HEXA-X-II

A holistic flagship towards the 6G network platform and system to inspire digital transformation for the world to act together in meeting needs in society and ecosystems with novel 6G services.

D2.1 Draft foundation for 6G system design

***DISCLAIMER**: Smart Networks and Services Joint Undertaking approval pending*

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6GSNS

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Abstract

This document is the first deliverable in Hexa-X-II work package 2 – "Draft foundation for 6G system design". The document provides the architecture design principles, an overview of the first draft of 6G end-to-end system blueprint, and the associated design process. In addition, the document describes the key 6G innovations related to the different layers and functionalities of the system blueprint. It also outlines the evaluation and validation framework of the 6G end-to-end system with proof-of-concepts, which will be further elaborated in the subsequent deliverables.

Keywords

6G, End-to-End (E2E) system, blueprint, platform, architecture design principles, proof-of-concept.

Disclaimer

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Executive Summary

This report is the first deliverable of Work Package 2 (WP2) – "Draft foundation for 6G system design" – and focuses on the guidelines for the 6G End-to-End (E2E) system design including the design principles, E2E system blueprint, design process, key 6G innovations, and the evaluation framework.

As a continuation of the 6G vision framed in the Hexa-X project, the interaction between the cyber-physical world and human world will be further evolved with the advancement of information, communication, and computation technologies towards a pervasive human centred cyber-physical world in 2030. To reach this 6G vision, Hexa-X-II has set up the goals to design the system blueprint of a sustainable, inclusive, and trustworthy 6G platform. 6G is expected to provide a wider range of services beyond only communication to users and different applications. As such, 6G will act as a platform providing a flexible set of functionalities to the applications, dependent on the current and future needs and requirements. In particular for communication networks, it is important to study the evolution from 4G to 5G and then towards 6G regarding the backward compatibility with respect to 5G and the migration aspects with respect to radio access networks, core network, and hardware. As an initial draft, Hexa-X-II provides ten architecture design principles for a 6G E2E system that are well aligned with the three design goals of sustainability, inclusiveness, and trustworthiness. In particular, extending the key 6G architecture principles introduced in Hexa-X, Hexa-X-II identifies additional principles as well as adjustments to the original ones: 1) Support and exposure for 6G services and capabilities; 2) Full automation and optimization; 3) Flexibility to different network scenarios; 4) Network scalability; 5) Resilience and availability; 6) Persistent security and privacy; 7) Internal interfaces are cloud optimized; 8) Separation of concerns of network functions; 9) Network simplification in comparison to previous generations; and 10) Minimizing environmental footprint and enabling sustainable networks. The foundation for a 6G E2E system blueprint is proposed in such a way to cover those architectural design principles that provide a framework for the novel technologies being developed for 6G. The initial E2E system blueprint consists of four layers, namely i) infrastructure and compute layer, ii) network functions layer, iii) network-centric application layer and iv) application layer. Moreover, it contains a multitude of pervasive functionalities such as a data collection framework, AI framework, security and privacy, and management and orchestration. These components will be selected based on the iterative E2E system design process as below:

- First, the design process will consider the components and/or subsystems provided by the technology usage through key value indicators (KVIs) and the performance requirements through key performance indicators (KPIs) defined in Hexa-X-II and other SNS programs,
- Then, an iterative design process with top-down versus bottom-up alignment will be conducted. The top-down approach involves an iterative design process wherein the system blueprint for the Hexa-X-II platform will be elaborated based on the 6G use-case requirements and the system architecture design principles. The bottom-up approach considers the different components of the system which are designed and provided in separate technical tasks in Hexa-X-II that bring out 6G system innovations.

A comprehensive list of 6G system innovations targeted in Hexa-X-II (and building on Hexa-X enablers) is presented by mapping on the different layers and pervasive functionalities of the 6G system blueprint.

The E2E system evaluation and validation activities in Hexa-X-II will be carried out through a mix of simulations and three industry-leading proof-of-concept (PoC) demonstrations, covering selected functionalities of the 6G platform. This process is starting with the design of the first system-PoC (named as PoC-A), that showcases the sustainability and trustworthy-oriented orchestration and management in 6G with the help of cobots operating in resource limited environment. The report is concluded with a summary of the ongoing work and an outlook on planned next steps which deliver the results of the first system-PoC and the design of other PoCs.

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Acronyms and abbreviations

Term	Description
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GC	5G Core
5G-PPP	5G Infrastructure Public Private Partnership
6G	Sixth Generation
AI	Artificial Intelligence

API	Application Programming Interface
AR	Augmented Reality
ARQ	Automatic Repeat
B2B	Business-to-business
B2C	Business-to-consumer
BLER	Block Error Rate
CaaS	Compute-as-a-Service
CD	Continuous Deployment
CE	Control Element
CHO	Conditional Handover
CI/CD	Continuous Integration/Delivery
CM	Continuous Monitoring
CN	Core Network
CNF	Core Network Function
CP	Control Plane
CRUD	Create, Read, Update, Delete
CSI	Channel State Information
CSP	Communication Service Provider
CT	Continuous Testing
D2D	Device to Device
DCI	Downlink Control Information
DLT	Distributed Ledger Technology
D-MIMO	Distributed MIMO
DN	Data Network
DSP	Digital Service Provider
DSS	Dynamic Spectrum Sharing
DT	Digital Twin
E2E	End-to-End
eMBB	enhanced Mobile Broadband
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute

EVM	Error Vector Magnitude
GDPR	General Data Protection Regulation
GHz	Gigahertz
GSMA	Groupe Special Mobile Association
GW	Gateway
HARQ	Hybrid ARQ
HW	Hardware
IBN	Intent-Based Networking
IBS	Intent-Based Systems
ISAC	Integrated Sensing and Communication
IETF	Internet Engineering Task Force
IoT	Internet of Things
JCAS	Joint Communication and Sensing
KPI	Key Performance Indicators
KVI	Key Value Indicators
LTE	Long Term Evolution
LTM	Layer 1-Layer 2 Triggered Mobility
MAC	Medium Access Control
MEC	Multi-access Edge Computing
MIMO	Multiple-Input and Multiple-Output
ML	Machine Learning
mMTC	massive Machine Type Communication
MN	Master Node
MNO	Mobile Network Operator
MR	Mixed Reality
MRSS	Multi-RAT Spectrum Sharing
NaaS	Network as a Service
NDT	Network Digital Twin
NF	Network Function
NFV	Network Function Virtualization
NR	New Radio

NSA	Non-standalone
NT	Network Tomography
NTN	Non-Terrestrial Network
NW	Network
OPEX	Overall Operational Expenditure
O-RAN	Open Radio Access Network
OTN	Optical Transport Network
OTTS	Over-The-Top Services
PDCP	Packet Data Convergence Protocol
PHY	Physical
PNF	Physical Network Function
PoC	Proof of Concept
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RCS	Radar Cross-Section
RF	Radio Frequency
RIS	Reconfigurable Intelligent Surfaces
RLC	Radio Link Control
ROADM	Reconfigurable Optical Add-Drop Multiplexers
RRC	Radio Resource Control
SBA	Service-Based Architecture
SDN	Software-Defined Networking
SLA	Service-Level Agreement
SLAM	Simultaneous Localization and Mapping
SN	Secondary Node
SNS	Smart Network and Services
SNS JU	Smart Network and Joint Undertaking
SoC	System on Chip
SoTA	State-of-The-Art

TCP	Transmission Control Protocol
THz	Terahertz
TLA	Trust-Level Agreement
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UP	User Plane
URLLC	Ultra-Reliable Low-Latency Communication
V2X	Vehicle-to-everything
VNF	Virtual Network Function
VR	Virtual Reality
WG	Working Group
WP	Work Package
XR	Extended Reality
ZSM	Zero-touch network and Service Management

1 Introduction

Hexa-X-II is the 6G Flagship project under the European Union's Horizon Europe research and innovation program Smart Network and Services Joint Undertaking (SNS JU). This document is the first deliverable of Work Package 2 (WP2) – Draft foundation for 6G system design.

1.1 Objective of the document

The objective of this document is twofold. First objective is to provide the architecture design principles and the first draft of 6G End-to-End (E2E) system blueprint together with the iterative E2E system design process. The second objective is to introduce the first iteration of the E2E system evaluation and validation framework which aims to showcase the innovative functionalities of the 6G platform.

1.2 Structure of the document

The document is structured as follows: Chapter 2 introduces the overall Hexa-X-II WP2 organization, main objectives, work plan, and deliverables. Chapter 2 also provides a high-level overview for the planned interworking between Hexa-X-II WP2 and other SNS strand B projects [6GSNS], and the participation in SNS working groups (WGs) [6GWG]. Chapter 3 describes the principles and foundations for 6G E2E system design together with an overview of the iterative design process of E2E system. Chapter 4 provides the planned 6G system innovations coming from WP2 tasks and other technical WPs. Chapter 5 is devoted to explaining the E2E system evaluation and validation framework planned in WP2. Finally, Chapter 6 concludes the report and highlights the next steps planned in WP2 work plan.

2 Hexa-X-II WP2 set-up

This chapter introduces the key objectives of Hexa-X-II WP2, the work plan, deliverables, and the interaction between Hexa-X-II and other SNS stream B projects and working groups (WGs).

2.1 Hexa-X-II WP2 structure and main objectives

Hexa-X-II is structured in 8 work packages, spanning a timeframe of 30 months [HEXA2]. WP2 is the main technical hub of the project. It collects the results from other technical WPs and integrates some of them in the proof-of-concepts (PoCs), with the aim of evaluating the proposed E2E 6G system holistically. As shown in Figure 2-1, the main objective of WP2 is to design a system blueprint aiming at a sustainable, inclusive, and trustworthy 6G platform, and to provide the E2E system validation (These terms will be introduced in Chapter 3). To achieve the given key objectives, in Hexa-X-II, the five tasks in WP2 will adopt a list of other technological objectives as follows:

- Provide the overall design of the 6G system and harmonize the E2E design principles, KPIs and KVIs, resulting in a 6G platform blueprint.
- Provide the overall design of the radio interface and protocol of the 6G platform, aiming at integrating new paradigms and features related to artificial intelligence (AI)/ machine learning (ML), edge/distributed computing, sensing, subnetworks, sustainable yet flexible radio design.
- Design an intent based E2E service management automation framework for multi-tenant support in multi-stakeholder scenarios.
- Develop a validation framework, focused exclusively on security, privacy, and the associated resiliency issues (threat identification, detection, and mitigation).
- Develop system PoCs to perform E2E evaluation of an implementation of the proposed 6G system with a set of selected components, and to validate if the system can reach at least a subset of the targeted 6G key performance indicators (KPIs)/ key value indicators (KVIs).

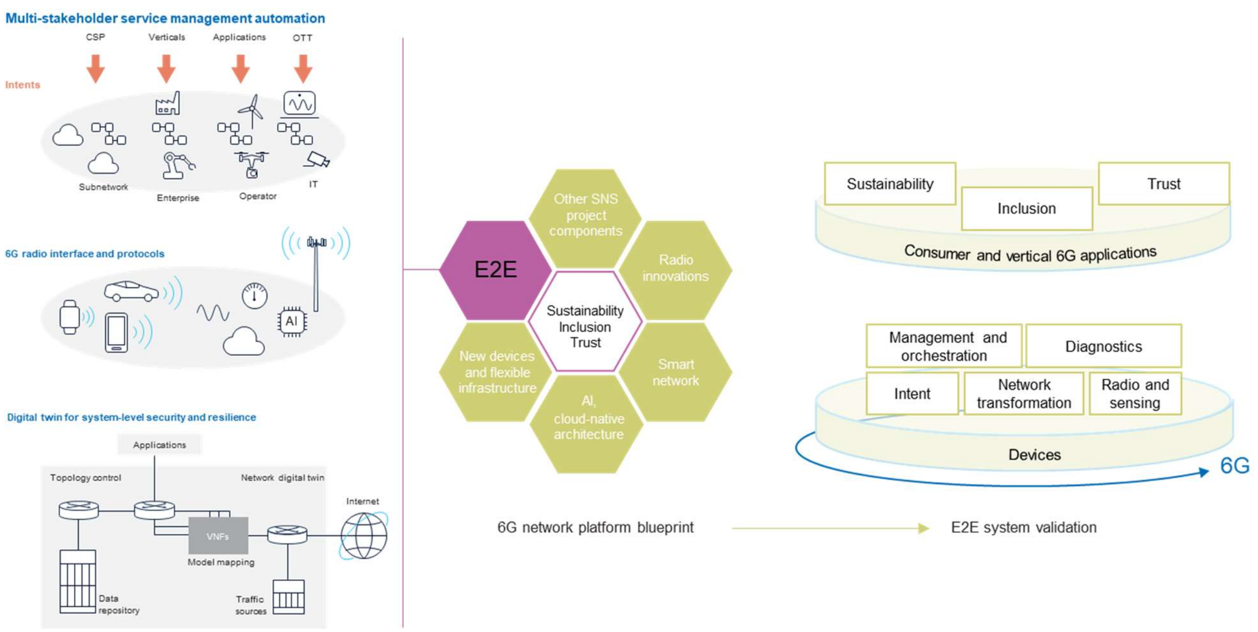

Figure 2-1: Overview of Hexa-X-II concept on E2E system.

2.2 Workplan and deliverables in WP2

WP2 will interact with WP1 regarding the use cases and requirements, KPIs and KVIs, and environmental and ecosystem aspects to be serviced in all tasks. WP2 will also closely collaborate with other technical WPs in Hexa-X-II (i.e., WP3-WP6) regarding architecture enablers, technology components and related analyses to determine how they can be integrated into the 6G system. Further details on this interaction and the iterative design process towards the 6G E2E system design are presented in Section 3.3. Moreover, in the validation part, WP2 will develop three industry-leading PoC demonstrations (numbered as System-PoC A, B and C and described in Chapter 5) covering selected innovative functionalities of the 6G E2E system. WP2 will provide validation results and feedback to technical WPs including WP1, WP3−WP6 and other WP2 tasks, and WP7 for impact and dissemination. WP2 will contribute to workshops with other SNS projects organized and conducted in the context of WP7.

To consolidate and publish the obtained results in four aforementioned phases, WP2 will produce six public deliverables as captured in Table 2-1:

Table 2-1: List of deliverables planned in WP2.

Deliverable Name	Purpose of deliverable
D2.1 Draft foundation for 6G system design (current deliverable) *(Delivered by June 2023)*	To provide the guidelines for the 6G system design and the methodology description for technology components selection and evaluation; To indicate the components considered for the first iteration of the System-PoC (A); To identify interworking with other SNS projects and WGs.
D2.2 Foundation of overall 6G system design and preliminary evaluation results *(Delivered by December 2023)*	To provide the foundation of the 6G platform blueprint, the early description of the components developed by WP2, and the preliminary evaluation results at the system level, including results from the first iteration of System-PoC (A).
D2.3 Interim overall 6G system design *(Delivered by June 2024)*	To provide an initial design of the overall 6G system; To discuss the synergies in terms of the technical enablers and components developed in other SNS Stream B projects; To provide initial description of components of WP2−WP6 relevant for the second iteration of System-PoC (B).
D2.4 E2E system evaluation results from the interim overall 6G system design *(Delivered by September 2024)*	To provide the evaluation results of the second iteration of the System-PoC (B).
D2.5 Final overall 6G system design *(Delivered by April 2025)*	To provide the final design of the overall 6G system; To discuss further synergies in terms of the technical enablers and components developed in other SNS Stream B projects; To provide the final description of components of WP2−WP6 relevant for the second iteration of System-PoC (C).
D2.6 Final E2E system evaluation results of the overall 6G system design *(Delivered by June 2025)*	To provide the final evaluation results of the System-PoC (C) based on the overall 6G system design.

2.3 Interaction and interworking with other SNS projects and WGs

As the SNS Phase 1 stream B-01-05 holistic system project, Hexa-X-II will provide the complete system perspective of the future 6G platform from an architectural and functional perspective as well as from an E2E, user-to-user (human and augmented) perspective, looking for possible integration of key results of other stream B projects as they become available [6GSNS]. As shown in Figure 2-2, there are four other strands in Stream

B which target new solutions related to 6G networks: (1) System Architecture; (2) Wireless Communication Technologies and Signal Processing; (3) Communication Infrastructure Technologies and Devices; (4) Secure Service Development and Smart Security. Altogether eighteen enabler projects are funded in SNS Phase 1 which are distributed over these four strands [6GSNS]. Hexa-X-II will interact with these projects on several perspectives including (i) identification of key 6G use-cases, requirements, and how they can be supported by the retained 6G architecture/technologies, (ii) identification of the most promising technologies, being evaluated under a complete system design approach, towards the realisation of the 6G vision, (iii) translation of societal/ethical use case needs, targets and objectives into technological requirements and identification of the technologies that can match these requirements, (iv) consolidation of 6G KPIs and KVIs as achieving SNS targets for EU research and innovation actions, and (v) identification of critical technologies for future standardisation work.

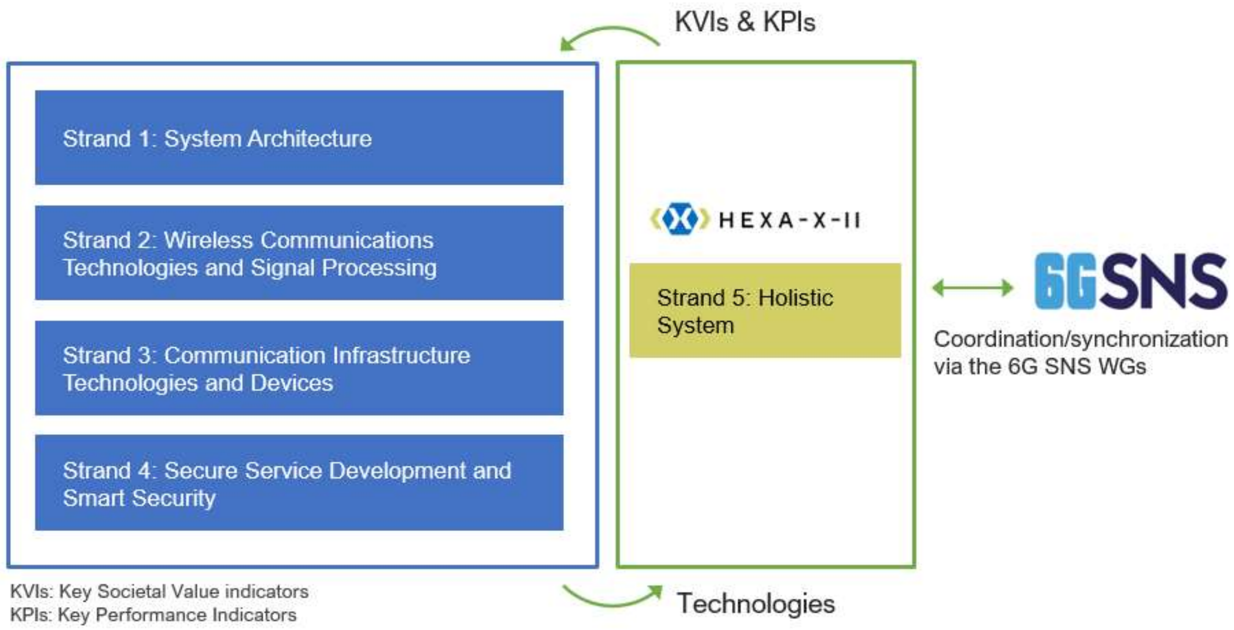

Figure 2-2: Interaction with the strands in the SNS stream B.

Hexa-X-II will also participate in the envisioned 6G SNS WGs such as 6G-IA WGs (Open SNS WG, 5G/Beyond 5G Architecture WG) and SNS strategic WGs that will be created globally and the continuity of 5G PPP WGs. During the upcoming months, the Hexa-X-II team will identify possible relations on technical topics with the current SNS stream B projects and Hexa-X-II, particularly related to WP2 E2E 6G system design and E2E PoC evaluation. Moreover, Hexa-X-II will continue with the 6G workshop series initiated by Hexa-X.

3 Foundation and design guidelines for 6G E2E system

The main objective of this chapter is to provide the foundation and guidelines for the 6G E2E system towards the realization of the 6G vision. In this chapter, three key terminologies are introduced and described.

1) ***6G platform*** is presented as the external view of a set of technologies and interfaces delivering 6G services to applications, ecosystems, verticals, users etc. for enabling value.
2) ***6G E2E system*** is defined as the technical realization of 6G platform which includes the technology enablers and their interaction.
3) ***6G blueprint*** is considered as a reference architecture that meets the E2E system needs with respect to hardware, software, and applications.

The chapter starts with the foundation for 6G E2E system in Section 3.1. To this end, the 6G vision established and promoted by Hexa-X and what is newly envisioned in Hexa-X-II are summarized in Section 3.1.1. The consideration of the desirable evolution towards 6G and the 6G platform are respectively discussed in Section 3.1.2 and 3.1.3. Then, the 6G architectural design principles identified in Hexa-X are revisited and augmented in Section 3.1.4. Based on these principles, the first proposal for the 6G E2E system blueprint is defined in Section 3.2 to guide the fine-tuning of technology developments of Hexa-X-II and their integration in the E2E system. The 6G E2E system design will be matured during the project in line with results from the evaluation and validation in terms of E2E performance. The iterative design process followed by the project to refine and consolidate the E2E system blueprint of the sustainable, inclusive, and trustworthy 6G platform is further defined in Section 3.3.

3.1 Foundation for 6G E2E system

3.1.1 6G vision

The 6G vision from Hexa-X [HEX21-D1.2] is built on the interaction between three worlds in the form of a cyber-physical world with humans at the centre: a) a human world of our senses, bodies, intelligence, and values; b) a digital world of information, communication, and computing; and c) a physical world of objects and processes. Continuing these concepts initiated in Hexa-X, Hexa-X-II envisions an E2E system blueprint of the sustainable, inclusive, and trustworthy 6G platform that should meet the future needs of serving and transforming society and business by 2030, as illustrated in Figure 3-1.

