Lastly, in a practical scenario, the adversary does not have the capability to introduce perturbations to all features of the input sample. However, despite all these limitations, there are proven ways in literature which increase the success of the attacker. Regarding the first limitation, it has been shown that a surrogate AI model might be sufficient to launch an effective attack due to the transferability nature of the adversarial samples [PMG+17]. Regarding the other limitation, the Universal Adversarial Perturbation (UAP) method [MFF+17] is proposed for cases where the complete input knowledge is not available. For instance: recent research studies [TEK23] indicate that the performance of an AI-driven Distributed Massive Input Massive Output (D-MIMO) system can be ruined by malicious User Equipments (UEs) or RUs which provide adversarial perturbations to the pilot signals. The results indicate that adversarial attacks with optimized perturbations can degrade the performance of the network in terms of both spectral and energy efficiency. Thus, smart defence techniques and mechanisms for assessing data provenance, as mentioned in Section 5.2.3 above, are required to overcome the effects of such attack threats.

One other important aspect to consider is the privacy-related threats associated with the utilization of AI/ML in communication networks. AI-driven systems are powered by massive amounts of data and most of the time, this data contains private information of users, service owners and infrastructure providers. And, it has been shown that AI models may potentially leak private information. There have been proven attack scenarios where an intruder can exploit the vulnerabilities in the target system for retrieving private information about user data and even extract the deployed model [TZJ+16]. Thus, it is important to pre-process the data used to train AI models and implement strong privacy and security measures to prevent unauthorized access to the models and their output. One of the best practices to protect the privacy of users which contribute to the training of AI-driven system is to employ privacy-enhanced collaborative learning strategies such as Federated Learning (FL) [MMR+17] which hides the private information of clients from the central server. Additional countermeasures such as differential privacy [WLD+20] can be employed in the FL algorithm by adding a small amount of noise to the updates coming from clients to the server. Also, these updates might be further protected from eavesdroppers by means of appropriate encryption methods.

5.3.2 Management and orchestration security aspects

Security aspects relative to M&O are detailed in Hexa-X D6.2 [HEX22-D62]. The overall structural view proposed in this deliverable is reproduced in Figure 5-3 below.

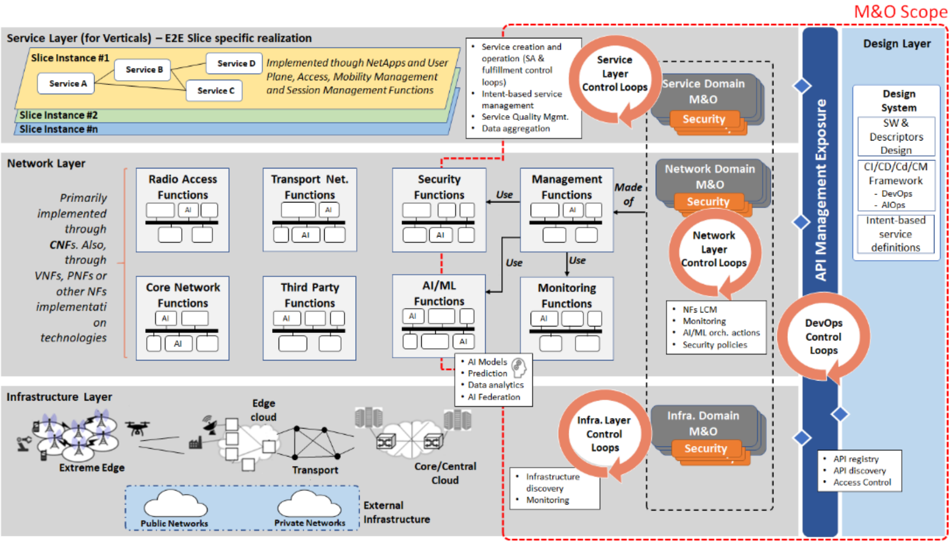


Figure 5-3: Hexa-X D6.2 structural view.

This figure depicts the 6G system as logically separated into three different layers: Infrastructure, Network and Services. To match this logical separation, specialized M&O orchestrators are present at each level. Within a given layer, several layers of M&O may exist. Each M&O is responsible for providing adequate services to the upper layer while consuming the resources offered by the lower layers. On the top, M&O of the service layer are responsible for maintaining the communication and slice services. M&O themselves are made of specialized network functions from the network layer, management functions, that can use the services of other specialized network functions such as monitoring functions or AI/ML functions to perform their tasks. Data-driven and AI/ML, in particular, are expected to bring additional functionalities to M&O such as automation, predictive orchestration, self-optimization or intent-based management. In the specific context of 6G, the M&O system does not only consider traditional core and edge resources, but also extreme edge ones, as well as resources provided by 3rd. In this context, one important challenge is to provide continuum orchestration from end to end, over multiple administrative domains owned by different stakeholders. Additionally, M&O is expected to follow cloud-native principles. The different network functions that compose and support the M&O system are primarily implemented through Cloud-native Network Functions (CNFs), although legacy or future type of implementation are also possible. A subset of monitoring functions can be dedicated to handle M&O security-related aspects. Those specialized M&Os are represented in orange in Figure 5-3 above. Just as generic M&O, the security M&O can rely on specialized network functions, such as security functions or AI/ML functions. In the remainder of this section, we will focus on greater details in the role and structure of the security M&Os.

As upper layers may request security guarantees for the service, each M&O can offload the handling of those requirements to a dedicated security M&O. Within its domain, a security M&O takes any necessary action to ensure that the services provided meet the security requirements regarding confidentiality, integrity, and availability. Following the cybersecurity framework guideline, it means that the security M&O performs the following actions:

- **Identify** the different assets under its supervision, the threats that weigh upon them, and the adequate security measures to apply.
- **Protect** those assets by deploying adequate security elements.
- **Detect** attack and attack attempts on those assets.
- **Respond** to those attacks by adapting the security measures.
- **Recover** from the attack if need be.

The nature of the assets to be defended depends on the nature of the security orchestrators, and may consist in slices, network services or pieces of infrastructure.

Identifying assets and applying the first set of security measures can be done before the service is deployed, typically by experts possibly assisted by dedicated tools. On the other hand, detection, response, and recovering of an attack should be done as fast as possible, to reduce the potential damages inflicted to the targeted service. In 6G, it means that those steps would be as automated as possible. Consequently, the security M&Os proposed architecture are automated closed loops made of monitoring, analysis, decision, and execution functions. While this is detailed in [HEX22-D62] Section 6.2.2, we can here briefly give some examples of how these functions can work. Monitoring typically includes direct observation of the raw traffic going through the network but can also retrieve data form a variety of sources, such as network functions log, network KPIs or other security orchestrators. The analysis may concatenate monitoring data and deduce if an attack is occurring in the network. If the situation cannot be evaluated with enough certainty, additional monitoring or tests may be required. The analysis engine complexity may range from very simple, acknowledging a signature-based detection from monitoring, to very complex, leveraging AI/ML techniques to assert Distributed Denial of Service (DDoS) attack for example. When an attack is characterized, the decision engine can take define an action plan to respond to the attack. This decision engine may typically be made of an expert system. The action plan is then executed by a dedicated module.

It should be noted that on each logical layer of the system (infrastructure, network, and services) there may be more than one layer of M&O orchestrators (and hence, security orchestrators), depending on the needs. For example, within the network layer, local orchestrators may be used to manage local services, such as (extreme) edge services, while being under the supervision of a global security orchestrator, located in a more central place. Security-wise, this organization is very important in 6G. Among other improvements, 6G is expected to run services on (extreme) edge premises. Those premises will typically be geographically distributed and have limited resources. Nonetheless, the services running over them may be crucial, and their disruption for any reason may cause important damages. For this reason, security has to be enforced efficiently even in those remote locations. However, running a standalone security orchestrator, involving resource intensive operations such as AI/ML training or extensive data analysis, may consume all the resources of the (extreme) edge premise. In a simple scenario, the security can then be divided into two security orchestrators. A local security orchestrator is in charge of gathering local monitoring, performing simple detection and analysis, and fast containment action, in order to temporarily stop the attack. At the same time, a central security orchestrator gathers the data coming from multiple local orchestrators (and possibly other sources). This data may include the analyses performed locally, but also the raw monitoring data, or the details of the containment plans, if need be. Based on those aggregated data, the central security orchestrator may then perform remediation actions to fully eradicate the attack and the root vulnerabilities.

In order to connect the different components of each individual orchestrator, and to interconnect orchestrators together into federation, the European Telecommunications Standards Institute Zero-Touch Service Management (ETSI ZSM) architectural framework [ETSI19] appears to be a promising solution. This framework is first described in [HEX21-D61], and its relevance to Hexa-X WP6 architecture is detailed in [HEX22-D62]. In particular, the ETSI framework covers aspects related to the security of interactions between entities ([ETSI21], [ETSI21a]-Draft), and cross domain connections [ETSI19].

The security M&Os of the different layers are recursive, a level N security orchestrator being able to gather information from any module of a layer N-1 security orchestrator, and in return sending orders to this N-1 security orchestrator. To monitor and analyze potential attacks, the security orchestrator may rely on monitoring data collected on the running service, data collected from layer N-1 security orchestrators, information issued by layer N+1 orchestrators, or other sources (e.g.: human input). To act upon the detection of an attack the security orchestrator may apply configuration changes to a running service (this action should be delegated to the security orchestrator in charge of this service, if different from the current one, to avoid conflicting actions), apply lifecycle management actions to a service, or escalate the problem to another entity (typically either layer N+1 security orchestrator, that may have extended rights, or a human administrator). This exchange of information between a security orchestrator and other entities is described in greater details in [HEX22-D62] Section 7.2.4.3.

5.3.3 Other security considerations for 6G technologies

While the aspects related to E2E architecture (corresponding to Hexa-X WP1), the application of AI (dealt with in Hexa-X WP4), the M&O stack (focus of Hexa-X WP6) and new services (within Hexa-X WP7) have already been discussed in the previous sections, the security considerations have been extended to the other technical activities within the project, and this section provides the most relevant results and references related to them.

D-MIMO as discussed in [HEX23-D23] may require enhancement of security procedures to allow user equipment to establish and maintain multiple security associations to multiple access points in the network. Further, more complex, and diverse fronthaul networks will be required, which may be more physically exposed to attackers and therefore need sound security concepts. Some more discussion of these aspects can be found in [HEX23-D23], Section 2.3.2.

6G localization and sensing was investigated in Hexa-X WP3, with [HEX23-D33] capturing the final results. Various use cases as described in this project make it imperative to ensure security and privacy for localization and sensing. The security technologies envisioned for 6G, such as secure AI/ML, quantum-safe cryptography and privacy enhancing technologies, are fully applicable to the processing, transport and storage of captured localization and sensing data. However, threats on the physical layer, i.e., attacks against the physical layer signals used for localisation and sensing, are not covered by this work, and require dedicated investigation and suitable protection measures. This was not in the focus of the work in this project, but some more considerations on this can be found in Section 3.3 of [HEX23-D33].

The considerations on architecture evolution made by Hexa-X WP5 and reported in Sections 5.1 and 5.2 of [HEX22-D52] advocate for taking full advantage of network virtualization, considering network function placement across the current network segment borders, according to the required service levels and the characteristics of the infrastructure, in an integral edge cloud continuum. Apart from the requirements on attestation and trusted execution already discussed in Section 7.2.1, this trend requires a specific evaluation of *functional isolation*. This would guarantee that the use of shared infrastructures across network segments does not jeopardize service levels and data protection obligations by facilitating layering violations. This isolation can be achieved by means of appropriate containment techniques on the virtualized computing infrastructure, whether based on virtual machines or other virtual containers, and by applying isolation techniques to the infrastructural connectivity mechanisms used to compose the network functions. There are proposals on isolation indicators [CO21] suitable to be applied as part of a trustworthiness assessment process in these cases.

6 Spectrum evolution aspects

In this section, spectrum evolution aspects relevant to extending spectrum utilisation in frequency ranges already in use (i.e., low, mid, and mm-wave) and in new potential frequency ranges (e.g., 7-24 GHz with special focus in 7-15 GHz in the centimetric range and 92-275 GHz in the sub-THz range [CEPT23], [GSM23] to address 6G service requirements are considered. It is important to highlight that within the 7-24 GHz range, the lower part of this range, i.e., up to 15 GHz, offers the best conditions due to its resemblance to current 5G mid-bands in terms of characteristics, i.e., multi-path propagation, building penetration. The section also addresses aspects concerning innovative concepts of flexible spectrum usage and management.

6.1 Extending spectrum utilisation

Possible technical enhancements to further optimise spectrum utilization concerning 3GPP technologies have been introduced in [HEX21-D12] and [HEX22-D13]. Techniques such as distributed cell deployments (i.e., cell-free/Distributed Massive Input Massive Output (D-MIMO)) can improve the use of available spectrum in the different International Mobile Telecommunications (IMT) frequency bands by enhancing spatial spectrum resource management. Considerations regarding the update and integration of elements are introduced below, based on the extensive technical studies carried out and the latest results available in Hexa-X project.

6.1.1 Distributed MIMO and advanced carrier aggregation

As described in [HEX21-D12] and [HEX21-D12], D-MIMO cell deployment (i.e., cell-free deployments) consists in a set of nodes acting as one cell-free network, improving the use of available spectrum in the different IMT frequency bands by enhancing spatial spectrum resource management. This is achieved by a novel combination of distributed antenna and transport solutions, which can increase the network spectral efficiency through central coordination.

Accurate 6G localization and sensing capabilities are expected to be enablers for enhanced techniques for flexible spectrum usage and management which could take the form of: (i) dynamic spectrum allocation schemes and automated licensing concepts for novel radio cell topologies, such as moving cells, cell-less concepts, and local cells covering moving objects or groups of objects, such as vehicles, ships, and drones; (ii) underlay spectrum usage schemes for very low range radio links; and (iii) automated interference and co-channel interference management with possible application of AI/ML concepts.

For localization and sensing, the main requirement is resolution, i.e., the ability to separate multipath based on the relative delays, angles, or Dopplers. To enable a high delay resolution, a large and phase-coherent bandwidth is needed. For example, when User Equipments (UEs)/passive objects are within 1 m of a device to be positioned, at least 300 MHz of bandwidth are needed. When UEs/passive objects are within 10 cm, at least 3 GHz of bandwidth are needed. This dependence on large phase-coherent bandwidth, limits the number of potential frequency bands where accurate positioning and sensing is possible. Carrier aggregation can be used to help make such large bandwidth available by stitching together smaller sub-bands that are not necessarily contiguous. However, while these smaller sub-bands do not need to be contiguous, having large gaps may lead to performance degradation due to the resulting ambiguities (e.g., an object may be visible at different distances, as seen by a receiver). As a matter of fact, in order for the resulting aggregated band to be phase-coherent, each sub-band must have a known and fixed phase relation to each other sub-band, during the transmission and reception time.

In addition to bandwidth, resolution can also be obtained in the spatial domain, through either large arrays or distributed cell deployments. In particular, the high potential of positioning in distributed MIMO for radio sensing and mapping derives from spatial diversity exploitation that can mitigate spatial blocking of the sensing signals. Multiple Transmission and Reception Points (Multi-TRP) sensing signal transmissions can also help to improve the sensing Signal Noise Ratio (SNR) in cases of transmit power limitations.

Accurate spatial resolution in D-MIMO is only possible if TRPs are phase coherent. This allows using carrier phase positioning in conjunction with delay-based positioning, while limiting its applicability to sub-10 GHz carrier frequencies to ensure phase coherency. Due to large overall aperture, UEs and passive objects lie in the near field of the entire D-MIMO system. This could be beneficial for positioning and sensing applications since wavefront curvature and wide aperture can be exploited as additional features to improve angular resolution and sensing accuracy.

At mm-wave and sub-THz ranges, the improved angular resolution is not available, but spatial diversity and high SNR still brings important benefits for localization and sensing. In any case, there are no special spectrum requirements for D-MIMO.

Fine positioning and sensing also require efficient spectrum usage where it comes to small/local area networks. This in turn demands for coordination mechanisms, e.g., 6G Network in Network (NiN) concepts introduced in [HEX22-D13]. In this context, limits and requirements for local spectrum usage need to be assessed first in order to subsequently develop suitable coordination mechanisms. For instance, when considering the potential use of THz spectrum for sensing, if there is no base-station coverage using that spectrum, other approaches need to be studied and implemented, such as NiN for interference-controlled operation and underlay sensing network approaches to potentially ensure service continuity, in particular at mm-wave and sub-THz bands.

Finally, for services and network applications, e.g., new flexible spectrum usage and management applications, which require high availability, the aforementioned spectrum will need to be available locally, in sufficient quantity and with a guaranteed periodicity (e.g., 3 GHz every 20 ms, for a duration of 1 ms). Designing systems that may be able to reuse communication data for localization and sensing would reduce the requirements on dedicated spectrum. One important aspect regarding coordination and online spectrum resource allocation is how mm-wave and sub-THz spectrum can be used by devices/network nodes for sensing, if there is no base-station coverage on that frequency band. Underlay network approaches operating at lower bands, would have a potential to ensure service continuity, in particular for controlling and coordinating spectrum at mm-wave and sub-THz bands. This would be important for e.g., interference coordination in 6G integrated radars in automotive applications.

6.1.2 6G NiN for interface-controlled operation in shared spectrum scenarios

6G Networks in Network (NiN) have been introduced in [HEX22-D13] and further developed in the following as prospective solutions that can allow interference-controlled operation in scenarios where one or several subnetworks are deployed in a larger, often wide-area network, using the same wide area network spectrum.

Subnetworks can be associated with vehicles, drones, machines, ships, trains, body area networks, or robots, but also be established by any coordinated moving group of sensors, e.g., a fleet of vehicles or drones. Subnetworks can be mobile, which implies frequent variations of distances between macro-network nodes (base stations) and subnetworks. The 6G NiN concepts comprise Intra-subnetwork (Intra-X), Inter-subnetwork (X2X), and Subnetwork-to-wide-area network (X2I) connectivity. While

X2I connectivity often relies on standard cellular links from a particular subnetwork node to the infrastructure, in the cases of Intra-X and X2X connectivity there is considerable work ahead if these are to be included in cellular specifications (e.g., they show similarities with Device to device (D2D) links but are not equivalent). In addition to technical and implementation issues (e.g., Intra-X radio resource management, Inter-X-aware interference-aware scheduling, etc.), certain NiN concepts may be relevant to the regulatory domain.

More specifically, a combination of Intra-X radio resource management and Inter-X interference-aware scheduling, both controlled by the wide area network, is required to address interference issues between subnetworks for avoiding undue capacity losses. On the other hand, the maximum overall interference level between subnetworks and wide-area networks will also require careful coordination with respect to both channel capacity and regulatory aspects. For the latter issue, additional regulation, sometimes even safety relevant, could be needed for Intra-X connectivity (e.g., to completely shut off Intra-X links in case of interference) and might for example result in a requirement that radio resource management is performed internally within the subnetworks as well. A possible example of this scenario is when the radio leakage of Intra-X connectivity in a dense deployment of machines and autonomous vehicles aggregates to such a high level that it disturbs the wide-area network connections for autonomous driving of the vehicles.

An example of such 6G NiN scenario has been introduced by [HEX22-D72] in the context of a smart factory environment, where the three types of 6G NiN connectivity, i.e., Intra-X links, X2X links, and X2I links coexist, resulting in quite a challenging, potentially highly interfered, radio scenario. Moreover, the radio scenario can be even significantly dynamic in long term, due to industrial demands such like flexible manufacturing. In such a scenario, the Intra-X links are expected to carry low-cost, low-data-rate, but ultra-reliable communications within a very-low-range underlay network, which contains a static set of communication devices and exhibits deterministic radio patterns usually known by the network. The devices are usually integrated by the machine manufacturers and therefore are supposed to contain no Subscriber Identity Module (SIM). Very commonly, Intra-X subnetworks have a star architecture where one specific device is responsible for coordinating the data exchanges. The coordinating device is also responsible for communicating with the other subnetworks (X2X) and the overlaying network (X2I). X2X links generally work over an intermediate range and dynamically adapt to the mobility of subnetworks (e.g., products, vehicles, machines). Their traffic patterns are mostly unknown but generally polycyclic and require a high degree of flexibility to allow redesigning the smart factory environment. X2I links contain various unknown and complex patterns and are generally required to cover the entire factory.

Aiming at minimizing interference in such a challenging radio scenario where all three kinds of links coexist, dynamic and intelligent spectrum sharing is carried out on different levels of the NiN architecture, by means of adapting the links in real time. Similar to the case of generic link adaptation in mobile networks, the degrees of freedom in 6G NiN link adaptation include time, frequency, Modulation and Coding Schemes (MCS), and transmission power. However, new challenges are brought to this task in various perspectives. First, since the design and implementation of Intra-X communication subnetworks are under the full control of machine manufacturers, they can apply different high-layer standards with protocols incompatible with each other regarding timing constraints, making an Inter-subnetwork negotiation of Intra-X traffic impossible. Second, unlike traditional Industrial Internet of Things (IIoT) solutions that rely on unlicensed spectrum (e.g., WiFi/Bluetooth/ Ultra-Wideband (UWB)) or specific D2D spectrum (e.g., sidelink channels), 6G NiN networks may use the same spectrum used by the wide-area network, which may cause concerns of the wide-area network operator, since interference occurs not only between Intra-X links in different subnetworks and between

Intra-X and the X2I links, but also between Intra-X links and external wide-area network links. This issue can be especially critical when the overlaying network and the NiN are not operated by the same stakeholder, i.e., when the overlaying 6G wide-area network is public. It is noted that in these cases mobile network operators use licensed spectrum and its protection is enforced by regulation, i.e., any guard bands between local assignments and adjacent nationwide assignments must be implemented by the local assignment holders. Nationwide assignment holders are not required to implement a guard band between their usages and adjacent usages (see e.g., [Bund21]. Third, as a novel deployment solution, NiN is lacking a framework to support centralized or coordinated spectrum management among different sub-networks. In fact, due to various reasons, such as subnetwork mobility, dynamic deployment, and operational cost, it can be extremely hard to aggregate and update the whole real-time spectral information from all underlaying subnetworks in a 6G NiN, making the option of centralized spectrum management practically impossible.

To address these issues, Hexa-X is proposing a multi-level scheme for dynamic spectrum allocation for 6G NiN scenario (see [HEX22-D72] for a more detailed description).

- On the macro level, a centralized dynamic spectrum licensing mechanism should be implemented, where the spectral context information, including the channel gains, the geolocational noise and interference conditions, as well as the underlay network deployment scenario, should be sensed by both the macro network access points and the underlay networks. Such information would be periodically aggregated at the macro network, where a dynamic spectrum licensing algorithm is executed to flexibly allocate the 6G spectrum resources to the overlay macro network as well as different underlaying subnetworks. This would allow the reduction of the long-term average interference (over multiple periods of information aggregation and licensing adaptation), especially between Intra-X links and X2X/X2I links. The length of such a licensing period would depend on the mobility level of underlaying subnetworks and might vary between minutes to hours.
- On the micro level, due to the very-low-range and low-data-rate characteristic of the traffic, for the Intra-X communication that is designed by the machine manufacturers, a Spread Spectrum (SS) and Time Division Multiple Access (TDMA) transmission scheme is suggested instead of Orthogonal Frequency-Division Multiple Access (OFDMA). The SS is a cost-efficient approach capable of increasing the effective Signal to Interference and Noise Ratio (SINR) while limiting its own interference to neighbour network/subnetworks without any frequency-specific interference information. Furthermore, regarding the interference from other Intra-X networks nearby, a wideband spectral sensing is combined with Machine Learning (ML)-driven pattern recognition and prediction of polycyclic interference, so that a time-domain predictive scheduling of the Intra-X traffic can be realized as a cost-efficient solution of real-time interference mitigation.