As a pre-requisite to meet the needs of the business and societal transformation, 6G will introduce a paradigm shift from the former generations (Gs) “built for performance” to add a new paradigm of “built for values and performance”. So far, networks have traditionally been measured according to their speed & capacity, reliability & latency, and scale & flexibility, but the 6G era will require a new architecture for a new set of values which will constitute design priorities for the Hexa-X-II project:

- Environmental sustainability and energy efficiency will be a design priority for 6G while being economically sustainable. Environmental sustainability is the responsibility to preserve natural resources and protect biodiversity and natural ecosystems to support health and wellbeing now, and in the future. Economical sustainability is about supporting long-term economic growth without negatively impacting social, environmental, and cultural aspects of the community.
- Trustworthiness is covering aspects of security, reliability, and resilience to attacks and operational failures, quality of service (QoS) guarantees, and user data privacy and security. The scope of trustworthiness will become wider in the 6G era to address concerns that may arise from the expansion of technologies such as joint communications and sensing and pervasive use of AI driven network operations.
- Digital inclusion is ensuring that everybody can contribute to and benefit from the digital world. This includes not only providing access to 6G networks and devices in remote areas that lack high connectivity access to digital services due to economic reasons, but also ensuring that individuals and communities have the digital skills necessary to use the new technologies effectively.

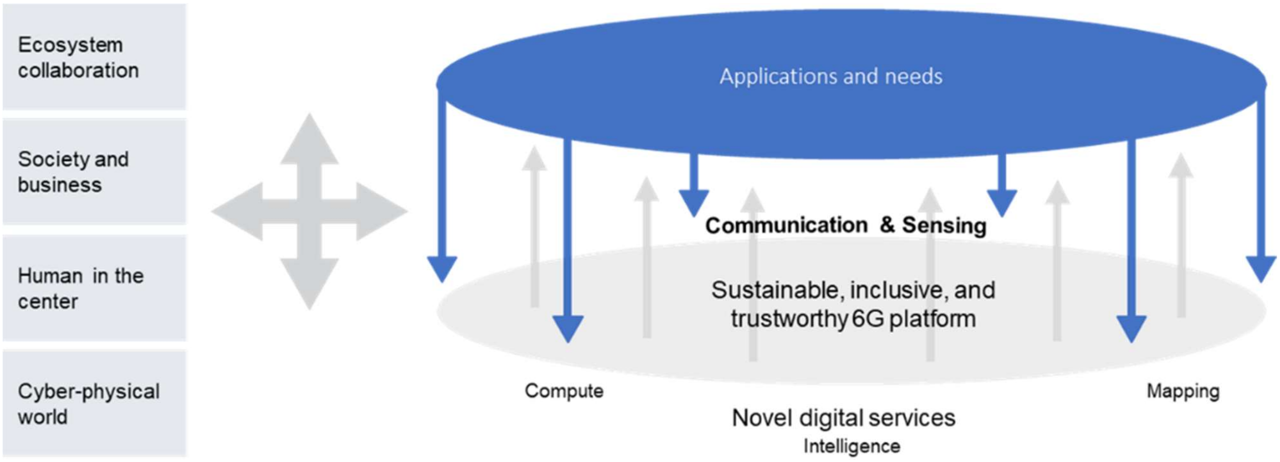

Figure 3-1: 6G platform vision in Hexa-X-II and what it can enable.

While supporting the transformation from the changing societal values, the 6G platform will also unleash new businesses by offering novel digital services that will radically transform communications in the next decade. It will introduce novel beyond-communication services, integrating sensing, AI, and compute services with communications:

- Compute services for applications in need of data processing, storage, and management. By enabling end-user devices to offload heavy or time-critical computations to the network, the 6G system can foster a wide range of mobile use cases, with lightweight, untethered devices (i.e., not enabling direct connection to the network) for example extended reality (XR) or zero-energy applications.
- Intelligent services such as AI functionality, analysis, and optimizations. These services will facilitate a systemic application of AI/ML techniques inside the network, providing a new foundation for air interface design and optimization, data processing, and automation of network operations, dealing with the complexity of orchestration across multiple network domains. Intelligent services will also help optimizing diverse vertical services and applications. For example, insights exploiting traffic and mobility data can be offered services to applications enabling them having a better understanding of current and upcoming network situations for the device-side clients.
- Mapping services cover spatial/temporal data services such as awareness and localisation of objects and surroundings, mapping, and synchronization. They will leverage high-precision localization (with centimetre-level accuracy), sensing (both radar-like and non-radar like) and imaging (at millimetre-level) capabilities brought by 6G and enabled by the use of wider bandwidth signals coupled with high band spectrum (>100 GHz) as well as the incorporation of Simultaneous Localization and Mapping (SLAM) with communications at lower frequencies.

Not surprisingly, 6G is expected to encompass and enhance the three communication-based usage scenarios of 5G (i.e., enhanced mobile broadband (eMBB), ultra-reliable low latency communication (URLLC) and massive machine type communication (mMTC)). However, 6G is also expected to introduce novel use case families for communications in the 2030s that may require combinations and extensions of several of the 5G usage scenarios, including, among others, immersive telepresence, massive twinning, collaborating robots/machines/drones [HEX22-D13]. The 6G platform will be an integral part and driver of the cyber-physical world of the 2030s, expanding human possibilities and assuring human control and focus (human in the centre).

A wide ecosystem collaboration, including mobile network operators, cloud providers, enterprises, vertical industries, integrators, application developers & application service providers, end users, etc., will be a prerequisite to creating values from novel services offered by the 6G platform. The 6G system design should not only accommodate various go-to-market strategies (e.g., retail vs wholesale) with business-to-business (B2B) services (e.g., industry segment) and business-to-consumer (B2C) services (e.g., mass-market), but also be prepared for unknown more fragmented value creation chains than a traditional linear chain (equipment supplier-communication service provider – customer) with novel services. These new services are typically composed of mashups combining capabilities from multiple stakeholders. All the players expect support for different use cases and requirements and can benefit from a platform that can be tailored to their specific needs.

This is the role of 6G networks as a versatile platform interfacing with a broad range of applications and responding them as needed, which is depicted in Figure 3-1.

To build an operational system that is both performance- and value-oriented, a redesign of the network architecture for 6G should be considered. The cellular mobile network architecture should evolve to be fully cloud native with the generalization of the core service-based architecture to the rest of the network. Moreover, it should transform with the convergence of network and cloud and integrate in-network computing to meet the needs from 6G applications. The architecture should also integrate natively the AI services to be extensively used in the network from the core to the end user as well as for the full automation of the network management and orchestration. The architecture should afford flexibility in the network topologies such as subnetworks, non-terrestrial networks, and meshed network to expand the network reach required by 6G use cases. Development of the new technologies required by the novel 6G architecture are accordingly split into i) network transformation mechanisms to support flexible topologies and beyond communication services, ii) spectrum and radio enablers, iii) technologies promising to facilitate flexibility and efficiency of the infrastructure and iv) network enablers and intelligence for software configuration and resource management. The 6G system blueprint will target the simplification of functions and protocols, the introduction of service-based interfaces between the radio access network (RAN) and core network (CN), and the enhancement of flexibility and programmability, etc. Building the E2E system requires a holistic view on interacting enablers that will transform the devices, the infrastructure, the network capabilities, the E2E management and orchestration, along with the performance, sustainability (e.g., energy efficiency, environmental footprint, or environmental impact), digital inclusion (e.g., service coverage in remote areas), and trustworthiness (e.g., security, privacy, and system-level resilience) considerations.

3.1.2 Evolution towards 6G

In the transition from 4G to 5G, there was a great push to allow a gradual transition from 4G RAN, known as LTE (Long Term Evolution), towards 5G RAN, known as NR, as well as from 4G CN EPC towards 5G CN (5GC). The reason was to allow the operators to flexibly upgrade RAN and CN independently. As seen in Figure 3-2, LTE and NR could be used as nodes, with either one or two nodes in any combination connected to either EPC or 5GC. This engendered a plethora of combinations, that each had to be standardized and would have to be configured, and tested, even though only a few combinations were eventually deployed, namely NR connected to 5GC, and LTE as MN and NR as SN connected to EPC (a.k.a. EN-DC).

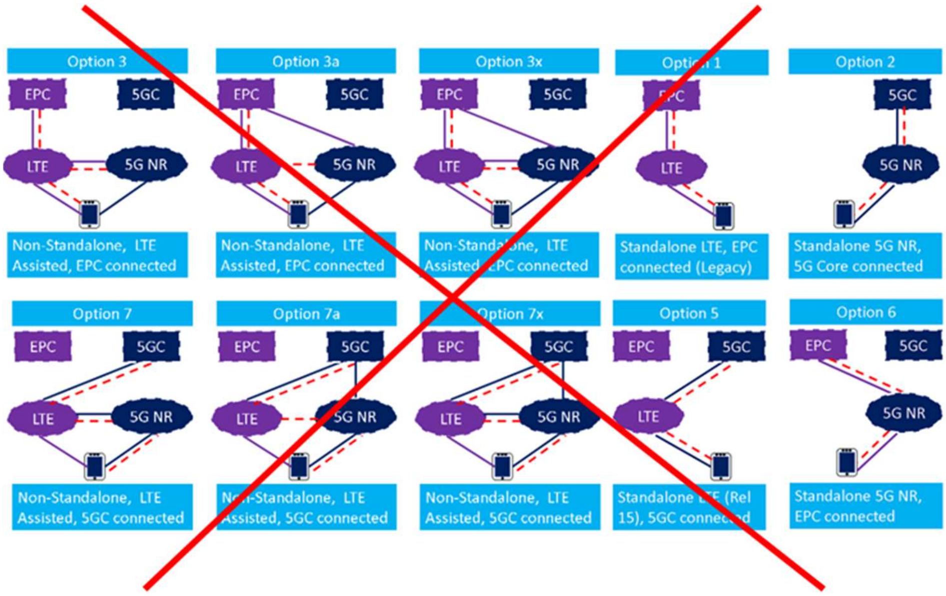

Figure 3-2: Avoiding the too many deployment options of 5G.

However, the transition from 5G to 6G should not allow as many migration flavours, since both NR and 5GC are more future proof than LTE or EPC were. Thanks to the 5G flexible frame structure, the currently used spectrum can gradually be reallocated from 5G to 6G through in-band spectrum sharing, as the 6G traffic increases. In particular, the sub-6 GHz bands are key to achieving the required coverage, especially for the initial access. In addition, the global spectrum allocations may yield new frequency bands, either in the centimetre band 7.125-15.35 GHz or above 100 GHz (sub-THz region), which can be used by the new 6G RAT (Radio Access Technology). Bearing in mind that there are limited options when it comes to new globally harmonized bands, it becomes evident that the ability to leverage existing 5G spectrum will play a pivotal role in the successful and cost-efficient migration to 6G.

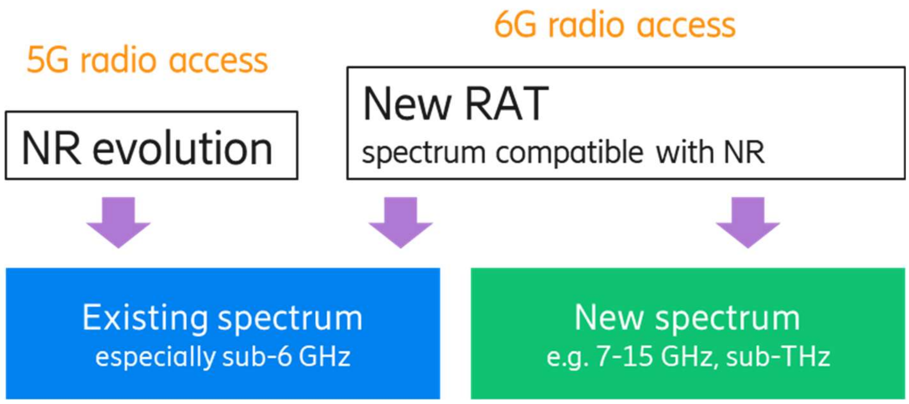

Figure 3-2: Spectrum for a 6G RAT.

On the radio interface, NR relies much less on always-on reference signalling compared to LTE, allowing incumbent resources to be reallocated from 5G to 6G without unduly impacting the legacy 5G performance. While traditional spectrum refarming is always a cumbersome alternative, a spectrally efficient Multi-RAT Spectrum Sharing (MRSS) solution between 5G NR and 6G is not only possible, but also needed to live up to the end-user expectations on 6G performance. Owing to 5G NR's flexible, beam-centric, and lean-carrier design, real-time and energy-efficient spectrum sharing between 5G and 6G cells would not be plagued by the overhead challenges and limited LTE UE capabilities experienced with 4G−5G Dynamic Spectrum Sharing (DSS). In practice, MRSS is envisioned to be deployed in low frequency bands for coverage and then supplemented with MRSS deployments in mid bands for capacity, thus eliminating the need for new site acquisitions and paving the way for a smooth rollout of 6G cells during the early 2030s.

With the introduction of the Service-Based Architecture (SBA), the 5GC got a more flexible and extensible design than earlier generations. The 5GC makes it easier to introduce new features. Thus, it will be possible to extend the 5GC with support for the new RAN features that comes with a new 6G RAT, as shown in Figure 3-3. This way, non-standalone (NSA) solutions with 6G RAT relying on 5G RAN and 5GC can be avoided, minimizing the number of architecture options for 6G.

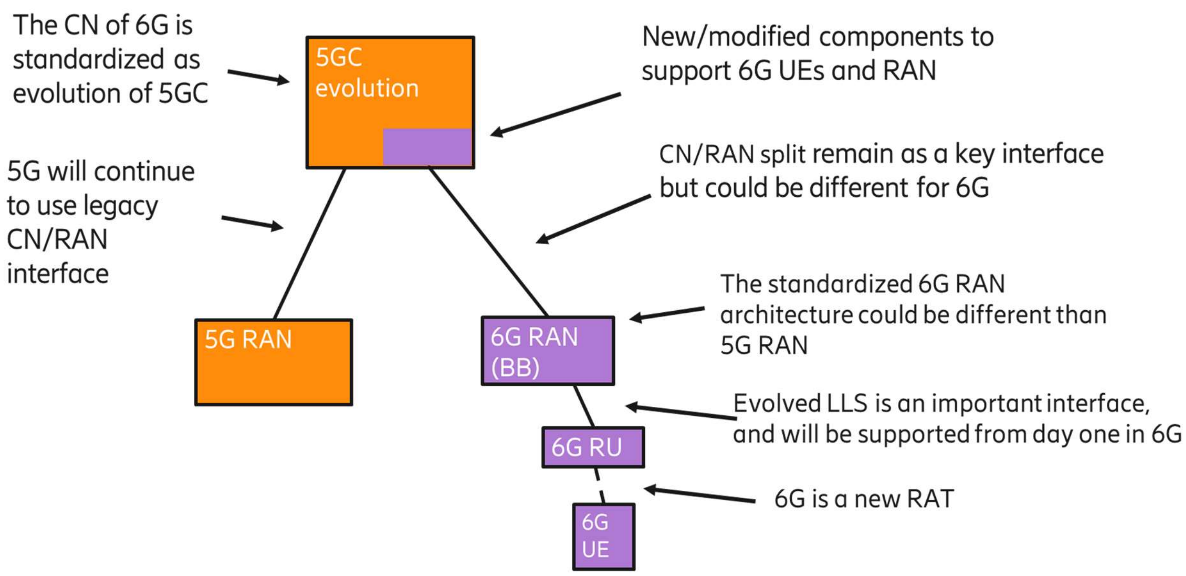

Figure 3-3: 6G RAN connected to an evolved 5GC.

It is expected that 6G will support "beyond communication" use cases which may require devices to offload some of the computations to the edge, reducing the processing requirements on devices allowing for more compute intensive applications. To reap the full benefit of the computational offloading, 6G will have to natively support computing services, as part of the system design, instead of relying on over-the-top offloading. This would require an improved communication between the UE edge nodes and base stations. At the same time, new and enhanced use cases will require different device characteristics. For all the aforementioned use cases and their associated target KPIs to be achieved, the existing mobile communications protocol stack needs to be redesigned for tackling issues such as jitter, packet loss, data rate fluctuations, E2E latency, seamless mobility, privacy and UE complexity. Finally, optimizations should be possible to be performed across the different layers on both the network and UE side, e.g., for joint optimization of communication and computing, allowing for dynamically adapting application QoS/ quality of experience (QoE) requirements to radio conditions, improving as a result the end-user experience while keeping the UE complexity low.

3.1.3 6G platform

As indicated in Section 3.1.1, unlike previous generations of mobile networks, 6G is expected to have a wider set of capabilities and functionalities beyond only communication to users and different applications. As such, 6G will act as a platform providing a flexible set of services to the applications, adapted to the current needs and requirements, see Figure 3-5. On the platform, the networks will expose a diverse set of APIs to applications, users, and verticals, which can be extended over time. On the platform, the networks will expose a diverse set of APIs to applications, users, and verticals, which can be extended over time.

The obvious focus is services related to communication functionality, but also management and orchestration services for applications and networks. Over time, a broader range of services can be offered to applications, where networks not only transport data (communication), but go beyond communication to process and store data (auxiliary services) and are a source of data themselves (information services such as Joint Communication and Sensing (JCAS)).

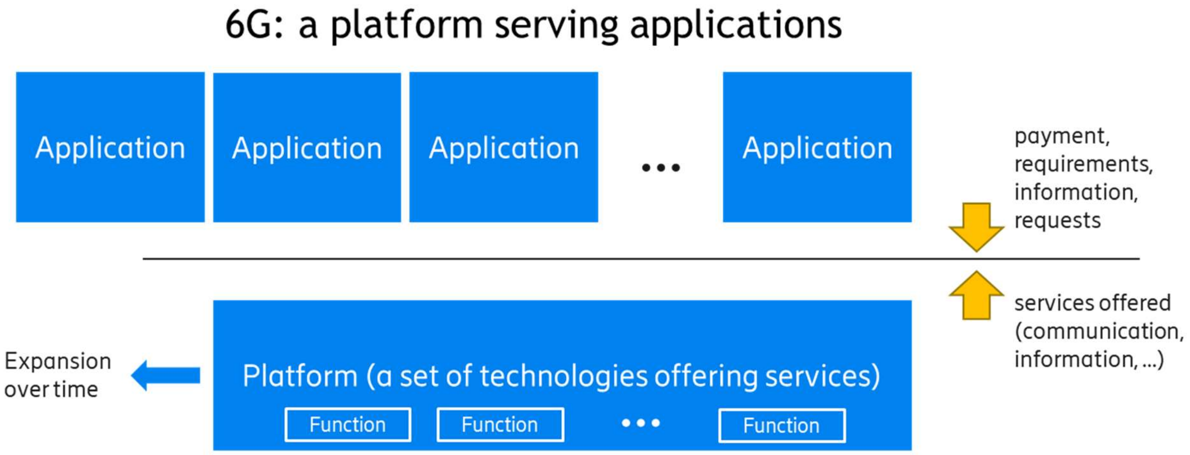

Figure 3-4: The 6G network as a platform.

3.1.4 Architecture design principles

The architecture work presented in [HEX21-D51] and [HEX22-D13] provides a useful starting point including eight architecture design principles for 6G. However, the development since they were published call for an update and extension of the principles as described below:

Principle 1 - Support and exposure of 6G services and capabilities: Design of the 6G system should enable efficient incorporation of 6G digital services, such as sensing and computational offloading. The architecture solution should also be able to expose new and existing capabilities to E2E applications. This means that the applications can be provided with enhanced capabilities for various network features and services. This can for example be used for achieving low and predictable latency, predicting and anticipating the future performance of a connection/application, predictive orchestration, sensing services, compute offload, etc.

Principle 2 - Full automation and optimization: The architecture should support full automation of network and service management operations, utilizing distributed AI/ML agents to manage and optimize the system without human interaction. Key features include observability and analytics as well as intent-based management. Trust and explainability aspects related to AI functionality are important to guarantee. The system should also support continuous orchestration over multiple stakeholders and domains, in an E2E approach.

Principle 3 - Flexibility to different network scenarios: The architecture should be designed to support digital inclusion, by adapting to network-of-network topologies such as subnetworks, non-public networks, autonomous networks, mesh ad hoc networks, new spectrum, and NTN, without degradation of performance. Addition of service capabilities and new service endpoints can be done at run-time without changes to existing E2E services. The network should support increased application awareness and adaptive QoS/QoE.

Principle 4 – Network scalability: The system architecture needs to be scalable to different networks and deployments. The architecture should support very small to very large-scale deployments, by scaling up and down network resources based on mobility and time-varying traffic needs and by utilizing the underlying shared cloud platform. The architecture should be scalable to also support multi-stakeholder deployments.

Principle 5 - Resilience and availability: The architecture should allow mobile network operators (MNOs) to build deployments with high resilience and availability. The architecture shall support separation of control plane (CP) and user plane (UP), and resilient mobility solutions as a method to provide service availability. Furthermore, the architecture should support subnetwork resilience e.g., if a subnetwork loses connectivity it should connect with another subnetwork to remove single point of failures.

Principle 6 - Persistent security and privacy: The 6G system should be able to address current as well as future threats in a resilient manner and incorporate security fundamentals in its design. Furthermore, the 6G system should inherently support the preservation of privacy and allow different levels of anonymity also for future services.

Principle 7 - Internal interfaces are cloud optimized: Network interfaces should be designed to be used in a cloud-native environment, utilizing state-of-the-art cloud technologies, design patterns, platforms and IT tools in a coherent and consistent manner. Care should be taken to design proper service separation to maximize the potential for service reuse and allow for service innovation with minimal integration efforts (plug-and-play).

Principle 8 - Separation of concerns of network functions: The network functions should have bounded context (separation of concerns) and all dependencies among services should be through their APIs, with minimal dependency on other network functions. This allows network functions to be developed and replaced more independently from each other and also allows efficient scaling of network resources. The functionality of network functions should not be duplicated.

Principle 9 - Network simplification in comparison to previous generations: The network architecture should be streamlined to reduce the complexity of RAN and CN functions with fewer (well-motivated) parameters to configure and fewer external interfaces, to maximize innovation, and to reduce time to market.

Principle 10 - Minimizing environmental footprint and enabling sustainable networks: The design of 6G system should ensure that the environmental footprints can be justified, and any increased footprint should be clearly motivated with added value, cost efficiency, and societal benefits. The architecture design should enable to disable or deactivate functions that are not in use, either short-term or long-term, to ensure zero power at zero load. It should also facilitate circular practices through higher modularity of components to limit the replacement to only the degraded part or compatibility with software update to extend the lifetime.

3.2 6G E2E system blueprint

The following sub-section introduces the first draft of 6G E2E system blueprint that should fulfil the architectural principles described in Section 3.1.4. The analysis of the high-level view of the 6G architecture of Hexa-X [HEX22-D13] and of the functional view perspective provided in the joint Hexa-X and 5G PPP Architecture Working Group book “Towards Sustainable and Trustworthy 6G – Challenges, Enablers and Architectural Design” [BLG+23], as well as information coming from discussions among the partners were the main sources of information to create the first draft of the 6G E2E system blueprint.

The services offered by the 6G platform will be delivered by its technical realization which is the 6G E2E system consisting of many interacting subsystems, see Figure 3-5. The 6G E2E system should be designed according to the architectural principles outlined in section 3.1.4 and provide an efficient framework for the novel technologies developed for 6G, as is described in Table 3-1.

Table 3-1: Mapping of architectural principles on the 6G E2E system design.

Architectural principle	E2E design impact	Related Hexa-X-II design goals
1: Support and exposure of 6G services and capabilities	Generic and dynamic exposure functionality; Integration of beyond-communication network functions and HW; Pervasive AI; Compute infrastructure	Sustainability, Trustworthiness, Inclusiveness
2: Full automation and optimization	Pervasive data and analysis framework; Pervasive AI framework; Pervasive service management and orchestration	Sustainability, Trustworthiness
3: Flexibility to different topologies	Pervasive service management and orchestration; Exposure of infrastructure towards network layer to make accesses transparent; Gateway UEs; Programmable transport	Sustainability, Inclusiveness
4: Network Scalability	Pervasive service management and orchestration; Network-centric exposure layer; Transport network functions	Sustainability, Trustworthiness
5: Resilience and availability	Pervasive service management and orchestration; Pervasive data and analysis framework; Pervasive AI; RAN functions; Transport network functions; core network functions (CNFs); Subnetworks	Trustworthiness

6: Persistent security and privacy	Pervasive security and privacy framework	Trustworthiness
7: Internal interfaces are cloud optimized	Cloud-native virtual network functions; Exposure interfaces between layers	Sustainability, Trustworthiness
8: Separation of concerns of network functions	Optimized functionality in CN and RAN; Self-sustained NFs	Trustworthiness
9: Network simplification in comparison to previous generations	Avoid many standardized deployment options / protocol splits; 5GC evolution to support 6G RAN; Simplified protocol and reduced UE-NW signalling	Sustainability, Inclusiveness
10: Minimize environmental footprint and enabling sustainable networks	E2E orchestration for energy-lean and cost-aware operation; Pervasive data and analysis framework; Modularization of network functions; Energy and cost-efficient infrastructure	Sustainability

A blueprint describing the 6G E2E system should capture the main functional areas and indicate important interfaces both internally and externally. An important objective is to show the relation to well-established communication network architectures (e.g., RAN, CN and transport network) and indicate how to integrate beyond-communication functions. In addition, it is important to demonstrate how services and functionality will be exposed to applications and users.

The initial draft of the 6G E2E system blueprint presented in Figure 3-5 consists of four key layers, i.e., Application layer, Network-centric application layer, Network functions layer, and Infrastructure and compute layer. It also consists of a multitude of pervasive functionalities that are represented in the blue box to the right. Additionally, the 6G E2E system blueprint also specifies the presence of interface/exposure (thin dashed lines) and control/intent/observability (bold dashed line), which are utilized by the various pervasive functionalities, as well as the network-centric and 3rd party applications (top two green boxes of Figure 3-5).

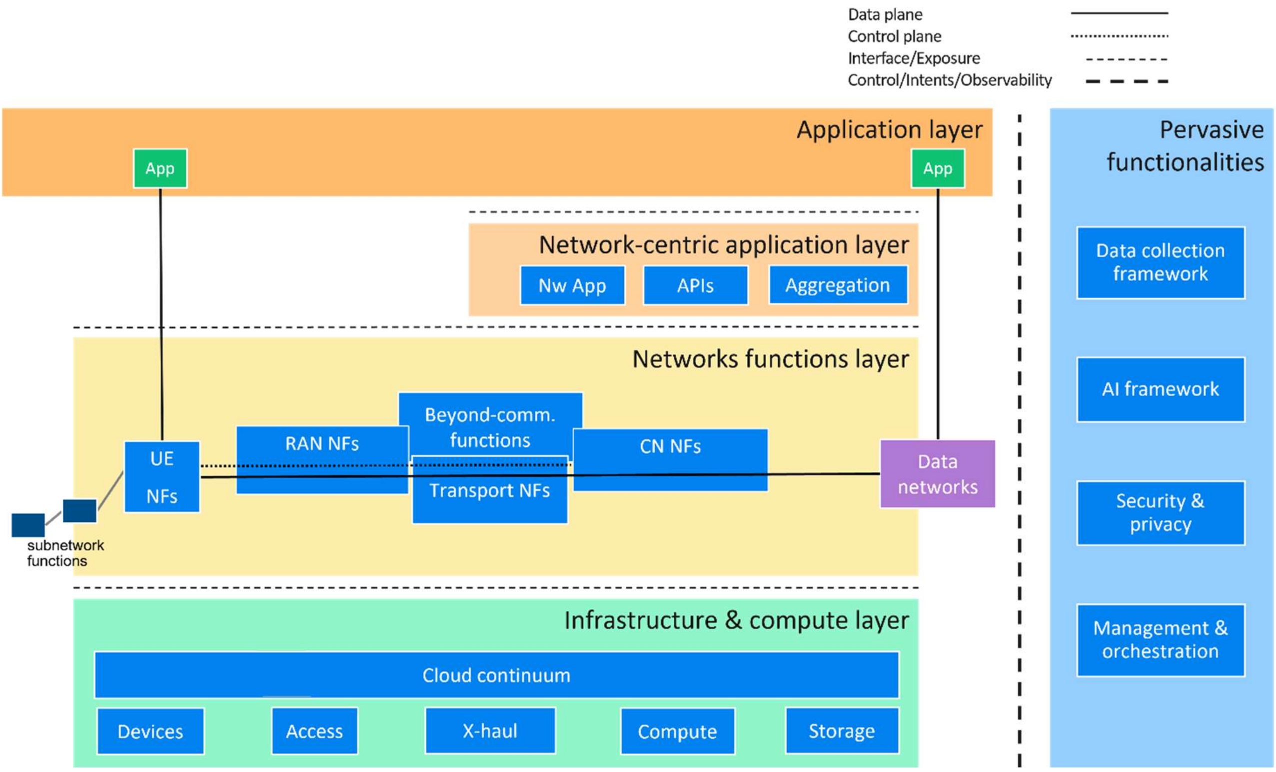

Figure 3-5: Initial 6G E2E system blueprint.

First, the **Application layer** mainly represents the applications that may have certain service expectations from the network itself. These expectations may depend on the application requirements, such as bandwidth, latency, etc. The Network functions layer and the Network-centric applications layer expose network information and network control APIs through the interface/exposure towards the application layer. This enables the application developers to specify their requirements to the network as well as to adjust the expectations of the applications based on network conditions. Operations APIs for the service management and orchestration can also be exposed to the application ecosystem actors (e.g., to vertical providers) through developer-friendly intent-based abstractions and human-oriented intent-based APIs [GSMA] [CAMARA].

The **Network-centric application layer** consists of network-centric applications, APIs, and aggregation. Network-centric applications are applications that can interact with the control plane of the Network functions layer to provide enriched services to vertical applications. Moreover, these network-centric applications can provide certain actions/updates to the network functions and thereby provide quick ways to modify the network functionality. Through the use of data collection, analytics and AI models, the network-centric applications can enable additional intelligent operation and optimization of the network (e.g., rApp in O-RAN). These applications, being more centred on network capabilities and under network control, have been presented as a separate layer from the application layer which is more end user or enterprise centric. In addition, this layer contains network-centric services exposed via APIs to developers of applications of the Application layer. Such APIs can be simplified (abstracted) or combined services that third-party application developers can consume with familiar tools and processes and still provide them access to a wide set of network capabilities (e.g., application flows steering) without the need to be network experts. These APIs may be standardized, e.g., through CAMARA. Aggregation relates to the actions needed to compose services that are realized via the aggregation of capabilities of the 6G network. The APIs could further benefit from the capabilities of a set of different 6G service providers, e.g., over multiple networks, connected through federation APIs.

Next, the **Network functions layer** consists of:

- **UE and subnetwork functions**: The protocol stack of the UEs is controlled through the network by using signalling procedures, such as those for resource allocation. Furthermore, UEs can collaborate amongst themselves, connecting device-to-device (D2D), in subnetworks wherein the gateway UE (GW-UE) can connect the subnetwork to the 6G system. In such scenarios the subnetwork devices manage coordination and communication amongst themselves either independently or via network-based coordination. Consequently, the subnetwork functions are displayed partially outside the network functions layer, indicating the possibility of some UEs, such as GW-UEs, still managed completely by the network and other subnetwork devices being managed by the GW-UE.
- **RAN functions**: Given the different RAN deployment scenarios answering to various stakeholder needs - centralized, distributed, cloud-based, disaggregated, etc., it can be envisioned that the network functions related to the RAN will consist of physical network functions (PNFs) and virtualized network functions (VNFs). Concretely, this increased softwarization will enable autonomous orchestration, programmability, and analytics-based close-loop resource control to these network functions.
- **CN functions**: Recent advancements in softwarization techniques as well as the service-based architecture of the 5G CN provide the right basis for 6G CN to be completely virtualized. Moreover, the virtualization of the CN functions enables flexible deployments which can involve the data plane related functions being close to the network edge whilst the control plane related functions can be either close to the edge or in a centralized location. This separate deployment of (CP and UP) functions will be supported by the presence of edge and central cloud infrastructure.
- **Transport network functions**: Software defined networking architecture for transport network infrastructure will enable the programmability of the system elements of this underlying fabric. Virtualized transport network functions can be dynamically designed, deployed, activated/deactivated, removed without or with minimal service disruption according to the evolutions of the transport infrastructures as well as the changes of transport service demands.
- **Beyond communication functions**: 6G network functions will extend the 6G capabilities to a new level beyond communications with, e.g., novel RF-based sensing. Network-based sensing data can be augmented by AI and fused with data generated from millions of IoT connected sensors. AI-related and compute-related functionality as well as 6G positioning and mapping functionality would also be implemented as beyond-communication functions. This processing will introduce new

functions/services distributed across the network. Beyond communication functions also cover new 6G capabilities to support novel use cases, e.g., provide advanced network-aware and mobility-aware computing services, data/analytics services, etc.
- **Data network**: The Data Network (DN) is related to the 3GPP architecture. It identifies functionalities related to services provided by the operator, the Internet access or 3rd party services. While data networks have not traditionally been considered as part of the mobile network, the increased usage of cloud infrastructure for current and future network deployments mandates that they should be considered partially within the scope of the operator network as well. For instance, the ETSI MEC (Multi-Access Edge Computing) and the O-RAN (Open Radio Access Network) Alliance organizations envision a new ecosystem and value chain where MNOs can open their edge computing (as data networks) to authorized third parties. This allows the latter to flexibly deploy applications towards subscribers. Within the recent context of time-critical edge applications, strong cooperations between the Data Network (e.g., edge computing) and the CN [23.548, 23.558] are needed to provide an optimal solution (or at least a good enough solution in a time and energy efficient manner) with regards to the application requirements in terms of E2E QoS (e.g., 3GPP SA2 and SA6).

Within the Network functions layer, the user and control planes are indicated with solid and dashed lines in Figure 3-5 respectively. Services and functionality in the Network function layer can be exposed through APIs directly to the Application layer, or through the Network-centric application layer.

The **Infrastructure and compute layer** consists of the actual low-layer (i.e., physical layer) infrastructure such as the device hardware, the access and X-haul infrastructure (base stations, satellites for non-terrestrial networks, packet routers & switches, optical transport network (OTN) switches, reconfigurable optical add-drop multiplexers (ROADM), fibres), compute and storage facilities and the cloud continuum. The transmission resources in the infrastructure layer allow the transmission of data from one end to another. These encompass the end-user devices, access, and X-haul infrastructure for providing required connection capacity and performance to carry the traffic of applications. The “Compute” (e.g., CPU, GPU) and “Storage” (e.g., hard disks) are resources provided by compute nodes that can be distributed across the E2E path, including end-user devices, edge computing and central data centres. All types of resources can be abstracted thanks to numerous virtualization technologies and presented to the Network functions layer via a cloud platform called “Cloud continuum”. While considering resources from the end devices to the central cloud, one could foresee a continuum of those resources between adjacent organizations. Thanks to the virtualization technologies, the Cloud continuum can easily and flexibly partition the underlying resources to enable a better utilization of those resources by the Network functions layer.

The **Pervasive functionalities** describe the functionalities and the frameworks that need to realize the full potential of 6G networks, i.e., by facilitating other layers of the 6G E2E system blueprint in Figure 3-5.

- The **data collection framework** will provide the necessary functionalities to support several different types of data and information to be collected from multiple domains and layers of the network and moved within the network (for analysis). Note that the movement and fusion of data will take place considering the privacy and ownership concerns of all stakeholders. Further, these actions should be compliant with local security and privacy laws, for example, General Data Protection Regulation (GDPR) in the EU, Cloud Act in USA, etc. Coupling data across applications and network will provide the opportunity to improve the network performance or enable network aware applications. It will support local processing of data required for responsiveness of real-time control and operations.
- The **AI framework** will support a systemic application of advanced AI/ML techniques at all stages of the system, i.e., domain specialized and cross-domain AIs, AI-embedded network functions and devices, and across all functionality/protocols layers.
- The **security & privacy** functionality is affecting all layers of the system blueprint and multiple aspects from the network design to the business and the operational aspects. It will address the identification and detection of security and privacy threats that may be implied from new aspects introduced by 6G at the devices, protocols, and architecture elements, and will comprise novel emerging mitigation techniques. Privacy enhancing technologies will also help to reduce the amount of sensitive information to be shared across different entities.

- The **management and orchestration** functionality will cope with novel and more complex services combining both network capabilities, and beyond communications capabilities such as sensing and computing. Smart network management will provide a uniform orchestration across a continuum of resources from extreme edge to edge to central clouds. Automation functionality will provide more and more degrees towards autonomy with fully automated closed-loop control, supported by intent-based management and AI/ML techniques. It will also comprise the Continuous Integration/Delivery (CI/CD) intrinsically associated to the development of software components.

Each of these aforementioned functionalities will impact some/most components of the infrastructure, network functions, network-centric applications, and the third-party applications. Hence, each of these layers has connections to these pervasive functionalities depicted in Figure 3-5 via the dashed line signifying interfaces for observability and intents.

3.3 Iterative E2E system design process

The development of technologies for the 6G E2E system will consider the framework for the value impact of technology usage through KVIs, and the related performance requirements through KPIs, see Figure 3-6. Starting from the use cases, and the scenario context of environment and stakeholders, the needed capabilities and requirements can be extracted and compared with a system performance. Simultaneously, the impact of the use cases should be studied in light of key values to show that the majority of the 6G use cases have a significant positive impact on e.g., sustainability. The Hexa-X-II technical WPs will develop technical solutions considering this framework of value impact and requirements (again see Figure 3-6). The solutions will need to be placed in the context of the 6G E2E system and will further need to be evaluated in context of the performance and impact expectations. This is the process of systemization, which will be performed in WP2 in interaction with other WPs in Hexa-X-II [HEXA2].

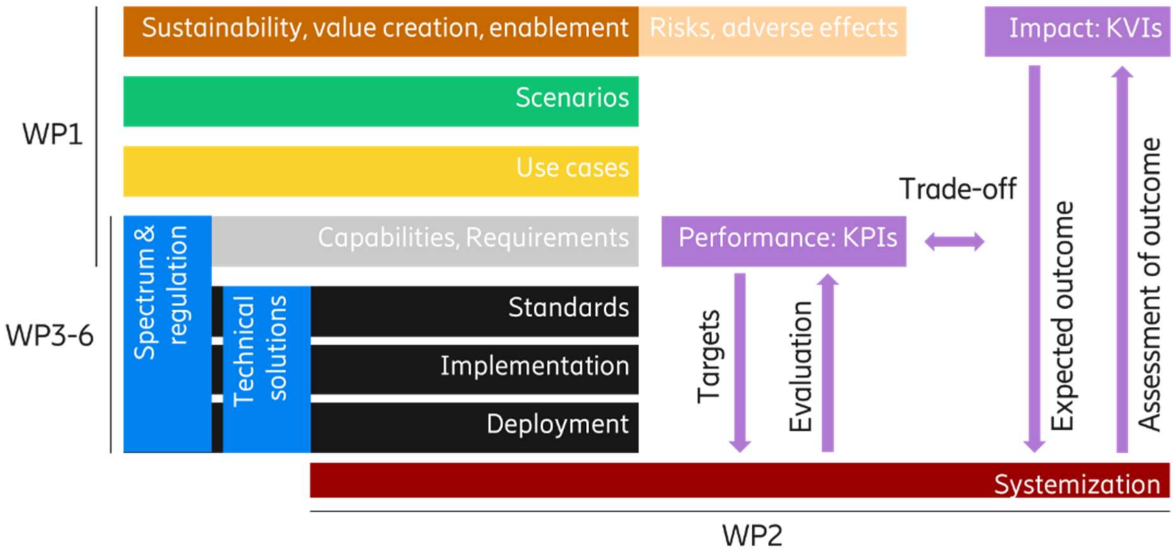

Figure 3-6: Hexa-X-II systemization process overview.

When systemizing technical solutions in context of expectations there will be an iterative process of targets and evaluations, where potential gaps can be identified and addressed in the technical development. Another important process will be to study potential trade-offs between performance targets and expected outcomes of technology usage. This process should be done considering the value creation (in economical, societal, environmental domains) and associated risks, and relevant priorities from different stakeholders.

At each iteration, a design of the blueprint of the sustainable, inclusive, and trustworthy 6G platform will be elaborated according to an iterative design process detailed hereafter in this section. Then, a series of system-PoC integrating a selected set of components in an E2E system will be built to evaluate and validate some key aspects of the proposed 6G system design. The description of the system PoCs and their evaluation and validation process are provided in Chapter 5. As it will not be feasible within this research project to have every component of the 6G system integrated into a system-PoC, the evaluation and validation process will be complemented as much as possible by the analysis of some simulation results, also detailed in Section 5. The results from the evaluation will then be taken into account in the next iteration of the system design process, ensuring the designed 6G system meets the targeted key values of E2E sustainability, inclusion, and trustworthiness. The next sub-sections detail the two sub-processes that form the overall 6G E2E system design process: i) the KPI/KVI-based iteration process and ii) the top-down versus bottom-up alignment process.

3.3.1 KPI/KVI-based design process

The iterative design process based on KPIs and KVIs is described through Figure 3-7, in which it can be observed that the 6G system is designed based on the use cases that it is meant to serve.

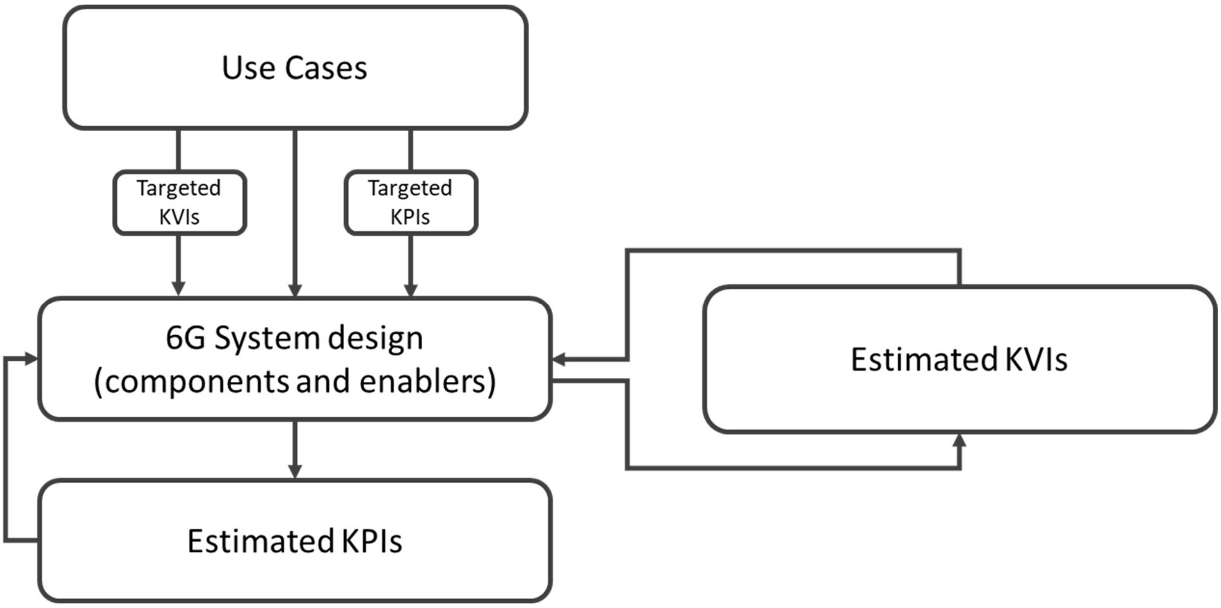

Figure 3-7: Iterative E2E system design process based on KVIs, values, and KPIs.