6.1.3 Use of artificial intelligence/machine learning

AI/ML-based techniques applications have extensively been considered in Hexa-X. Some of them are considered below highlighting specifically how they can enable improvements in the efficiency of spectrum utilisation.

One example of such techniques is provided in [HEX22-D42] Section 2.1.3.2, where an AI/ML empowered receiver is employed for Power Amplifier [PA] non-linearity compensation.

An extended performance evaluation has been carried out (see [HEX22-D42] Section 2.1.4) which quantifies the performance gain of this proposed AI-enabled receiver in comparison with the legacy method in terms of throughput and spectral efficiency. The simulation results (as shown in the figure below) confirm that 17% spectral efficiency improvement can be achieved using AI methods (using neural network at receiver) for modulation orders up to 64QAM in mid-band spectrum (3.5 GHz carrier frequency, 10 MHz bandwidth).

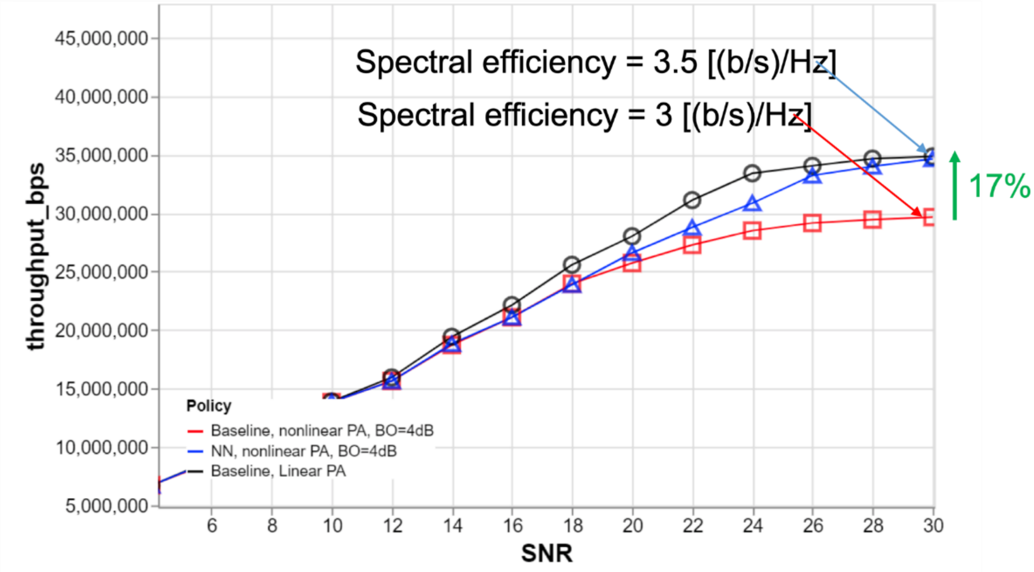


Figure 6-1: Spectral efficiency improvement using AI methods.

AI-enabled techniques can also be used to facilitate spectrum sharing scenarios for non-wide area networks, where data bases are used to assign spectrum resources to multiple users e.g., with different spectrum usage and access rights in the context of NiNs, as studied in Hexa-X WP7.

6.1.4 Spectrum (and computing) resources dynamic orchestration in edge cloud server offloading

Future wireless networks will host more and more computing resources able to provide on services on demand (e.g., control applications and in-network intelligence). In such scenarios, different services with heterogeneous requirements will have to share the same resources in terms of spectrum, but also computing pools.

Among possible spectrum sharing scenarios, a scenario where computation offloading services share the same spectrum (and computing) resources has been studied in Hexa-X, especially in WP7 [HEX23-D73], where detailed explanation of the proposed scenario, features, and method are presented. In particular, the proposed scenario two systems are envisaged to share the same spectrum, i.e.:

- System 1: a UE uploading data to an edge cloud server, e.g., to upload data (such as contextual data for remote control), with target packet error rate, within a predefined threshold on the E2E delay, with the latter including communication and computation time.
- System 2: a UE uploading data to the same edge cloud server through another access point, and opportunistically using the same spectrum as System 1 to maximise its data offloading rate under E2E delay constraints (entailing communication computing), while guaranteeing System 1 to attain the desired performance requirements (Packet Error Rate (PER), and delay).

Both systems share the same edge cloud server, whose requirement is to consume less power than a predefined threshold. Wireless and computing resources are dynamically orchestrated to guarantee this power constraint, as well as system 1 and system 2 service requirements, which are different from each other, as explained above.

The described scenario calls for to an interference-aware joint allocation of radio and computing resources. A method has been proposed in [HEX23-D73] to dynamically identify the bottleneck of system 1 data offloading rate (i.e., number of tasks offloaded per unit time): is it the edge server power consumption, or the interference level necessary to guarantee system 1 requirements? This question is autonomously answered by the method via learning and adaptation of the best resource-allocation strategy and allows for full spectrum sharing between two systems with diverse applications and requirements, which also share computing resources. Results show that an acceptable trade-off between system 2 performance (data offloading rate and E2E delay), system 1 requirements (PER and E2E delay), and edge server power consumption is possible, and autonomously identified through an adaptive algorithm that requires low complexity solutions of a per-slot deterministic problem, even though the original problem is defined as a long-term optimization. The feature required for this optimisation is a cooperation between the two systems, although distributed solutions can be envisioned to reduce the overhead to exchange the necessary information (see [HEX23-D73] for more specific implementation aspects, e.g., regarding coordination system architecture). Finally, scaling the solution to a multiple (more than 2) systems scenario would require other considerations on complexity and heuristic solutions for the per-slot problem to keep low complexity. The last two considerations, although their importance, go beyond the scope of this studies and are left for future investigations.

6.1.5 Digital twin-based human presence model for flexible and dynamic spectrum management at high frequencies (mmWave, sub-THz, and above)

A radio-aware digital twin concept where the Digital Twin (DT) has also knowledge of the radio environment has been introduced in [HEX23-D73]. This extra knowledge can be used to greatly improve the network Key performance Indicators (KPIs) and Key value indicators (KVIs) with techniques like predictive Radio Resource Management (RRM). The DT needs to have up to date information of the radio environment which it can get by combining information from classical DT (3D map with location of the objects) and radio environment sensing (pilots, radio measurements, positioning, sensing, radar/lidar). The higher the radio frequency, the smaller objects matter from propagation point of view. Especially on higher frequencies (mmWave, sub-THz, THz) we must also take into account the presence of humans (e.g., workers on factory floor or warehouse). The measurements [HEX23-D73] show clearly that human body and body parts can have big impact in radio propagation (blockage). From spectrum point of view, it is assumed that the 6G radio network consists of one or more subnetworks, each operating in its own specific frequency bands. The modelling of the impact of human presence on industrial deployment of digital twins has been studied and it has been concluded that at these frequencies having extremely dynamic and agile spectrum management is essential for DT with presence of humans (and other kind of “uncontrolled” objects). This is most critical for Ultra-Reliable and Low Latency Communications (URLLC) type of service which require simultaneously very high reliability and low latency. The link conditions might deteriorate very rapidly and the connection needs lots of redundancy and diversity in frequency and spatial domain. For example, the narrow beam might get blocked by a human body or human hand. In all these examples, as said, predictive RRM represents an effective means to improve the network KPIs and KVIs.

6.2 Initiatives to enable new spectrum for mobile/IMT: an overview

The issue of adding new bands to the existing mid and high bands to further improve the Beyond 5G (B5G) and 6G spectrum framework has been described in [HEX21-D12] and [HEX22-D13]. An update of the different positions and options under consideration concerning the allocation of new frequency bands and identification to IMT is provided below.

In addition to the 6.425-7.125 GHz frequency band (i.e., the upper 6 GHz band) which will possibly be allocated and identified for IMT in Europe (and whole Region 1) at WRC-23 in November 2023, other frequency bands are also of relevance to 6G, for example the range 7.125-15.35 GHz and some bands in the 92-275 GHz range (sub-THz spectrum). More specific frequency bands/ranges could enter the scope of WRC-27 for possible mobile allocation/IMT identification.

Two new frequency ranges have been proposed so far for discussion at WRC-23 and possible allocation/IMT identification at WRC-27 to support future IMT (IMT-2030) developments, i.e., 7.125-15.35 GHz and 92-275 GHz. The 7.125-15.35 GHz range is particularly considered as the new essential range for 6G, while the latter one is considered complementary, serving niche 6G scenarios.

On the range 7.125-15.35 GHz, further assessment is necessary to determine sharing possibilities of IMT with other radiocommunication services allocated on a primary basis. In general, narrowing down the options to more appropriate and viable bands or ranges would help increase possible support.

On the range 92-275 GHz range, there are existing allocations to the mobile service within the range and this would need consideration. Similarly, narrowing down the options to more appropriate and viable bands or ranges would help increase possible support.

Concerning the technical feasibility of IMT bands above 100 GHz, and future technology trends with reference to spectrum, studies are ongoing in International Telecommunication Union – Radiocommunication Sector (ITU-R) on the technical feasibility of IMT in bands above 100 GHz for the development of IMT for 2030 and beyond, based on radio wave propagation assessments, measurements, technology development and prototyping, along with IMT deployment scenarios that have been considered and described in the mentioned studies. The development of IMT for 2030 and beyond is expected to enable new use cases and applications with extremely high data rate and low latency, which will benefit from large contiguous bandwidth spectrum resource with around tens of GHz. This suggests the need to consider spectrum in higher frequency ranges above 92 GHz as a complementary of the lower bands. To overcome major challenges of operating in bands above 92 GHz such as limited transmission power, the obstructed propagation environment due to high propagation losses and blockage, there are studies ongoing in ITU-R about enabling antenna and semiconductor technologies, material technologies including Reconfigurable Intelligent Surfaces (RIS) and MIMO and beamforming technologies as potential solutions. Given the large bandwidth and high attenuation characteristics of bands above 92 GHz, some typical use cases are also envisaged to be studied, such as indoor/outdoor hot spots, integrated sensing and communication, flexible wireless backhaul and fronthaul.

6.3 Further considerations

Licensed spectrum will continue to represent the preferred regulatory regime for the many use cases where reliability, connection availability, and latency requirements need to be ensured. Moreover, unlicensed spectrum for 6G is expected to play a role as a complement for indoor and short-range communications where use cases and required system capabilities are non-critical. For such use cases the very high frequency ranges (sub-THz) considered for 6G would be more suitable, since the propagation characteristics make interference easier to manage

It is foreseeable that the focus will be on the 7-15 GHz frequency range. The use cases that would most benefit from this range are new bandwidth-hungry use cases, providing performance capabilities for e.g., hologram-based communications and advanced Extended Reality (XR) applications, where also very low latency and reliability are of utmost relevance, and smart cities applications, where advanced sensors generate large amounts of data. It is envisaged that use cases supported in this frequency range would be both indoor and outdoor with different levels of coverage, including the ones benefiting from or requiring outdoor mobility-as well as-indoor settings where it is not practical to rely on dedicated indoor coverage, e.g., for cost or performance reasons.

In general, the use of higher frequencies implies shorter coverage, if all other parameters are considered unchanged. Moreover, the larger the bandwidths the more the required power would be to achieve the same coverage and achieving higher output power is more difficult at higher frequencies.

Finally, it is important to note that the 6 GHz band is being discussed under the 5G/5G-Advanced timeframe, although it can pave way to be considered for re-farming to 6G. It is also important to emphasize that the performance within the 7-24 GHz range differs, e.g., the lower within this range, the closer to mid-bands performance and thus the wider the area that can be covered, while higher in this range, the closer the performance gets to that of the mm waves. Hence, it is foreseen that 7-15 GHz would be the essential range for additional spectrum for 6G.

There are many use cases for 6G with quite different bandwidth requirements. The more bandwidth-hungry 6G use cases are expected to need up to around 500-750 MHz of additional spectrum in the centimetre range and as much as around 10 GHz in the sub-THz range, per network.

Legacy technologies are expected to continue to be used also when the new technologies for 6G will be deployed. Therefore, it is important to design coexistence on common bandwidth resources with legacy technologies, allowing for a smooth migration to 6G for Mobile Network Operators (MNOs). With 5G we are already assisting to the implementation of dynamic spectrum sharing for mobile technologies (5G/4G) within the same carrier and this will certainly continue to be developed in standards and implemented in networks.

7 Sustainability

7.1 Hexa-X sustainability targets

7.1.1 Previous work on sustainability – energy efficiency is not enough

During the last decade, many Information and Communication Technology (ICT) actors including manufacturers and networks operators have made a great effort towards sustainability mainly by improving energy efficiency of equipment and networks and also by increasing the ratio of clean energy used during their operations. This green strategy led them for example to increase their purchased renewable energy and to enhance their equipment and capital goods by introducing energy efficiency in their procurement processes. Those initiatives led to maintain the energy consumption of the ICT sector under control and lower the CO2 emissions induced by operations, namely scopes 1 and 2 emissions associated with owned and purchased energy sources respectively. This first step allows the ICT sector to be one of the first drivers for increasing green energy as stated by the International Energy Agency (IEA) (Figure 7-1) and highlighted by the United Nations Framework Convention on Climate Change (UNFCCC) Race to Zero [UNFCC]. In recent years, around half of the global corporate renewables procurement is attributed to ICT sector.

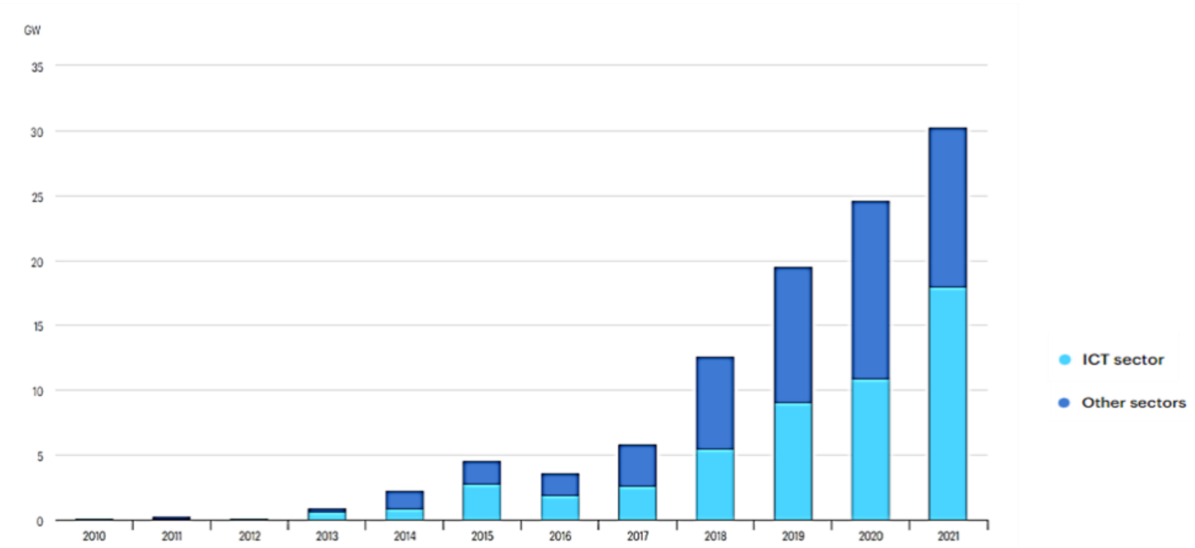


Figure 7-1: IEA, Global renewable energy power purchase agreements by sector, 2010-2021. IEA, Paris. Licence: CC BY 4, [IEA21].

It is crucial to reduce the overall energy consumption and enhance the energy efficiency of networks to achieve decarbonization goals that are aligned with the science-based trajectory established by International Telecommunication Union (ITU), Global System for Mobile Communications Association (GSMA), and General European Strategic Investments (GeSI) in collaboration with International Energy Agency (IEA) for Science Based Targets initiative (SBTi) (ITU-T L.1470) [L1470], and for the ICT sector to achieve net zero goals in accordance with ITU L.1471 and ISO net zero guidelines.

However, fighting against the global warming to achieve net zero, or balance the amount of GreenHouse Gas (GHG) emissions produced with the amount removed from the atmosphere, and to respect the Paris agreement [UNF15], further impose the ICT sector to consider all its emissions including value chain emissions, i.e., scope 3 emissions, which are associated with the value chain, such as emissions from suppliers, transportation and distribution of products, waste disposal, and the use and end-of-life treatment of devices. Energy efficiency is still essential but not enough to reduce the GHG emissions from the ICT sector footprint perspective. Hexa-X project stated different objectives both in support of this ambition (sustainable 6G), and to address the positive indirect effect when using 6G to help with the decarbonization of other sectors (6G for sustainability).

7.1.2 Hexa-X sustainability KPIs, scops and baselines

When first established, Hexa-X project defined three KPIs (see Figure 7-2) to tackle key sustainability issues [HEX21-D12]. The baseline considered for these three KPIs is 5G New Radio (5G NR) system. It's always difficult to resume sustainability to some "performance" indicators but the aim was to set a clear direction towards 'sustainable 6G' and "6G for sustainability". In particular, it is hard to identify reasonable quantitative objectives before a technology is even defined. From this perspective the targets could be seen as an expression of a high ambition and to set the direction of the project. More details regarding these three KPIs can be found in [HEX22-D13].

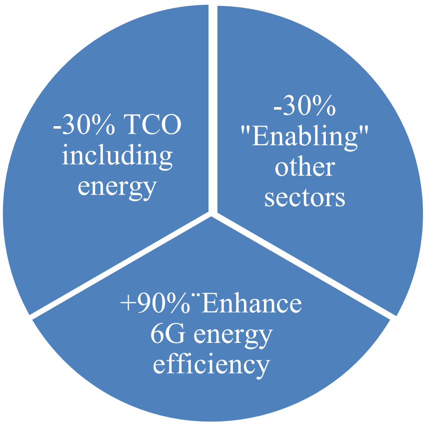


Figure 7-2: Hexa-X project Sustainability targets.

7.2 Sustainability KPIs evaluation and main achievements

7.2.1 Enablement effect

7.2.1.1 Description and scope of analysis

The ICT sector impacts the climate on three different levels: 1) first-order effects associated with the carbon footprint of ICT equipment throughout their lifecycle from the extraction and processing of raw materials, to manufacturing, usage (including energy consumption of the equipment and related support activities), and end-of-life treatment; 2) second-order effects associated with the usage of an ICT solution in non-ICT sectors; 3) higher-order effects or indirect effects linked to behavioural changes induced by the adoption or the widespread of an ICT solution in society. A positive second-order effect is often referred to as the enablement effect (6G for sustainability). The enablement effect is typically associated with solutions or services that could help reduce or avoid GHG emissions [L1400].

To assess a reduction of emissions in another sector due to the use of ICT (e.g., remote maintenance), two scenarios must be considered. First, the reference scenario, or the baseline, considers the emissions of a reference activity without the ICT/6G solution (e.g., driving to the site to perform a task). Second, the ICT/6G scenario, where the emissions are those occurring in a scenario with an ICT/6G solution applied (e.g., performing the maintenance task from main office using Extended Reality (XR)).

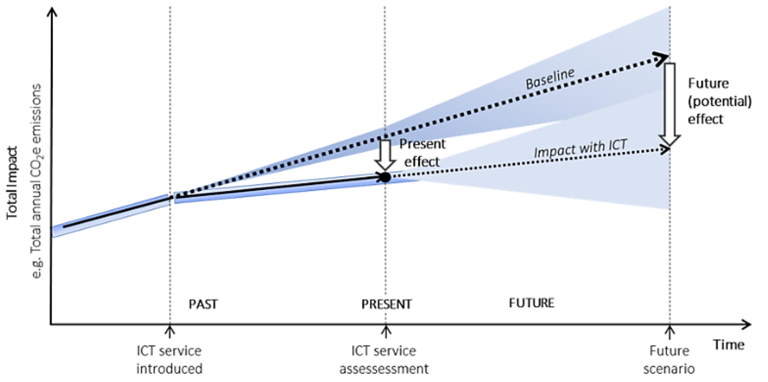


Figure 7-3: Enablement assessment approach based on a hypothetical comparison of two scenarios.

One of the Hexa-X objectives calls for enabling reductions of emissions by more than 30% CO2 equivalent in 6G-powered sectors of society. This means that 6G-powered industries should reduce their GHG emissions by nearly 30% (considering first- and second-order effects) compared to a reference scenario which is not powered with 6G (a simplified illustration of a comparison is shown in Figure 7-3). At this point, it has not yet been possible to establish the levers for 6G´s contribution to future emission reductions or to quantify its impact as the application of use cases is not yet sufficiently detailed. This does not imply that such levers and impacts are missing, but a more detailed understanding of 6G capabilities and use cases is needed before the levers could be established, and before any emission reduction potential could be quantified or verified as additional compared to today´s situation with 5G (see also Annex B). As 6G use case applications evolves a more detailed analysis of potential 6G emission reduction levers will become possible. Currently, to progress the understanding of 6G, this document performs a detailed analysis of the basis and implications of the enablement objective to give guidance for future target setting and observations to consider for future quantitative assessment of 6G´s enablement potential.

To further advance the understanding of 6G´s enablement potential the following subsection starts by qualitatively analyzing the strategies and levers to unleash emission reductions with specific reference to two Hexa-X Use Cases (UCs), from the perspectives of technological advances and policymaking. Then, we provide an educated reading of the ITU [L1480] recommendation, which was introduced to provide stakeholders with a consistent methodology for the quantitative assessment of the enablement effect. The analysis focuses specifically on how to apply the methodology to assess the impact of future technologies such as 6G, and it therefore provides guidelines for further research to proceed to quantitative analysis on solid basis. As highlighted in [HEX22-D13] (specifically Section 6.5.1 and 6.5.2), previous studies suggest that a thorough assessment of the enablement effect is very hard to achieve due to lack of standardized methodologies. Since then, ITU [L1480] recommendation has been published which details the assessment methodology, however it gives only limited guidance on how to assess future technologies although it provides an important methodological foundation setting key principle. Moreover, since 5G technology is still under deployment and 6G and its levers to reduce emissions are not known yet, difficulties in identifying the baseline scenarios and the relevant levers/effects become obvious, and the entire process suffers from a broad model uncertainty and unavailability of data. Assumptions could be possible, but each would be somehow arbitrary, and the sheer number of assumptions would result in significant uncertainties, and any obtained quantitative value could hardly be considered technically robust.

Therefore, rather than focusing on quantitative analysis, the most appropriate way to meet the Hexa-X objective of the enablement effect is to give a solid basis for further research in this area by providing well-grounded guidelines and methodology that could be applied as soon as 6G technology and use case applications would be detailed enough and relevant data would be available.