The use cases provide the requirements, which consist of a preliminary set of KPI ranges and KVIs, i.e., the targeted KPIs and targeted KVIs, that are expected to be delivered by the 6G system. Next, an initial 6G system design is done considering the use cases requirements in terms of functionalities and enablers. Consequently, in this initial design an integration of the various possible components and enablers is provided. The components and enabler selection methodology is explored in Section 3.3.2. Then an evaluation of the 6G system design is performed, which provides the estimated KPIs and KVIs. These evaluations are done through the system-PoCs and the simulation-based approaches detailed in Section 5 and then fed back for iteratively improving the 6G system design.
It must be noted that trade-offs exist when designing any system based on KPIs and KVIs, as conformance to certain KVIs, and hence the associated values, can lead to degraded performance. Thus, such trade-offs should be considered in this iterative design process. Specifically, the evaluation will involve firstly whether the proposed components and enablers conform to the agreed upon KPIs and KVIs corresponding to the use case. The different components and enablers in the E2E system will contribute individually to several additive KPIs such as latency, cost, energy consumption and even reliability. The overall design process will study the apportionment of E2E additive KPIs as provided amongst critical components integrated within the E2E design. The targeted budget for each component could be compared to the measured KVIs provided by the evaluation and validation processes.

Distinct strategies or design choices will be applied depending on the pursued values. For example, the sustainability value will have an energy reduction objective, among others, which requires considering *the system-level integration of multiple technologies* such as energy-efficient radio, adaptive transport protocols, AI/ML for dynamic resource and service optimization, and zero energy devices. Then, Hexa-X-II will assess the overall consistency of operations across the different components of the 6G system and will v*erify the capabilities to fulfil the targeted KPIs and KVIs*. The trustworthy value will require the assessment of possible additional risks introduced, what translates in assuring the AI based components are explainable, interpretable, and fair to avoid any bias, as well as in evaluating how privacy and security are preserved. This requires considering the *consistency in holding the properties* of trustworthiness from end to end at each sub-layer of the system layer, to be analysed through the security assessment mechanisms. This is also applicable to the enablers of a trustworthy relationship between the stakeholders involved in the E2E service delivery chain.

3.3.2 Top-down versus bottom-up alignment process

The above KPIs/KVIs iterative design process should be considered together with a top-down versus bottom-up alignment process (see Figure 3-8).

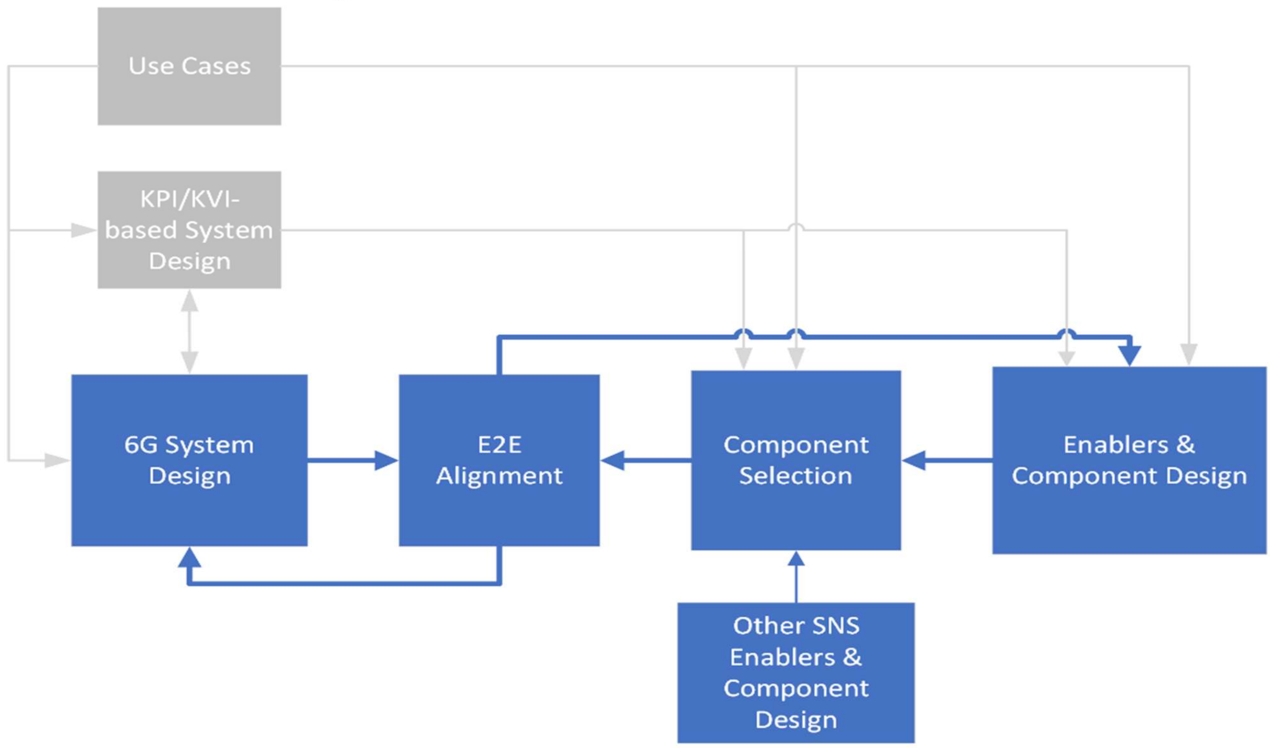

Figure 3-8: Iterative E2E system design process reconciliating top-down and bottom-up approaches.

The former involves an iterative design process wherein the system blueprint for the sustainable, inclusive, and trustworthy 6G platform will be elaborated based on the 6G use-cases requirements and the system architecture design principles (top-down). As new use cases and associated KPIs/KVIs will be studied during the project lifetime, the system requirements will be frequently revisited, and the considered set of technology innovations will be refined or augmented.

Conversely, consideration of the technical achievability will give feedback for fine-tuning the use cases and for the consolidation of KPIs and KVIs. The different components of the system are designed and provided in separate tasks (bottom-up). The component selection process will consider pros and cons of each promising enabler and component developed or considered in Hexa-X-II, in particular their contribution to the 6G E2E architecture objectives and will require a close collaboration between different WPs. A checklist of what can be considered in technical components/enablers for the alignment with the E2E performance and operation targets can then be used as feedback by WPs as a reference point for on-going development of enablers. The E2E alignment process especially carries out several analyses that are further detailed below. The analysis results will serve to continually update the 6G system blueprint as well as the component design, as enablers and components become mature within the project.

It is noted that during the component selection process, enablers as well as components and/or subsystems provided by other SNS projects will be analysed. Figure 3-8 illustrates the iterative E2E System Design process based on the reconciliation between the top-down and the bottom-up information flows. It must be noted that the grey part of the figure represents simplified representation of use case dependency and the previous KPI/KVI based iterative system design process. Next, the E2E alignment box in Figure 3-9 necessitates to conduct a thorough analysis in terms of compatibility, commonality, simplification, and unified exposure of the components derived from distinctive WPs and tasks in Hexa-X-II.

Compatibility analysis: When integrating different enabler components together in an E2E system, it is crucial to verify the capability of these enablers to work with each other. For example, whether a proposed protocol/interface provides compatibility to work with other parts of the 6G system. Additionally, the security and privacy implications of the use of these enablers and their interplay must be assessed, incorporating the required controls for addressing them.

Commonality analysis: As distinctive design activities (e.g., in different WPs) apply the same design principles, it might happen that similar components will be elaborated in separate ways for distinct enablers. The analysis work will look for and detect those component commonalities and help in the selection of one common component. This allows for some mutualization amongst Hexa-X-II design activities. Similarly, different replicas of the same information spread across the system in a distributed manner could possibly be centralized and reused.

Simplification of functionalities: the detection of commonalities could be considered as the first step to simplification (e.g., the same configuration function could be used to configure both the RAN and the Core pub/sub buses). Optimization of the interaction between functions or modules could also be performed to reduce the latency budget (e.g., E2E User Plane latency or Control Plane procedure latency) and meet the requirements. Within this context, one may consider the possibility of merging some adjacent components, turning their mutual interfaces into internal interfaces. Impact evaluation should be provided in this case.

Unified exposure analysis: the analysis will check for uniformization across the various exposure of new interfaces between the network and the vertical service providers The security exposure functions, provided by the 6G platform for developing new secure and robustness services using API framework, should be also analysed. The exposed APIs can provide analytics, such as network energy measurement, latency, throughput, localization, and sensing information.

3.3.3 Specific considerations in the E2E system design process

Building on the above iterative design process, three specific considerations of the E2E system design processes are further elaborated below They are introduced in left side of Figure 2-1 as the key building blocks of Hexa-X-II WP2 concepts, First, the aspects related to the iterative design process for RAN integration in the E2E system devise what needs to be examined and gives examples of related research questions that require interaction and coordination among components. Second, the iterative design process is discussed with respect to the management and orchestration framework in the E2E system. Third, the framework for security, privacy and resilience validation of the E2E system design is further detailed.

Iterative design process for RAN integration in the E2E system

The selection and integration of different components of the radio protocol stack to derive the overall design of the radio interface and protocols requires a thorough examination of each enabler/component/subsystem, and alignment with the E2E operation and performance of the 6G system. There is a need to consider not only the advantages but also disadvantages and restrictions of each selected component. An even more challenging part is that performance of the enablers and components, which will be part of the work in this project, cannot be predicted accurately at the start. This calls for a tight, frequent, iterative interaction and coordination between the overall radio system integration and the design of individual radio enabler/components/subsystems.

The CN needs to be aware of what is achievable in the RAN and manage its operations accordingly. The radio on the other side, needs to take into consideration the CN policies (e.g., KPIs/KVIs to maximize, authorized QoS configurations, operator policies) for its own internal operations. This knowledge needs close interactions between the design of the radio protocol stack and radio interface and different areas that may influence RAN operation to define the functionality division between CN and RAN. Below are examples of the research areas that will be investigated within the project:

- The analysis of network modularization that defines the balance between network function granularity and the number of required interactions between RAN and CN, the support for a data-driven architecture that fosters the adaptability of the internal RAN operation based on the dynamically changing and heterogeneous network conditions, or the focus on beyond communication services, where RAN needs to trade-off between the KPIs/KVIs being prioritized (e.g., sensing and computation versus sustainability and energy efficiency, performance-driven operation versus value-driven operation).
- The design of the protocol radio stack and radio interface is also relevant to subnetworks, multi-connectivity, and privacy-preserving data collection and learning.
  - Subnetworks which may consist of multiple user devices communicating with each other with or without the aid of the network, will enable the adoption of a decentralized architecture, which will allow the base station to offload functionalities to subnetworks. To achieve that, new re-defined roles and functionalities of the nodes in the subnetworks will be required.
  - Multi-connectivity enables the usage of multiple frequency ranges and carriers, the aggregation of different RATs, the simultaneous communication with both terrestrial and non-terrestrial nodes, as well as the integration of subnetworks to the parent network.
  - Privacy-preserving data collection and learning will facilitate data collection in a framework that ensures trustworthiness and meets all privacy requirements of the users and complies with any privacy-related regulations.

Each developed radio-related enabler/component/subsystem aims to optimize performance or enable new services to meet a KPI/KVI requirement. An iterative design process requires a continuous feedback loop from the system integration point of view to each enabler/component/subsystem, on e.g., what aspects need to be further considered. Below are some indicative and non-extensive examples of research questions that already illustrate the need for interaction and coordination:

- How to integrate cell-free/distributed MIMO into the classical mobile cells that may still exist in rural areas, and consequently revising the concept of what is a cell and its impacts on the mobility procedure?
- What is the performance of a sensing algorithm when considering realistic assumptions on the transport network (e.g., to achieve base station synchronicity) and on radio signalling (e.g., how fast it can be)? How to design a sensing algorithm with these assumptions in mind?
- What are the computation and the storage requirements for an AI-enabled radio air interface, and its applicability in ultra-low power/cost device?

Iterative design process for management and orchestration framework in the E2E system

To effectively address the interaction between the network and application layers in the E2E system, an iterative design process for the management and orchestration framework is crucial. This process should focus on utilizing the Network as a Service (NaaS) paradigm to expose capabilities through developer-friendly, easy-to-use APIs. In the context of 6G, the network layer will undergo significant evolution, transforming from 5G Communication Service Providers (CSPs) to 6G Digital Service Providers (DSPs). These DSPs will offer services beyond traditional communications, encompassing network components such as RAN, transport, CN, cloud, AI, and applications. On the other hand, the application layer will consist of third-party entities like verticals, OTTS (Over-The-Top Services), hyperscaler marketplaces, and application service providers. To ensure seamless integration and provisioning, carefully selected scenarios derived from defined use cases will provide valuable insights into the types of tenants, such as verticals, hyperscaler/OTT marketplaces, and application service providers. Additionally, the high-level service requirements specified in the E2E SLA (KPI and KVI) will guide the provisioning and monitoring processes. Addressing E2E service management automation is critical to support multiple tenants in multi-stakeholder scenarios involving verticals, OTTs, and hyperscaler marketplaces, as well as multiple DSPs (e.g., network operators). It is essential to provide visibility and transparency throughout the service delivery process, empowering tenants to monitor performance and ensure that their specific requirements are met. To achieve these objectives, new enablers will be designed, leveraging the latest advances in intent-based networking mechanisms and advanced ML-powered engines for E2E service management automation. Furthermore, a thorough analysis will be conducted to determine the seamless integration of management and orchestration enablers for capability operators and providers, including Network, Cloud, AI, and Applications, within the E2E service management automation framework.

Framework for security, privacy, and resilience validation of the E2E system design

Security and general resiliency aspects should be addressed (threat identification, detection, and mitigation) focusing on the 6G differential aspects, and incorporating extended residual aspects, i.e., already being considered for existing mobile networks but that may have new implications and dimensions in the 6G environment. To perform an adequate valuation of these implications as the 6G technology evolves and consolidates, a validation framework addressing exclusively security, privacy and resilience issues will be produced, combining simulation and emulation modes of 6G environments. This validation framework will be used to characterize and identify the security and privacy threats, as well as resilience issues, and the techniques to address them. As specific threats and other relevant issues of all nature are identified, the application of emerging technologies to address them will be assessed and verified by means of a high-level validation framework, applying the Network Digital Twin (NDT) mechanisms originally defined by the Internet Engineering Task Force (IETF) [IETF], focused on security and resilience network properties. This NDT will be the scenario of the different validation experiments, as the results of the other technical activities require the evaluation of security, privacy, and resilience implications of specific approaches.

4 Overview of 6G system innovations

The 6G system innovations listed in this chapter are organized and described in accordance with the four layers and pervasive functionalities defined in the 6G E2E system blueprint, as presented in Chapter 3 (see Figure 3-6). The requirements listed in this section are also based on the main innovations targeted in Hexa-X-II. In all technical WPs of Hexa-X-II, new enablers will be defined at an early stage and will be refined throughout the duration of the project. In addition to that, some enablers/components from other SNS projects will also be examined for integration in further iterations of the design of the 6G E2E system. Note that other avenues of innovation, which may arise during the course of this project or beyond the project, are not precluded.

4.1 Innovations supporting the application layer and innovations for the network-centric application layer

This section provides an overview of the innovations addressed by Hexa-X-II, which are identified as the supporting innovations for the application layer and the relevant innovations to the network-centric application layer. This is described with respect to the impact to and interaction with the network function layer, E2E service aggregation, controllable capability exposure and beyond communication service exposure.

4.1.1 Impacts to and interaction with the network function layer

The 6G system is expected to support several new use cases and services such as service robots, immersive telepresence, personalized user experiences, and native AI capabilities for multiple intelligent application scenarios. The 6G system also enables hosting of applications within its environment, with increased in-network application resources (compute, storage, and value-added capabilities, such as AI/ML) that require distributed coordination and collaboration (e.g., scheduling, deployment, optimization) with network resources. In other words, the 6G system is envisioned to be more open, distributed and data centric than 5G, with unprecedented quantities of data with strict QoS requirements. These trends at the application layer pose challenges to the network function layer on the QoS framework, and provides opportunities, e.g., for cross layer optimization.

- The 6G system calls for further research into the QoS framework. One direction is to go beyond performance-oriented design (to consider values) and being able to capture and incorporate QoE into the QoS framework to enable a customer/user-centric approach for service delivery. Another direction is to consider new indicators to assure the quality of network native AI services (e.g., AI data, training, inference, and verification services) with respect to multiple dimensions such as connections, computing, algorithm, or data. These indicators set from the application level could be further mapped with the typical QoS requirements for data, algorithms, computing, and connections.
- The 6G system enables more options for cross optimization with applications. For instance, one can optimize across the different layers on both the network and UE side to dynamically adapt application QoS requirements to radio conditions, improving as a result the end-user experience and keeping the 6G system complexity low. As one example, for low throughput applications, signalling overhead/interaction between network and UE can be reduced, for gains in latency, power consumption, system efficiency and complexity.

4.1.2 E2E service aggregation

6G E2E systems are complex and involve multiple stakeholders at both the infrastructure and service levels. These stakeholders include network operators, cloud operators, and other service providers. Managing 6G E2E services requires the involvement of several service providers to compose an E2E service. For example, an application may require 6G network resources such as RAN, transport, and CN services from one network operator, transport network resources from another network operator, and cloud computing resources from a hyperscaler. In this new scenario, a key element is the service aggregator. The service aggregator is responsible for interfacing with different service providers and exposing their services to third parties such as verticals. The service aggregator plays a vital role in ensuring that E2E services are delivered to customers as specified in the E2E SLA. The service aggregator acts as a single point of contact for third parties seeking E2E services in the 6G ecosystem. It provides a unified and consistent interface to the various service providers and acts as a broker between them. The service aggregator handles the complexity of orchestrating the multiple services required to deliver the E2E service, ensuring that the E2E SLA is met. Overall, the service aggregator is a crucial component of the 6G E2E service delivery ecosystem. It plays a vital role in enabling the efficient and effective delivery of E2E services across multiple service providers, ensuring that customers receive the high-quality services they need. The service aggregator role could be taken by a third party or by a network operator, for example in a federation.

4.1.3 Controllable capability exposure

Capability exposure represents a paradigm shift whereby certain 6G telco capabilities become programmable objects that can be accessed via Application Programming Interfaces (APIs). These APIs allows to expose capabilities to authorized consumers, offering tailored experience with choice, scalability (coverage and compute resource), visibility (monitoring) and control (configuration). Different functions (from different layers and different administrative domains) may need to gain access to the capabilities of the same resource (e.g., network function, sub-network, network slice), thus becoming resource tenants. In this vein, it is needed to provide the resource operator with controllability and auditability means to expose capabilities to different tenants, ensuring they do not conflict with each other.

On the one hand, *controllability* means that the operator can provision segregated yet customized spaces to different tenants. Each space provides a bounded, well-defined context for a tenant, specifying the set of capabilities this tenant can consume, and under which conditions. To that end, the operator should provision the space with the following information:

- The concrete **CRUD operations** (i.e., create, read, update, and delete) this tenant is authorized to consume over **which properties/attributes** of the resource.
- The **authentication policies** assigned to the tenant. These include authentication protocol, authenticate factor, credential policy and authentication context (e.g., time, location, identity status, etc.).

On the other hand, *auditability* means that every interaction between a resource operator and tenant needs to be logged with accurate timestamps (for traceability) and support non-repudiation (for SLS verification).

For a function that is defined for a resource tenant, it is important for that function to be able to discover i) the portfolio of capabilities available for consumption on the resource, and their endpoints; ii) supported data models; and iii) credential types for authentication and authorization. The resource operator shall provide these discovery means, either directly or indirectly, leveraging on the existing solutions that one can find in today's microservice architectures, some of them already integrated in 5G SA networks.

Such an approach to capability exposure has relevant implications regarding security, privacy and, in general, resilience. The controllability and auditability properties described above require a comprehensive approach to *identity management*, considering:

- All possible identities in the network (including human/non-human entities, as well as the roles for them)
- The dynamic and inherently more complex interactions among identities foreseen in 6G scenarios.
- The requirements on stronger security (to quantum-safe mechanisms) and privacy preservation.

In addition, this kind of features can become an enabler for additional services, within the network itself or relying on the network, such as the support for massive digital twinning, the integration of private networks, the edge-cloud continuum computation, or the use of distributed AI or knowledge sharing. These features can be provided following the as-a-service model, so security enhancement and privacy preservation become a network infrastructural service.

Capability exposure allows new monetization opportunities, such as those captured under the Network as a Service (NaaS) concept. Propelled by initiatives such as GSMA's Open Gateway [GSMA] and Linux Foundation's CAMARA [CAMAR], NaaS paves the way for turning 6G into a programmable service platform for tenants (e.g., application service providers, enterprise customers and aggregators) to develop new use cases and products. From Hexa-X-II system standpoint, NaaS enables the integration of tenant applications (application layer) with telco resources (network layer and network-centric layer), with frictionless integrations between them. This is a win-win scenario for the stakeholders evolved. For Hexa-X-II system provider, it represents a business opportunity to generate new revenue streams, and one of the ways to better monetize investment in evolving the technologies and capacities of the infrastructure. For tenants, it releases them from the constraints associated to traditional over-the-top, best-effort service delivery approaches, using now offered capabilities to provide enhanced user experiences and enrich digital ecosystem with new services (e.g., Web3, XR, etc.).

4.1.4 Beyond communication service exposure

Hexa-X-II will develop a concept for networks beyond pure communication. Examples of beyond communication services comprise sensing, mobility data, enhanced localization and tracking, and compute-as-a-service (see Figure 4-1). Networks in general collect and possess a wealth of data. In 6G this will be amplified, in terms of data and resources. The use cases of JCAS include enhanced localization and tracking, monitoring and management of V2X (Vehicle-to-everything) and UAVs (Unmanned Aerial vehicles), or Smart Home/Factory. Device offloading enabled via Compute-as-a-service (CaaS) provides a mechanism to move computation from a mobile device to a connected site with more suitable compute and storage capabilities. The motivation to trigger offloading of computational tasks from a device dynamically can be based on reducing computational response times, balancing compute and energy trade-offs, etc. The network function layer will expose certain data (e.g., sensing, compute) to third parties to facilitate the development of new applications and services that utilize the network data and vice versa.

Hexa-X-II will develop the architectural enablers capable of exposing the new services. Hexa-X-II will also develop requirements for a future-proof architecture, including interfaces and protocols, that support these new services by providing support for access, control, processing, and exposure of the service data. The commercialization of the exposure capabilities needs to be supported by the business support system, allowing to onboard these services into products and cater for the associated business aspects such as SLA management and monetization.The exposure of both standardized and proprietary capabilities (e.g. via APIs) should be easy and quick to create and manage using a standardized solution, only requiring capability-specific implementation and not extra standardization for each new service. The creation needs to consider both technical set-up as well as business set-up.