7.2.1.2 Qualitative analysis of 6G enablement

Literature highlights that systematic approaches are required to tap into enablement effects. Technology itself can be an enabler for some UCs, but is not sufficient in general; therefore, to unleash the 6G enablement effect, the adoption of the new technology should be accompanied by suitable strategies and policies to promote cultural change and new personal behaviors.

Assessing enablement effects is based on a comparison between a scenario with an ICT solution, and a reference situation with a reference activity. This assessment is hypothetical by definition as the two situations cannot exist simultaneously. Specifically, for Hexa-X it is noted that the reference situation is not a situation without ICT, only a situation without 6G, potentially a situation with 5G in full operation. In this situation it is assumed that 6G will both introduce new use cases, but also make some existing 5G use cases more widespread (e.g., due to lower costs and/or higher practicality). Hence, the additional enablement effect of 6G (compared to 5G) should be considered also for those cases.

To further elaborate on this, two Hexa-X UCs have been selected, namely “Fully merged cyber-physical worlds” and “Merged reality game/work”, with specific reference to their application to flexible/remote work and travel avoidance. Please note that these two UCs do not belong to the “Enabling sustainability” family: in fact, the enablement effect is certainly not limited to specific UCs, and it applies across most of them. In the following, from a qualitative analysis perspective, a focus on the strategies to unleash the enablement effect is provided, followed by a technological analysis.

7.2.1.2.1 Strategies to unleash enablement effect

Previous studies on flexible work show that, even with 5G, only a small portion of the theoretical enablement potential can be exploited: for instance, in [BSH+20] for the use case “Flexible work” an estimated gain of 72 ktCO2e (pessimistic scenario) or 876 ktCO2e (optimistic scenario) is provided against a potential of 3999 ktCO2e (Theoretical scenario). Therefore, this study should analyse how 6G can unleash further enablement gain, in line with the Hexa-X objective.

It is generally acknowledged that face-to-face meetings currently have some advantages over virtual meetings, e.g., in terms of effectiveness of information exchange, ease of building trust, and ultimately facilitating commitments and agreements [JAN17] [LCC+15] [WSH97] [BSH+20]. The reason being that non-verbal communication, body postures, etc. cannot be conveyed in virtual meetings. Furthermore, key customary actions (e.g., handshake for a reached deal) cannot be performed.

To be successful in increasing the adoption of flexible work it is certainly important to improve the effectiveness of collaboration tools [BSH+20]: immersive/augmented/mixed reality solutions offered by technology like virtual meeting rooms, holograms, tactile feedbacks can enhance the experience to a more satisfying level. However, it must be highlighted that quite often the choice of holding a meeting face-to-face or online is not only an individual choice: company policies are at least as important as personal preferences, and these rules/policies are driven by different factors. This is an example of why, although technology is a relevant enabler, suitable strategies and policies should be put in place to unleash any additional 6G enablement effect.

It is true that digital media are better at spreading information rather than habits, and they can hardly build trust (it is more difficult for people to read each other); however, digital media can be very effective in consolidating a trusted relationship and reinforcing habits [PEN14]. In general, an initial face-to-face meeting and acquaintance between strangers can be conducive to subsequent fruitful remote collaborations. This is particularly true for specific phases of activities such as:

- Onboarding of new personnel,
- Kick-off meetings,
- Problem settings,
- Team building,
- Brainstorming sessions

Organizations should develop and implement systematic flexible work strategies encompassing different aspects ranging from working culture, policies (such as travel and meeting policies), office and ICT infrastructures [BSH+20]. The adoption of flexible work should also be supported by policy makers through suitable campaigns supporting specific training, facilitating sharing of experiences on flexible work adoption, as well as establishing efficient fiscal policy [BSH+20].

Flexible work, along with the benefit of a more satisfying work-life balance, also bears the risk of negative impacts on individuals' well-being (e.g., overworking, workplace ergonomics, etc.) [BSM11] [LEU05] [BSH+20].

Many different sectors can benefit from enablement effect, e.g.:

- Enhanced remote control of factory robot/machinery or field vehicles in agriculture can curtail the need to physically commute to factories and farms resulting in safer job, better work-life balance and lowering GHG emissions; this need to be promoted and supported by appropriate policies.
- Similarly, enhanced remote professional consultation/intervention via mixed reality solutions can curtail the need of business travel in several professions and should be recommended and incentivized.
- Mixed reality artistic creation can enable artists to express themselves without the footprint of real materials and manufacturing allowing people to enjoy (or be a part of) it from anywhere: this should be stimulated and endorsed.

Compared to previous technologies, 6G could widen and increase the enablement to other sectors affecting all aspects of individual life, if appropriately supported by conducive actions, e.g.:

- Entertainment and sport events can promote virtual enhanced attendance curtailing the need to physically travel to venues.
- In the personal domain, expand the social media experience through holographic gatherings yielding an experience similar to reality curtailing the need to physically travel.
- Based on the above, there is clearly a role for 6G to play towards making flexible work and virtual meetings more attractive for individuals and organizations, thereby offering the potential to reduce travelling. However, to what extent this will change travelling patterns is hard to model at this stage, making a quantitative assessment of the associated 6G enablement effect too uncertain.

7.2.1.2.2 Technological analysis: a focus on wider adaptation of merged reality use cases via 6G

When looking at Merged Reality (MR) use cases and their acceptance/implementation, several obstacles still hinder the technology from fully emerging. Among those, sickness/nausea caused by MR sessions, along with a lack of mobility when wearing an MR headset, are perhaps the most prevalent [ECL17]. Technological aspects give the underlying cause of these obstacles. In the following subsection, we list several of them and discuss how 6G technology may improve the situation.

Foremost, MR may cause motion sickness because of latency issues ("cyber-sickness") [AKY22]. A delay between user movements in the real (physical) world and the virtual world makes users feel dizzy and (or) nauseous. Low lag is crucial to maintaining durable communication between users for socialization via MR. These shortcomings will probably improve with the advent of 6G, which will offer much lower latencies.

At least occasionally, reports indicate that the MR visual experience is mediocre (or even poor) [ECL17]. The problem stems from using low resolutions when transferring visual content. With its increased bandwidth and data throughput, 6G will improve technical conditions and thereby also enable an improved visual experience. This is particularly important for the upload link since, in MR, large amounts of data transfer must occur in both directions. Future MR applications will involve increased computations and increased usage of Artificial Intelligent (AI). In this regard, use of 6G for MR applications will also leverage the in-network AI as a Service (AIaaS) and Compute as a Service (CaaS) capabilities that 6G will provide. More specifically, accurate predictions of body and head motion with field-of-view may reduce requirements placed on latency and data rates.

The MR applications are also computationally intensive. Together with 6G's low latency characteristic, it will provide the required computational power through Mobile Edge Computing (MEC) [AKY22].

That will make parts of the hardware on MR headsets obsolete, and therefore the weight and size of the equipment will decrease. Thus, a potential goal could be to reduce their functionality to only display images/projections rendered in MEC.
To increase the practicality of MR via wireless technology, it is crucial to use low-power communication, computation, and networking protocols enabled by 6G. Consequently, the energy saved can allow the implementation of a smaller battery to minimize the weight of the equipment.

Integration of 6G technology for MR applications can and will enhance security in several ways [PGO+21]. 6G will ensure, with its robust security protocols and secure communication channels, secure storage of any information regarding the user of MR equipment. The blockchain integration and the advanced encryption methods of 6G can also help to build a decentralized platform to store the vast amount of data generated by MR technology. With 6G, MR systems can monitor and detect security threats in real time and protect the information against hackers trying to access sensitive data. This data may include not just purchase histories or credit card information of the users but also users' personal information such as feelings, physical appearance, behaviors, judgments, etc. This protection is even more critical for some use cases, such as surgeries and military operations.

7.2.1.3 “Educated reading” of ITU-T L1480

A more detailed version of this section where L.1480 is applied to two different scenarios, including comprehensive scenario descriptions and consequence trees, can be found in Annex B.

Until recently, consolidated detailed methods and standards describing a clear methodology to evaluate the enablement effect of an ICT solution on other sectors´ GHG emissions have been lacking [CBH+20]. Previous studies [HEX22-D13] suggest that standards have provided high-level guidance only, but thorough assessment has been out of scope so far. With [L1480] which became effective in late 2022, the standards situation has improved. By its structure and definition of relevant terms, it brings transparency, consistency, and comprehensiveness to enablement assessments of ICT solutions. Due to this, [L1480] has been selected as the methodological foundation of the enablement objective. The [L1480] analytical framework is based on comparison between a situation where a well-defined ICT solution is in place (ICT solution scenario) against a situation where it is not (reference scenario).

In an educated reading trial, it was examined how the proposed [L1480] methodology could be applied to future technologies, in particular with respect to two selected Hexa-X UCs (namely “fully merged cyber-physical worlds” and “merged reality game/work”) with specific reference to their application to flexible/remote work and travel avoidance. The reading takes into account the current state of technology development, and a new reading at a later point in time could help advance the application of [L1480] with future technologies.

The [L1480] methodology gives detailed instructions of how the assessment procedure is to be carried out, while specifying different assessment depths (tier 1-3) and different scale levels (organization, city, country, worldwide level). In the following, definition of the aim and type of the assessment, the assessment depth, the scope, and identification of resulting second order effects are discussed, acknowledging the high uncertainty of any assessment due to the current lack of detailed specification of 6G system and its capabilities. The objective is to examine the feasibility of applying [L1480] to future technologies and, whenever possible, identify any methodological gaps and potentially propose solutions. From the scientific perspective this will be the main value of the assessment. Below, the different steps of [L1480] are discussed at a high level with the mentioned use cases in mind, and the applicability of each step for 6G at this state is reflected.

Step 1 – Define the goal of the assessment (possible to implement)
Step 2 – Scoping (possible to implement)
Step 3 – Modelling, data collection and calculation (not feasible to implement yet) including quantification of second order effects through first order effects and change in GHG emissions in reference activities
Step 4 – Interpretation of results (not feasible to implement yet) including evaluation of method, data quality analysis, sensitivity and uncertainty analysis

Step 5 – Reporting (possible as soon as the assessment can be made)
Step 6 – Critical review (possible as soon as the assessment can be made)

Step 1 – Define the goal of the assessment (possible to implement for 6G at this stage)

1.1) Define the aim and type of the assessment (Clause 10.1.1 of L.1480)

L.1480 can be applied to several types of assessment. In case of a future technology, "a general usage of one or several ICT solution(s) (clause 12)" may be preferred over "specific implementation of one or several ICT solution(s) (clause 11)". However, it might be easier to visualize a specific case to understand implications and limitations. In any case, the scale at which the assessment is performed will depend on data availability (and reliability).

In general, it is considered to focus the assessment of the application of a solution at a defined scale of operation for 1 year timespan (sufficiently long) in 2035, which is sufficiently far in the future where 6G deployments are assumed to be stable and running.

1.2) Define the assessment depth (clause 10.1.2 of L.1480)

As 6G scenarios represent future technologies and are suggested to be examined for a 1-year timespan in 2035, an assessment considering net second order effects and identification of contextual factors and higher order effects (Screening / First Approximation, called tier 3 in L.1480) would be the only option.

Step 2 – Scoping (possible to implement for 6G at this stage)

Scenario definition (added for own clarification):

For our purpose, by way of examples, we refer to two scenarios where 6G enables i) completely automated factories where no human needs to be present (reducing size of factory, reducing heating and lighting in the factory) and ii) virtual remote maintenance work (or problem fixing) which reduces business-related travelling.

The description of the scenarios considered should be as detailed as possible, focusing on what 6G could bring to them, and also encompassing second and potentially higher order effects, challenges and uncertainties.

2.1) Define the scope by:

• *Defining the ICT solution(s) and their main second order effects (clause 10.2.1 of L.1480);*

The ICT solution under study in our example could be a Virtual Reality (VR)/Extended Reality (XR)-based solution (including Digital Twin (DT)) based on the future 6G mobile communication standard.

Geographical coverage could be Europe (or EU only).
Temporal coverage could be the year 2035, i.e., a 1 yr. timespan where we assume 6G to be stable, completely deployed, running and use-cases mainly realized.

It is noted that for a tier 3 assessment, quantification of second order effects can be based on secondary sources and qualified estimates.

• *Defining the functional unit (clause 10.2.2 of L.1480);*

The functional unit could be one of the following:

- Scenario 1: Overall days of operation (factory) during one year
- Scenario 2: Maintenance work occasions during one year

The functional unit should be defined in a way that is valid both for the scenario with the 6G solution applied, and to the reference situation. The functional unit is the unit which emissions values are referred to and it is associated with the value provided by the 6G solution and the reference activity.

- *Defining the assessment perspective (clause 10.2.3 of L.1480);*

  The perspective of the assessment is in this case ex-ante, addressing a future potential.

- *Defining the composition of the ICT solution(s) and identifying the contributors to its overall first order effects (clause 10.2.4 of L.1480);*

  This is challenging, since 6G is not defined yet. First order effects refer to the life cycle impact of the overall ICT solution including additional components (hardware and software) needed compared to an off-line or earlier generation solution, e.g., for the considered scenarios, more technological devices installed and deployed (e.g., remote work robot/assistant), more virtual conference and IT systems required. At a later point when the architecture and requirements (e.g., on absolute electricity consumption) are settled in further detail, these could be used to make a first estimate of the expected GHG emissions of operation, and embodied emissions could be estimated based on the relation between use stage and embodied emissions.

- *Identifying and defining the reference scenario(s) (Clause 10.2.5 of L.1480);*

  The reference scenario in this assessment is the assumed situation without the 6G solution, i.e., here a situation with only 5G technology being available to perform the desired activity within the described scope (EU, year 2035).

- *Identifying additional second and higher order effects of the ICT solution(s) and any relevant contextual factors, and document those together with main second order effect and the first order effects following the guidelines for establishment of a consequence tree (clauses 10.2.6 and 10.2.7 of L.1480);*

  This would be done by creating a "Consequence tree" in order to structure second and higher order potential effects, with respect to considered application. As a first approximation this could be done when the emission reduction levers of 6G are identified, and the usage scenario is understood. A first version of the consequence tree would not demand an exact specification of the 6G solution as such. (See Annex B for an example).

- *Selection of effects to be quantified (clause 10.2.8 of L.1480);*

  Based on the consequence tree and a first approximation of the order of magnitude per effect a selection of the ones to quantify is performed.

- *Defining the system boundaries of the ICT solution(s) and the reference scenario(s) (clause 10.2.9 of L.1480)*

  This step is not feasible to perform for the 6G solution at this point. Modelling the reference scenario may be feasible to some extent based on today´s solutions – however modelling their future evolution would be more uncertain.

The next steps, step 3 to step 6, are related to the quantitative analysis. However, modelling, data collection and calculations (step 3) as well as the subsequent steps (interpretation, reporting, review) which build on the results from step 3, are considered unfeasible from today's perspective without an unreasonable amount of uncertainty as the entire process suffers from broad unavailability of information and data. It seems not feasible to perform the quantitative part of the methodology since we consider 6G capabilities not well-defined enough and the two above mentioned use cases are not mature enough for this type of assessment. Furthermore, as already noticed, we see difficulties in identifying the reference scenario as 5G is still under evolution and deployment, and with the solution scenario where concrete data is lacking. Assumptions could be possible, but they would be arbitrary, and any obtained quantitative value could hardly be considered technically robust.

In conclusion, at this stage a through quantitative assessment of the enablement effect is hard to achieve since the entire process would suffer from significant uncertainties and lack of data. 6G is largely unknown yet: a more detailed understanding of 6G capabilities and use cases is needed before the levers for 6G's contribution to future emission reductions could be established, and before any emission reduction potential could be quantified on solid technical basis.

From the methodological perspective, the situation has improved with the availability of Recommendation ITU-T [L1480]. In this section it was examined how the proposed [L.1480] methodology could be applied to future technologies, thus providing well-grounded guidelines that could be applied as soon as relevant information and data would be available.

7.2.2 Energy efficiency

Energy is a transversal topic that concerns each stakeholder of a future network. To achieve tremendous performance, each single active component, processing, function, service, and system of the network consumes energy. As 6G aims to improve the classic Key Performance Indicators (KPIs), such as peak throughput for extremely demanding services, compared to previous generations, physics laws cannot avoid that absolute energy consumption of dedicated equipment will increase. However, 6G innovations target to decrease the energy consumption per transported data unit (i.e., Energy Efficiency (EE) metric) by a factor 10 (i.e., 90% reduction), following the trend observed for previous generations. Furthermore, the 6G EE approach must be deployed from local to global scale and should implement a **consumption agility regarding the other classic KPIs** (data rate, latency...) for each given use case. Hence such an optimization of energy targets the "quasi zero watt at zero load" that is a permanent scaling of the Radio Access Network (RAN) infrastructure hardware supporting the network operations regarding the instant need, i.e., mainly the traffic load level.

This energy-agile approach is possible since sub-systems (hardware/software) are becoming more reconfigurable (multi-modes, x-agile, etc.) in order to face the large diversity of scenarios. This is retrieved in almost all the 6G levers detailed hereafter. The goal has been to estimate the trends and when possible, the order of magnitude of main technologies that allows 6G to reach a factor ten target on EE improvement.

7.2.2.1 Energy efficiency: definition and baseline

EE is defined as the energy consumption per transported data unit (Wh/bit) in the RAN perimeter. On the operational field, it is quite simple to assess through measurement (Direct Current (DC) power and data volume transmit/process/store over a period of time). A standardized methodology can be found in ETSI 203-228 [ETS20]. Nevertheless, it is more delicate to assess EE from preliminary studies on 6G elementary technologies. One can evaluate relative EE improvement as a first step. Then model-based of each component for global EE assessment should be available during the early design phase (e.g., aeronautics system model approach [PHA+12], or integrated energy consumption model on LTE macro/small cell from European earth project [Ear12]).

The baseline is also important to specify. The 5G NR Stand Alone (SA) is selected with two traffic loads scenarios: high 80% and low 20%. Depending on the 6G solutions domain to be compared, some details should be added. For instance, if the performance of a 6G antenna array associated with its Radio Frequency (RF) front-end is analyzed, a 64 TRx on FR1 with 100 MHz bandwidth is commonly used in the literature [ETS20], as a reference for 5G baseline.

7.2.2.2 6G technology levers for improving energy efficiency

As introduced, the different technology levers are more or less relevant depending on the traffic load scenario. For instance, path loss reduction is considered in mmWave high-data rate scenario, whereas sleep modes and adaptive waveforms are promising for low-data rate ones. Other levers like infrastructure-sharing and new generation of electronic components can be categorized in the load-independent solutions as they are beneficial in all cases.

Assessment on EE target

RF power amplifier technology plays an important role in the energy budget (about 40% of radio and 15% of overall communication services for Frequency Range 1 (FR1) macro-Base Station (BS)) [VWD+22]. Introduction of Gallium Nitride (GaN) technology, Power Amplifier (PA) optimized energy efficient modes depending on the load, waveform optimization for PA linearity requirement reduction, …) should target 20% improvement in FR1 bands compare to current 5G ones. For FR2 and sub-THz bands, the RF output power constraint is high and Analog to Digital Convertors (ADCs) and digital processing consumptions are the most impacting one. Thus, an improvement factor should mainly rely on efficient sleep mode implementation. Notice that antenna array hybrid architecture will have to optimize the complexity (number of RF chains, channelization) versus global EE, for such very high data rate radio and their specific deployment.

Electronic components efficiency could leverage very high impact on EE improvement factor since this hardware category supports both the low-level functions of signal baseband, but also high-level ones like AI computation. To overcome the Moore Law's stagnation, Microelectronics community (R&D institutes and industry) roadmaps target factor from 100 to 1000 EE improvement at the elementary computing unit, in the coming decade, with new technologies such as resistive memories, 3D-integration, in-memory computing, and neuromorphic computing [LEQ+21]. However, to benefit from such reduction at the equipment or even system level, engineering communities should work closer and jointly co-design between each level (transistor process steps, circuits, architecture, software and application algorithms). The overall computing EE improvement factor is delicate to assess at this stage, but one should target at least a 50% reduction compared to equivalent electronics used on initial 5G hardware.

Artificial Intelligence, multi-goals optimization and adaptive air interface. This new lever could bring very promising energy savings (-20% target) and optimizations while maintaining an equivalent Quality of Service (QoS). AI can be introduced in numerous domains, like linearity optimization of PA for high-traffic load. In the lower-traffic scenario, multi-goals AI will optimize Peak to Average Power Ratio (PAPR) and so global PA consumption by selecting the appropriate waveforms and guard sub-carriers. AI will also be able to adapt the needed resources to the user demand. Moreover, AI can also be used to detect energy consumption anomalies and over-dimensioned sites that could be reengineered to match the network resources to the targeted QoS.

Sleep-modes and network orchestration. Sleep modes have been one of the main levers for decreasing the energy consumption of wireless networks in the last decade. Their performance is closely related to the physical (PHY) and Medium Access Control (MAC) layers design as well as to the signal characteristics. The main improvements have been achieved with the Orthogonal Frequency-Division Multiplexing (OFDM) structure which allows rapid sleep modes generally called micro-Discontinuous Transmission (micro-DTX). Also, the Multiple Input Multiple Output (MIMO) configuration now allows switching off part of the antenna transceivers depending on the traffic demand. 6G PHY/MAC layers design should then natively consider sleep mode implementation to enhance their efficiency. New techniques such as lean carrier and deep sleep modes could then be implemented without any loss in QoS or user experience.

Path loss reduction techniques. Path loss in wireless communications is typically large. This loss comes from radio waves not reaching the intended receivers. The radio energy in these radio waves is thus wasted for communications purposes. In addition, radio waves reaching non-intended receivers will cause interference, thus degrading their capability to correctly receive signals intended for them. With precise beamforming, such losses can be substantially reduced. Network densification is another enabler since the expected distance between transmitter and receiver is then reduced. Combining densification with optimized sleep-modes and network orchestration has shown to enable overall energy savings [FML+21]. Here, various Distributed MIMO (D-MIMO) techniques [HEX21-D22], including Integrated Access and Backhaul (IAB) [MMF+20] Reconfigurable Intelligent Surface (RIS) and Network-Controlled Repeater (NCR) [GMM+23] all have a strong potential, but need further research to understand how to best optimize their use in various deployment and usage scenarios.

Infrastructure sharing solution consists in pooling and sharing the base station sites and/or its equipment for a given geographical area between two or more Mobile Network Operators (MNOs). Such sharing is currently rarely deployed but aims to improve coverage and/or capacity, and Operating Expenditure (OpEx) savings too. 6G should enhance this to reap the benefits on a wider scale where both EE improvement and energy consumption saving are estimated to 30% compared to the legacy configuration (no sharing) [KBA+15]. The previous levers are synthesized in the following Table 7-1.

Table 7-1: Technological levers to improve EE.