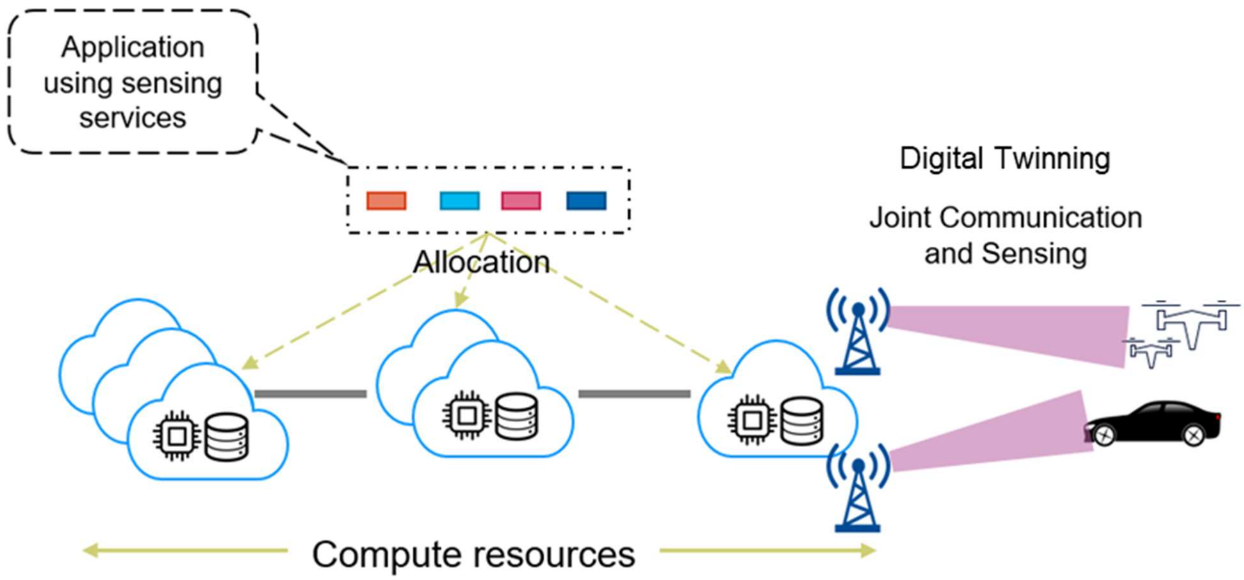

Figure 4-1: Example for Hexa-X-II concept for beyond communication service exposure.

4.2 Innovations of the network functions layer

This section provides an overview of the innovations relevant to the network functions layer addressed in Hexa-X-II. Particularly, this includes the innovations related to the network function modularization, beyond communication functions, RAN functions, context awareness management, and new access and topologies.

4.2.1 Network function modularization

Hexa-X-II will develop a functional architecture that enables a sustainable, inclusive, and trustworthy and flexible network, utilizing a common cloud-native approach for RAN and CN. The deployment of a network architecture should grow and scale in well-defined steps, by adding well-defined functionality in meaningful increments, i.e., modules, to ensure operational effectiveness and interoperability. An architecture of "modules" as building blocks will lead to plug-and-play deployments that can grow and change based on demand needs. 6G will also introduce new types of services beyond classical communication such as JCAS, that need new supporting network functions that will be introduced in a stepwise, on demand manner. Network modularity is about finding the right balance between network function granularity and the number of required interactions between the network functions and offered services so that the network capabilities can be added, replaced, or removed in a flexible manner. In this context, a module is a grouping of network functions with their service provider and consumer components in such a way that feature interactions are primarily within a module and the signalling between modules and the subsystems composed from one or multiple modules are minimized. A network module can be a recursive entity containing other modules. A module should be able to adapt itself into a given execution environment and change its configuration accordingly. This would lead to (re-)definition of the key horizontal (e.g., interface between RAN and CN, and inter-RAN interfaces) and vertical interfaces based on the capabilities of the modules, e.g., depending on peculiarities of radio access(es). This also calls for a need to migrate to interfaces using atomic functions exposing APIs based on web-based technology, utilizing libraries and other enablers (e.g., development tools, specification tools, code generators, security mechanisms) which are broadly available.

4.2.2 Networks beyond communication

Hexa-X-II will develop a concept for networks beyond pure communication, capable of offering new services leveraging aspects such as sensing, localisation, as well as computing (and storage).

JCAS (considered equivalent to Integrated Sensing and Communication, ISAC) is an emerging functionality that is anticipated to be incorporated in the current and future wireless communication networks. The main rationale behind JCAS is the reuse of the communication infrastructure for sensing the surrounding environment. The objective of JCAS is to detect, localize, map, track, and characterize targets in terms of features using RF signals transmitted from communication nodes. In general, JCAS can be categorized into two broad categories, i.e., radar-based sensing and Channel State Information (CSI)-based sensing. In radar-based JCAS, the range, velocity, position, and Radar Cross-Section (RCS) of a target are extracted using the processing of a number of transmitted pulses. In CSI-based JCAS, information regarding a number of targets and their features is obtained by monitoring the CSI and the change of the CSI of the underlying channel between the sensing transceivers and the existing targets. JCAS has a wide range of applications, including use cases such as health care monitoring, security, car safety, weather monitoring.

JCAS utilizes the same resources for both sensing services and communication services, leading to contradicting requirements for those resources. These requirements will be considered when designing the Hexa-X-II architecture, interfaces, and protocols. An example of the coupling between the services is the utilization of sensing capabilities for location dependent communication resource management. Integrating JCAS functions comes with its own challenges, for example, to minimize interference and improve spectrum utilization, minimize energy consumption, and reduce maintenance costs, consider impacts of JCAS on QoS of the network data service, as well as impacts to the network performance in a large-scale deployment.

Apart from utilizing computing resources to process the data and to enable the provisioning of its new services, the network will expose them as a standalone service to applications, to support computation offloading of their computation-intensive tasks. Particularly, striving to reap the benefits of the surrounding environment intelligence, end applications are getting more computationally intensive, making it difficult for the computationally and battery-constrained user devices to cope with the applications' delay and energy requirements. In this context, Hexa-X-II will develop the architectural enablers to support computation offloading as a service across the computing continuum comprising multiple tiers, including edge and the cloud. This creates a new landscape where radio and computing resources should be jointly treated, considering that tightly integrated computing and networking capabilities exist from the edge of the network to the CN. Emerging resource allocation and energy consumption challenges should be addressed, considering that communication between the user device and the remote server consumes considerable energy, which can outweigh the benefits of task offloading. Furthermore, as mentioned in section 3.1.4, the beyond communication services should inherently support the preservation of privacy and allow different levels of anonymity also for future services.

4.2.3 RAN related innovations

Regarding RAN, Hexa-X-II will work on supporting new radio capabilities, e.g., applying AI in radio interface design, further enhancements in MIMO schemes, support of reconfigurable intelligent surfaces, sensing, sub-THz etc. Hexa-X-II will also further enhance traditional radio features, such as mobility, radio resource management, and work on radio protocol innovations to support flexibility and sustainability. To this end the innovations within the RAN functions scope can be grouped into the following sub-topics:

4.2.3.1 Flexible PHY radio interfaces

6G radio design needs to fulfil a wide range of use cases requirements while taking societal oriented KVIs into account. In addition to the conventional use cases, some emerging use cases have extreme communication requirements beyond the capabilities of current 4G/5G systems, whereas others require positioning and sensing services. As a result, disruptive radio technologies covering all radio frequency ranges are needed to address KPI requirements such as data rate, latency, reliability, as well as KVI requirements on sustainability, trustworthiness, and inclusiveness at the same time. These include innovations to improve the efficiency of existing systems, to explore new spectrum, and to integrate sensing in the radio design.

To achieve the aforementioned 6G requirements, current 4G/5G systems require improvements in terms of coverage, spectral efficiency, implementation efficiency, and energy efficiency. This will be accomplished by applying new enabling technologies such as AI/ML to enable cost-efficient radio transceiver design that adapts to changes in radio channel and to mitigate or compensate radio hardware impairments. Moreover, distributed MIMO (D-MIMO) and reconfigurable intelligent surfaces (RIS) have the potential to improve throughput, reduce latency, and increase availability under practical constraints. For extreme requirements, the radio design must push the limits of physical-layer capabilities for improving an individual KPI such as peak data rate, latency, and reliability and/or combinations of various KPIs, while taking the tight power consumption, complexity, physical and hardware limitations, and cost constraints into account. Accordingly, novel broadband (in the order of 1−10 GHz) air-interface techniques will be developed to enable the efficient use of the sub-THz (100 to 300 GHz) spectrum, which will unlock data rates in the order of hundreds of Gbps with improved spatial multiplexing and without compromising reliability. The air interface shall allow scalability and flexibility to enable access to 6G services for a wide variety of devices. This requires that the communications complexity meets the device type including self-powered devices and low-cost devices. Furthermore, several innovations are required for the design of new waveforms and beamforming architectures to work at extreme operating frequencies and enable energy-efficient transceivers with low-cost implementation. Radio sensing will be considered as a core functionality of 6G radio design, where innovative solutions are required for integrating flexible radio frontends, spectrum sharing mechanisms, and multiple options of architectures and waveforms to meet the diverse and dynamic requirements of both functions. This integration allows efficient use and coordination of spectrum access and reducing the hardware cost and resource draining, through novel resource allocation methods.

These technologies will be integrated in a flexible radio architecture that operates at different frequency bands with reconfiguration capabilities. For practical implementation, the flexibility of the hardware architecture will be restricted to a limited number of options, with more degrees of freedom in the software, e.g., modulation and coding. Moreover, novel and flexible spectrum access and sharing techniques will be developed for both new and existing frequency bands, including license-exempt bands. The optimal configuration is decided at a higher layer by inferring the network and channel conditions, to efficiently utilize the available resources for fulfilling KPIs and KVIs. For this purpose, sensing data collected from different devices in a privacy-preserving way and different nodes can be exploited by applications to improve the radio performance.

4.2.3.2 Flexible radio protocols

In this subsection, a high-level vision is revealed within each technical area of Control/User-plane design, security support and interaction with CN protocol, followed by guiding principles applied for all radio protocols across various technical topics.

For the control plane in 6G RAN, one of the key layers for the radio interface is the Radio Resource Control (RRC). The RRC protocol has been used in 3G, 4G and 5G on the air interface. RRC has had a stable form, covering multiple releases and technologies, which also means it has carried along both positive but also negative aspects. Having many complex independent configuration options within one monolithic RRC protocol leads to a design with one key component which can be error prone, due to high complexity. Such design leads to a 'single point of failure' where a more resilient, flexible, and efficient system design is desirable. 6G RRC should target RRC connection being decoupled in its basic setup from the architectural deployment option. The design principles should also enable a coherent RRC logic along with: CN (E2E) signalling, security, user plane components, mobility, and energy efficient operations (on both UE and network side), as well as efficient use of AI/ML methods.

Additionally, work on new protocols and/or enhancements of legacy protocols is needed to enhance latency and allow QoS assurance. For radio user plane design, 6G aims at a simple, scalable, sustainable user plane for secured user data delivery while fulfilling new QoS requirements. Moreover, radio resource management, including 6G data recovery and re-ordering mechanisms, shall also be optimized. Currently in legacy cellular protocols there are multiple retransmission mechanisms such as Transmission Control Protocol (TCP) layer retransmissions, Automatic Repeat Request (ARQ) on RLC and Hybrid ARQ (HARQ) on MAC. These retransmission mechanisms may lead to the stalling of the delivery of packets to their respective higher layers till the complete segment is correctly and orderly received. This entails a certain delay that ends up being significant for specific applications with very tight latency requirements. Hence, work is needed to investigate the current retransmission protocols to ensure enhanced latency with assured QoS, and application-layer congestion management schemes to allow E2E and application-aware optimization, in addition to legacy cellular standards.

Enhancements to RAN protocol security should also be (re)-considered in light of any changes to the overall 6G security architecture. There are also needs to study an enhanced and simplified security protocol for UE processing where the increasing peak data rates and the real-time demands require more and more hardware to perform ciphering/integrity protection on the modem side on a per packet basis. Additionally, the current protection (i.e., in 4G and 5G) happening on Packet Data Convergence Protocol (PDCP) neglects the protection of meta-data in L2 headers, which became later an apparent drawback. The points above trigger the need to rethink the mechanism of protection in legacy cellular networks to enable UEs with lower complexity while ensuring more secure communication over the 6G network.

The radio protocol needs to evolve on its own, in addition to accommodating new radio technologies. One direction is simplification, e.g., simplifying the control of the radio interface (i.e., RRC protocol, the interplay between DCI, MAC CE and RRC signalling, PDCP encryption, investigation of streamlining various encryption procedures in the CN and in the RAN). Another direction is to investigate radio protocols with cloud-native friendliness, e.g., one needs to re-think which radio protocol layer can be put in the cloud and the impact therein. Additionally, the radio protocol itself needs to be flexible to handle various scenarios instead of multiple solutions each handling one task, e.g., considering whether it is feasible to have one multi-connectivity solution instead of both Dual Connectivity and Carrier Aggregation as in 5G. Finally, adaptable protocols for an enhanced utilisation of physical resources are required. In the current cellular protocols, there are procedures that may entail a loss in the utilisation of the available physical resources in the network, which could have been more efficiently utilized. Hence, introduction of flexible protocols for an enhanced utilisation of network resources is needed to allow for an overall improvement in the network's performance.

4.2.3.3 RAN mobility procedures

Mobility is one of the main procedures which ensures that a user can remain connected to a suitable cell in the wireless network by performing a handover of the device to a neighbouring cell e.g., if the radio conditions of the serving cell deteriorate. In 6G, enhancements may be needed to ensure that mobility procedures can be designed such that they apply independently from the network architecture. Failure to deliver robust mobility and for example perform a successful handover in a timely manner, can have a detrimental impact on the user QoE. The 6G solution must ensure consideration of all relevant KPIs at the same time (e.g., number of radio link failures, number of handover failures, interruption time). 6G mobility solutions should balance signalling overhead and complexity while guaranteeing the continuous connectivity. Solutions need to support different scenarios including also high throughput, low latency and high reliability as required by the different use cases.

More specifically, 6G RAN mobility procedure needs to enhance both useful features introduced in 5G and 5G-advanced, e.g., conditional handover (CHO), Layer 1-Layer 2 triggered mobility (LTM), and incorporate latest technologies on e.g., AI/ML, even higher frequency support, D-MIMO.

CHO is to increase the robustness of mobility procedures by sending the configuration of the potential target cells to the UE earlier and executing one of those target cell configurations when the conditional handover condition is met. This is to avoid radio link failure or handover failure due to triggering the handover too late or too early. CHO comes with problems such as unnecessary handover preparations between the UE and the NW nodes as well as in between the NW nodes, inefficient dedicated resource utilization at the network and storing multiple handover configurations at the UE. LTM also serves to transmit the configuration of the potential target cells to the UE while the execution of a target cell configuration is by the UE receiving a L1/L2 command (e.g., MAC CE) rather than higher layer command in RRC. The motivation is to reduce interruption time coming with the RRC reconfiguration in legacy L3 handover. It has similar issues as CHO. Thus, in both cases, a UE may need to either perform a handover to a non-prepared cell, which brings the drawbacks of the normal handover, or to be configured with many potential target cells, which leads to increasing handover preparation signalling for both UE and network. A 6G mobility procedure needs to tackle these shortcomings (which may be more severe due to a large number of handovers due to a smaller cell coverage in a high frequency band) and support a unified mobility procedure with, e.g., better integrated CHO and LTM.

Further, the 5G measurement framework needs to be enhanced. For example, in FR2, the UE would need to sweep multiple Rx beams to derive the cell quality measurements per cell to determine whether the measurement reporting criteria is fulfilled which leads to degradation of throughput and increased power consumption. This may become worse in 6G due to the usage of even higher frequency bands and measurement requirements.

Last but not the least, 6G mobility procedures may leverage the AI/ML capabilities of both UE and network to perform data-driven mobility decisions which consider not only signal measurements but also multiple data sources as an input to reduce energy consumption of UE and network, to minimize service interruption time and to guarantee QoS at the target cell. One radio technology that has been discussed is D-MIMO, in which the cell boundary becomes unclear and there might be a need to have a more dynamically association of UE with transmission reception points or access points than what has been the case in 5G.

4.2.3.4 Energy efficient RAN design

One requirement is to be able to scale the traffic efficiently while reducing absolute energy consumption compared to today's 5G technology. To achieve this, a toolbox of techniques will be needed at the UE and the base station. At least three main building blocks are foreseen to enable an energy efficient design in 6G: component-level energy-efficient design (e.g., at power amplifiers); energy saving techniques at base station and UE side (e.g., enabling efficient power usage techniques); energy-efficient network deployments (e.g., micro densification).

Technical innovations described in the above subsections of the RAN functions related innovations are building blocks for the sustainable RAN design. Namely, they provide options for upper layer protocols to select the most suitable operation mode and the assignment of resources in each situation to optimize energy performance. In addition to these innovations developed in the project, one should not forget about what has already been possible. For example, to achieve maximum energy efficiency, special focus should be paid on the desired data rate and the spectral efficiency, e.g., to maximize energy efficiency with an acceptable data rate and spectral efficiency by changing the modulation and multiantenna transmission schemes or adapting the duty cycle, in comparison to previous generations in which the aim is more on data rate and spectral efficiency maximization. Additional considerations include incorporating the channel status into the design of the radio transceiver, providing different configurations based on the required level of robustness against potential aggressors, supplying tailored interfaces for the operation in an E2E environmentally aware system.

4.2.4 Context-awareness management

Hexa-X-II will also focus on programmable and E2E context-awareness management to enable efficient support of modular and flexible networks (as shown in Figure 4-2). The E2E services and applications can span different networks deployments and sub-networks, hence the transport should facilitate the connections among them for seamless support of the services and applications. The E2E context awareness management enables the network to optimize the E2E connection spanning over each component of the network (application, edge computing, RAN, CN, Transport). The main purpose is to dynamically adapt to the so-called context, meaning that the expected E2E QoS for the services are fulfilled. The E2E context-awareness management leverage on effective automation and orchestration mechanisms to facilitate the interaction among such components.

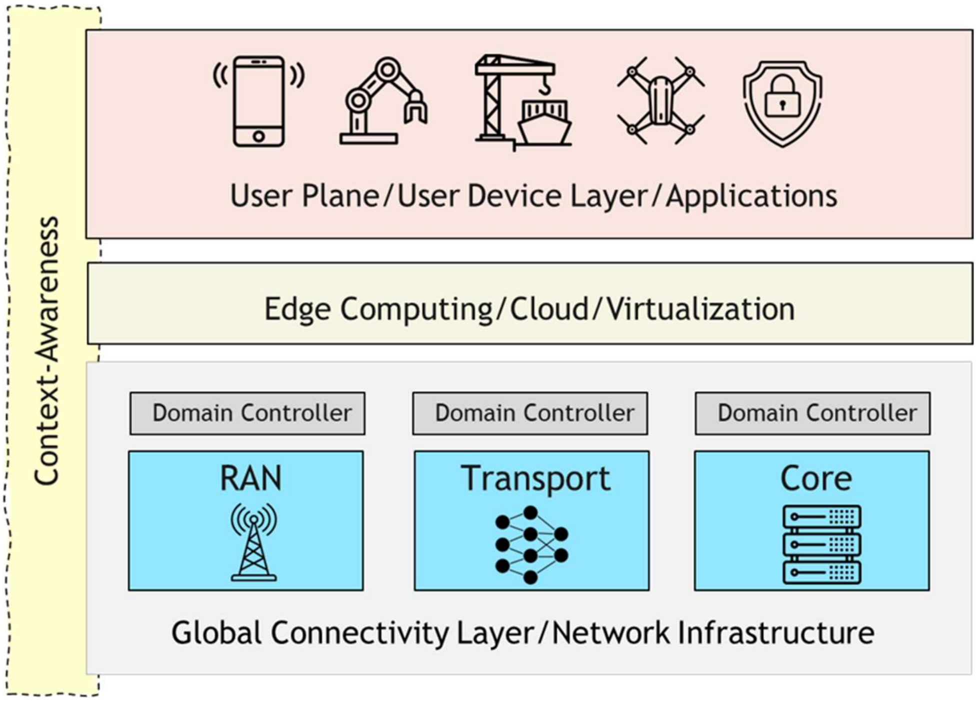

Figure 4-2: Concept of context-awareness management.

4.2.5 New access and topologies

Hexa-X-II will develop an improved architecture for network topologies such as NTNs, subnetworks, sub-THz networks and local D2D communications (as depicted in Figure 4-3).

The focus will be on defining the role of each node, their functionality (e.g., control plane procedures), and the coordination between different types of nodes. The interactions within and between different subnetworks, including terrestrial and non-terrestrial networks, as well as different types of multi-connectivity need to be studied in 6G to achieve a seamless user/application experience. To facilitate the operation of subnetworks and flexible topologies, the integration of trustworthiness therein will be investigated, with a focus on the concept, framework (e.g., resource allocation framework and unified decision making) and management procedures of such flexible topologies. In addition, architectures with efficient inter-satellite-link hops in NTNs will be explored. The evolution of the 5G dual connectivity and carrier aggregation features and the aggregation of various access networks will also be investigated in the context of multi-connectivity. These flexible topologies will support different outdoors/indoors use cases, including urban, rural, and critical situations (disaster recovery), and they will be essential for reducing the digital divide, while using the available resources efficiently in order to increase the digital inclusion, the civil protection and the service coverage.

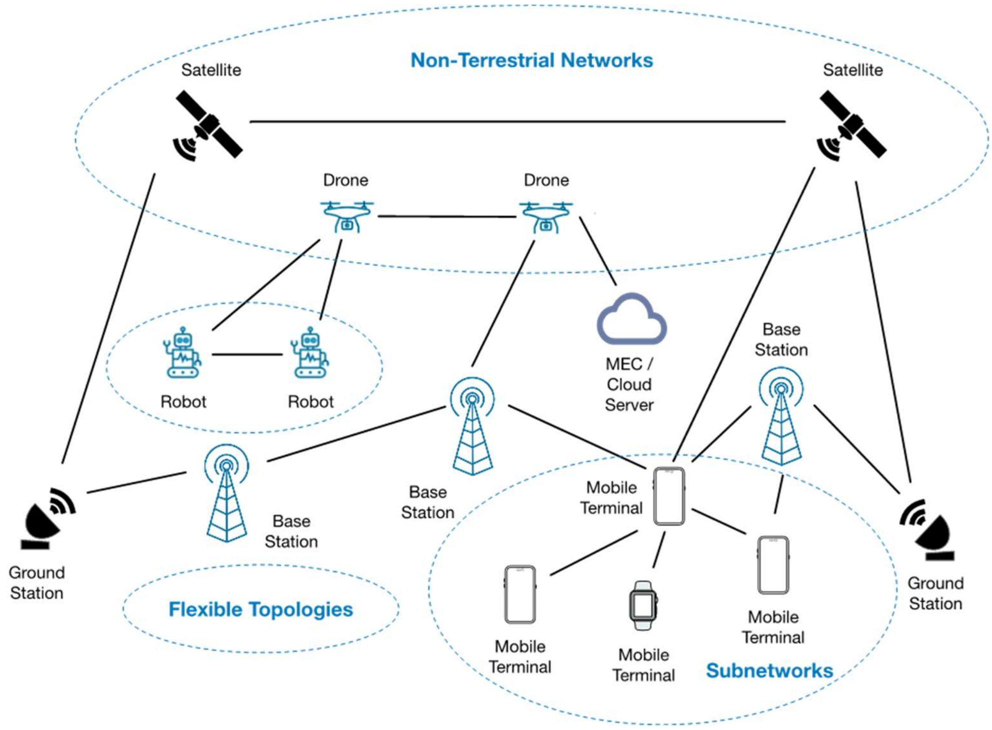

Figure 4-3: Hexa-X-II focus areas on new access and topologies.

4.3 Innovations in the infrastructure and compute layer

This section describes the Hexa-X-II innovations which cover the infrastructure and compute layer. Although, there are multiple components (e.g., devices, compute, X-haul, storage, etc.) mentioned in the infrastructure and compute layer in the system blueprint in Figure 3-5, here only the most prominent Hexa-X-II innovations are organized under two main topics named as cloud transformation and device and flexible infrastructure.

4.3.1 Cloud transformation

The cloud infrastructure will be a fundamental pillar of the 6G network infrastructure, driven by network virtualisation. The 6G mobile network needs to be transformed to be able to use all benefits of a distributed cloud. Hexa-X-II will address this topic defining an architectural framework in which the cloud is a fundamental part of the E2E 6G architecture. This also includes the transformation of the cloud, by the integration of edge and end-user devices, into a compute continuum, supported by a softwarized network continuum. This compute continuum will integrate the computational capacity of end-user devices, internet of thing (IoT) devices, local edge devices in the compute continuum, edge micro/pico-datacentres and cloud hyper-scales under a common set of resources that the network can exploit, while optimizing the energy consumed and improving sustainability. In addition, Hexa-X-II will work on the required evolution of the virtualisation management modules and their interfaces, including support to implement multi-domain deep network slicing (even supporting per slice network protocol stacks) on an E2E basis, considering far edge, edge, and core. A framework for E2E orchestration in the computing continuum will be developed as part of the overall management and orchestration pervasive functionality depicted in the current Hexa-X-II system blueprint. This will include heterogeneous multi-cloud coordination and capability discovery (public cloud, private cloud, core/central cloud, edge clouds) as well as the implications on how to support telco grade reliability, function discovery, or load balancing. The deployment of network applications over the computing continuum will be supported, considering that applications are becoming more distributed in nature, following the microservice-based development paradigms and the need to support strict QoS requirements. The orchestration mechanisms will be accompanied by E2E monitoring solutions, while, where applicable, open APIs will be provided for the interaction among multiple providers in the continuum.

4.3.2 Future devices and flexible infrastructure

Hexa-X-II will study and deliver novel 6G device/infrastructure technologies for satisfying the 6G requirements (as summarized in Figure 4-4). This work will cover four topic areas including identifying new device types/classes and their interactions with the physical world, evolving hardware implementations of 6G transceivers, evolving specialized system-on-chip (SoC) connectivity for specific 6G applications, and designing energy/material/cost-aware devices.

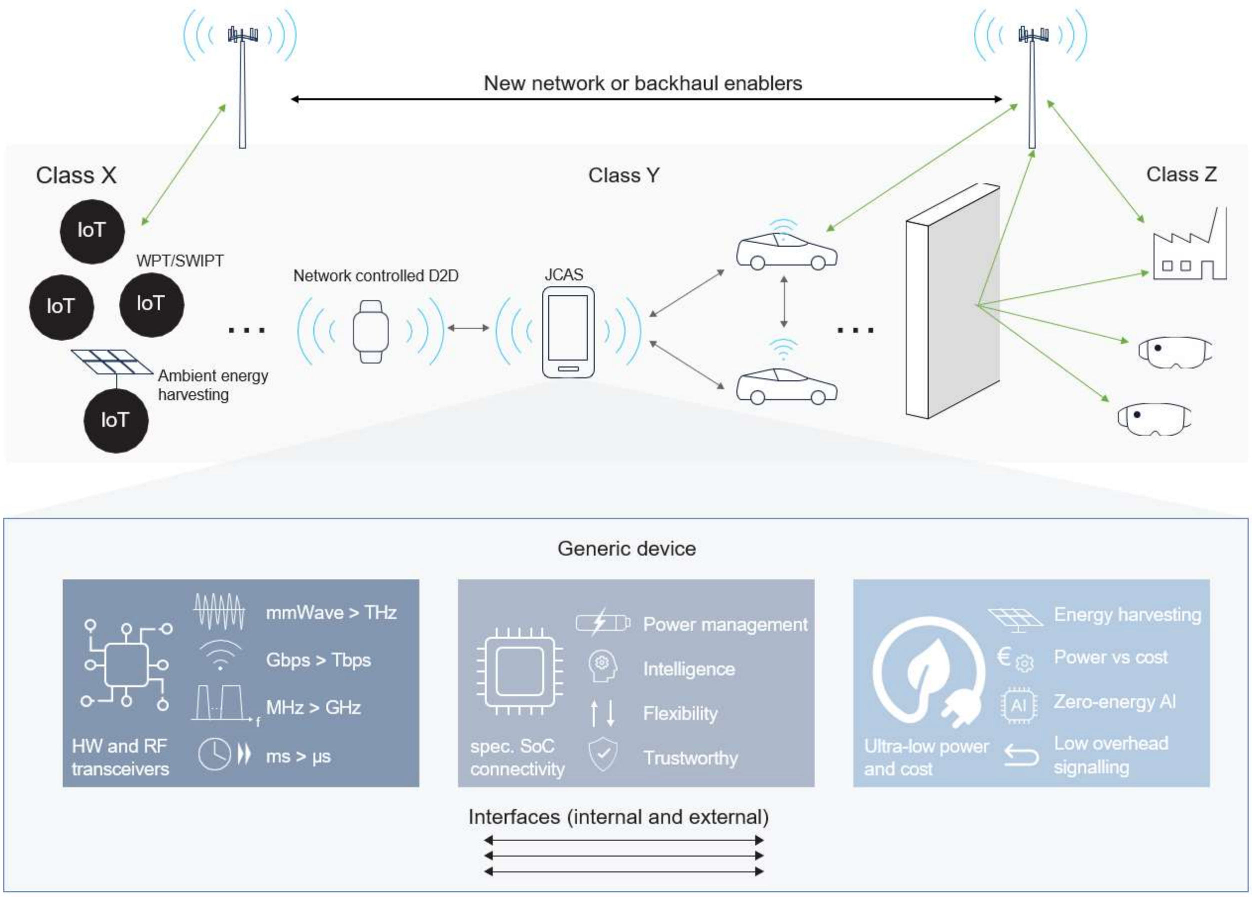

Figure 4-4: Summary of Hexa-X-II innovations on future devices and flexible infrastructure.

Hexa-X-II will focus on identifying new device types/classes, considering 6G services and capabilities and based on different aspects of KPIs and KVIs, which would primarily revolve around future radios and their communication capabilities. Other aspects of device implementation (e.g., device lifetime, material efficiency and sustainability, power consumption, computational power, and internal interfaces) will be examined along with needed infrastructure enablers to realise the identified device types or their sub-types. Moreover, flexibility to different topologies such as involving network (NW)-controlled flexible topologies that employ technologies such as sidelink (SL)/D2D and novel services such as JCAS will be considered along with the associated security and privacy aspects. The expected outcomes beyond SoTA include (i) classifying the new device types and radio requirements beyond current 5G devices to be addressed specifically in 6G, (ii) identifying high-level sketches for primary device classes with key performance parameters from radio performance to energy consumption for different device types/classes, and (iii) documentation of the key assumptions in all device categories.

The device/HW implementation will be evolved to enable new radios needed in future 6G networks. Transceiver architectures and circuits will be proposed to cover the most challenging carrier frequencies (up to sub-THz) and wider bandwidths. Beamforming and multi-antenna technologies will be a key ingredient in many new networks, and dimensioning RF architectures for the best trade-off between performance and energy efficiency will be essential. Both the terminal side (for human and non-human) and infrastructure side will be considered. Performance simulation will require detailed models of the E2E PHY link, especially including analogue hardware non-idealities in those new bands. Hexa-X-II will extend its scope towards JCAS and antenna integration challenges. This requires further investigation on the radio architecture and circuits and poses further challenges in terms of power and cost. A key approach is to optimise hardware and reuse waveform whenever feasible. Finally, RIS-based solutions will be investigated and integrated towards more energy-efficient network. The expected outcomes beyond SoTA include (i) radio architectures for different device classes, different (mm-wave/sub-THz) operating frequencies, bandwidths, and multi-antenna topologies addressing the new requirements of 6G applications, (ii) proper modelling of both performance and energy efficiency of those architectures, (iii) radio architectures supporting JCAS with minimal hardware overhead and addressing antenna integration challenges, and (iv) efficient RF architectures including RIS-based solutions.

To ensure that the devices meet the functional and non-functional requirements, the project adopts an application-specific system optimization approach. This approach supports various device categories, ranging from zero-power devices to ultra-high throughput and low latency devices. The development of SoC architectures will be addressed that combine processing elements such as general-purpose and application-specific processors, signal processing and AI accelerators, memory, and on-chip interconnect for specific 6G device types. In this regard, scalability (i.e., in terms of number of devices) is a crucial aspect, to tailor the system architecture to specific performance needs. In addition to performance criteria, the project focuses on system sustainability. This includes optimizing SoC sizing, component arrangement, and particularly smart use of resource. Moreover, the project also explores concepts to improve system flexibility, enabling system adaptation to different deployment and operational conditions and requirements. To ensure trustworthy system operation, the project develops and investigates HW/SW concepts for trustworthy systems and integration of associated components in the SoC platform. The impact on cost/performance metrics will also be analysed. Overall, Hexa-X-II aims at developing hardware components that will enable the connectivity of 6G devices. With a focus on system optimization, scalability, sustainability, flexibility, and trustworthiness, the project aims to deliver solutions that meet the specific needs of different device categories and deployment scenarios.

Finally, Hexa-X-II will assess and model energy/materials/cost/performance trade-offs for 6G IoT devices. For this, the underlying technology boundaries, materials efficiency and circularity, and energy-aware AI-based optimisation will be studied. Hexa-X-II will develop technologies for *AI-assisted energy management* (per device or device group), zero-energy operation, and low-complexity/cost communication, protocols, and signalling. A special research focus will be placed on energy harvesting, backscatter communication, and RF wireless power transfer technologies. The expected outcomes beyond SoTA are (i) performance trade-off figures for 6G IoT devices, (ii) edge and on-device AI mechanisms promoting energy-efficient operation, including intelligent wake-up, scheduling, energy management, onboarding/offloading computation tasks, and tiny AI, and (iii) zero-energy 6G IoT solutions, including energy harvesting-enabled wireless systems, backscatter communications, and RF wireless power transfer, and required communication protocols and signalling.

4.4 Innovations in pervasive functionalities

Hexa-X-II will consider the following pervasive functionalities organized as data collection framework, AI framework, security and privacy, and management and orchestration. The related innovations will be designed to provide the appropriate levels of programmability, flexibility, scalability, and reliability to support the 6G use cases and applications and fulfil the associated KPIs and KVIs.

4.4.1 Data collection framework

One of the biggest obstacles in effectively managing distributed applications and services is the need to transition from traditional monitoring tools to modern cloud-native observability tools. Traditional tools are not tailored to distributed microservice environments and interactions among containers, as they are typically geared towards monolithic applications. Additionally, while tracing techniques have long been employed by developers to track an application's behaviour-related metrics, they are not well-suited for microservices-based applications, and do not account for the horizontal scaling abilities of these applications. The concept of cloud-native observability has emerged as a means of providing insight into the health and status of applications within cloud-native elements like microservices, containers, and orchestration tools. However, modern approaches to observability need to take into account the necessity of integrating with existing or emerging monitoring tools. The existing monitoring mechanisms in open-source orchestration engines are not designed to support advanced monitoring that caters to the unique characteristics of distributed applications and the observation of metrics related to interactions among application components. Additionally, multiple third-party tools exist to support distributed tracing and logging mechanisms, albeit with limited integration with the aforementioned monitoring tools. Over the collected data from modern observability tools, various analysis pipelines can be executed, including the pipelines to implement the ML techniques.

Network Tomography (NT) has emerged as one of the prime methods for efficient network monitoring, mitigating the need for special-purpose cooperation from all network elements (nodes/links) and reducing associated traffic footprint on the total load and the required computational resources compared to packet-level and flow-level monitoring tools [KSK+21]. It is a typical example of an ill-posed inverse problem (there may be multiple solutions that fit the measurements equally well, or no unique solution), which regards the inference or estimation of unobserved parameters based on indirect measurements [KGK+20]. Most tomographic approaches require estimating a possibly large number of parameters, e.g., link loss rates, delay distributions, and traffic intensity, which are spatially distributed. To face these challenges, one can abandon complex statistical models of traffic and employ regularization techniques to impose constraints on the problem.

Network slicing is a key technology in 6G networks allowing the creation of multiple virtual network instances, each customized to support specific use cases with different requirements on performance, latency, reliability, and security. Managing and monitoring the performance of network slices are challenging tasks, as it requires detailed knowledge of the internal behaviour of each slice, how it interacts with other slices and the underlying physical infrastructure. To ensure quality and performance of slices, it is essential to monitor the network resources, traffic patterns, and SLAs associated with it. NT plays a crucial role in enabling such monitoring. It provides network operators with a detailed and real-time view of the performance of each slice, enabling them to quickly detect and diagnose any issues that may arise and take corrective action as needed. This can ensure the optimal performance and QoS for each slice, improving the overall user experience and satisfaction (reverse approach [YFW+18] [RHR+21]). NT can help identifying and diagnosing network issues that affect multiple slices, such as congestion, link failures, or security breaches. By using a common NT framework for all slices, operators can gain a comprehensive and unified view of the network status and take proactive measures to ensure service continuity and user satisfaction (direct approach [RSR20]).

4.4.2 AI framework

AI will have a more prominent role in 6G, with a data-driven architecture that supports distributed intelligence and a distributed AI platform. The main drivers for AI in 6G are new opportunities for leveraging the 6G infrastructure flexibility, coping with network and service management complexity, and supporting new revenue streams via novel services with benefits both for society and industry. Hexa-X-II will address requirements and develop enablers for a data driven architecture framework for resource management, service management and mechanisms addressing vertical applications.

Further on, the collaboration between different computing entities within the RAN or even across the computing continuum will be supported to allow for cooperative intelligence over wireless networks. One form of cooperative intelligence that is very popular lately for effectively handling and processing vast amounts of data is distributed machine learning. Distributed machine learning refers to the training of a machine learning model in a distributed manner over multiple computing entities while relying on the communication between them to coordinate and synchronize the model updates. Although from a computing perspective, the distributed model training can achieve fast reasoning, the quality of the communication between the entities may impede its efficiency. Particularly, the inherent unreliability of the links along with wireless resource limitations in terms of available bandwidth and power may result in transmission errors, while generally affecting the convergence speed of the distributed training process. At the same time, effectively selecting the entities to take part in the distributed learning process and form cooperative intelligence is a hard task given their personal communication, computing, and energy limitations.

The data-driven architecture will also allow AI empowered schemes for in-network communication purposes. AI will enable cost efficient radio transceiver design that adapts to changes in radio channel and to mitigate or compensate radio hardware impairments. The novel AI-empowered schemes will cover aspects from waveform and modulation, radio channel estimation, and high throughput decoding, to E2E optimisation of radio transceivers. It targets to outline a framework for the standardized AI in L1 for enabling AI/ML-specific features over the air and supporting AI-capable devices in harmony with legacy devices in the radio network.

4.4.3 Security and privacy

With Level of Trust as one of the key values in 6G (as introduced in [HEX22-D13]), security, privacy, and system level resilience must be well addressed in the E2E system design. Towards a secure and privacy-aware 6G network, Hexa-X-II aims at providing a general validation framework for security and resilience network evaluation in 6G environments, which is supposed to combine simulation and emulation modes following the Network Digital Twin (NDT) framework being defined by the Internet Engineering Task Force (IETF) [IETF]. Such a framework will allow for early assessment and complete characterisation of specific security and privacy threats, resilience issues, and technical solutions to address these challenges.

Efforts towards such a framework must begin with a comprehensive analysis of the 6G threat landscape, which outlines the overall threat model and classifies various risks in security, privacy, and resilience into different categories. A systematic classification with a well-established threat taxonomy (e.g., the ENISA's [ENISA]) will deepen our understanding in the nature and extent of threats in 6G, and therewith help us design, deploy, and validate the essential countering measures.

Regarding the identified threats, Hexa-X-II will leverage various novel technical solutions to enhance the security, privacy, and resilience of 6G systems. The potential technologies will cover multiple areas, such as AI, quantum-safe crypto, distributed ledger technology (DLT), attestation, and context awareness. Moreover, different validation mechanisms will be implemented to assess the threats as well as the proposed solutions. More specifically, the resilience KPIs, e.g., latency, packet acceptance rate, availability, and service reliability, will be assessed through an E2E simulation framework that is based on discrete events, performed at packet level with a queuing systems and stochastic process. Meanwhile, security and privacy KPIs will be evaluated based on NDTs.

Solving the identified threats is not an isolated action that a provider needs to apply but also the service clients need to know about it before, during and after any service in order to feel sure and to trust that the future service requests will continue being properly provided and secured. Based on this, the need of an entity focused on the management of trust (i.e., trust manager/orchestrator) could be a proper solution. Trust is a feeling that somebody has on somebody else or something, so for this reason this trust management entity should be the responsible to turn trust from a subjective feeling towards an objective parameter. One possibility to do it is by using the concept of reputation. Reputation refers to the fact of how good somebody or something is to achieve the expected objective/outcome. Based on this idea, a Trust Manager should be able to evaluate somehow the trustworthiness of all the elements and players involved in the E2E system. The definition of trust should be done using an evolved SLA data object called: Trust Level Agreement (TLA).

4.4.4 Management and orchestration

The Hexa-X-II network management framework will be designed to provide the appropriate levels of programmability, flexibility, scalability, and reliability to support the 6G use cases and applications and fulfil the associated KPIs and KVIs. To achieve that and to overcome the limitations of classical management and orchestration plans for transport and cloud networks that are currently based on monolithic software, a novel cloud-native micro-services approach will be used. The management and orchestration plan will leverage flexible function and resource allocation through heterogenous domains, as well as flexible topology realisations. Monitoring and telemetry interfaces as part of the aforementioned data collection framework (cf., Section 4.4.1) will exploit real-time streaming to gather the state and the energy consumed by the network elements, enabling sustainable networking through energy-driven decision-making and will be the first enabler for the creation of digital twins (DTs), to feed AI-assisted autonomous networks.

Several main innovations in the Management and Orchestration context in Hexa-X-II are related to the introduction of higher level of automation in network operations in a zero-touch approach by means of AI/ML. Furthermore, the intent-based management approach will simplify the interface to operations leveraging the systemic application of advanced AI/ML techniques for closed loop control (cf., Section 4.4.4.1 for details)

Other key innovations will be related with the multidomain and multi-stakeholder end-to-end management approach. 6G is expected to rely on a continuum of high number of heterogenous resources from extreme edge/devices (including end-user devices), edge nodes up to cloud resources, connected through multiple network domains whose boundaries will be blurred through horizontal federation or by the aggregation of elements across domains. This leads to much higher complexity from the management perspective. A distributed but coordinated continuum management across domains will be required, jointly for both network and compute resources (cf., Section 4.4.4.2 for details).

4.4.4.1 Network Automation

Future 6G network automation refers to the automation of network management and orchestration processes beyond the capabilities of traditional 5G networks. This involves the use of advanced technologies such as AI, ML, and advanced analytics to optimize network performance, reduce latency, and improve overall network efficiency. However, automation in future 6G mobile networks should also include the adoption of cloud native principles to be able to bring the development and operational teams in multi-stakeholder and multi-domain scenarios closer. One important step to achieve this goal is the integration of DevOps practices in the overall system architecture. However, this is quite a challenge due to the characteristics of telco environments as it involves the MNO and external vendors with different methodologies.

In the Hexa-X project, a conceptual solution was proposed by the Management and Orchestration Work Package [HEX22-D62] that aims at solving these constraints, the “Design System” building block. This building block focuses on three automation aspects:

- Software design: It covers any activities or tools at the software provider (i.e., vendor, AI model provider, etc.). It comprises: (i) interfaces and low-level composition of network elements, those aid the service providers in the composition and delivery of complex services; (ii) specification, provides guidelines to properly manage the given solutions within 6G infrastructure.
- DevOps and AIOps framework: It includes continuous pipelines as Continuous Integration, (CI), Continuous Deployment (CD), Continuous Testing (CT) and Continuous Monitoring (CM) processes. Besides, it also includes any operational activities that could be supported by AI/ML algorithms (AIOps) for management and orchestration. The objective of this framework is to increase the automation level in any software realising network operations and easing the relation between operational teams (e.g., MNOs) and development teams (e.g., vendors).
- Intent-based Management: “Intents” ease the creation of services abstracting the underlying resources/technologies from the service definition. In this way, slice developers typically from vertical industries, could provide only high-level specifications, defining just intents with the characteristics of the network capabilities from a service perspective. Such intents could be defined using a formal language, or even natural language (i.e., with the help of a natural language processing AI model).