Levers	Targeted EE improvement	Improvement factor by 2035 (30% traffic load)
Spectral efficiency	+20% band FR1 +100% band on FR2	1,2 2*
Infrastructure network sharing	30%	1.3
PA technology	20% (in FR1)	1,2
Signal / baseband processing (Semiconductors, circuit architecture)	50%	1.5
Other technologies independent from 6G (e.g., cooling)	10%	1.1
6G sleep modes (micro DTX, mMIMO muting, cell switch off)	30%	1.3
AI, multi-goals optimization and agile air interface	20%	1.2
Adaptive architecture (RAN acceleration, centralization, densification)	Up to 40%	1.4
Reduced pathloss (D-MIMO, RIS…)	Local deployment	1 (no estimation)
Total potential		between 7 and 11 improvement factors
*For equivalent power		

In conclusion on energy efficiency, a factor 10 of reduction compared to 5G baseline seems a reachable target. To reach it, R&D community should follow their roadmap, translate the laboratory performance into the products, and finally, find innovative collaborations to codesign from hardware to applicative layers with the purpose to optimize energy consumption. At last, these levers are rather RAN focused (most impacting), but it should be noticed that other parts of the 6G system should also contribute to the EE goal.

7.2.3 Total cost of ownership

6G is expected to enable sustainability, including the economic, social, and environmental aspects, on a global level. In this sense, one of the Hexa-X's main objectives is to provide insight and methodology to achieve an overall reduction of the Total Cost of Ownership (TCO) of at least 30% with respect to 5G [HEX22-D13]. In [HEX21-D51], TCO for mobile networks is discussed, including the one-time Capital Expenses (CapEx) and recurring OpEx associated with introducing a new mobile communication system.

The following section details the methodology used for the TCO analysis and presents a *qualitative* TCO assessment in one of the Hexa-X developed use case. The aim is to define the relative network cost items as well as optimization methodology through the adoption of technological enablers identified in the project. Finally, the impact of some enablers is quantified to provide an estimate of the potential reduction they can yield.

7.2.3.1 TCO assessment methodology

To define the TCO of a 6G network and achieve a reduction of at least 30% in comparison with the previous generation, a methodology has been developed by the project. It follows the results obtained and reported in the Global System for Mobile Communications Association (GSMA) study [GSM19], which compares TCO for legacy 4G and 5G. As also widely reported in [HEX22-D52], the GSMA work identified five main cost items, i.e., ***RAN infrastructure***, ***energy consumption***, ***Core Network (CN) infrastructure***, ***backhaul***, and ***other network-related expenses*** (e.g., personnel, network management and maintenance), on which to evaluate the cost variations between the two cellular network generations. In this GSMA study, changes in costs are assessed in relative terms, meaning that the percentage of variation of each cost item is compared to the 4G baseline architecture. Moreover, it is worth noting that the TCO cost items are listed based on their weight on the overall TCO [GSM19]. This means that RAN infrastructure has a higher impact on TCO than energy consumption, which in turn has a higher impact than the CN and so on.

The GSMA study under analysis includes, for the RAN infrastructure cost item – which is responsible for 45-50% of the overall network TCO – both passive infrastructure such as towers and cabinets, as well as active infrastructure like radio antennas, baseband processing, cooling equipment. Always in accordance with [GSM19], energy consumption is the second most significant cost, representing 20-25% of TCO, and this cost is increasing due to three main factors: the use of massive MIMO, network densification (resulting thus in more sites), and the growth of mobile data traffic. The CN infrastructure has a lower impact on the TCO, but the introduction of 5G core (5GC) has the potential to generate substantial savings through the use of e.g., Virtual Network Functions (VNFs) and distributed cloud architecture. The backhaul cost component follows the same trend as energy consumption, mainly due to traffic growth, which requires high-performance backhaul networks. Fibre results being the best technology to meet the needed requirements in terms of latency and throughput, but, at the same time, also the most expensive [BCG18].

Relative TCO evaluations for a cellular network require the identification of a baseline architecture for assessing the potential cost benefits of specific key network enablers. As mentioned earlier, for the Hexa-X TCO assessment, 5G is the baseline architecture since it represents the set of products that portray the existing enterprise, the current business practices, and technical infrastructure [FCI01]. However, it is not straightforward to identify a 5G architecture as 3rd Generation Partnership Project (3GPP) has considered and evaluated various architectural options for the fifth-generation mobile networks. The first release of 5G technical specifications, i.e., 3GPP Rel-15, introduced different ways of deploying a 5G network by combining elements from 4G as well as new elements introduced for 5G. These different network configurations are classified into two categories: SA, which comprises those architectures encompassing one radio access technology only (i.e., either E-UTRA or New Radio (NR)), and Non-Standalone (NSA), which includes architectural options making use of up to two radio accesses (i.e., both E-UTRA and NR) combined in a Dual Connectivity fashion. While this second configuration allowed 5G to be brought to market quickly with minimal modifications to the existing 4G network, it does not include the 5GC, thus being not optimised for 5G use cases other than mobile broadband [GSM19]. Consequently, the preferred architectural choice turns out therefore to be 5G NR SA, which will be the baseline architecture for the Hexa-X TCO assessment.

For TCO evaluation, the aforementioned GSMA work considered different 5G deployment strategies, i.e., *(i) Rapid, full-scale*, *(ii) Enterprise-focused*, and *(iii) Capacity-backfilling*, concluding that the 5G rollout strategy choice significantly impacts the relative TCO evaluation. The former and the latter are similar, with the difference that the *Capacity-backfilling* deployment is a more cautious (i.e., measured) strategy that guarantees a coverage of 50% of the population (against 80% of *Rapid, full-scale* strategy) and addresses only enhanced Mobile Broadband (eMBB) services. Further details are reported in Table 7-2.

Table 7-2: Three deployment strategies as considered by GSMA for 5G [GSM19].

	Strategy #1: *Rapid, full-scale* 5G deployment	**Strategy #2: *Enterprise-focused* 5G deployment**	**Strategy #3: *Capacity-backfilling* 5G deployment**
Target use cases	New 5G use cases in both consumer and enterprise segments	Existing and selected new enterprise use cases	Existing use cases, capacity backfilling and eMBB services
5G network rollout	Rapid 5G rollout covering 80% of the population with high capacity 5G network by 2025	Fast-paced deployment covering 65% of the population with high capacity 5G network in enterprise hubs by 2025	Measured 5G deployment covering 50% of the population with additional 5G capacity by 2025
2018-2025 data traffic CAGR (Compound Annual Growth Rate)	40% CAGR	30% CAGR	20% CAGR
2025 vs. 2028 traffic multiple	10x	6x	3x

As an example, Figure 7-4 depicts the outcome of the TCO assessment for the *Rapid, full-scale* deployment scenario from the GSMA work. For this deployment strategy, the adoption of 5G is costly for an operator and it can lead to an overall increase of costs of up to 71%. However, the study shows how this increase can be mitigated by deploying proper 5G cost optimisation tools, which can lead to a reduction of 32% (from 71% to 39%) of the overall 5G network TCO increase. It is important to highlight that this work considered the holistic concept of TCO that subsumes both CapEx and OpEx. Moreover, for *5G Optimized Case*, the proper histogram in Figure 7-4 represents the average annual TCO over a period of 5 years for a European mobile operator rolling out a 5G network in 3.4-3.6 GHz band.

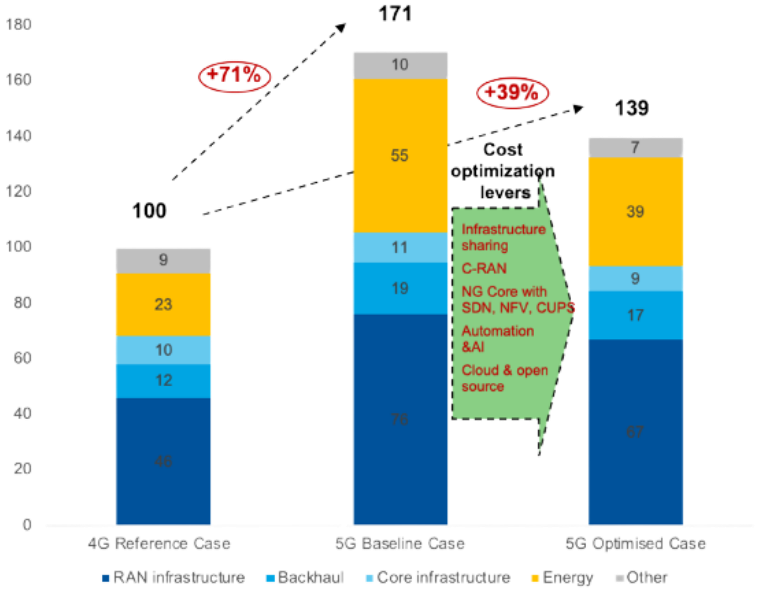


Figure 7-4: TCO comparison between 4G, 5G, and 5G Optimized Case for the Rapid full-scale 5G deployment.

The qualitative and quantitative TCO evaluations conducted within the Hexa-X project are based on the impact of *technical enablers* required for the implementation of a specific use case – which can be mapped onto a 5G deployment strategy – on the five cost items defined by the GSMA work [HEX21-D51]. The technical enablers considered are the ones identified and developed by the Hexa-X technical WPs, which can be grouped as follows:

- **Enablers for the intelligent networks**: UE and network programmability, dynamic function placement, network analytics, network automation, AIaaS.
- **Enablers for the flexible networks**: Integration of sub-networks, flexible topologies (Device to Device (D2D), mesh networks, campus networks), edge-to-network-to-cloud integration.
- **Enablers for the efficient networks**: Efficient RAN/CN signalling, function refactoring, CaaS.
- **Enablers for the 6G RAN**: High data rate radio links, distributed large MIMO, localization and sensing.
- **Enablers for the service management**: Continuum management and orchestration, AI-driven orchestration.

Before delving into the TCO analysis, it is worth pointing out that this activity is a complex and challenging task since 6G is a new system, whose architecture is in process of being defined, and the chosen baseline architecture, i.e., 5G NR SA, is still in a deployment phase in most of the countries worldwide [EBS+22]. As a result, 5G costs – especially OpEx – cannot be derived based on the actual experience of having such kind of network in place and properly operating. Moreover, 3GPP Rel-18 is going to standardize the so-called 5G-Advanced, an evolution with respect to the current standard, which could have an impact on the TCO of the baseline architecture considered in this work.

7.2.3.2 Qualitative TCO evaluation for the "fully merged cycler-physical worlds" use case

This section reports a TCO analysis for a specific use case, i.e., "*fully merged cyber-physical worlds*". The selected use case is one of the 27 proposed use cases by the Hexa-X project and part of "*Telepresence*" use case family [HEX22-D13]. The reasoning behind choosing this use case is two-fold: *(i)* it is particularly in line with the Hexa-X vision of 6G being the enabler to connect the three worlds (i.e., human, digital, physical) [HEX21-D12], *(ii)* it matches the characteristics of a specific GSMA's deployment scenario considered, namely the *Rapid, full-scale* 5G deployment. On the contrary, use cases that can be mapped to the *Capacity-backfilling* deployment strategy were not considered, as they do not fit with the demanding requirements of 6G use cases and they solely address 5G eMBB services (as per GSMA's description). Likewise, also the *Enterprise-focused* deployment strategy is not taken into account in this analysis, despite the potential relevance of use cases belonging to this strategy.

As discussed earlier, the 6G architecture is still under definition. However, since the data and information on the *Rapid, full-scale* deployment strategy is the most available – and this provides a more solid foundation for the investigation and increases the likelihood of obtaining significant and meaningful results – this section details TCO aspects for this specific use case.

The details of the use case "*fully merged cyber-physical worlds*" can be found in [HEX21-D12] and further elaboration in [HEX22-D13]. It involves the use of MMR and holographic telepresence to enable advanced augmented reality bringing immersive experiences with more than visuals and audio. This use case can improve remote working as well as virtual meetings (e.g., appearing to be in the office while being anywhere else in the world), tele-consultations and e-learning, being thus a potential enabler to effectively counteract pollution and GHG emissions. By its inherent characteristics, this use case requires low latency, high data rates and adequate reliability to avoid an incomplete experience or even nausea. Since users will interact with both digital and physical elements, the requirements on the network may be not guaranteed by 5G and a significant amount of computational effort will be needed by end devices.

Table 7-3: Hexa-X technical enablers impact on the TCO cost items for the "Fully merged cyber-physical worlds" use case [HEX-D53].

	RAN infrastructure	Energy consumption	Backhaul	CN infrastructure	Other NW costs[(1)]
Intelligent networks enablers	x	x	x		x
Flexible networks enablers	x	x	x	x	x
Efficient networks enablers					
6G RAN enablers	x				
Service management enablers		x			x

(1) This includes people, network management and maintenance costs

Table 7-3 reports the outcome of the qualitative analysis conducted, which is also widely discussed in [HEX23-D53]. Each row reports a technical enabler family, whereas each column represents the cost items considered. It is worth mentioning that technical enabler families that most reduce the TCO are those affecting the RAN infrastructure, i.e., intelligent network, flexible networks, 6G RAN enablers, as it has the highest impact on the overall network TCO. It is also interesting to note that due to the characteristics of the use case, which is based on the *subnetwork* concept, the enablers for flexible networks are playing an important role in the TCO evaluation and they can help reduce all five cost items.

7.2.3.3 Quantitative TCO evaluation for the "fully merged cyber-physical worlds" use case

This section presents a quantitative estimation, expressed as a percentage, of the impact of some of the previously introduced technical enablers on TCO. The following quantitative assessment of cost savings for 6G networks – based on data and information available in literature – aims at demonstrating the possible TCO reduction enabled by the deployment of the technical enabler families. However, it is worth noting that, even though the obtained results are based on reliable works found in literature, they are nevertheless predictions, that may be subject to uncertainty for the reasons already discussed.

The first phase of this analysis focused on literature review in order to identify related works that leverage the technical enabler families identified by the Hexa-X project to make similar TCO evaluations. The literature search was particularly challenging not only for the scarcity of relevant works but also because the use cases covered in such investigations needed to be mapped to the selected deployment strategy (i.e., *Rapid, full-scale* 5G deployment) to be suitable for this study. Therefore, this work provides a quantitative TCO impact analysis for two families among the ones identified, i.e., 6G RAN enablers, Service and Management enablers. For the remaining three families (i.e., intelligent networks, flexible networks, and efficient network enablers), no suitable literature providing accurate data to make evaluations with some degree of reliability has been found.

The findings of the literature search are reported in Table 7-4, which outlines the potential percentage reduction introduced by the two technical enabler families on the overall TCO. In [CBG+21], the authors show how the service management enablers (such as AI-driven orchestration) can impact positively the network costs up to 10%. A much higher contribution comes from the 6G RAN enabler family, whose impact can reach 50% [VWD+22]. In order to quantify these savings on the five cost items identified by the GSMA work, it is needed to leverage the qualitative analysis reported in Table 7-3. The analysis shows that the 6G RAN enabler family impacts only the *RAN infrastructure*, resulting in halving the costs for this cost item. In contrast, the service management enabler family affects the *energy consumption* and the *other network-related* costs by 10%, which has thus to be "distributed" on the two cost items. To do that, it is reasonable to assume that the impact of this enabler family follows the "weight" that these two cost items have on the overall TCO (as shown in Figure 7-4): *energy consumption* accounts for 39%, *other network-related* costs 7%, resulting in a ratio 1:5.6. As a result, the reduction introduced by the enablers for service management has an impact of 8.5% on the *energy consumption* cost, 1.5% on the *other network-related* costs.

Table 7-4: Quantitative estimation of the impact on the cost items of some Hexa-X technical enablers for the "Fully merged cyber-physical worlds" use case.

Tech enabler family	Potential improvement	Cost items affected	Cost item reduction
6G RAN	50%	RAN infrastructure	50%
Service management	10%	Energy consumption	8.5%
		Other network-related costs	1.5%

Based on Table 7-3 and the histogram in Figure 7-4, this analysis can provide a quantitative TCO saving estimation. By re-scaling the histogram to set the overall TCO to 100 (down from the initial 139), it is possible to determine the cost sharing for each cost item:

- RAN infrastructure 48.2%
- Energy consumption 28%
- Backhaul 12.2%
- CN 6.6%
- *Other network-related* costs 5%

With the introduction of the 6G RAN enablers, the RAN infrastructure cost item can be reduced from 48.2% to 24.1% of the overall TCO. Likewise, the service and management enablers help to reduce the energy consumption cost item from 28% to 25.7%, as well as the other network-related costs by 0.08% (from 5% to 4.9%). Figure 7-5 depicts the potential weight of each cost item when applying the two technical enabler families, resulting in 26.4% reduction of the total 6G network TCO compared to the baseline architecture, i.e., 5G NR SA.

The purpose of this analysis was to investigate the potential of the technological enablers to reduce the 6G network TCO. As already discussed, the 6G architecture is still in process of being defined, making it difficult to find reliable data for making reliable evaluations on the impact of each technological enabler family on the cost items. However, it is worth highlighting that this study only considers two out of the four enabler families that impact the cost items, thus – assuming that also the other two families can introduce positive effects – it is reasonable to expect that the 30% reduction target is something provable by future research. Conclusively, as 6G architecture will be defined and more precise data will become available, further studies will be able to provide a more in-depth analysis of TCO comparison between 6G and 5G NR SA.

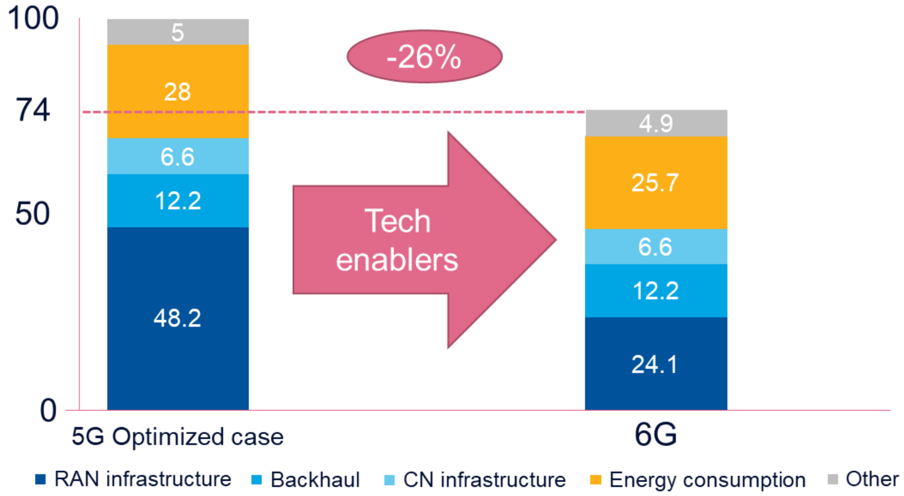


Figure 7-5: TCO comparison between 5G optimized case [GSM19] and 6G for the "Fully merged cyber-physical worlds" use case.

7.3 Considerations regarding the role of industry, policy makers and academia

Hexa-X have identified the following stakeholders and have identified some of their connections to 6G development: regulators and policy makers, MNOs, infrastructure and technology vendors, service and application providers, users, and research community [Mat22]. Users decide which ICT solutions and services they use and their requirements on sustainability need to be identified and incorporated into R&D early on. Users need real-life unbiased data for decision making without greenwashing. MNOs operate the communication infrastructure resulting in GHG emissions. MNOs should disclose data on sustainability to different stakeholders including customers as well as developers and researchers to promote the development of sustainable solutions. The research community including academia trains future talents and is in the process of including sustainability into education, training, and research activities. The research community is the source of unbiased research results for decision making to make impact. Service and application providers, including developers, need to design sustainable solutions to solve the major sustainability challenges. Regulators and policy makers define the rules and conditions that the ICT solutions and service must fulfil. Upcoming sustainability-based conditions should not be too different between countries to avoid market fragmentation. Technology vendors develop the infrastructure that needs to incorporate sustainability principles and minimize environmental impact and resource consumption.

Technical requirements on sustainability:

- To academia, research, and technology institutes: Further studies are needed to model EE behavior of each component/sub-systems/computation hardware, regarding different traffic loads (high but also almost zero ones). Such unitary hardware consumption models will be used to assess performance of a larger system and allow to optimize performance/energy consumption regarding the scenario requirements. However, it seems difficult to get a single entity (from academia or industry) that could collect and aggregate all these models. An open consortium of stakeholders will probably more relevant in order to derivate future energy consumption trends regarding 6G usages all along the operational period.
- To industry: plan to natively implement the EE vs performance (QoS, data rate, latency) trade-off. One difficulty of EE and TCO KPI target definition is that we cannot, early in the 6G design, assess the EE performance of component under development. Or at least to plan by design the ability to monitor the most consuming subcomponents in order to implement future EE optimization during the operational decade period.

- Organizations and companies in all sectors should not only develop, implement and adopt innovative ICT solutions and services capable of reducing GHG emissions and footprints but also widen and drive their adoption through policies, incentives and appropriate labor organization and management; this should be supported by policy makers through suitable campaigns.

All initiatives towards zero watt @ zero load (sleep modes …)

- To network providers: make it possible for 6G users to dynamically evaluate/proxy the EE of their usage.
- To IT, applications programmers, but also general public: Recommendation at higher level, in order to induce less no useful transmitted bit at the application layer; we could edit a metric that allow to gauge to inflation by giving a ‘virtual’ cost to the transmitted info and let the user judges the usefulness of the app regarding its consumption.

8 Conclusions

This document presented the updated analysis of trends in society and technology relevant for the design of 6G. Hexa-X vision on 6G was also presented. This is a strong vision formulated by a strong flagship project: 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 can generate unprecedented economic opportunities towards the 2030 timeframe. Identification of 6G business aspects helps with economical understanding of 6G. Future work should build on top of the vision and the identified trends and aspects, taking into account results of further work globally. One strong avenue for such work is the next European level 6G flagship Hexa-X-II.

The mapping of Hexa-X use cases and requirements to other ICT-52 projects, research papers, and whitepapers showed already a significant level of alignment within the community. With 6G research now shifting more to a system and realization phase, further critical discussion of the associated KVIs is needed. Hexa-X provided a starting point for the assessment of the 6G system in terms of sustainability, inclusion, flexibility, and trustworthiness. However, the associated trade-offs between KPIs and KVIs, and challenges with respect to quantification of KVIs as highlighted in this document, as well as the strong relation of KVIs to the respective use cases that are being realized still poses plenty of open questions for future research.

This report provided the latest version of Hexa-X E2E architecture. The presented architecture developed based on the progress in all technical work packages of the project as well as reflecting the 6G vison and supporting the requirements from the envisioned use cases. Moving forward, this E2E architecture design can be used as foundation for more comprehensive studies on individual enablers and eventually provide a concrete conclusion on the design of the 6G E2E architecture.

The growing demand for larger computational resources, increased connectivity, and higher bandwidth to support the digital economy has led to higher network traffic loads, causing the overall energy consumption in the ICT sector to rise. The development of 6G networks brings new opportunities and challenges for achieving sustainability goals while fulfilling the growing demands on the digital economy. Unlike previous generations, new approaches should be adopted in the design of 6G infrastructure and operations building on the UN SDGs and adapting them for the ICT sector. 6G technology is likely to be influenced by diverse environmental sustainability trends, such as decarbonization in energy sources and processes, adoption of circular economy principles, development of sustainable product designs, use of green alternative materials, production of modular and durable equipment, etc. The enablement potential of 6G in helping other sectors reduce their emissions will be leveraged with emerging technologies and innovative solutions, such as edge computing, automation, intelligent energy management systems, etc. The role of industry, academia, and other decision-makers and stakeholders in achieving sustainable development of 6G is crucial especially for the identification of their needs in terms of ICT solutions and sustainability requirements.