Hexa-X-II will use this conceptual solution as a baseline to further define and implement the automation aspects. In the following subsections some of those aspects are further elaborated.

4.4.4.1.1 AI/ML for Management and Orchestration

Hexa-X-II will design and implement AI native control mechanisms (using the aforementioned AI framework in Section 4.4.2 for management and orchestration functions that will be applied to implement AI-based control loops at all architectural layers (infrastructure, network and application) and multiple domains.

AI native: The design and implementation of AI native control mechanisms in Hexa-X-II will be part of the network management architecture to fulfil 6G KVIs with especial attention to energy efficiency optimisation. Novel AI/ML solutions will be designed and implemented, making use of intelligence to improve overall network management. Depending on the management procedure's requirements, these solutions will be centralized or distributed. Besides, AI security and privacy will be increased in Hexa-X-II using privacy enhancing technologies, making them robust to possible adversarial attacks to minimize impact on applications and services. NDT technology will also be tightly integrated with AI-based control, providing general verification loops, and increasing algorithm trustworthiness.

AI-based control loops: Hexa-X-II will design and implement management and orchestration functions and workflows to provide: closed loop automation; enabling zero-touch dynamic actions for real-time reconfiguration; medium-/long-term resource re-optimisation applied to the service, network, and infrastructure layers. The closed loop automation approach will enable a continuous service assurance guaranteeing optimal usage of the resources, reducing the overall operational expenditure (OPEX) while reaching the relevant 6G KPIs/ KVIs. To this aim, AI algorithms and control mechanisms will be used to support closed loop control applied to a variety of scenarios, including predictive orchestration for optimal resource utilisation and autonomous resource management for the distributed placement of user plane functions. Besides, automated deployment of closed loop functions will guarantee real-time reactions compatible with 6G KPIs in terms of latency and service continuity. Also, Hexa-X-II will take care of the coordination of multiple control loops with different time granularities and domains or layer scopes over distributed environments, to guarantee the overall consistency of the network automation strategies across resources from multiple domains.

4.4.4.1.2 Intent-based Management

Intent-based Systems (IBSs) aim to become an access gateway for tenants without any experience about managing and interacting with the resources available in the layers below the application layer. By providing an abstraction layer that separates the application layer from the underlying infrastructure, besides, IBSs make it easier for tenants to manage and interact with resources that are often located in different geographical locations or distributed across multiple data centres.

Intent-based management and orchestration allows a higher degree of automation and programmability on networks as it enables the abstract and technology-independent declaration of the requirements, limitations, aims, and context of the intended connectivity. Hence, the focus shifts from network design and management to the needs and expectations of the applications and services that will leverage network connectivity. In [HEX22-D62] a proposal for upgrading the existing intent-based mechanism was presented, below the key points are summarised:

- Assurance checks: The intent-based mechanism would generate the initial configuration of the system/network, and then the system would provide ongoing assurance checks between the intended and operational state of the network, utilising multiple data-driven processes.
- Profiling techniques: Would aid in classifying, extracting, and validating transmitted service data. The management and orchestration system would be able to provide enhanced support to automatically validate the intents defined by the users and increase the efficiency of the intent's interpretation.
- AI/ML techniques: Would open a plethora of possibilities regarding the interpretation and translation of verticals' intents, enable a sort of "self-learning" about how to correctly interpretate and translate the customers' intents into specific management and orchestration actions.
- Big data and monitoring: The system's monitoring stack would allow to collect and process service and network KPIs, enabling the automatic and dynamic detection of potential changes in the initial service intent which will allow to react accordingly during the runtime or even prevent those situations using forecasting algorithms based on the collected data.

Hexa-X-II will use this proposal as a baseline to upgrade and enrich the existing functionalities offered to translate vertical users' intents. The IBS solution developed within Hexa-X-II shall have the capability to make the service requests from the users as easy and agile as possible and allowing the possibility to use a wide range of vocabulary (i.e., each user may speak differently) to deploy similar services, including sustainability specific targets as a key novelty.

Another aspect that the Hexa-X-II IBS solution can improve is the security and compliance of IT environments. To do so, intent-based requirements are defined to specify the desired behaviour of the system and guide the IBS to automatically enforce service performance and security policies, and to ensure that the infrastructure is always achieving the expected tenant requirements and in compliance with the relevant regulations and industry standards. To fulfil this aspect, an interesting possibility is to study and evaluate the use of Service Level Agreements (SLAs) and TLA associated to the network slices and their services deployed. Based on this, it is key to ensure that the right SLA and/or TLA is properly selected when an intent is received. For this reason, the IBN solution within the Hexa-X-II project should be capable to identify and select the most suitable SLA/TLA to accomplish each tenant requirements, monitor them and in case of a violation, to decide the best possible solution to resolve that violation.

In relation to the previous aspects, the co-existence of many different services and their specific service performance, security and trust requirements among multiple tenants can result in intent conflicts. These conflicts can arise when multiple tenants request conflicting actions or compete for resources, leading to performance issues or downtime. Therefore, a key aspect of IBS in a multi-tenant environment is the design and implementation of an intent-based conflict resolution solution. In this regard, Hexa-X-II will focus on intent-based conflict resolution based on the work presented in [ZSM011]. Using the ETSI Zero-touch network and Service Management (ZSM) closed-loop concept, the IBS solution developed in Hexa-X-II shall be capable of detecting and resolving intent conflicts in real-time, applying the fairest conflict resolution actions with the main objective to respect and minimize the impact on the other tenants' services.

4.4.4.2 Inter-domain network management

The 6G network should be able to integrate multiple networks (network-of-networks concept) and consume uniformly integrated and exposed compute resources (cloud continuum concept). In the real world, integrated networks can be owned by multiple network providers; the same issue concerns the data centres that compose the cloud continuum. Moreover, in the cloud continuum concept, the extreme-edge resources, which in many cases may be owned by end-users, should be integrated. This raises the necessity of conducting research on identifying the business interface between the end-user and the network/service operator that consumes the end-user resources. Yet another business interface may be needed between operators, whose resources should be added dynamically or periodically added to cloud continuum.

The above-described scenarios contribute to the efficient use of all available resources, speed up network deployment by using resources owned by different parties and reduce the total cost of ownership. There are, however, some problems to be solved before such scenarios can be implemented. The first group of issues concerns the definition of the business interfaces between stakeholders in which subsystems are integrated. Such interfaces should define which type of information should be exchanged between different stakeholders, considering that some stakeholders can be reluctant to provide complete information about their networks or resources; therefore, only partial information can be exploited for integration. Yet another problem concerns the management of the network-of-network type solutions that need an E2E management system. In a multi-stakeholder scenario, it means the integration of different management systems that, in some cases, should be done in a quick, automated manner. One of the solutions is partial delegation of the management of domains that compose the network-of-networks to the entity responsible for such a chain. Network slicing is one of the technologies that can be used in such a case. It must be noted that besides limited sharing of information between stakeholders and limited management capabilities of third-party owned subsystems, limited trust is an important issue to be considered (aligned with the security framework explained in 4.4.3), and utilization of mechanisms such as DLT will be investigated for this purpose.

5 E2E system evaluation and validation framework

This chapter describes how Hexa-X-II will validate the E2E system with respect to proposed KPIs and KVIs. The E2E validation will be conducted through Proof-of-Concepts for applications with features powered by 6G such as robots, and XR. The 6G enablers, that will be evaluated in the E2E validation, will be related to network transformation, management and orchestration over the 6G continuum, network control programmability and telemetry, 6G devices, radio protocols and sensing combined with mechanisms validating the KVIs and KPIs such as diagnostics.

5.1 Overview of the E2E system evaluation and validation activities

To develop and describe the 6G platform at system level, and to evaluate it considering the requirements on 6G services, Hexa-X-II will develop three industry-leading Proof-of-Concept demonstrations (identified as System-PoC A, B and C) covering selected innovative functionalities of the 6G platform. On an abstract level, the aspects that will be included in each prototype of the E2E system and in the corresponding validation can be summarized in the following groupings:

- Enablers, components, and mechanisms developed in Hexa-X-II and/or in other “beyond 5G” and 6G, H2020 and SNS Stream B projects; these will be integrated to form successive versions of the holistic 6G system,
- 6G-powered applications, including, for example, massive twinning, cobots with human intelligence in the loop, XR, internet of skills/senses means, as well as others in need of challenging 6G aspects,
- Means for assessing KPIs and KVIs by conducting diagnostics, creating test conditions, orchestrating functionality, and resources to create systems under test, and important KPIs and KVIs will be validated.

The goal of transitioning from the early development phase of 6G technology to a coherent 6G systemization driven by the need for sustainability, trustworthiness, and inclusion, requires a holistic view encompassing devices, infrastructure, novel radio, and network capabilities, E2E management and orchestration, along with security, and system-level resilience considerations.

Hexa-X-II system-PoCs are designed to showcase extended capabilities (compared to 5G), for example, in terms of diagnostics supporting resilience, fault-tolerant infrastructures, fault handling and trustworthiness, orchestration of devices supported by AI and other decision-making mechanisms for multi- and inter-domain cooperation, flexible topologies, device disaggregation, enhanced localisation capabilities, internet of senses and holography, and other technologies.

Three System-PoCs were chosen to demonstrate the technical maturity and capability of research work carried out in R&I areas of 6G, i.e., architecture design, 6G radio evolution and innovation, future devices and flexible infrastructure, and smart network management, up to technology readiness levels (TRLs) of industrially relevant environments (TRL 5), and also considering the feasibility of achieving targeted 6G KPIs and KVIs. Each System-PoC will encompass a set of Component-PoCs which provides a wide range of technical enablers for addressing project objectives and meanwhile keep the overall efforts and complexity at a reasonable level.

- The first System-PoC (A) will focus on smart network management aspects for demonstrating management mechanisms (Component-PoC #A.1) in the first year of the project, leveraging Hexa-X [HEXA] achievements and ensuring the progression of 6G journey from incorporating strong inputs from Hexa-X and other 6G EU, national and international projects, to the first public PoC.

During the remainder of the project, the complexity of System-PoCs will increase with the integration of more Component-PoCs as follows (see Figure 5-1).

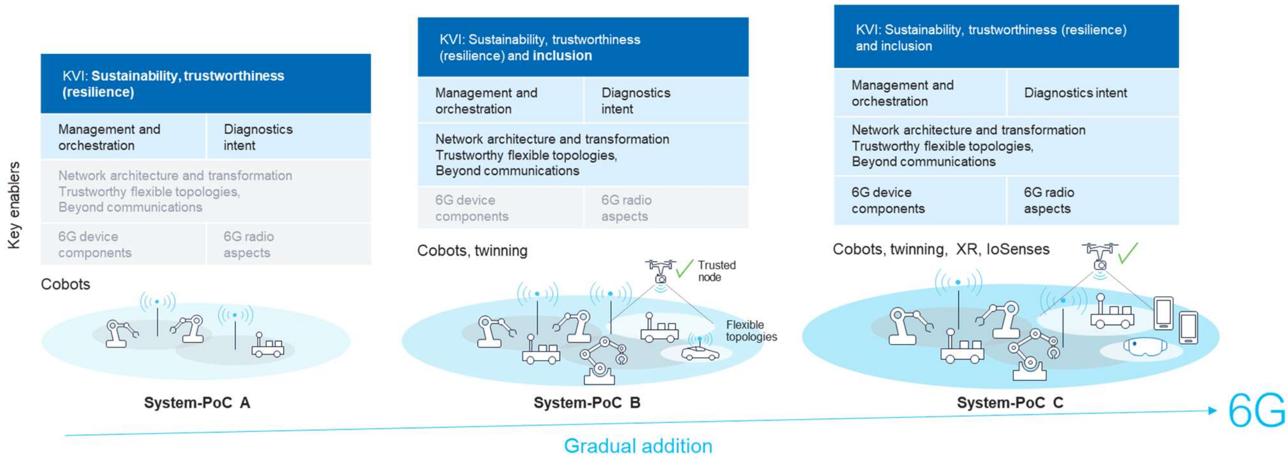

Figure 5-1: PoC gradual evolution.

- The second System-PoC (B) will mainly focus on network architecture elements and refinements of management.
- The third System-PoC (C) will focus on radio and devices aspects and refinements of 6G architecture design and smart network management.

The System-PoCs will be gradually incremented throughout the project by integrating algorithmic and/or hardware aspects rising from the Component-PoCs. The results from the PoCs (TRL5) will be fed back to the other WPs for the refinement of respective enablers, in 2 iterations (M12, M21) and also to the final PoC refinement in M30. Figure 5-1visualises the progressive development of the System-PoCs over the course of the project.

5.2 System-PoC A: sustainability and trustworthy-oriented orchestration in 6G

The undertaking of evolving from the first stages of 6G technology to the development and description of the 6G platform on system level starts with designing System-PoC A. Here, a group of cobots is assumed to be conducting a task in a resource-limited environment. The type of tasks the cobots are supposed to perform, could be either manufacturing or rescue ones. The triggering condition, that will be studied, is when the energy levels on some devices go below a critical threshold or have some sort of failure. The expected behaviour is for the energy-depleted or malfunctioning devices to be removed in order to get charged or repaired, respectively, while the rest of the devices continue performing the task. To this end, management and orchestration will assign the tasks to the devices such that the lifetime of the operation will be maximized, from the energy viewpoint.

To address these objectives Component-PoC #A.1 will be developed, with the goal of sustainability and trustworthiness-oriented orchestration in 6G. The input data will be the available elements and their capabilities including their capabilities of control and programmability, the energy consumption of the elements, their deployment aspects and the service requirements. Within this context, AI mechanisms for control and programmability of 6G focusing on energy consumption aspects will be demonstrated and resources will be assigned in a manner that optimizes energy consumption while considering security and performance. The solution will use programmability and consider zero-touch to automate the reconfiguration and energy-aware self-optimisation at runtime as well as the usage of a NDT for action verification or intelligent agent bootstrapping. Since AI takes a critical role, the AI models providing these functionalities should also be hardened-by-design to protect against possible security and privacy attacks targeting the AI model itself. The output of this Component-PoC will be control and programming commands to network elements and decision enforcement.

System-PoC A is mainly related to use cases about DTs for manufacturing and interacting and cooperative mobile robots. Figure 5-2 shows a representative flow of System-PoC A. In this figure, a multi-domain environment is illustrated. It is assumed that some cobots are utilized in an industrial environment. A low-battery issue is assumed to happen in one of the cobots, requiring another cobot to be used in order to ensure continuation of normal operation. The multi-platform and multi-domain orchestrators will be utilized for autonomous repair operations. Also, the utilization of remote repairing and cobot manipulation through XR will be part of this system PoC. Change of policies can also be enforced through intents. In the following subsections, aspects on resilience through autonomous repair operations are discussed. Also, repairs through multi-domain orchestration and through XR are investigated. Intent-based solutions for network service delivery and conflict resolution are also provided.

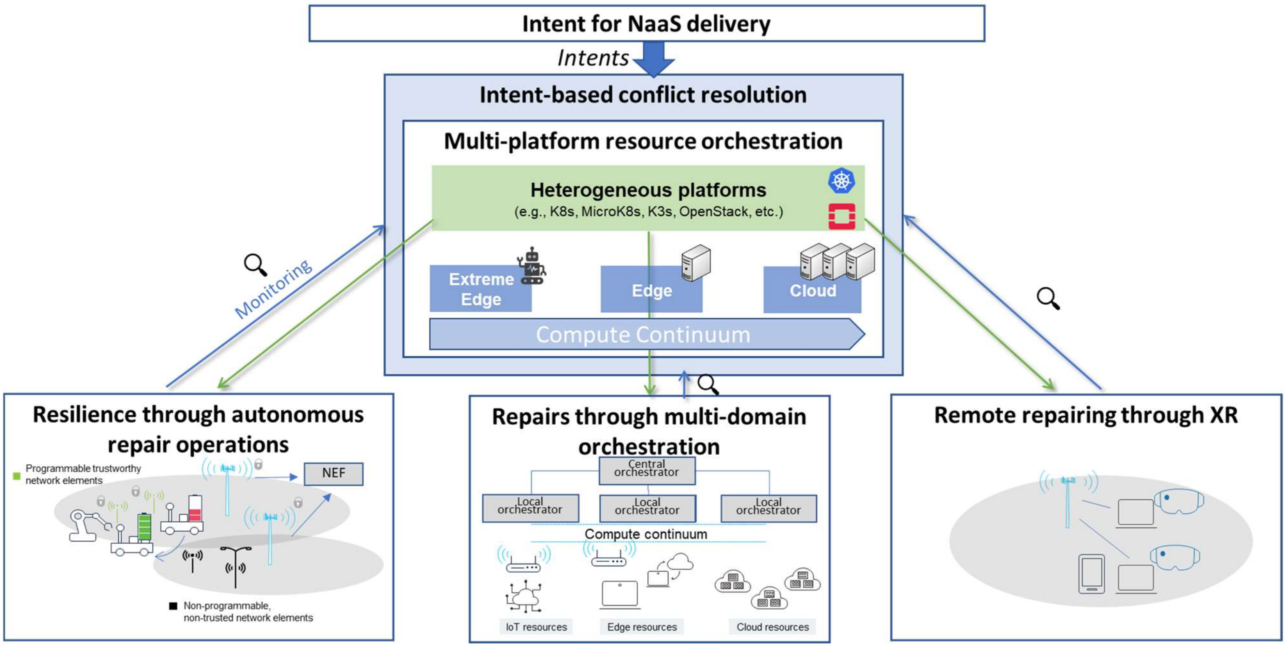

Figure 5-2: Overview of Hexa-X-II System-PoC A

5.2.1 Resilience through autonomous repair operations

Resilience through autonomous repair operations on networks refers to the ability of a network to automatically detect and repair faults, failures or damages that occur within the network without requiring human intervention. This is achieved using various technologies such as AI, machine learning, and automation. Smart networks are designed to have the ability to detect and mitigate problems in real-time in multiple domains. For example, upon fault detection in a smart grid, the system can automatically reroute power to avoid outages. Similarly, in a smart transportation network, the system can detect and respond to accidents, rerouting traffic, and dispatching emergency services as needed.

Autonomous repair operations on smart networks can greatly improve the reliability and resilience of these systems, reducing downtime and minimizing the impact of disruptions [WFZ+14]. This can have significant benefits for industries that rely on these networks, such as healthcare, transportation, and energy. Proper planning, testing, and monitoring are crucial for ensuring that these systems operate safely and effectively. Besides the network resilience and to validate the system in an E2E manner, resilience in terms of business continuity is also critical, involving various resources and vertical business-specific operations.

5.2.2 Repairs through XR and multi-domain orchestration

XR technologies, which encompass Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), offer various advantages for network repairs and monitoring. These technologies have the potential to enhance the efficiency and effectiveness of network repairs by enabling remote collaboration between experts and technicians [WFZ+14].

With AR and MR, technicians can share their field of view with remote experts who can guide them through the repair process or provide troubleshooting assistance. This feature can expedite the repair process, minimize downtime, and reduce costs associated with travel. XR technologies also offer 3D visualization of network topology and diagnostics, which can assist managers in making decisions about repairs and improvements. For instance, managers can visualize the network topology in 3D to identify problematic areas and prioritize repairs. Real-time data visualization is also possible with XR, which can project diagnostics such as signal strength or throughput on top of the real world to help technicians locate issues more quickly.

Multi-domain orchestration refers to the offering and management of applications and services over compute and network resources that may belong to multiple providers [WFZ+14]. Multi-domain orchestration is a key research area for 6G networks, and several approaches are being developed to address the challenges of managing complex, heterogeneous networks, and computational resources. These approaches aim to enable frictionless integration and seamless coordination between different network domains, providing a unified view of the network and enabling E2E service orchestration. Different orchestration approaches may be applied, including hierarchical orchestration, federation-based orchestration, and distributed orchestration. Hierarchical orchestration builds on i) the 'abstraction' principle, and ii) the parent-child relationships across orchestrators. In hierarchical orchestration, the infrastructure is divided into multiple hierarchical levels, with each level responsible for managing a specific aspect/part of it. In the federation-based orchestration, federation of infrastructure domains is provided, where each domain retains its own management and orchestration mechanisms. In the distributed orchestration, distributed orchestration functions are activated across the infrastructure, enabling each domain to manage its own resources and services. The domains communicate with each other, enabling E2E service orchestration. This approach enables high scalability and fault tolerance, making it suitable for large, complex networks. In the PoC, various orchestration solutions are considered based on the requirements that must be fulfilled for the efficient and secure provision of the developed services.

5.2.3 Intent-based orchestration solutions

Among the new possibilities being discussed within the Hexa-X-II project context, there is the analysis task to design a solution with the capability to manage network and services resources based on intent requests to allow non-technical users to ask for specific services without the need to know how to manage the available resources in the multiple infrastructure domains. Up to now, intent-based solutions have been mainly used to provide a way to orchestrate services in a user-friendly manner (e.g., by using natural language). A possible evolution could go in the direction of extending this methodology towards the definition of criteria for the automation of the service, other than the definition of the service itself. In terms of design and methodology of working for this new solution, the use of ETSI ZSM framework seems to be a very interesting option towards the achievement of an automated solution that complements the intent-based capability with the resolution of problems without the intervention of the final user. ETSI ZSM just started investigating such a topic in [ZSM016]. This new intent-based component aims to be part of the Management and Orchestration tasks within PoC-A. Further details such as the architecture, sequence diagrams and other characteristics will be properly described in future Hexa-X-II deliverables.

5.3 Functional components of System-PoC A

This section details the functional components (both hardware and software) that System PoC-A consists of. This includes cobots, XR, the orchestration solutions applied across the computing continuum and various intent-based solutions used for delivering NaaS, that are going to be considered in System PoC-A.