Concerning spectrum, several aspects relevant to e.g., extending spectrum utilization in frequency ranges already in use (i.e., low, mid, and mm-wave) and in potential new frequency ranges (e.g., 7-15 GHz in the centimetric range and 92-275 GHz in the sub-THz range to address 6G service requirements have been considered. Furthermore, linked with relevant studies carried out in the technical work packages, enhancements to further optimise spectrum utilization (i.e., , distributed MIMO and advanced carrier aggregation for 3GPP technologies and interference-controlled operation in 6G “Networks in Network” (NiN) shared spectrum scenarios) have also been addressed, as well as the use of AI/ML in certain spectrum usage scenarios (for e.g., throughput and spectral efficiency improvement, AI-assisted spectrum sharing in non-wide area networks scenarios, spectrum and computing resources dynamic orchestration in edge cloud server offloading, Digital Twin-based human presence model for flexible and dynamic spectrum management at mm-wave/sub-THz/THz frequencies). An overview on initiatives to enable new spectrum for mobile has been also addressed, complemented by a set of additional high-level spectrum-related elements that were deeply considered at both Task and Project level. The way to solve the 6G spectrum puzzle has just started, however the first steps have already begun and in the right direction.

The nature of network security requires an integral approach, addressing simultaneously E2E properties and the interactions among different layers to properly address security threats. The Hexa-X security team has addressed the architectural mapping of security components, analyzed the effect of the relevant technologies on network service trustworthiness, and proposed mechanisms for assessing this trustworthiness, with a specific emphasis on the influence of AI techniques, their explainability and their impact in privacy. These results constitute a sound foundation for further development and standardization of security 6G technologies. Further experimentation will be required to consolidate the features and characterize the application environments of these security technologies.

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Annex A: Positioning of Hexa-X use cases with use cases identified by other projects of ICT-52

This annex provides more details on the positioning of Hexa-X work on use cases and requirements with respect to the outcomes from other ICT-52 projects. This analysis is not meant to be exhaustive but identifies, for each use case family, use cases with similarities or which could fit into Hexa-X use cases. The KPIs identified are mentioned, with a comparison with Hexa-X KPIs identified for similar use cases.

Robots to cobots

	Use cases	KPIs, gaps and divergencies
6G BRAINS	*[6GB21-D21], [6GB21-D22]* - Airports Services and Baggage Handling - Smart Transportation Vehicles: Localisation and Video Processing Offloading	- Localisation accuracy: 1 mm to 1 cm every 20 ms (1-5 cm in Hexa-X) - High data rate up to 3 Gbit/s for video transmission (related to Hexa-X fully merged cyber-physical world)
AI@Edge	*[AI@21-D21]* - Edge AI assisted monitoring of linear infrastructures using drones in BVLOS operation	- No KPIs and KVIs definitions of target values
DEDICAT 6G	*[DED22-D23], [DED22-D61]* - Smart warehousing	- Low E2E latency and high energy efficiency - Proposes additional KPIs related to product quality check and safety of workers
REINDEER	*[REI21-D11]* - Human and robot co-working	- High reliability: 99.999% (99.9999% in Hexa-X) - Low latency: 1 ms (range 0,5-50 ms in Hexa-X)
RISE-6G	*[RIS22-D23], [RIS22-D24]* - AGV loc. and navigation - Collaborative manufacturing	- Localisation accuracy: 1-10 cm (1-5 cm in Hexa-X) - No specification of service latency, reliability, availability

Telepresence

	Use cases	KPIs, gaps and divergencies
DEDICAT 6G	[DED22-D23], [DED22-D61] - Enhanced experience	- E2E latency below 200 ms (20 ms in Hexa-X) - Per user bit rate > 5 Mbit/s (no per user figure in Hexa-X) - Reliability: 99.999% (99.9% in Hexa-X) - Availability: 99% (same as Hexa-X) - More than 50% traffic offloaded to mobile access points (no Hexa-X definition)
REINDEER	[REI21-D11] - Augmented reality for sports events	- User mobility under 2 m/s (no definition in Hexa-X) - Number of connections (defined in Hexa-X as connection density)

	- Augmented reality for professional applications - Virtual reality home gaming	- Localisation accuracy - High peak sum rate: 150 Mbit/s of UHD video stream - Low latency: less than 1 ms for VR and less than 100 ms for other games (relatable to Hexa-X fully merged cyber physical worlds)

Massive twining

	Use cases	KPIs, gaps and divergencies
AI@Edge	[AI@21-D21] - Virtual validation of vehicle cooperative perception	- Low latency: no specified target values
REINDEER	[REI21-D11] - Real-time digital twins in manufacturing	- Reliability: greater than 99.999% (Hexa-X range 99.9-99.999999%) - E2E latency: 1-50 ms (Hexa-X range 0.1-100 ms) - User experience data rate: 1 Mbit/s UL and DL + 20 Mbit/s/m2 traffic volume density (Hexa-X specifies peak and average data rate) - High position accuracy (Hexa-X provides several target values)
RISE-6G	[RIS22-D23], [RIS22-D24] - Kitting process monitoring - Component position in a container - Railway	- High positioning accuracy, enhanced by the use of RISs (less evidently investigated in Hexa-X despite some technical contributions)

Enabling sustainability

	Use cases	KPIs, gaps and divergencies
6G BRAINS	[6GB21-D21], [6GB21-D22] - Animal Tracking in Indoor Farming Scenarios	- Localisation accuracy: 1 mm-1cm and 1 degree orientation accuracy - Broadband access for mMTC from 10 to 20 thousand animals - No energy efficiency figures
DAEMON	[DAE21-D21] - Reconfigurable Intelligent Surfaces Control - Energy-aware VNF control & orchestration	- RISs control energy consumption below 100 mW - 50% energy saving thanks to network intelligence assisted VNF placement (investigated by Hexa-X to some extent in technical work packages) - UN SDGs explicitly mentioned
DEDICAT 6G	[DED22-D23], [DED22-D61] - No use cases dedicated to sustainability, but target vales proposed	- Factor of 10 of energy consumption reduction in edge devices and potentially in the system overall
RISE-6G	[RIS22-D23], [RIS22-D24] - No use cases dedicated to sustainability, but target vales proposed	- Energy efficiency with and without RISs (no target values specified) - EMF protection for workers, or specific public and private areas

Hyperconnected resilient infrastructures

	Use cases	KPIs, gaps and divergencies
AI@Edge	[AI@21-D21] - Public safety or disaster events	- n/a
DEDICAT 6G	[DED22-D23], [DED22-D61] - Secure and resilient orchestration of large IIoT networks	- n/a

Trusted embedded networks

	Use cases	KPIs, gaps and divergencies
REINDEER	[REI21-D11] - Patient monitoring	- More relaxed requirements with respect to Hexa-X, in terms of data rate, latency, spatial resolution, reliability and availability

Annex B: Assessment of enablement effect

Analysis of the objective on the enablement effect

Background

The original enablement objective of Hexa-X refers to [Ber15] in direct proximity of the target level of >30% impact.

"Societal impact targets: enabling reductions of emissions of (>30%) CO2 eq. in 6G-powered sectors of society [Ber15]"

Rather than an exact measure of the possible decarbonization effect of 6G (not feasible to analyse at the time of the application), this should be seen as an expression of the aspiration of Hexa-X and an ambition to drive the development of Hexa-X in a sustainable direction. At this point, with more knowledge about Hexa-X and with the methodologies for analysing such effects advancing with the arrival of ITU-T L.1480 [L1480], the project has revisited the target and analysed its implications based on this new knowledge base.

The article [Ber15] that was referred to in the enablement objective, derives an enablement potential of 15% for ICT in a 2030 timeframe as one of its reduction scenarios, the High-Level Reduction Scenario. The 30% level could thus be seen as a doubling of this reduction level.

To understand what it would take for 6G to double this already challenging potential, this section will revisit the original source to study its applicability and relevance as a basis for expressing the 6G ambition.

Analysis of [Ber15]

The methodological approach taken in [Ber15] include five main steps to estimate the global potential reductions in GHG emissions from the studied ICT solutions including (i) use of recognized sources to model future global overall GHG emissions and their allocation between end-user sectors[2] as a basis for deriving addressable emissions; (ii) gathering data on GHG emissions reductions due to ICT solutions while applying a life cycle perspective to the extent possible; (iii) defining reduction scenarios and setting reduction factors for the different ICT solutions; (iv) calculating the potential reductions of the global GHG emissions for target year for each scenario, and applicable solutions and reduction factors; and (v) taking measures to avoid double-counting within and between sectors as far as possible.

In this section different aspects of these different steps are analysed from the perspective of current applicability and limitations, and key findings are summarized as observations (See Summary of observations).

The underlying **research question** of [Ber15] concerns the technology potential of reducing greenhouse gas (GHG) emissions in different end-user sectors. As such it specifically factors out any restrictions in realizing this potential due to policy, behaviors or financial limitations which impact the likelihood of benefitting from these potentials. Consequently, to make the research question of Hexa-X compatible with [Ber15] the objective of "*enabling reductions of emissions of (>30%) CO2 eq. in 6G-powered sectors of society*" should be seen as aiming at a technology potential under favorable policy and other conditions rather than at actual reductions. Given the development of the discourse regarding enablement potentials since the objective was agreed, it is recommended to give sustainability objectives for technologies a more explicit framing in terms of contextual factors such as assumed developments of policy, finance, and behavioral preferences (see Observation I).

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[2] End-users of energy, fuels, and raw materials

From a **time, boundary perspective,** it is noted that Malmodin and Bergmark published their article in 2015 [Ber15], with reference literature from 2000-2014. This impacts the knowledge level regarding the impact of individual solutions. Moreover, the reference future scenario for global emissions in 2030 is based on IPCC AR4 [IPCC4]. The applicable IPCC AR [IPCC5] at the start of Hexa-X was AR5, and during the last year IPCC has published AR6 [IPCC6]. Similarly, the allocation of GHG emissions to individual sectors is based on data from the World Resource Institute (WRI) covering the period 2000-2005 and the assumption that the relative shares of emissions between end-use sectors would remain. For future objectives and to understand the applicability of [Ber15] as a basis for setting such objectives the implications of more recent sources for global GHG emissions and their allocation to end-use sectors needs consideration. Finally, year 2030 is seen in [Ber15], not as an exact point in time, but from a 2015 perspective, a year far enough into the future for technology to be developed and deployed and for policy and other conditions to develop. However, emission reductions refer to this future year and not to an aggregated effect from a baseline year until the target year. It is also noted that reductions are not set in relation to a baseline year but to a forecasted situation in the target year without the ICT solutions applied.

In accordance with the chosen time boundary and references [IPCC4] the global emissions, the selected **baseline for global emissions** in [Ber15] was set to 63,5 Gt CO_2e as average of the six min scenarios for 2030. To provide an up to date baseline for 6G development, the scenarios, the global emission level, the allocation between end-use sectors and the applicable year would need to be reassessed (see Observation II-IV).

The **ICT solutions assessed** of [Ber15] were categorized as "smart xxx" including smart grid, smart buildings, smart transport, smart travel, smart work, smart services, and by external reference, smart agriculture. For each of these, a measured effect of solutions in use before 2015 were collected. As relevant realizations of the solutions as possible were preferred, however measured data for widely adopted applications of solutions were only available to a limited extent. The **emission reduction potentials for the different categories of solutions** are calculated by [Ber15] in relation to addressable emissions. The **emission reduction potentials** are defined for two scenarios i) Medium Reduction Potential Scenario (MRPS) and ii) High Reduction Potential Scenario (HRPS). MRPS is mainly representing the median of the potentials shown in the reference applications identified for each solution, HRPS corresponds to the highest potential from the references which was considered relevant in a global scenario. These solution reduction percentages are decreased compared to the data sources if these are e.g., considered too limited in coverage or seen as having potential early adopters' biases. In contrast, these percentages are next applied to **all** applicable emissions within a sector, i.e., economic, or other restrictions, such as scalability, are not considered when defining the addressable emissions. Hence, the **addressable emissions** are not considering limitations due to high prices or deployment restrictions. In a study aiming to capture actual effects rather than technological potentials, such factors would need consideration when building the scenarios (see Observation V-IX).

The potential GHG emission reduction per solution

Table B- 1: Expected applicability of [Ber15] emission reduction potentials to 6G´s additional effect. In the table, the orange colour denotes a potential but not yet established additional potential by 6G. Summarizes the solutions considered by [Ber15] as well as their relevance for any additional potential of 6G. The table does not consider whether there are other potential solutions where 6G may contribute to emission reductions.

Table B- 1: Expected applicability of [Ber15] emission reduction potentials to 6G´s additional effect. In the table, the orange colour denotes a potential but not yet established additional potential by 6G.

ICT solution	MRPS/ HRPS % of solution*	Addressable emissions % of emissions from (sub)sector	Expected applicability to 6G incremental potential (rational)
Smart grids: Smart metering	5 / 10	Residential buildings energy: 57% of Buildings sector	**Addressable emissions**: Not related to ICT

ICT solution	MRPS/ HRPS % of solution*	Addressable emissions % of emissions from (sub)sector	Expected applicability to 6G incremental potential (rational)
			Reduction potential: None (2G-5G systems good enough) - the potential is set by behaviours
Power grid optimization	15 / 30	Transmission and distribution electricity losses: 8% of electricity, 2% of global emissions	**Addressable emissions**: Not related to ICT **Reduction potential:** Maybe, but levers for an additional potential by 6G have not yet been identified.
Facilitating renewable energy sources	2 / 7	Electricity production: 25% of global emissions	**Addressable emissions**: Not related to ICT **Reduction potential**: Maybe, but levers for an additional potential by 6G have not yet been identified.
Smart buildings: Smart building solutions for offices, stores, hotels, schools, etc.	10 / 15	Energy consumption in offices, stores, hotels, schools, etc.: 31% of Buildings sector	**Addressable emissions**: Not related to ICT Reduction potential: No (2G-5G systems good enough)- the potential is set by behaviours
Smart building solutions for healthcare, food stores and services, etc.	3 / 5	Energy consumption in healthcare, food stores and services, etc.: 9% of Buildings sector	**Addressable emissions**: Not related to ICT **Reduction potential:** Maybe, in case of additional potential for remote healthcare using 6G, but an additional potential by 6G has not yet been identified.
Smart transports: Route optimization, fleet management	10 / 20	All road transport: 58% of Transport sector	**Addressable emissions:** Not related to ICT **Reduction potential:** Maybe, but levers for an additional potential by 6G have not yet been identified.
Facilitating the choice of transport mode with help of ICT	5 / 10	Shift from air to train/ship, 10% of Transport sector	**Addressable emissions:** Not related to ICT **Reduction potential:** Maybe, but levers for an additional potential by 6G have not yet been identified.
Smart work: Telemeetings, etc.	20 / 30	Air business travel: 7% of Travel sector	**Addressable emissions:** Partly related to ICT

ICT solution	MRPS/ HRPS % of solution*	Addressable emissions % of emissions from (sub)sector	Expected applicability to 6G incremental potential (rational)
			Reduction potential: Maybe if new 6G applications (XR etc) could reduce travel need, but additional potential by 6G has not yet been identified
Telemeetings, etc.	10 / 20	Car business travel: 12% of Travel sector	**Addressable emissions:** Partly related to ICT **Reduction potential**: Maybe if new 6G applications (XR etc) could reduce travel need, but levers for an additional potential by 6G have not yet been identified.
Telemeetings, etc.	12.5 / 25	Hotels used for business, 1.6% of Building sector	**Addressable emissions:** Partly related to ICT **Reduction potential:** Maybe if new 6G applications (XR etc) could reduce travel need, but additional potential by 6G has not yet been identified
Reduced office space, due to ICT	10 / 20	Office buildings: 7% of Buildings sector	**Addressable emissions:** Partly related to ICT Reduction potential: Maybe if new 6G applications (XR etc) could reduce office presence, but levers for an additional potential by 6G have not yet been identified.
Teleworking	15 / 30	25% of private car travel is allocated to employees who could work from home to some extent: 17.5% of Travel sector	**Addressable emissions:** Partly related to ICT **Reduction potential:** Maybe if new 6G applications (XR etc) could reduce travel need, but levers for an additional potential by 6G have not yet been identified.
Smart travel: Smart public travel	5 / 10	Private car travel: 35% of Travel sector	**Addressable emissions**: Limited connection to ICT **Reduction potential:** Maybe if new 6G applications (XR etc) could reduce travel need, but levers for an additional potential by 6G have not yet been identified.

ICT solution	MRPS/ HRPS % of solution*	Addressable emissions % of emissions from (sub)sector	Expected applicability to 6G incremental potential (rational)
Fleet car management	8 / 15	Commercial car travel: 12% of Travel sector	**Addressable emissions:** Not related to ICT **Reduction potential:** Maybe, but levers for an additional potential by 6G have not yet been identified.
Route optimization	5 / 10	All road travel: 82% of Travel sector	**Addressable emissions:** Not related to ICT **Reduction potential:** Maybe, but levers for an additional potential by 6G have not yet been identified.
Smart services: e-commerce solutions, products-to-services	5 / 10	All transports and industry: 100% of Transport sector 100% of Industry sector	**Addressable emissions:** Not related to ICT **Reduction potential:** Maybe, but levers for an additional potential by 6G have not yet been identified.
Smart agriculture incl. land use:	7 / 13	Agriculture including land use: 100% of Agriculture sector	**Addressable emissions:** Not related to ICT **Reduction potential:** Maybe, but additional potential by 6G has not yet been identified. Besides, the baseline value has higher uncertainties

Table B- 1 gives a summary of 6G use cases considering the knowledge of their added potential compared to [Ber15]. (See Observation X)

Table B- 2: Status of knowledge regarding 6G use cases added potential.

6G use cases [HEX22-D13]	Identified added potential compared to 5G
E-health for all	See smart services (Table B- 1)
Digital twins for manufacturing	Detailed lever not yet identified
Fully merged cyber-physical world	Detailed lever not yet identified
Interacting & cooperative mobile robots & flexible manufacturing	Detailed lever not yet identified
Immersive smart-cities and integrated micro-networks for smart cities	Detailed lever not yet identified
Infrastructure-less network extensions and embedded networks	Detailed lever not yet identified

In summary, at this point it has not yet been possible to establish the levers for 6G´s contribution to further emission reductions as the application of use cases is not yet sufficiently detailed. This does not imply that such levers are missing, but a more detailed understanding of 6G capabilities and use cases is needed before the levers could be established, and before any emission reduction potential could be quantified or verified as additional compared to today´s situation or 5G. As 6G use case applications evolves a more detailed analysis of potential 6G emission reduction levers will become possible. In line with this, the current state of understanding is summarized in Table B- 3.

Table B- 3: Summary of potentials in relation to overall global emissions from [Ber15] and the current understanding of the added emission reduction potential of 6G.

ICT solution category	HRPS	MRPS	Added potential compared to 5G
Smart grid	3,9%	1,6%	Lever not identified or detailed
Smart buildings	1,4%	0,9%	Lever not identified or detailed
Smart transport	1,1%	0,6%	Lever not identified or detailed
Smart travel	1,9%	0,9%	Possible lever: by enabling additional groups of workers access to remote work
Smart work	1,9%	0,9%	Possible lever: by enabling additional groups of workers access to remote work
Smart services	3,2%	1,6%	Lever not identified or detailed
Smart agriculture	2,9%	1,3%	Lever not identified or detailed
Total[A]	**15%**	**7%**	Uncertain

[A] *Rounded values compensated for double calculations and rounding effects. All values are set in relation to global emissions.*

Restrictions of the methodology applied by [Ber15]

As described in [Ber15] the approach taken has several limitations that should be considered when communicating future results of similar assessments for 6G.

- As published data on achieved reductions often do not consider the footprint of ICT itself, the footprint of the ICT solution must be calculated and extracted from the positive effect investigated in [Ber15]. Thus, for a future quantification of 6G, the effect of its own footprint would need to be considered as well. This is in line with ITU-T L.1480 [L1480]. Thus, the footprint of the ICT solution has to be calculated and extracted from the positive effects.
- The strength of the approach was considered by the authors to be its transparency compared to other similar studies, and the association with measured achievements of ICT in specific applications. While the latter is hard to achieve for a future technology, the importance of the transparency principle increases.
- Different scenarios were applied due to the high built-in uncertainties. This approach should be even more important to follow when assessing future technologies (in contrast to the existing ones explored by [Ber15]).
- Uncertainty sources include the many assumptions needed, the limited availability of case studies and the use of scaling from individual case studies to global potential. On top of this the uncertainties related to future development are added.
- The GHG reduction potentials set by [Ber15] were based on the limited number of case studies available at the time of data collection. The authors particularly suggest that reduction potentials can – and should – be amended as more references relating to actual emission savings become available. Particularly, ICT solutions for agriculture and smart consumer and services should be seen as more uncertain. From the perspective of estimating the effect of a future technology a gradual refinement of quantifications could be expected.
- Furthermore, [Ber15] acknowledges that the potential and the addressable emissions could be detailed in order to set more well-founded reduction potentials for individual services. For instance, a better understanding of how e-learning affects travelling requires that the share of trips related to training and education is known. This detailing of addressable emissions could be considered from the start in a future quantification of 6G if feasible.

- The IPCC scenarios used for the forecast of overall emissions may have taken some general technology improvements into account when developing their basic scenarios which could have led to a partial double-counting of the potential related to facilitated integration of small-scale renewable energy. From a 6G assessment perspective it would be important to evaluate how IPCC has considered technology development in their AR6 scenarios [IPCC6].
- IPCC mitigation scenarios were not considered and could have been studied as well while making sure to avoid double-counting of potentials. This opportunity remains relevant for a 6G assessment.
- Reduction potentials were applied on forecasted 2030 emissions which are higher than the emissions of the baseline year. Hence, in absolute numbers there might not be a reduction compared to today. Rather, ICT may slow down the expected increase in overall emissions. The difference between a percentage reduction and the absolute emissions needs to be clarified in communication around results.
- The GHG reductions potential forecasted in [Ber15] are to be seen as a potential for the assessed solutions which is reachable based on the technology available today. Additional opportunities for reductions may exist due to new technology or the new use of existing technology. On the other hand, the reductions potential forecasted represent technological potential only. As most input data emerge from small scale projects, often driven due to cost/energy or GHG saving initiatives, it seems reasonable to assume that realization of global potentials demands involvement of policy makers, companies, and the general public, through mechanisms such as policy measures, and collaborations between industry and the public sector.
- The [Ber15] study was focused on ICTs (positive) effects in other sectors, while not evaluating if ICT might also have negative effects beyond its direct footprint. More recently such estimates are often referred to as cherry picking as any adverse effects are omitted. Hence, for coming assessments and communication regarding 6Gs emission reduction potential the selection of use cases needs further consideration.

Summary of observation

Based on the above analysis some key observations are made as summarized below:

Observation I: The [Ber15] paper focuses on a GHG emission reduction potential offered by technology but says nothing about the likelihood for such reductions to happen. Technology in itself can enable the potential to reduce GHG emissions, but the actual outcome will depend on political, financial and behavioral aspects. It is concluded that the 30% level should be considered technological potential, although this is not clearly visible in the objective text. For future targets, it is recommended to give sustainability objectives for technologies a more explicit framing in terms of contextual factors such as assumed developments of policy, finance, and behavioral preferences.