5.3.1 Cobots

As smart networks become more complex, physical collaborative robots (i.e., cobots) will likely become an increasingly important tool for network operators and can play a valuable role in smart network management by improving efficiency, reducing downtime, and enhancing safety. Cobots can communicate with each other and with human operators to coordinate tasks and share information. This can help ensure that the network is operating efficiently and effectively. Additionally, they can be deployed to inspect, maintain, and repair various components of smart networks, including themselves. They can perform these tasks with high accuracy and efficiency, which can reduce downtime and increase the lifespan of network components.

One potential application for cobots is in network QoS monitoring, which involves measuring the performance of a network in terms of factors such as bandwidth, latency, and packet loss. Organizations can leverage cobots equipped with sensors and cameras to gather additional real-time data on physical state of the equipment, such as temperature, or visual inspection from a video stream. This data can then be analysed to detect patterns and possible issues, which enables IT teams to take proactive measures to address them before they become more severe. In addition, cobots offer a degree of flexibility and scalability that traditional network monitoring solutions lack. They can be conveniently relocated or repositioned to monitor different parts of the network, and additional cobots can be introduced as the network expands or undergoes changes. The environment of all Hexa-X-II's system PoCs will consist of a set of cobots conducting a task, along with other network devices.

5.3.2 XR

XR refers to a range of technologies that enable users to experience a digitally enhanced version of reality. XR among other uses can be employed to manage and optimize the performance of a smart network in several ways, such as, visualization, remote monitoring and control, training and simulation, and collaboration. As to the visualization aspect, XR technologies can be used to create immersive 3D visualizations of network data. This can help network managers to better understand the topology and performance of the network, identify potential issues, and make informed decisions about network upgrades and optimizations. Regarding the remote monitoring and control, XR can be used to remotely monitor and control network equipment and infrastructure. For example, technicians can use XR headsets to view and diagnose issues in real-time, and control equipment using hand gestures or voice commands. Training and simulation refer to the fact that XR can be used to provide training and simulation environments for network technicians and engineers. This can help to reduce the cost and risk associated with hands-on training and enable technicians to gain experience with complex network configurations and troubleshooting scenarios. Finally, with collaboration it is meant that XR can enable network managers and technicians to collaborate in virtual environments, regardless of their physical location. This can improve communication and coordination and help to resolve network issues more quickly and efficiently.

Even though XR will be integrated in system PoC C, which comes later in the project, in system PoC A it will be a legacy tool to show the current state of the art. Furthermore, XR will allow us to expose the benefit of multi-sites and it is expected to be a key enabler for the enterprise metaverse.

5.3.3 Multi-platform resource orchestrator

Various management and orchestration frameworks are going to be considered in Hexa-X-II, including frameworks applicable to the various parts of the computing continuum, frameworks that focus on network services provision, 6G applications provision, as well as frameworks that tackle the interplay between network and application providers. To support evaluation and validation activities, there is a need for the specification of performance evaluation metrics that can be applicable across the various orchestration platforms and enable their joint assessment and comparability. Such metrics may include convergence times for decision making processes, especially in cases where automation processes are activated; SLAs assurance statistics; reaction and recovery times in case of failures. In the case of collaboration across orchestration platforms, the delays introduced in the various interaction interfaces should be also considered and evaluated. Moreover, resource management at the extreme edge is one of the key topics of 6G system, considering the proliferation of devices belonging to that network segment and the capabilities they provide to deploy complex applications close to the users.

Various orchestration solutions applied across the computing continuum are going to be considered in the PoCs. The considered infrastructure across the computing continuum includes IoT devices (e.g., cobots) and UEs, radio access infrastructure (e.g., gNB), edge/cloud computing infrastructure (set of servers made available in various locations) and transport/access network infrastructure (e.g., Software-defined Networking (SDN) switches). Where applicable, the management of these resources will be considered, taking advantage of emerging open-source solutions that manage multi-cloud workflows. Automation and distributed intelligence characteristics will be supported based on the application of AI techniques and the development of AI-assisted orchestration mechanisms. Decision making will be supported in a distributed way, where local decisions may be made by cluster managers in the far edge/edge/cloud part of the infrastructure, while global decisions may be made by centralized orchestration entities. Scaling and compute offloading mechanisms will be supported at both the edge and the cloud part of the infrastructure.

In Hexa-X-II, an E2E intent-based solution will be designed, developed, and evaluated with the objective to be used within the context of the PoC. This new solution will manage the intents deployment based on the high-level service requirements defined by the multiple tenants allocated across the different domains. Once the intent-based solution has properly managed and obtained the necessary outcomes by processing the tenants' requirements, the right service will be deployed with the necessary resources across multiple domains using the different elements of smart network management. A specific multi-platform Resource Orchestrator will be implemented, offering the capability of operating over extreme edge, edge, cloud continuum, with the aim to unify resource modelling and management over heterogeneous platforms (e.g., K8s [K8s23], MicroK8s [MicK823], K3s [K3s23], OpenStack [OS23], etc.) and provide an abstracted resource view towards the service orchestration logic. The main capabilities offered by the resource orchestrator include i) dynamic discovery and continuous monitoring of different kinds of resources available extreme edge (to handle their volatility), edge and cloud continuum nodes, ii) the definition of strategies to address mobile network connectivity implications on the orchestration of resources, and iii) resource allocation and migration strategies based on extreme edge nodes' characteristics constraints, including the usage of prediction algorithms to foresee the evolution in time of dynamic constraints (e.g., battery level, energy consumption, availability and quality of the connectivity of the node, computing load from concurrent user applications, etc.). RO is expected to be part of PoC A, where its main feature will be assessed. Further evolution of the component may include the possibility of creating RO federations, enabling the possibility of pooling and managing resources from multiple and heterogenous cloud platforms potentially belonging to different stakeholders.

5.3.4 Intent Based Mechanisms

In Hexa-X-II intent-based solutions will be sought for reaching the innovation goal of service management automation. Intent will be used as a solution to deliver NaaS, enabling the integration of Hexa-X-II managed resources and 3rd party applications, with direct (frictionless) and open interactions between them. Intent usage will scope two objectives:

- Customer-facing APIs, used to make Hexa-X-II capabilities available for external consumption. The proposal is to use intent as the language to reach out targeted 3rd parties, including application developers, hyperscalers, verticals, public institutions. These 3rd parties typically have no telco expertise, and demand APIs which i) hide unnecessary telco complexity, avoiding low-level network or IT system configuration parameters; and with semantics which focus on their business and operational needs; ii) have minimal impact on their backend systems, i.e., APIs which are easy-to-consume and require low coding effort.
- Digital service management. Intent can be used as single unified solution to manage the lifecycle of any digital service (e.g., feasibility check, provisioning, assurance), as soon as the service properties are captured in a well-defined intent model, such as the one proposed in [28.312] (see Figure 5-3 below). This assertion leverages on the inherent properties of intent construction: model-driven approach and asynchronous mode support.

One further aspect in which Hexa-X-II will focus on intent-based conflict resolution is based on the work presented in [ZSM011]. Using the ZSM close-loop concept, intents should be properly resolved with the best and fairest solution possible among all intent-based deployments.

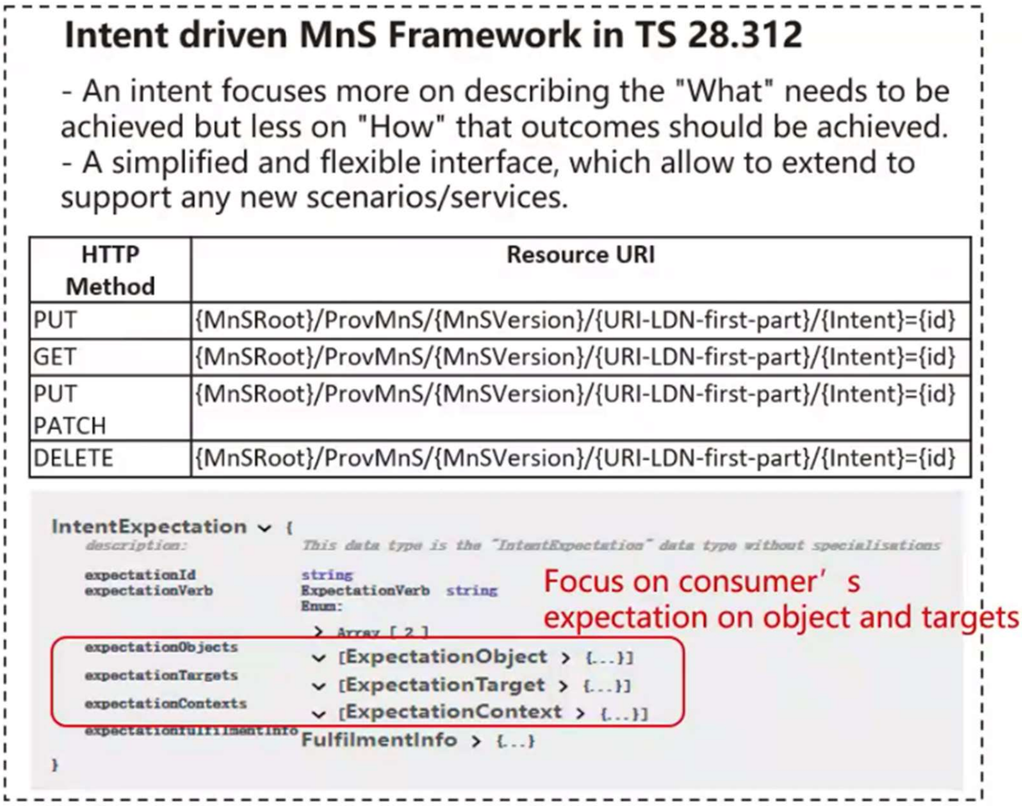

Figure: 5-3 Intent driven MnS Framework

5.4 KPIs & KVIs related to system-PoC A

Below are the targeted KVIs in System PoC A and the KPIs that will be measured in order to ensure the quality, reliability and performance of the system. As mentioned earlier, the System PoC A deals with management and orchestration aspects and it will be important to measure specific attributes which can show the impact of intents and decisions for the problem resolution. Such attributes can expand beyond common, usual ones (e.g., throughput, capacity) towards reliability, intent deployment time, recovery time etc.

5.4.1 Sustainability and trustworthiness

System-PoC A in Hexa-X-II mainly focuses on the feasibility to achieve the target KVIs of sustainability and trustworthiness. The operations of the cobots with an energy efficient perspective will maximize the lifetime of the operations which will contribute to the sustainability of the system. The improved human-machine interaction in the system PoC-A with the intelligent cooperation among cobots via management and orchestration of the 6G continuum, and resource-usage efficiency will increase the overall sustainability. This will impact the overall operations in the manufacturing process by maximizing the lifetime of the operations in a resource limited environment. Handover of the operations in a general failure will assure the resilience of the system and thereby enhance the trustworthiness.

5.4.2 Technical KPIs

KPIs provide a way to measure and track specific metrics related to network performance and/or user experience. They play a critical role in ensuring that 6G networks meet the demands of emerging high-bandwidth and low-latency applications. In this context, identifying and monitoring the right KPIs will be essential for optimizing network performance, ensuring the QoS, and delivering a seamless user experience. Some KPIs that are important to monitor and optimize include:

- **Reliability**: Network reliability refers to the percentage of time that the network is available and functioning correctly. High network reliability is required to minimize disruptions to service and prevent lost revenue.
- **Latency**: Latency measures the time it takes for data to travel between two points in the network. It is typically expressed in milliseconds (ms) or microseconds (μs). In the context of 6G, low latency is crucial for applications that require real-time interactions, such as virtual reality, telemedicine, and autonomous vehicles.
- **Provisioning Time**: this KPI measure the time taken to enforce a provisioning request of a managed entity (CNF, Network Service, Network Slice, etc.) to the underlying infrastructure, measured from when the request reaches the provisioning interface up to the managed entity provisioning is fulfilled.
- **Termination Time**: Time to terminate a managed entity (CNF, Network Service, Network Slice, etc.), from the termination request up to the release of its assigned resources. This provides a measure of the promptness in re-availability of the resources after released by a service.
- **Recovery Time**: this KPI measure the time to recovery of a managed entity (CNF, Network Service, Network Slice, etc.) after an outage, providing a measure of the reactiveness of the network in minimizing service downtime.
- **Intent Deployment Latency**: Time to have the complete E2E intent-based service request properly deployed and available to be used by for the final user. This latency will start when the service user intent-based requests reach the IBN solution until the confirmation of the intent-based service is available for the user.
- **Intent Conflict Resolution Latency**: Time to achieve the complete resolution (i.e., service completely working in normal status) since an intent-based conflict is detected, up until it is solved.

5.5 Simulation based approaches

As 6G is in its research phase, most of component and enabler validation and verification is carried out with simulations. Especially for physical and link layer of RAN validation and development, including, e.g., new waveform design for 6G, simulations play a central role. For this, the E2E system validation and verification needs to consider including the simulation models as a part of the system evaluation methodology in addition to PoC implementation and validation. This will create requirements for the interfacing of the simulation models, whether they are discrete event simulations with pseudo-data or bit-accurate simulations or emulations.

WP2 collects the information from different technical work packages as well as WP2 tasks to identify the simulation models developed and used for research and development. This information is further analysed, and suitable models selected for use case validation and if some of the models and/or results of simulations/ emulations can be integrated to PoC E2E validation. Based on the initial analysis, majority of planned simulations are related to link-level simulations and few system level simulations. The tools include specific Python-based software or, e.g., Matlab-based simulations. The following sections provide the initial view for simulation-based evaluation methodology, frameworks, and approaches.

5.5.1 Evaluation methods of selected use cases

Based on the selected use case from WP1, resilience KPIs will be assessed through an E2E simulation framework. A first step will be to analyse the essential functions related to the use case requirements and associated KPIs/KVIs. For example, if the use case is very sensitive to latency at user plane level, the model will focus on user plane functions. In case of mobility, signalling functions will be addressed. A second step will be to identify call flows related to this use case and to build the associated E2E service function chain. For each function, virtualization layer will be modelled including physical resources (servers), virtual resources (containers or pods) and orchestration (scaling and self-healing mechanisms). Resource capacity is included in the model. Simulation is based on discrete events, performed at a packet level with queuing systems and stochastic processes. For the time being, KPIs like latency, packet acceptance rate, availability and service reliability can be evaluated. This approach could be integrated in a multi-agent modelling tool.

5.5.2 Digital twin-oriented approach for connectivity

Digital twinning will be used to evaluate the communication performance in selected use case(s) to support the validation performed by implemented PoCs. 6G radio transceiver solutions will be developed in technical WPs during the project, and some of the technical solutions will not be mature enough to be evaluated as a part of architecture in the implemented hardware PoCs during the project timeframe. DT-based evaluation is envisaged to be more feasible, and flexible, for communication performance evaluation in WP2, by collaborating with the technical WPs during the solutions development. Digital replica of the selected novel technical solutions will be implemented as part of E2E simulation framework to support their performance evaluation when integrated to the E2E network architecture. E2E framework will include modelling of communication flow between application service, CN, RAN, and user equipment (UE) as illustrated in Figure 5-4. In this DT-based evaluation, the focus will be on O-RAN based network architecture, which is one of the relevant options considered for 6G deployments. An important component of the O-RAN architecture is the RAN intelligent controller (RIC), which will be used to execute AI/ML algorithms targeted for RAN performance optimization, by controlling, e.g., novel D-MIMO and/or beam management solutions. E2E simulation framework development will include digital models of 6G transceiver solutions, to the extent that is possible during the project timeframe. Therefore, in relation to the 6G system blueprint presented in Figure 3-5, here the studied pervasive functionality is the NDT framework, which includes functionalities from the Application (creating communicated traffic between CN and UE), Network-centric application (RIC and APIs), and Network functions layers (O-RAN approach, UE and CN).

Main objective is to evaluate the RAN control algorithms, with AI-driven transceivers, and effect on the communication performance in the studied use case, as a part of E2E network architecture. Main objective is to evaluate the RAN control algorithms, with AI-driven transceivers, and their effect on the communication performance in the studied use case, as a part of E2E network architecture. Simulation-based evaluation of individual radio solutions will be done in technical WPs, while the goal of WP2 work is to enable selection, and support development, of the proposed solutions as a part of the architecture. Communication performance indicators such as block error rate (BLER), error vector magnitude (EVM), throughput, signal coverage and communication latency, may be considered, depending on their importance in the studied use case. In addition, the selection of performance indicators will be done so that they will support/complement the performance evaluations which have been done in technical WPs. Results of the DT-based evaluation will be included in the upcoming deliverables.

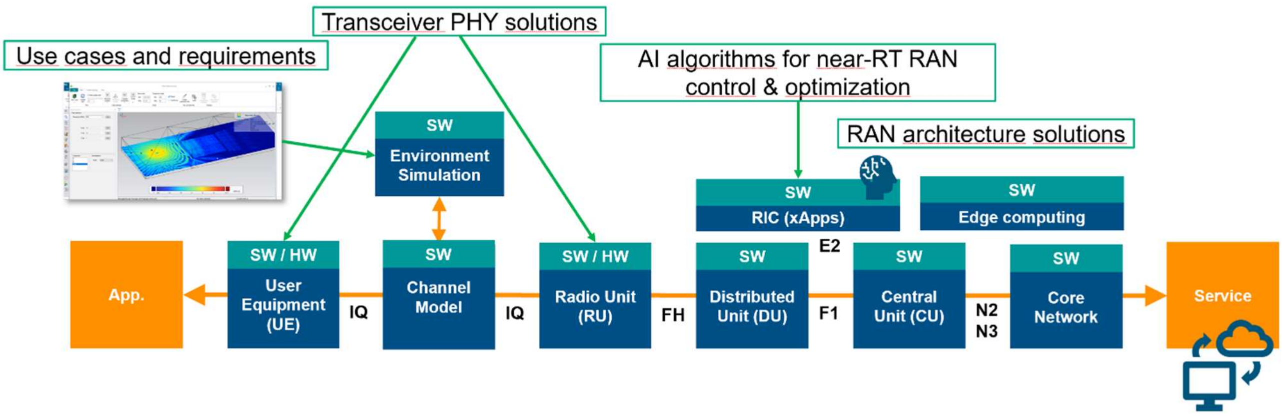

Figure 5-4: High-level architecture of the DT-based performance evaluation.

6 Conclusions and next steps

This report provides the draft foundation for 6G system design, including the definition and initial view of 6G blueprint and the architecture design principles. This document also presents the iterative E2E system design process, 6G innovations to form the 6G E2E system, and E2E system evaluation and validation framework. The document acts also as initial requirements and guidelines of 6G blueprint and 6G platform towards other technical WPs to develop 6G system enablers/ innovations. These requirements and guidelines will be further defined and revised in the upcoming deliverables.

The initial view of 6G system design principles as well some of the needed functional components and enablers are based on available public information from the preceding 5G PPP projects, especially Hexa-X. As the other Hexa-X-II technical WPs are still in the initial phase, their inputs will be considered for the further fine-tuning of these design principles. In addition, the initial view has been influenced by the 5G PPP working group actions and produced white papers, for example on definition of 6G related and generic KPIs and KVIs for the E2E system validation process. The deliverable also provides the description of iterative design process and how the decisions for E2E system validation framework would be performed.

One of the key parts of the deliverable is the identification of innovations related to 6G E2E system validation. In the document, an overview of 6G system innovations is presented, which should be included and considered for system validation. These innovations are mainly categorized into four key areas starting with the innovations supporting the application layer and for the network-centric application layer. Secondly, for the network function layer, the innovations are discussed with respect to network function modularization, network beyond communication, RAN related innovations, context-awareness management, and new access and topologies. Thirdly, the innovations in infrastructure and compute layer include the innovations related to cloud transformation, future devices, and infrastructure. The fourth category of innovations covers pervasive functionalities which include many innovations with respect to data collection framework, AI framework, security and privacy, and management and orchestration. The management and orchestration innovations are especially discussed in terms of AI/ML based approaches for 6G network automation and intent-based networking. It is also foreseen that the aforementioned innovations as well as the architecture design principles may need further refinements in later phases of the project and some new KPI and KVI definitions from E2E perspective would be needed. However, it is still too early to make the additional definition, and this will be further discussed in the later phases of the project. Lastly, the deliverable discusses the E2E system evaluation and validation framework with respect to KPIs and KVIs which is planned in three phases. In this initial phase, the system-PoC (i.e., named as system PoC-A) is planned with cobot and XR applications to showcase sustainability and trustworthiness-oriented orchestration in 6G. In the later phases, PoC-B and PoC-C will be also demonstrated.

Considering the initial guidelines provided by this report, the technical work in WP2 will be further conducted to the design of the foundation of overall 6G system. This may lead to a more detailed and stable description of the 6G E2E system in the next deliverable. The 6G E2E system design process will also consider the KPI/KVI and 6G use cases defined in Hexa-X-II and consolidate the technical work conducted in other WPs. During the coming months, the first iteration of the system PoC (A) will be running, and the preliminary evaluation results will be obtained. The components of the system PoC (A) will focus on smart network management aspects for demonstrating the essential managements mechanisms.

The results of the above-described work will be reported in deliverable D2.2 and published in Hexa-X-II webpage [HEXA2].

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Annex A: Terminology

6G platform: The external view of a set of technologies and interfaces delivering 6G services to applications, ecosystems, verticals, users etc. enabling value.

6G E2E system: The technical solution and realization consisting of enablers tied together into a system - integrated and interacting technology enablers. Basically, E2E system is the technical realization of the platform.

6G blueprint: Reference architecture meeting an E2E need: hardware, software, and application.

Architecture design principles: Define the underlying general rules and guidelines for E2E system deployment.

Component: A functional element or a subsystem in 6G system that provides a certain functionality or a capability.

Design guidelines: Sets of recommendations on how to apply design principles to provide a positive user experience

Digital services (Network/Application): Services which are delivered over the network and the nature of which renders their supply essentially automated and involving minimal human intervention.

E2E Proof-of-Concept: Realization and demonstration of use case specific critical solutions of 6G E2E system and 6G blueprint.

Enabler: An innovation or a functionality that helps a 6G capability to happen. A part of the whole system, realized by one or several components.

Functional architecture: Architectural model that identifies system function and their interactions.

Methodology: A body of methods, rules, and postulates employed by a discipline.