Observation II: The global emissions scenario of [Ber15] is outdated. The global emissions scenario used as a baseline is no longer based on latest IPCC science and the allocation between sectors is not based on recent developments. To provide an up-to-date baseline for 6G development, the scenarios, the global emission level, the allocation between end-use sectors and the applicable year would need to be reassessed.

Observation III: Hexa-X does not define a target year and is not expected to be in full use year 2030, so the time perspective is likely to be different from [Ber15], meaning that the overall emissions and the allocation between end-use sectors may need to consider a different year.

Observation IV: The Hexa-X baseline situation could be argued to be either of two options (both different to that of [Ber15]): i) the situation for the reference year with 5G already widely deployed ii) the situation for the year when Hexa-X application was approved with a more limited deployment of 5G. These options would demand different approaches.

Observation V: Additional 6G potential could emerge from three different sources: additional reduction potential of the identified solutions, potential reductions form new solutions, increase or wider application of the solutions to optimize or replace activities associated with the addressable emissions.

Observation VI: Addressable emissions have not been restricted with regards to economical and other factors that could limit actual application of the assessed ICT solutions. Hence, the way the addressable emissions are defined by [Ber15] are in most cases independent of the emission reduction potential per ICT solution and will from that perspective not change when 6G is applied but will depend on other contextual factors.

Observation VII: None of the emission reduction potential values of [Ber15] have been estimated using L.1480, and methodologies have evolved since 2015 which will impact how a quantification of 6G should be done.

Observation VIII: The footprint of the ICT solution is not subtracted from the positive effects but would need to be considered to align with [L1480]. If not included this would need to be clearly communicated.

Observation IX: Since the study is old some of the potential reductions could be expected to already have been integrated into the applicable baseline.

Observation X: 6G might have the potential to impact the reduction potential of many solutions. However, the levers for 6G to do so have mostly not yet been identified or detailed as the use cases and capabilities of 6G are not yet defined at a level that allows for establishing such levers.

Rather than an exact measure of the possible decarbonization effect of 6G (not feasible to analyse at the time of the application), the 30% GHG emission reduction target should be seen as an expression of the aspiration of Hexa-X and an ambition to drive the development of Hexa-X in a sustainable direction. At this point, with more knowledge about Hexa-X and with the methodologies for analysing such effects advancing with the arrival of ITU-T L.1480 [L1480], the project has revisited the target and analysed its implications based on this new knowledge base.

The article [Ber15] that was a reference for setting the enablement objective and was therefore further analyzed in this appendix. It was concluded that [Ber15] could not be directly applied to derive the potential enabling effects for 6G´s potential GHG emissions reductions. However, the approach applied, in combination with later methodology work, in particular (ITU L.1480, 2022), gives valuable insights for future quantifications of 6G´s emission reduction potential summarized in this appendix as Observations. Overall, this appendix summarized the complexities involved when deriving a reasonable 6G potential and analyzed the current knowledge level regarding the additional levers of 6G that could drive emission reductions. This analysis is expected to be helpful when continuing the study of 6G´s enablement potential.

Application of ITU-T L.1480 future technology scenarios

The assessment is performed according to ITU-T L.1480. The assessment procedure steps are summarized in Figure B- 1.

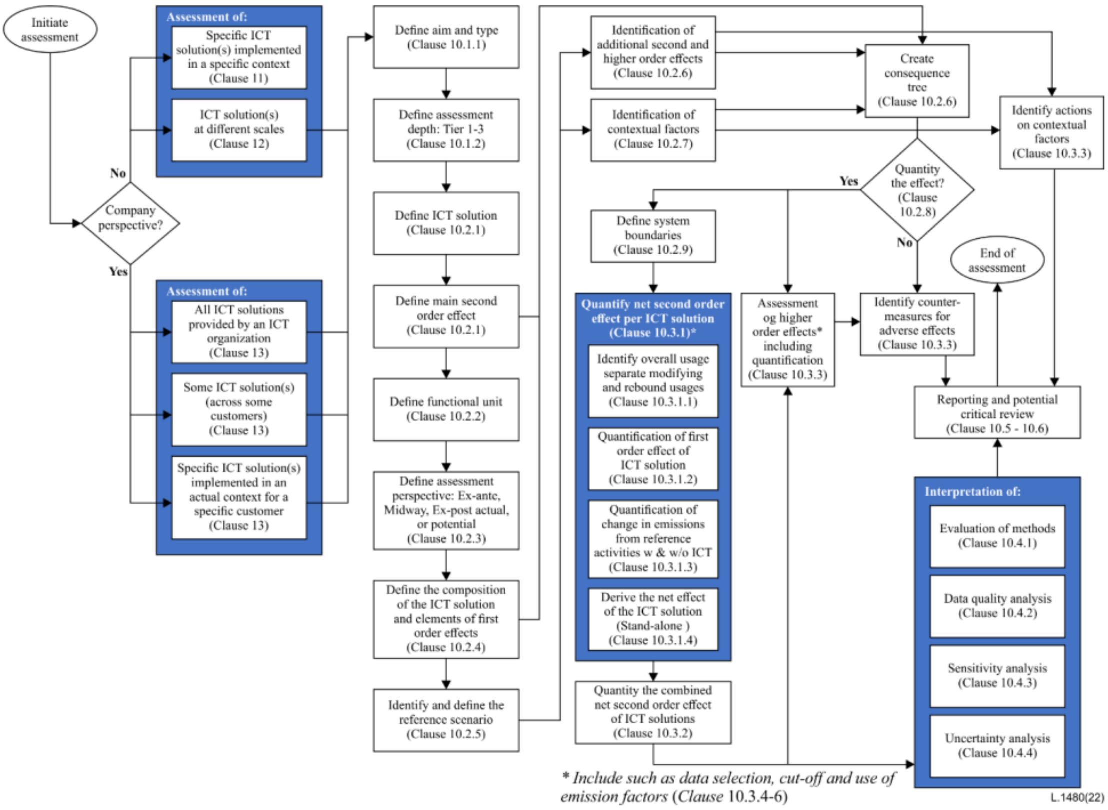

Figure B- 1: Sketch of assessment workflow from ITU-T L.1480.

In order to evaluate the feasibility of applying the L.1480 standard to the non-existent ICT solution 6G, indicative colors are used according to the following code to indicate the feasibility of the different steps of the L.1480 procedure:

- PiP: Possible in principle at this stage
- PvC: Potentially very challenging
- NF: Not feasible at this stage (due to lack of data, etc.)

Step 1 – Define the goal of the assessment

1.1) Define the aim and type of the assessment (Clause 10.1.1 of L.1480-PiP-)

L.1480 can be applied to several types of assessment. In case of a future technology, "a general usage of one or several ICT solution(s) (clause 12)" may be preferred over "specific implementation of one or several ICT solution(s) (clause 11)". However, it might be easier to visualize a specific case to understand implications and limitations. In any case, the scale for which the assessment is performed will depend on data availability (and reliability).

Receiver/audience of assessment: Hexa-X stakeholders including Hexa-X-II. ITU.

1.2) Define the assessment depth: Tier 1, Tier 2, or Tier 3 (clause 10.1.2 of L.1480-PiP-)

Tier 1 assessments: Tier 1 assessments shall assess net second order effects and shall also assess impact from contextual factors and higher order effects, by quantitative means if such assessment is considered robust, or else by qualitative means. These assessments are the most in-depth ones.

Tier 2 assessments: Tier 2 assessments shall assess net second order effects and shall identify contextual factors and higher order effects. These are assessments of intermediate depth which do not assess the magnitude of higher order effects.

Tier 3 assessments: Tier 3 assessments shall consider net second order effects and should identify contextual factors and higher order effects. These are the simplest assessments and are not considered rigorous.

As 6G scenarios represent future technologies and are suggested to be examined for a 1-year timespan in 2035, an assessment with depth tier 3 (Screening / First Approximation) would be the only option.

Step 2 – Scoping

2.0) Scenario definition:

(In L.1480, this refers to Clause 10.2.1-PiP-. "Definition of the ICT solution(s) and the main second order effect" for Solution scenario, and Clause 10.2.5 -PiP-. "Identification and definition of reference scenarios" for reference scenario. Defining a fictive, high-level scenario is feasible, the challenge is to find a basis for realistic assumptions.)

For our purpose, by way of examples, we refer to two fictive scenarios where 6G enables i) completely automated factories where no human needs to be present (reducing size of factory, reducing heating and lighting in the factory) and ii) virtual remote maintenance work (or problem fixing) which reduces business-related travelling.

- *<u>Scenario 1: 6G-enabled fully automated and optimized operations within a factory</u>*
    - *Description: A warehouse equipped with 6G-technology where operations and tasks are fully performed by autonomous robots and machines with minimal, mostly virtual, human intervention.*
    - *Reference Scenario: The presence of human workers in a factory requires appropriate lighting, heating, and cooling, adequate ventilation, and noise control among other facilities, in order to maintain a comfortable and safe working environment. Workers need to travel to work on a daily basis, resulting in increased GHG emissions. Increased waste could result from restauration, restroom and other break facilities. Manual performance of tasks can be inefficient (resulting in increased waste in terms of resources and energy), error-prone, time consuming, and subject to potential safety risks, production variabilities, and human limitations.*
    - *ICT solution scenario: Seamless communication and coordination between robots, automated vehicles, and other machines, using real-time data exchange to enable efficient inventory management, optimized routing and scheduling, and predictive maintenance. Human-machine interactions are only virtual, which results in reductions in factory size, and emissions linked to transport, lighting and heating. Energy waste could be reduced as climate could be automatically controlled using energy management systems (to cool down the space when needed). Predictive analytics to forecast energy demand and supply could optimize energy usage, and energy storage systems help reduce waste of energy generated from renewable energy sources. This is enabled with reliable and high-speed 6G network, low-latency edge computing, and AI algorithms for data analysis and decision-making.*
    - *Challenges and uncertainties:*
        - *Reconfiguration of existing infrastructure*
        - *Development of necessary robotic and automation technology (energy costs)*
        - *Cybersecurity threats and attacks*
        - *Implementation and maintenance costs*
        - *Feasibility of the fully automated situation in a complex manufacturing setting*

- *Scenario 2: Virtual maintenance work and error-fixing enabled by MR instead of on-site visit.*
    - *Description: regular maintenance work as well specific error-fixing which has formerly done by specialists travelling to the affected factory sites is – in a future scenario - transferred into a virtual/remote session where the specialist depends on 6G-enabled MR technology.*
    - *Reference situation: a system/machine is broken, an operative problem has occurred, and production is negatively affected (time pressure). Solution is that a system expert travels (usually by plane) to the destination where the affected site is located. Within hours (or days) of analyzing the problem and running local tests, he/she detects the origin of error and at least starts the problem fixing. After completion he/she flies back.*
    - *ICT solution scenario: a system/machine is broken, an operative problem has occurred, and production is negatively affected (time pressure). In this scenario a local/on-site worker (without expert knowledge) and a system expert (with expert knowledge) collaborate to find and fix the problem. Particularly, the ICT solution 6G in context of the use case Merged Reality Game/Work enables the virtual remote work of the system expert by providing him/her (ultrafast) and detailed on-site impressions (visually, and even more) and interactions. The complete physical presence of the system expert is not necessary anymore. Within hours (or days) of analyzing the problem and running local tests, he/she detects the origin of error and at least starts fixing the problem remotely.*
    - *Challenges and uncertainties:*
        - *Remote maintenance work/problem fixing can potentially be started earlier than in reference scenario (since travel time is omitted)*
        - *Remote maintenance work/problem fixing can potentially take more time than in reference scenario (due to still-existing gap between MR and reality itself)*
        - *Cybersecurity threats and attacks*

2.1) Define the scope by:

• Defining the ICT solution(s) and their main second order effects (clause 10.2.1 of L.1480-PvC-);

The ICT solution under study could be a VR/XR-based solution (including digital twin) based on 6G mobile communication standard which does not exist today. Geographical coverage could in this example be the EU. Temporal coverage could be the year 2035, i.e., a 1 yr. timespan where we assume 6G to be stable, completely deployed, running and use-cases mainly realized.

It is noted that quantification of second order effects can be based on secondary sources and qualified estimates.

At this point only a high-level fictive solution can be defined. To define a detailed composition of a 6G system for the suggested case would not be possible at this stage.

• Defining the functional unit (clause 10.2.2 of L.1480 -PiP-);

The functional unit could be one of the following:

- *Scenario 1: Overall days of operation (factory) during one year*
- *Scenario 2: Maintenance work occasions during one year*

The functional unit should be defined in a way that is valid both for the scenario with the 6G solution applied, and to the reference situation. The functional unit is the unit which emissions values are referred to and it is associated with the value provided by the 6G solution and the reference activity.

• Defining the assessment perspective (clause 10.2.3 of L.1480-PiP-);

Perspective of the assessment is ex-ante, addressing a future potential.

- Defining the composition of the ICT solution(s) and identifying the contributors to its overall first order effects (clause 10.2.4 of L.1480-PvC-);

This is challenging, since 6G is not defined yet. First order effects refer to the overall ICT solution including additional components (HW and SW) needed compared to an off-line or earlier generation solution, e.g., for the considered scenarios, more technological devices installed & deployed (e.g., remote work robot/assistant), more virtual conference and IT systems required. At a later point when the architecture and requirements (e.g. on absolute electricity consumption) are settled in further detail, these could be used to make a first estimate of the expected GHG emissions of operation, and embodied emissions could be estimated based on the relation between use stage and embodied emissions.

- Identifying and defining the reference scenario(s) (Clause 10.2.5 of L.1480-PvC-);

The reference scenario in this assessment is the assumed situation without 6G solution, i.e., with only 5G technology being available in the described scope (EU, year 2035).

- Identifying additional second and higher order effects of the ICT solution(s) and any relevant contextual factors, and document those together with main second order effect and the first order effects following the guidelines for establishment of a consequence tree (clauses 10.2.6 and 10.2.7 of L.1480-PiP-);

Creating a "Consequence tree", as illustrated in Figure B- 2, *in order to structure second and higher order* ***potential*** *effects, with respect to considered application, as indicated in L.1480:*

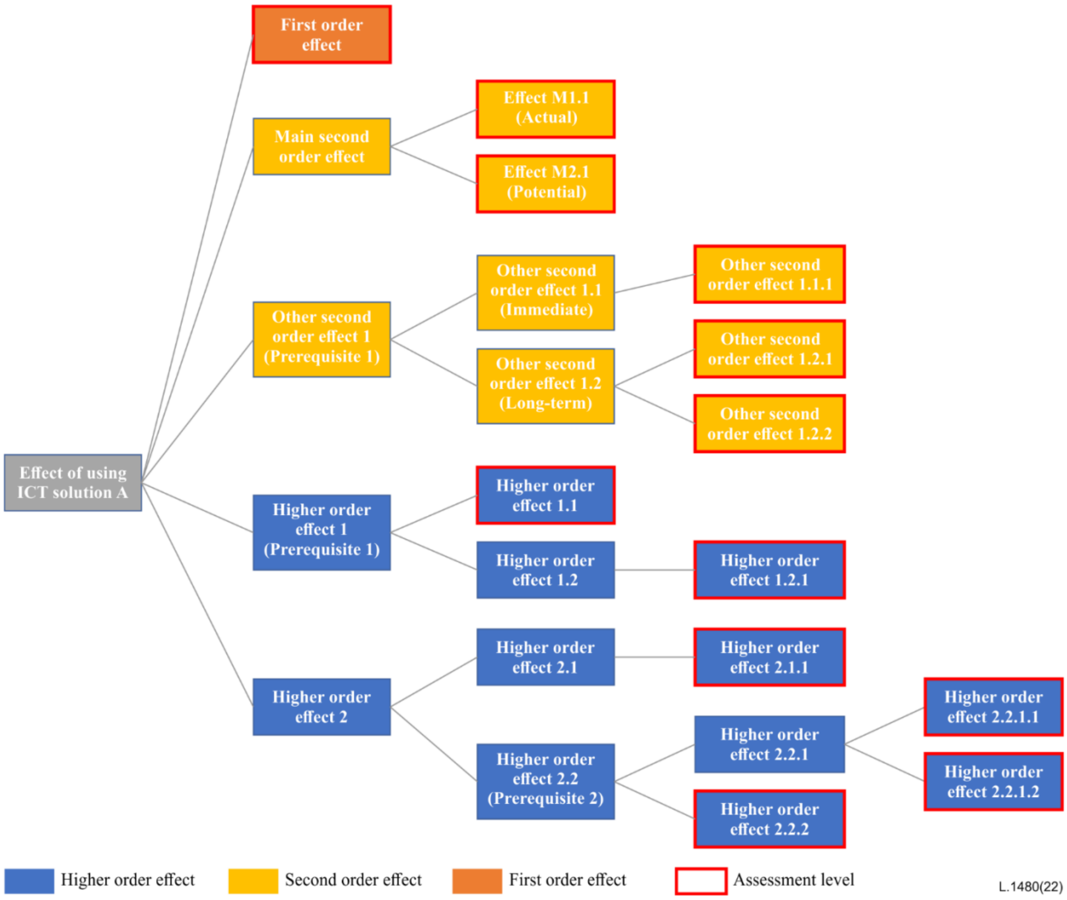

Figure B- 2: Sketch of exemplary consequence tree from ITU-T L.1480 (Figure 3).

➔ ***Consequence tree for 1st scenario: Fully automated factory.***

- *First order effects:*
    - *GHG emissions due to the use of energy and materials associated with the development, production, deployment and operation of necessary robotic, automation technology and of ICT equipment,*
    - *End of life treatment due to the generation of e-waste due to the disposal of outdated or obsolete ICT equipment*
- *Main second order effects:*
    - *Reduction of energy consumption used for climate control (lighting, heating, cooling, etc.).*
    - *Reduction of factory size and greenfield demolition*
    - *Reduction of energy consumption linked to transport of workers*
- *Other second order effects:*
    - *Improved efficiency of energy usage enabled by highly automated factory systems (gain in productivity/efficiency)*
    - *Reduction of waste (efficient use of resources, better material handling and sorting)*
- *Higher order effects:*
    - *Increased emissions linked to improved productivity: Automation has a positive impact on productivity due to several factors such as reduced labor costs, insurance costs, and human error, improved accuracy, efficiency, and product quality. Increased productivity often leads to a decrease in prices which could result in a higher demand and thus higher GHG emissions (rebound) from increased production of goods and services. This extensive production can offset the environmental benefits of automation.*
    - *Increased emissions linked to extensive data collection and storage: Automation technologies require large amounts of data storage and processing, which can lead to increased energy consumption and GHG emissions associated with the data centers.*

➔ ***Consequence tree for 2nd scenario: Remote maintenance work***

- *First order effects:*
    - *GHG emissions due to the use of energy and materials associated with the development, production, deployment and operation of necessary MR and remote technology and of ICT equipment,*
    - *End of life treatment due to the generation of e-waste due to the disposal of outdated or obsolete ICT equipment*
- *Main second order effects:*
    - *Reduction of maintenance/problem fixing-related business trips*
- *Other second order effects:*
    - *Increased energy usage linked to workers remote working at site where worker is living/working*
- *Higher order effects:*
    - *Increase of remote/virtual robots/machinery that assist remote maintenance work and error-fixing (must be held available at sites),*
    - *Increased emissions linked to improved maintenance efficiency and production costs: Remote maintenance has a positive impact on production costs due to reduced travelling/commuting. However, increased productivity often leads to greater GHG emissions (argumentation see above).*

Please note again that all effects listed above are to be considered as ***potential effects*** *(depending on the characteristics of a very concrete scenario). Moreover, this is a first approximation which may not represent a comprehensive set of effects.*

- Selection of effects to be quantified (clause 10.2.8 of L.1480-PiP-);

Once all effects have been identified, inserted in the consequence tree and structured, the effects that shall be part of the quantitative assessment shall be selected.

This step is feasible in principle but omitted here as it prepares the subsequent quantitative analysis steps. It would also rely on an estimation of the relative magnitude

of emissions between the different parts of the tree.

- Defining the system boundaries of the ICT solution(s) and the reference scenario(s) (clause 10.2.9 of L.1480-PvC-)

This step is challenging as it relies on the composition of the ICT solution as well as the formerly selected effects (see above). Hence, it is not feasible at this point.

The next steps, step 3 to step 6, are related to the quantitative analysis. However, modelling, data collection and calculations (step 3) as well as the subsequent steps (interpretation, reporting, review) which build on the results from step 3, are considered unfeasible from today's perspective without an unreasonable amount of uncertainty as the entire process suffers from broad unavailability of information and data. It seems not feasible to perform the quantitative part of the methodology since we consider 6G capabilities not well-defined enough and the use-cases are not mature enough for this type of assessment. Furthermore, as already noticed, we see difficulties in identifying the reference scenario as 5G is still under evolution and deployment, and with the solution scenario where concrete data is lacking. Assumptions could be possible, but they would be arbitrary, and any obtained quantitative value could hardly be considered technically robust. For the sake of completeness, the closing steps from L.1480 are briefly listed below.

Step 3-NF- – Modelling, data collection and calculation

3.1) Quantify the second order effect of each assessed ICT solution through:

- Identifying the overall usages of the ICT solution while separating modifying and rebound usages (clause 10.3.1.1 of L.1480).
- Quantifying the aggregated first order effect of the ICT solution(s) (clause 10.3.1.2 of L.1480).
- Quantifying the change of GHG emissions due to changes in the reference activities (clause 10.3.1.3 of L.1480).
- Deriving the net effect of the ICT solution(s) in a standalone scenario (clause 10.3.1.4 of L.1480)

3.2) Quantify the combined induced effect of several ICT solutions addressing the same emissions (clause 10.3.2 of L.1480).

3.3) Assessment of higher order effects including quantification (clause 10.3.3 of L.1480)

Step 4-NF – Interpretation of results

Perform interpretation of results through:

4.1) Evaluation of the applied method (clause 10.4.1 of L.1480).

4.2) Data quality analysis (clause 10.4.2 of L.1480).

4.3) Sensitivity analysis (clause 10.4.3 of L.1480).

4.4) Uncertainty analysis (clause 10.4.4 of L.1480)

Step 5-NF – Reporting

5.1) Perform reporting according to the guidance (clause 10.5 of L.1480)

Step 6 -NF– Critical review

6.1) Perform critical review according to the guidance (clause 10.6 of L.1480)

Annex C: Terminologies

Term	Acronym	Term description	Reference
Abstraction Model	N/A	Process of focusing on the important characteristics and behaviour of a concept and realizing this as a set of one or more elements in an information or data model.	https://www.etsi.org/deliver/etsi_gr/ENI/001_099/004/02.01.01_60/gr_ENI004v020101p.pdf
Access Point	AP	A device with radio functionalities including possible baseband capabilities that allows UEs connecting to the network without considering functional splits. A generic term that is being used on behalf of Transmission & Reception Point (TRP), Radio Unit, Distributed Unit in different contexts,	
Accuracy, precision, and resolution of a measurement	N/A	Different definitions exist in the literature. Accuracy can refer to the statistical bias (difference between the mean of the measurements and the true value), but also to the percentile performance (e.g., a positioning system with 95% accuracy of 5 meters indicates that 95% of the errors are within 5 meters). Precision refers to the spread of the measurements around the mean and is thus related to the (co-)variance of the measurements. Finally, resolution refers to the ability of the measurement system to distinguish nearby signal sources (e.g., a radar with 1 GHz bandwidth has a resolution of 0.15 m so that two objects with a distance exceeding 15 cm can be distinguished).	D3.1
Active learning	N/A	The selecting of important samples from a large unlabelled dataset for labelling (by querying an oracle) to accelerate model training with a labelling budget.	D4.1
Adjacent channel leakage power	ACLP	ACLR is used as a measure of out-of-band emission, i.e., the amount of power leaking into adjacent channels. It is defined as the ratio of the filtered mean power centred on the assigned channel frequency to the filtered mean power centred on an adjacent channel frequency	D2.2
AI agent	N/A	Network entity carrying one or more (trained) ML models; it can be instantiated across the network, i.e., at network infrastructure or device side.	D4.1

AI agent availability	N/A	Availability (or readiness) of an AI agent to accept inferencing requests and address them with high accuracy.	D4.1
AI agent density	N/A	Density of devices with AI/ML components considering specific traffic patterns during data sharing.	D4.1
AI agent reliability	N/A	Capability of an AI agent to accept inferencing requests and provide high accuracy output in a timely manner (within a deadline set by the requesting application).	D4.1
AI deployment flexibility	N/A	Flexibility to deploy same system in multiple scenarios without many modifications to the AI models. Goes hand in hand with generalisability	D4.1
AI function	N/A	Functional entity in which an AI agent carrying a (trained) ML model can be instantiated.	D4.1
AI orchestration function	N/A	AI function functionality for AI agent discovery and selection.	D4.1
AI policy enforcer	N/A	AI function functionality to implement a recommended policy.	D4.1
AI success monitoring function	N/A	AI function functionality performing inferencing accuracy, communication efficiency, and security monitoring.	D4.1
AI system transparency	N/A	Property that enables interpretability and, thus, the explanation of the decision-making process of AI system.	D4.1
AI Trustworthiness	N/A	AI-based models should perform optimally as intended by design without any unauthorised manipulation.	D4.1
AI/ML fairness	N/A	Ability of the AI/ML agent to perform a decision free from discrimination and bias.	D4.1
AI/ML flexibility	N/A	Ability of the ML model to adapt to different conditions/environments in a timely fashion.	D4.1
AI-enabled network energy efficiency	N/A	Training/inference energy optimisation in edge/IoT ecosystem.	D4.1
AI-native communication networks	N/A	AI-native communication networks is leveraging AI to design communication systems end-to-end (from RAN to core network functions) so as to adapt to different radio environments and optimally serve the needs of the application.	D1.4

Amplitude phase shift keying	APSK	A digital modulation scheme that conveys data by modulating both the amplitude and the phase.	D2.3
Analog-to-Digital Converter	ADC	An electronic integrated circuit used to translate analog electrical signals to digital or binary form consisting of 1s and 0s	D2.1
Analogue baseband	ABB	It is a part of a communications transceiver that operates with low-frequency baseband signal from 0 Hz to a certain frequency. It serves as the interface between the high frequency modulator and the digital baseband. The baseband transmitter includes circuits for digital-to-analogue conversion and low pass filtering, whereas the receiver comprises low pass filtering and analogue-to-digital conversion circuits.	D2.2
Analogue multicarrier	N/A	A multicarrier waveform, which is generated using analogue circuits. Specifically, a wideband is divided into multiple narrower band channels (subcarriers). The analogue signal for each subcarrier is generated by a dedicated transmitter chain, consisting of a digital-to-analogue convertor (DAC), a lowpass filter, a mixer and local oscillator, and power amplifier operating at baseband or intermediate frequencies (IF). The multicarrier signal is obtained by the superimposing the individual subcarriers using a combiner. On the receiver side, multiple receiver chains are employed. A receiver chain includes a low-noise amplifier (LNA) mixer and local oscillator, lowpass filter and analogue-to-digital convertor (ADC). This approach aims at providing a feasible implementation of 6G ultra-wideband waveform to address the challenges of high-speed and high-resolution DAC/ADC with a single transmitter and single receiver chains.	D2.1
Analogue radio-over-fibre	AROF	An analogue transmission over fibre technology, where light is amplitude modulated by a radio signal and transmitted over an optical fibre link to facilitate wireless access.	D2.3
Analogue-to-digital converter overshoot	N/A	Situation where signal is too large for the A/D converter input range causing so clipping or saturation for the signal.	D2.3

		ADC output will be 11111... also for signals higher than maximum causing distortion for the received signal deteriorating the reception of most waveforms used in communications applications.	
Analytics Logical Function	AnLF	Function that performs inference, derives analytics information, and exposes analytics service.	D4.1
Angle-of-arrival (also direction-of-arrival)	AoA / DoA	Measurement of Angle (in azimuth and/or elevation) of a signal incoming to an array from a certain direction, measured in the coordinate system of that array.	D3.1
Angle-of-departure (also direction-of-departure)	AoD / DoD	Measurement Angle (in azimuth and/or elevation) of a signal outgoing from an array towards a corresponding direction, measured in the coordinate system of that array.	D3.1
Antenna gain	N/A	The ratio, usually expressed in decibels, of the power required at the input of a loss-free isotropic reference antenna to the power supplied to the input of the given antenna to produce, in a given direction, the same field strength or the same power flux-density at the same distance. When not specified otherwise, the gain refers to the direction of maximum radiation.	D2.1
Application (software/program)	N/A	Software that is specific to the solution of a problem usually submitted by an end user. For clarification prefixes could be used, e.g., end user application, network application. Note: Application (software/ program) and service is often used as synonym. In our context application is used for software with user interface (UI).	D3.1
Architecture (Rel. to Software Systems)	N/A	Defines the high-level structure and organization of a software-based system. This includes the objects, their properties and methods, and relationships between objects.	https://www.etsi.org/deliver/etsi_gr/ENI/001_099/004/02.01.01_60/gr_ENI004v020101p.pdf
Area traffic capacity	N/A	The maximum number of bits that can be transmitted per unit area per second	D2.1

Artificial Intelligence	AI	The science and engineering of making computer behave in ways that, until recently, we thought that required human intelligence.	D4.1
Availability	N/A	Availability is indicated by the percentage of time during which all required QoS parameters are satisfied (correct operation). The required QoS parameters and their target ranges are service and use case specific.	D7.1
Backhaul	N/A	It is the link between the cell site and core network	D2.3
Backoff	BO	The Backoff of a power amplifier refers to operating at a level below the saturation point to ensure the amplifier remains within its linear operation region even with an increase in the input power level.	D2.1
Bandwidth scalability of waveform	N/A	The possibility of adapting the waveform bandwidth to available bandwidth.	D2.1
Baseband bandwidth	BB BW	It refers to the highest frequency of the baseband signal. This bandwidth corresponds to the	D2.1
Basic transmission loss (of a radio link) $\boldsymbol{L_b}$	N/A	The ratio, usually expressed in decibels, for a radio link between the power radiated by the transmitting antenna and the power that would be available at a conjugately matched receiver antenna input if the antennas were replaced by isotropic antennas with the same polarisation as the real antennas, including the attenuation effects on the propagation path, but with the effects of obstacles close to the antennas being disregarded. $L_b = L_{bf} + L_m$ [dB] where L_m is the loss relative to free space. The loss relative to free space, L_m, may be divided into losses of different types, such as: absorption loss (ionospheric or atmospheric gases, precipitation, clouds, etc.); diffraction loss as for ground waves; effective reflection or scattering loss as in the ionospheric case including the results of any focusing or defocusing due to curvature of a reflecting layer; polarisation coupling loss; this can arise from any polarisation mismatch between	D2.1

		the antennas for the particular ray path considered; aperture-to-medium coupling loss or antenna gain degradation, which may be due to the presence of substantial scatter phenomena on the path; beam spreading loss; effect of wave interference between the direct ray and rays reflected from the ground, other obstacles or atmospheric layers; clutter loss; building entry loss.	
Beam alignment	N/A	It is the process of testing different beams at least at one of the two end communicating point.	D2.1
Beam failure rate	N/A	This measure determines the connection breaks per timer interval because of beam tracking fails to keep the connection.	D2.3
Beam recovery	N/A	It is the state of beam management machine that represents a deterioration in the link quality criteria.	D2.3
Beam search	N/A	It the process of searching for and identifying the optimal direction or angle at which the antenna array should steer its beam to establish a wireless communication link.	D2.1
Beam steering	N/A	It is the process of controlling the direction in which a signal is transmitted or received by an array of antenna. This is achieved by adjusting the phase and amplitude of the signal at each antenna element in the array to create constructive and destructive interference patterns that effectively steer the signal in a desired direction.	D2.1
Beam training	N/A	It is a process used to determine the optimal beamforming vectors (i.e., the best direction and angle) for transmitting and receiving signals between a transmitter and a receiver. This can be achieved by sending signals in different directions, where the receiver measures the quality of signal in each direction and reported back to the transmitter.	D2.3
Beamforming	N/A	A signal processing technique used in combination with antenna arrays to achieve a defined directional antenna characteristic enabling directional signal transmission or reception. This is achieved by individual weighting of the signals of each antenna element in such a way that signals at particular angular	D2.1

		directions experience constructive interference while others experience destructive interference.	
Behavioural hardware modelling	N/A	It aims at creating abstracted mathematical models of hardware components that focus on input-output relation, rather than the specifics of the hardware internal working architecture. It can be used to simulate the response of the hardware component to certain inputs.	D2.2
Bema management	N/A	It is defined as the processes of establishing as well as maintaining a wireless connection for a system utilizing any form of beamforming.	D2.3
Bistatic sensing	N/A	Sensing (see Sensing), whereby the transmitting and receiving nodes are not co-located.	D3.1
Block error rate	BLER	It is a metric used to quantify link performance, by measuring the ratio of data blocks, or packets, that contain at least one-bit error. These data blocks can be defined in various ways, such as by using one codewords per block, or grouping multiple codewords into a single packet. High BLER values can indicate poor link quality,	D2.1
Bottom-up approach	N/A	It refers to the method of building a system starting from the lowest level components.	D2.1
Campus network	N/A	A campus network is a network made up of an interconnection of Local Area Network (LANs) within a limited geographical area.	D5.1
Carrier aggregation	CA	In the context of radio design, it refers to the superposition of signals from multiple bands to generate wideband waveforms. This technique can be used for designing ultrawideband 6G radio by dividing the available bandwidth into multiple narrower bands, each with a dedicated signal chain.	D2.3
Centralized unit	CU	In the context of base station functionality split, the CU is responsible for the non-real-time processing and higher-layer functions in the network, such as mobility management, session management, and control plane functions. The CU is usually located at a more centralized location, serving	D2.3

		multiple cell sites or even multiple distributed units (DUs).	
Channel hardening	N/A	A fading channel behaves as if it was a non-fading channel	D2.1
Channelization	N/A	In the context of radio design, channelization refers to the process of dividing ultrawideband into multiple narrower bands, each with a dedicated signal chain.	D2.1
Classification problem	N/A	Problem that requires the algorithm to associate its input to one or several discrete target values, often called labels.	D4.1
Closed loop control	N/A	Self-regulating mechanism in which outputs of a system are provided to a system that compares the current state to a desired state (or set of states); the comparison is then used to adjust the behaviour of the system	https://www.etsi.org/deliver/etsi_gr/ENI/001_099/004/02.01.01_60/gr_ENI004v020101p.pdf
Cloud Computing	N/A	A model that offers compute resources like CPU, network, and disk capabilities on-demand over the internet. Cloud computing gives users the ability to access and use computing power in a remote physical location	https://github.com/cncf/glossary/blob/main/content/en/cloud_computing.md
Cloud Network	N/A	A computer network within or make part of a cloud computing infrastructure.	D6.1
Cloud-native	N/A	It is an architecture model to build and run software applications by exploiting the scalability, and resilience of cloud computing.	D6.1
Coherent Processing Interval	CPI	Duration in which a signal is received and during which the geometric parameters remain constant.	D3.1
Common phase error	CPE	In multi-carrier waveforms, the lower offset frequency components of the phase noise cause so-called common phase error (CPE) due to long symbols that can be compensated in the receiver by proper phase noise tracking reference signals	D2.3
Communication-Control-Codesign	CoCoCo	Joint (cross-layer) study and optimisation of control applications in I4.0 scenarios and the underlying communication service. Often extended to Communication-Computation-Control-Codesign to reflect the importance of (local) computation capabilities.	D7.1

Communications Services Provider	CSP	Company or organisation, making use of an electronics communications network or part thereof to provide a service or services on a commercial basis to third parties.	https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.03.01_60/gs_NFV003v010301p.pdf
Compute-as-a-Service	CaaS	The basic CaaS principles relate to an offload of processing tasks to external compute resources. In CaaS, external compute resources can be made available to a specific entity or user device through a well-defined open interface,	D5.1
Confidential Computing	CC	Technologies ensuring that the data in use are protected against threats from malicious insiders with administrative privilege, direct access to hardware and, malwares that exploit bugs in the environment in which application runs on.	D4.1
constrained-envelope Continuous Phase Modulation	ceCPM	A phase-modulated single-carrier waveform with a controlled degree of envelope variations	D2.1
Container	N/A	A piece (package) of software within the code and all its dependencies. An evolution of a Virtual Machine.	https://www.docker.com/resources/what-container
Containerised Network Function	CNF	NF implemented by means of (one or more) containers	D6.1
Continuous learning	N/A	When new information is learnt without forgetting previous knowledge.	D4.1
Continuous Phase Modulation – DFT spread OFDM	CPM-DFTS-OFDM	DFTS-OFDM where symbols are samples from a CPM modulator	D2.1
Core Network	CN	An architectural term relating to the part of 3GPP System which is independent of the connection technology of the terminal (e.g., radio, wired)	https://www.etsi.org/deliver/etsi_tr/121900_121999/121905/16.00.00_60/tr_121905v160000p.pdf
Cramér-Rao Lower Bound	CRLB	A type of error bound (EB), based on Fisher information theory.	D3.1
Crest factor	N/A	A parameter of a waveform, such as alternating current or sound, showing the ratio of peak values to the effective value.	D2.1
CRUD Operations	CRUD	Set of functions required to manage the instantiation (creation), maintenance (update) and termination (deletion) of the network elements.	https://www.etsi.org/deliver/etsi_gs/MEC/001_099/001/02.01.01_60/gs_MEC001v020101p.pdf

Data Age of Information	Data AoI	A time-evolving measure which characterises information freshness at the receiver (e.g., at the cloud edge where an ML model is updated). The AoI at a given time instant is defined as the time difference between the focused timestamp and the time at which the observed state (or data packet) was generated.	D4.1
Data economy	N/A	Capability of achieving high inferencing accuracy with a smaller amount of learning data.	D4.1
Data poisoning	N/A	A process by which an adversary injects malicious points in the training dataset to influence the learning process and degrade the algorithm's performance.	D4.1
Data privacy protection	N/A	Data collection procedures to train the model should adhere to any regulations plus ethical obligations.	D4.1
Data quality	N/A	How useful and relevant the data are to model training - assuming the same quantity, higher quality data achieve better model convergence and flexibility.	D4.1
Decision problem	N/A	Problem requiring an algorithm to select a set of best actions provided a context.	D4.1
Deep Edge	N/A	Same as Extreme Edge	D6.1
Dependability	N/A	Dependability is the “ability to perform as and when required” [IEC61907]. Dependability consists of the attributes: availability, reliability, safety, integrity, and maintainability [ALB+04]. End-to-end dependability refers to dependability from the application perspective, encompassing multiple services (c.f. Productivity)	D7.1
DFT-spread OFDM	DFTS-OFDM	An OFDM waveform where a DFT is applied to symbols prior to their mapping onto subcarriers	D2.1
Differential Privacy	DP	Concept enabling quantifying privacy by bringing a bound on the probability that two datasets can be distinguished.	D4.1
Digital predistortion	DPD	It refers to signal processing techniques in the digital domain to correct the transmitter non-linearity.	D2.3
Digital Signal Processing	DSP	The use of digital processing, such as by computers or more specialized digital	D2.1

		signal processors, to perform a wide variety of signal processing operations	
Diplexer		A diplexer is a passive device that implements frequency-domain multiplexing	D2.1
Distributed learning with frugal AI	N/A	Distributed learning enables models to be trained without expensive communication of acquired data. Frugal AI enables learning models based on small amounts of data.	D4.1
Distributed unit	DU	In the context of base station functionality split, the DU handles the real-time processing of the baseband signals, such as signal processing, channel coding, and scheduling. It is located closer to cell site.	D2.3
Dynamic Function Placement	DFP	DPS the act of dynamically place network functions. This is done by deploying intelligent algorithms to orchestrate differentiated services optimally across multiple sites and clouds, based on diverse intents and policy constraints of dynamically changing environments.	D5.1
Dynamic range	N/A	Analogue-to-digital-convertor (ADC) dynamic range, is defined by the ratio between the largest and smallest values that the ADC can reliably measure without clipping.	D2.1
Edge AI	N/A	Concept incorporating collaborative multi-agent architectures, ML model decomposition and data parallelism principles.	D4.1
Edge Learning	N/A	New concept incorporating training of machine learning models and/or the consequent inference, on data collected and shared at the edge of the network, i.e.i.e., typically in edge cloud architectures. This paradigm requires a joint management and orchestration of communication, computation, and training/inference related parameters, to explore the best trade-off between energy consumption, latency, and learning performance (e.g.e.g., model convergence, inferencing accuracy, etc.). Both standalone and federated architecture are involved	D4.1
Edge Network	N/A	Brings computation and data storage as close as possible to the location request.	D6.1

Effective channel	N/A	In the digital signal processing (DSP) model for communications system, effective channel represents the transfer function between the output of the DSP transmitter, and the input of DSP receiver. This function summarizes the wireless channel, hardware impairments, synchronization error in addition to the additive noise.	D2.1
Element Management	N/A	Managing a single element, e.g., software update or configuration change for a specific device.	https://www.itu.int/rec/T-REC-M.3010-200002-I/en
End-to-end learning	N/A	Learning and optimising the transmitter and receiver jointly in a single process.	D4.1
Energy performance	N/A	It is defined is defined as the energy consumption required to fulfil a set of performance requirements.	D2.3
Error bound	EB	Fundamental lower bounds on the error covariance of a parameter that is estimated (e.g., position error bound (PEB), clock error bound (CEB))	D3.1
Error vector magnitude	EVM	It is a measure used to quantify the performance of a digital communication system. It provides an indication of the quality of the modulated signal, by measuring the difference between the ideal and the actual received signal. EVM is equivalent to the SNR of modulated symbols, such as quadrature amplitude modulation (QAM), and it is used to determine the symbol error rate (SER).	D2.1
Explainability	N/A	Ability of the AI/ML agent to provide justification for a recommendation based on model output.	D4.1
Explainable AI	XAI	The process of explaining why an AI agent performs, after an internal processing, a certain decision to the final user in understandable terms.	D4.1
Extreme Edge	N/A	Network domain where devices could be limited in computing and storage capabilities.	https://ieeexplore.ieee.org/document/8607067
Far Edge	N/A	Same as Extreme Edge	D6.1
Flexibility	N/A	Flexibility refers to the ability of the utilised technology and realised deployment to adapt to different tasks. This can be captured by the cost (monetary and resources) associated with the required change and by the	D7.1, D1.4

		complexity induced with the change (grade of re-use of components).	
Flexibility to different topologies	N/A	The ability of the network to adapt to various scenarios such as new non-public networks, autonomous networks (subnetworks), mesh networks, new spectrum, etc., without loss of performance and easy deployment. Addition of service capabilities and new services endpoints require no changes to existing end-to-end services.	D5.1
Fog Computing	N/A	A decentralised structure where networking, storage and computing resources are between the cloud and data source.	D6.1
Fog Network	N/A	Same as Extreme Edge network	D6.1
Frame Error Rate	FER	Ratio of data received with errors to total data received. Used to determine the quality of a signal connection. If the FER is too high (too many errors), the connection may be dropped.	D2.1
Fronthaul	N/A	It refers to the connection between the baseband unit (BBU) and the remote radio head (RRH).	D2.3
Full Network Automation	N/A	Full Network Automation is driven by high-level policies and rules without minimal human intervention. Networks will be capable of self-configuration, self-monitoring, self-healing, and self-optimisation	D5.1
Generalisability	N/A	AI-based models should be able to adapt to unseen scenarios and perform effectively.	D4.1
Generalised Optimal Sub-Pattern Assignment	GOSPA	An error metric between sets of detected and ground truth objects, generalising the RMSE.	D3.1
Goal-oriented communications	N/A	Paradigm in which communication is designed to guarantee the correct accomplishment of a common goal, e.g.e.g., control actions, learning and inference at the edge, etc. Therefore, performance indicators do not necessarily involve the correct reception of all collected data, but the ones (or their representation) needed to achieve a target level of effectiveness, i.e. goal achievement	D4.1

Grating lobes	N/A	Undesired beams forming off the main beam direction. This effect happens in antenna array when the spacing between elements exceed halve the wavelength.	D2.1
Ground truth	N/A	True state (e.g., true position of an object or UE).	D3.1
Half-power beam width	HPBW	It measures the angular width (in degrees) on the main lobe of an antenna radiation pattern where the signal power is half that of the peak value.	D2.2
Hardware impairments	N/A	Limitations, inaccuracies, or errors that arise because of non-ideal characteristics of the hardware components. These include, amplifier non-linearities, phase noise, quantization error, I/Q imbalance, and frequency offset.	D2.1
Hardware implementation boundaries	N/A	Performance limits due to technologies for hardware implementation. Often these comes from physics including material properties etc.	D2.3
Homomorphic Encryption	HE	A form of encryption that allows the computation on ciphertext using specific operations without accessing to secret key nor requiring any decryption.	D4.1
Hybrid beamforming	N/A	It is a beamforming architecture, which comprises multiple signal chains, each is connected to an antenna array, with analogue steering capabilities in terms of phase and gain control. Digital precoding is can be performed in the digital baseband along the signal chains.	D2.2
Hybrid Network Function	HNF	NF implemented using diverse technologies (e.g., virtual machines, containers, physical elements or other).	D6.1
Inferencing accuracy	N/A	Applicable to many AI functionalities, depends on (and can be traded off for) data volume, inference latency, channel quality in data sharing.	D4.1
Integrated Access and Backhaul	IAB	The new radio (NR) technology in 3GPP that provides not only the access link to the UEUE, but also flexible wireless backhaul link connecting the base stations to the core network.	D2.1
Integrated sensing and communication	ISAC	See joint communication and sensing	D3.3
Intent-based Networking	IBN	Technology proposing to transform a hardware-centric, manual network into a	https://www.cisco.com/c/en/us/solutions/intent-based-networking.html

		controller-led network that captures business intent and translates it into policies that can be automated and applied consistently across the network.	
Interactivity	N/A	Interactivity is the extent to which humans contribute to changing their environment via telepresence in real-time. Interactivity is determined firstly by the performance characteristics of the computing and communication platform and secondly by adherence to agreed dependability parameters.	D7.1
Interface	N/A	Shared boundary between two functional units, defined by functional characteristics, signal characteristics, or other characteristics as appropriate (e.g., API: Application Programming Interface, UI: User Interface, webinterface: Can be API or UI, interface is bound to web protocols).	D3.1
Internet of Robotics	N/A	Concept of integrating robots with IoT devices to enable robots to actions based on sensory data from IoT devices	D1.4
Internet of Senses	N/A	A technological paradigm where various sensing modalities such as vision, touch, hearing, and smell are combined to enable to allow human beings to have digital sensory experiences similar to that in the real world	D1.4
Interpretability level	N/A	Measure of explainability, reasoning, contribution of input factors.	D4.1
Joint communication and sensing	JCAS	Using the communication system for supporting sensing functionalities.	D3.3
Joint Transmission Coordinated Multi-Point	N/A	Coherent transmission from clusters of base stations to overcome the inter-cell interference within each cluster	D2.1
Large distributed and cooperative MIMO systems (D-MIMO)/Cell-free massive MIMO	N/A	Spread of a large number of antenna elements across the network (even in the form of single-antenna base stations), which provides enhanced coverage and reduced pathloss.	D2.1
Latency	N/A	Duration between initialisation of sensing/localisation procedure and acquiring localisation/sensing estimate. See also: update rate.	D3.1

Latency of AI/ML	N/A	AI/ ML components which support (near) real time decisions also have strict time constraints for inference or training.	D4.1
Layer 1-mobility	N/A	A procedure where serving RUs/beams subset (via joint transmission) is updated for the UE triggered by lower layer signalling during mobility	D2.3
Learning struggler	N/A	Network device (end user or network infrastructure ones) having insufficient compute, memory and/or storage resources to update a local model in a timely fashion per e.g., a learning synchronisation requirement	D4.1
Lens Antenna	N/A	A microwave antenna that uses a shaped piece of microwave-transparent material to bend and focus the radio waves by refraction.	D2.1
Life-cycle Management	LCM	Set of functions required to manage the instantiation, maintenance and termination of a software component (e.g., NF or NS).	https://www.etsi.org/deliver/etsi_gr/NFV/001_099/003/01.05.01_60/gr_NFV003v010501p.pdf
Localisation (synonym: positioning)	N/A	The process of estimating the location of a connected device from sensor measurements. The location can be in 2D (horizontal plane) or 3D (including altitude).	D3.1
Location accuracy and timeliness for AI/ML	N/A	Location estimations enhanced by intelligent fusion with further models (mobility, maps, etc.) and additional data sources - time granularity to be considered jointly with location accuracy.	D4.1
Long-range wireless connectivity	N/A	Communication links at distances beyond 100 m	D2.1
Lower layer split	LLS	Refers to the split of lower layer functionalities (RF front-end and layer 1) between a distributed unit (DU) and radio unit (RU). Note that this has an influence on the requirement on the logical interface between DU and RU.	D2.3
Lower millimeter wave	Lower mmW	Frequency range 30 – 100 GHz	D2.1
Machine Learning	ML	The study of computer algorithms that allow computer programs to automatically improve through experience.	D4.1

Maintainability	N/A	Maintainability is the ability of a system to “be retained in, or restored to, a state in which it can perform as required under given conditions of use and maintenance” [IEC61907]. The attributes retainability and recoverability are also sometimes used.	D7.1
Mapping	N/A	Generating a map of landmarks (natural or artificial features used for navigation) based on sensing measurements.	D3.1
massive MIMO	N/A	Each base station is equipped with a large number of antenna elements and serves numerous user equipments simultaneously by means of highly directional beamforming techniques	D2.1
Microservices	N/A	Microservices are an architectural and organizational approach to software development where software is composed of small independent services that communicate over well-defined APIs. These services are owned by small, self-contained teams.	https://aws.amazon.com/microservices/?nc1=h_ls
Mid-range wireless connectivity	N/A	Communication links at distances (100 m-200 m)	D2.3
Millimeter wave	mmW	Frequency range 30 – 300 GHz	D2.1
ML complexity gain	N/A	Implementation complexity reduction compared to a non-ML method.	D4.1
ML model complexity	N/A	Computational complexity of AI/ML models during either training or inference phases.	D4.1
ML model convergence	N/A	Related to training of the ML model. This indicates the loss function value that has been settled with increasing training epochs.	D4.1
Mobile Network Operator	MNO	Telecommunications service provider organisation that provides wireless voice and data communication for its subscribed mobile users.	https://ec.europa.eu/eurostat/cros/content/Glossary:Mobile_network_operator_(MNO)
Model Predictive Control	MPC	Control method to assist complex rule-based systems by learning a close-to-optimal control.	D4.1
Model Training Logical Function	MTLF	Function dedicated to training ML models, which can be then consumed on-demand by the AnLF.	D4.1
Monostatic sensing	N/A	Sensing, whereby the transmitting and receiving nodes are co-located.	D3.1

Multi-access Edge Computing	MEC	System which provides an IT service environment and cloud-computing capabilities at the edge of an access network which contains one or more type of access technology, and in close proximity to its users.	https://www.etsi.org/deliver/etsi_gs/MEC/001_099/001/02.01.01_60/gs_MEC001v020101p.pdf
Multiple-Input and Multiple-Output	MIMO	The use of multiple antennas at the transmitter and the receiver	D2.1
Narrowband/wideband/		These terms are relative to the carrier frequency of a modulated signal. Narrowband is defined when the bandwidth is up to 10 % of the carrier, and wideband when the ratio exceeds 10 %.	D2.1
Network Domain	N/A	The highest-level group of physical entities.	https://www.etsi.org/deliver/etsi_tr/121900_121999/121905/16.00.00_60/tr_121905v160000p.pdf
Network Element	NE	A discrete telecommunications entity which can be managed over a specific interface.	https://www.etsi.org/deliver/etsi_tr/121900_121999/121905/16.00.00_60/tr_121905v160000p.pdf
Network Function	NF	A functional building block within a network infrastructure, which has well-defined external interfaces and a well-defined functional behaviour. In practical terms, a Network Function is today often a network node or physical appliance.	https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.01.01_60/gs_NFV003v010101p.pdf
Network Functions Virtualisation	NFV	Principle of separating network functions from the hardware they run on by using virtual hardware abstractions.	https://www.etsi.org/deliver/etsi_gs/MEC/001_099/001/02.01.01_60/gs_MEC001v020101p.pdf
Network of networks	N/A	Defined as a network that can both incorporate different (sub)network solutions as well as a network that easily (flexibly) can adapt to new topologies (same thing as Flexibility to different topologies also)	D5.1
Network Scalability	N/A	The network architecture needs to be scalable both in terms of supporting very small to very large-scale deployments, by scaling up and down network resources based on needs, e.g., varying traffic, utilising underlying shared cloud platform	D5.1
Network Service	NS	A composition of Network Functions and defined by its functional and behavioural specification.	https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.01.01_60/gs_NFV003v010101p.pdf
Network Service Meshes	N/A	Network service mesh is intended to support application-to-application and function-to-function communications in	D5.1

		6G networks and scenarios through dynamic and automated virtual network services, to be allocated on-demand, based on application requirements (similar to DFP).	
Network Service Provider	NSP	Type of provider implementing Network Services.	https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.03.01_60/gs_NFV003v010301p.pdf
Node Energy Efficiency	Node EE	Ratio of bitrate supported by the node when transmitting or receiving and the power consumed by the node	D2.1
Noise Figure	NF	The measures of degradation of the signal-to-noise ratio (SNR), caused by components in a signal chain..	D2.1
Non-Terrestrial Network	NTN	Satellites and other flying objects such as HAPS and UAVs.	D5.1
Optical Wireless Communication	OWC	A form of optical communication in which unguided visible, infrared (IR), or ultraviolet (UV) light is used to carry a signal. It is generally used in short-range communication.	D2.1
Orientation estimation	N/A	Estimating the 1D, 2D, or 3D orientation (e.g., roll, pitch, yaw) of a connected device.	D3.1
Out-Of-Band Emission	(OOB) Emission	Emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process.	D2.1
Peak data rate	N/A	The maximum achievable data rate under ideal conditions (in bit/s), which is the received data bits assuming error-free conditions assignable to a single mobile station, when all assignable radio resources for the corresponding link direction are utilised (i.e., excluding radio resources that are used for physical layer synchronisation, reference signals or pilots, guard bands and guard times).	D2.1
Peak-to-Average Power Ratio	PAPR	The peak amplitude squared (giving the peak power) divided by the RMS value squared (giving the average power)	D2.1
Phased Array	N/A	An array of antenna elements which creates radiation patterns that can be electronically steered to point in different directions without moving the antenna	D2.1
Physical Network Function	PNF	NF implemented by means of (one or more) physical elements	D6.1

Positioning reference signal	PRS	Standardised pilot signal in time a frequency, used for ToA estimation.	D3.1
Power Added Efficiency	PAE	The overall efficiency of the power amplifier, including the effect of the gain of the amplifier and the input power. It is the ratio of the difference of output and input power to the DC power consumed.	D2.1
Power Amplifier linearity	N/A	The ability of the amplifier to produce signals that are accurate copies of the input, generally at increased power levels.	D2.1
Prediction problem	N/A	Problem that involves forecasting the likelihood of outcomes based on historical data.	D4.1
Privacy	N/A	The right of individuals to control or influence what information related to them may be collected and stored and by whom and to whom that information may be disclosed.	https://www.etsi.org/deliver/etsi_etr/200_299/232/01_60/etr_232e01p.pdf
Productivity	N/A	The fraction of time an application can operate as intended (i.e., targeted availability and reliability). Application-specific considerations can influence the achieved productivity given the availability and reliability characteristics of the underlying (consumed) services and the level of resilience of the application.	D7.1
Programmability	N/A	A framework that gives the possibility to update the program for specific features in a network entity	D5.1
Q-learning	N/A	Model-free general approach that requires no knowledge on the system to be controlled, rather just the reward (Q) function.	D4.1
Radio Network User plane latency	N/A	The contribution of the radio network to the time from when the source sends a packet to when the destination receives it (in ms). It is defined as the one-way time it takes to successfully deliver an application layer packet/message from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface in either uplink or downlink in the network for a given service in unloaded	D2.1

		conditions, assuming the mobile station is in the active state.	
Radio unit	RU	In the context of base station functionality split, the RU is responsible for the radio frequency (RF) functions, such as transmitting and receiving signals, as well as the conversion between digital and analogue signals	D2.3
Ray path transmission loss	N/A	The transmission loss for a particular ray propagation path taking into account the antenna gains in that ray path direction. The use of this term is restricted to those cases, for example for multipath propagation, where several propagation ray paths are considered separately. The ray path transmission loss may be expressed by: $L = L_b - G_{tp} - G_{rp}$ [dB] where G_{tp} and G_{rp} are the plane-wave directive gains of the transmitting and receiving antennas for the directions of propagation and polarisation considered.	
Receiver	RX	An electronic device that receives radio waves and converts the information carried by them to a usable form	D2.1
Reconfigurable intelligent surfaces	RIS	A RIS is a two-dimensional surface of engineered material whose properties are reconfigurable rather than static that can shape how the surface interacts with wireless signals enabling a new dimension to fine-tune the wireless propagation environment	D2.2
Regression problem	N/A	Problem of matching a function that outputs continuous values	D4.1
Reinforcement Learning	RL	ML technique used to learn sequences of actions that an "agent" should perform, given its state and its environment state, to maximize the expectation of reward for those sequences of action.	D4.1
Reliability	N/A	Reliability is the probability to perform as required for a given time interval, under given conditions [IEC61907, 22.104].	D7.1
Resilience	N/A	Resilience is defined as the ability of an application to react and adapt to challenging conditions by altering its behaviour to maintain dependability.	D7.1, D1.4 https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.01.01_60/gs_NFV003v010101p.pdf

Resilience and availability	N/A	This means that the network (architecture) shall be resilient in terms of service and infrastructure provisioning using multi connectivity, and separation of CP and UP, support of local network survivability if a subnetwork loses connectivity with another network, removing single point of failures	D5.1
Resistance to adversarial attacks	N/A	Capability to perform as intended when faced with adversarial attacks.	D4.1
Resources Orchestration	N/A	Subset of network functions that are responsible for global resource management governance.	https://www.gsma.com/futurenetworks/wp-content/uploads/2017/05/Virtualisation.pdf
Root mean squared error	RMSE	Square root of the average error norm between an estimate and the ground truth.	D3.1
Round-trip-time	RTT	Measurement of roundtrip delay between a BS and a UE. Involves a ToA estimate at each side.	D3.1
Safety	N/A	Unavailability (or degradation) of the service must not have catastrophic consequences (e.g., injuries, death) on users and environment. (Monetary) consequences resulting from safety requirements not being met can be quantified as "cost of service failure".	D7.1
Scalability	N/A	Ability to dynamically extend/reduce resources granted to a Network Function as needed. This includes scaling up/down and scaling out/in	https://www.etsi.org/deliver/etsi_gs/NFV/001_099/003/01.01.01_60/gs_NFV003v010101p.pdf
Schreier Figure-of-merit	FoMS	It is a quantities measure used to assess the performance of Analogue-to-digital converter (ADC), given by $FOM_S = SNDR + 10\ log(\frac{f_s/2}{P_{ADC}})$ where where P_{ADC} is ADC power consumption, f_s is the sampling rate, $SNDR$ signal-to-noise and distortion ratio $SNDR = 6.02\,\text{ENOB} + 1.76$, and ENOB is the effective number of bits.	D2.3
Secure Multi Party Computation	SMPC	A computation paradigm that enables a set of parties to execute a joint computation of their sensitive	D4.1

		data while revealing nothing except the information learned from the output.	
Security	N/A	The protection of information availability, integrity and confidentiality.	https://www.etsi.org/deliver/etsi_etr/200_299/232/01_60/etr_232e01p.pdf
Semantic communications	N/A	Communications that go beyond the common paradigm of guaranteeing the correct transmission and reception of data (irrespective of the meaning they convey), by targeting the correct interpretation of the data at the receiver	D4.1
Sensing	N/A	A sensor is any device, module, machine, or subsystem that detects events or changes in its environment. Sensing is then the operation of the sensor, in our case possibly including transmission and/or reception of signals and generation of measurements from these signals.	D3.1
Sensor fusion	N/A	Combining information (measurements or densities) from different sensors, such as radio signals, radar, lidar to obtain an improved estimate.	D3.1
Service	N/A	Distinct part of the functionality that is provided by an entity through interfaces. Note: Service and application (software/program) is often used as synonym. In our context service is used for software without UI.	D3.1
Service Based Architecture	SBA	A modular architecture introduced for 5G for the first time in which the control plane functionality and common data repositories of a 5G network are delivered by way of a set of interconnected Network Functions (NFs), each with authorisation to access each other's services.	D5.1
Service Consumer	SC	An application, service, or software module that requires a service.	https://www.sciencedirect.com/book/9781558609006/java-web-services-architecture
Short-range wireless connectivity	N/A	Communication links at distance below 100 m [10 -100m]	D2.1, D2.3
Short-range wireless connectivity	N/A	Communication links at distances (10 m-100 m)	D2.3
Simultaneous Localisation And Mapping	SLAM	Process of jointly tracking the UE location and mapping the landmarks in the environment	D3.1

Simultaneous Wireless Information and Power Transfer	SWIPT	Technique to improve spectral efficiency, relying on the fact that the RF signal carries both energy and information, and thus energy harvesting and information decoding from the same received RF signal can be achieved.	D7.1
Sparse Neural Network	Sparse NN	Class of NN architectures exploiting the sparse activity and sparse connectivity properties.	D4.1
Spectral Efficiency	SE	The information rate that can be transmitted over a given bandwidth in a specific communication system. measured in bits/s/Hz.	D2.1
Spectroscopy	N/A	It is the study of the frequency dependence of the interaction between electromagnetic (EM) radiation and matter, e.g., atoms and molecules. Examples include absorption, emission, scattering and reflection.	D2.1
Spiking Neural Network	SNN	NNs the neurons of which imitate the behaviour of biological neurons; in an SNN, only active neurons transmit information	D4.1
Stored channel model	N/A	It refers to a method of generating channel for simulation purposes based on measured channel responses.	D2.3
Sub-array-based radio frequency architecture	N/A	A radio frequency (RF) architecture, that consists of multiple signal chains connected to antenna sub-arrays. Each sub-array comprises multiple phase and amplitude steered antennas pointed towards beam containing one data stream or sometimes multiple streams. With array gain and spatial filtering, the content of each stream is possible to digitize and process in data converters and digital size with reasonable sampling rate, resolution, and power consumption.	D2.3
Sub-TeraHertz	Sub-THz	Refer to upper millimeter wave region, i.e, frequency range 100 – 300 GHz	D2.3
Supervised learning	N/A	ML techniques used to learn the mapping from an input x to a desired output y. Those techniques require the knowledge of the expected output, making them suited for problems where data are annotated or labelled.	D4.1
Survival time	N/A	Survival time represents the time an application can continue operation	D7.1

		without the reception of an anticipated signal/response by a consumed service.	
Synchronisation	N/A	Estimating the clock bias and drift of a connected device with respect to a reference. For multiple transmission and reception point (multi-TRP) based localisation, synchronisation means time synchronisation among TRPs.	D3.1
System Energy Efficiency	System EE	Ratio of the sum of bitrates in a system with several nodes (e.g.e.g., a base station and several users in a cell) and the sum of power consumptions of all the nodes.	D2.1
Tactile Internet	TI	A network or network of networks for remotely accessing, perceiving, manipulating, or controlling real, or virtual objects, or processes in perceived real time by humans or machines.	https://ti.committees.comsoc.org/
Tag	N/A	Unit, that enables communication, sensing and localisation (less complex device in comparison to UE often with focus on size, weight, costs and battery lifetime)	D3.1
Telepresence	N/A	Telepresence is the human experience of presence in an environment by means of a platform which exchanges data with humans via bidirectional communication links. There is a mixed reality (MR) continuum from real world to augmented reality (AR), to extended reality (XR) to virtual reality (VR).	D7.1
TeraHertz	THz	Frequency range 300 GHz – 3 THz	D2.1
TeraHertz gap	THz gap	It is a frequency range in the THz region, where it is difficult to generate and detect electromagnetic waves using techniques either in electrical or optical domains.	D2.1
Time-difference-of-arrival	TDoA	Measurement of the difference between arrival times of the first signal paths at a receiving device from two different transmitters.	D3.1
Time-of-arrival	ToA	Measurement of arrival time of a first signal path at a receiving device.	D3.1
Top-down approach	N/A	It refers to the method of building a system starting from the requirements down to the design of sub-systems and components.	D2.1

Tracking	N/A	For localisation: continuous localisation of the same connected device over a given duration. For sensing, continuous localisation of the same target or targets over a given duration.	D3.1
Transceiver	N/A	An electronic device which is a combination of a radio transmitter and a receiver.	D2.1
Transmission and Reception Point	TRP	A device performing transmission and reception, and allowing UEs connecting to the network.	D2.1
Transmission loss (of a radio link) $\boldsymbol{L}$	N/A	The ratio, usually expressed in decibels, for a radio link between the power radiated by the transmitting antenna and the power that would be available at a conjugately matched receiver antenna input if actual antenna radiation patterns are substituted with no losses in the radio-frequency circuits. The transmission loss may be expressed by: $L = L_b - G_t - G_r$ [dB] where G_t and G_r are the directivity gains of the transmitting and receiving antennas, respectively, in the direction of propagation.	D2.1
Transmitter	TX	An electronic device which produces radio waves with an antenna	D2.1
UE-centric coherent transmission	N/A	In UE-centric coherent transmission, clusters of BSs are formed such that each UE is served by a few of its closest BSs, i.e., each BS cooperates with a per-UE defined sub-set of BSs.	D2.1
Unsupervised learning	N/A	ML technique used to learn “relations” or patterns in an unlabelled input set x and provide a representation in an output space of smaller dimensionality y preserving properties on those relations.	D4.1
Update rate	N/A	Rate at which location or sensing outputs are reported. At most once per latency.	D3.1
Upper millimeter wave	Upper mmW	Frequency range 100 – 300 GHz	D2.1
Vendor	N/A	Entity that supplies SW and/or HW components.	https://www.etsi.org/deliver/etsi_gs/ZSM/001_099/007/01.01.01_60/gs_ZSM007v010101p.pdf
Vertical Industry	N/A	Companies, industries and public sector organisations operating in a specific sector.	https://www.gsma.com/spectrum/wp-content/uploads/2021/07/Mobile-Networks-Industry-Verticals.pdf

Very-short-range wireless access	N/A	Communication links at distances less than 10 m	D2.3
Virtual Machine	N/A	A compute resource that uses software instead of a physical computer to run programs and deploy apps. One or more virtual "guest" machines run on a physical "host" machine. Each virtual machine runs its own operating system and functions separately from the other VMs, even when they are all running on the same host.	https://www.vmware.com/topics/glossary/content/virtual-machine
Virtual Network Function	VNF	NF implemented by means (one of more) virtual machines.	D6.1
Vividness	N/A	Vividness is the characteristic richness of telepresence that depends on how the computing and communication platform represents the environment to human senses. The capabilities of the computing and communication platform are determined by the number of sensors and actuators and the sensor and actuator resolutions.	D7.1
Walden Figure-of-merit	FoMW	It is a quantities measure used to assess the performance of Analogue-to-digital converter (ADC), given by $FOM_W = \frac{P_{ADC}}{2^{ENOB} f_s}$, where P_{ADC} is ADC power consumption, f_s is the sampling rate, and ENOB is the effective number of bits, which depends on the signal-to-noise and distortion ratio (SNDR).	D2.2
Wave-material Interaction	N/A	The wave material interaction specifically refers to reflection, diffraction, scattering and penetration.	D2.1
Wireless energy transfer	WET	Radio frequency based wireless energy transfer provides energy over-the-air using so-called power beacons (PBs)	D7.1
Zero-Crossing Modulation	ZXM	A waveform that applies temporal oversampling and 1-bit quantisation at the receiver to achieve reasonable spectrum efficiency with improved energy efficiency and the relaxation of hardware requirements.	D2.1
Zero-energy devices	N/A	Devices that from the end-user perspective operate without a battery and instead harvest the energy necessary for communication from the surroundings – from vibrations, from	D1.4

		light, from temperature gradients, and/or radio-waves.	
f_{max}	N/A	The frequency where unilateral gain (U) becomes unity, or zero dB i.e. the upper frequency limit when a transistor can provide amplification. It depends on the (semiconductor) technology and line width of a particular transistor.	D2.1
$\boldsymbol{L_{bf}}$	N/A	The ratio, usually expressed in decibels, for a radio link between the power radiated by the transmitting antenna and the power that would be available at a conjugately matched receiver antenna input if the actual antennas were replaced by loss free isotropic antennas located in a perfectly dielectric, homogeneous, isotropic and unlimited environment, the distance between the antennas being retained. If the distance **d** between the antennas is much greater than the wavelength $\boldsymbol{\lambda}$, the free-space attenuation in decibels will be: $L_{bf} = 20\log_{10}\frac{4\pi d}{\lambda}$.	D2.1