D1.1: Requirements and Use Case Specifications

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Abstract	The 6G-XR project is dedicated to building an advanced infrastructure for Extended Reality (XR) services, and deliverable D1.1 outlines the requirements for enabling XR use cases of the project. The project aims to conduct trials and assessments at designated test facilities to evaluate its Key Performance Indicators (KPIs) and Key Value Indicators (KVIs).
Keywords	Extended Reality (XR), 5G/6G, Holographic Communications, 3D Digital Twin, Energy Optimization, Network Slicing, Resolution adaptation, Control plane optimization

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EXECUTIVE SUMMARY

This report is the first deliverable of Work Package 1 (WP1) – “End-user Requirements and Architecture Design Co-creation” of the 6G-XR project. The key purpose of D1.1 is to elaborate on the technologies that will be used to enable the Extended Reality (XR) use cases over the advanced 5G/6G test facilities.

6G-XR project has identified three different application areas that would benefit from the large-scale deployment of B5G/6G networks: (i) Real-Time Holographic Communications, (ii) Collaborative 3D Digital Twin-like Environment, and (iii) Energy Measurement Framework for Energy Sustainability. Within the scope of the project, the first XR application area has three use cases:

- UC1 - Resolution Adaptation or Quality on Demand
- UC2 - Routing to the Best Edge
- UC3 - Control Plane Optimizations

The 2nd application area has a single use case:

- UC4 - Collaborative 3D Digital Twin-like Environment

And the 3rd application area also has a single use case:

- UC5 - Energy Measurement Framework for Energy Sustainability

The available test facilities at the project's north node (UOULU 5GTN and VTT 5GTN) and south node (5GBarcelona and 5TONIC) will be used to trial each of the use cases, with the objectives of testing and validating the project's Key Performance Indicators (KPIs) and Key Value Indicators (KVIs).

Deliverable D1.1 offers a comprehensive description of use case scenarios, encompassing the requirements essential for enabling the trials of the project's use cases.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
3GPP	The 3rd Generation Partnership Project
6G	The 6th Generation mobile network
5G	The 5th Generation mobile network
5G-A	5G-Advanced
5GC	5G Core Network
5G PPP	The 5G Infrastructure Public Private Partnership
5GTN	5G Test Network
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
AMF	Access and Mobility Management Function
AMI	Advanced Metering Infrastructure
API	Application Programming Interface
AR	Augmented Reality
B2B	Business to Business
B2C	Business to Consumer
B5G	Beyond 5G
BSoTA	Beyond-State-of- the-Art
BSR	Buffer Status Report
CAD	Computer Aided Design
CCC	Cell Configuration and Control
CDF	Congestion Detection Function
CG	Cloud Gaming
CNC	Computerized Numerical Control
CO2	Carbon Dioxide
CP	Control Plane
CPU	Central Processing Unit
CSS	Cascading Style Sheets
CU	Central Unit
DC	Data Channel
DCS	Data Channel Server
DL	Deep Learning
DRX	Discontinuous Reception
DSP	Digital Signal Processing
DT	Digital Twin
DU	Distributed Unit
E-UTRA	Evolved Universal Terrestrial Radio Access
E2E	End-to-End
EARFCN	E-UTRA Absolute Radio Frequency Channel Number
EI	External Interface
eMBB	enhanced Mobile Broadband
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
FMI	Finnish Meteorological Institute
FPS	Framerate Per Second
gNB	5G NodeB
GPU	Graphics Processing Unit

GSMA	Groupe Speciale Mobile Association
HLS	Higher Layer Split
HPC	High Performance Computing
HTML	Hypertext Markup Language
HVAC	Heating, Ventilation, and Air Conditioning
HW	Hardware
IMS	IP Multimedia Subsystem
IMSDC	IMS Data Channel
IOPS	Input/Output Operations per Second
IoT	Internet of Things
IP	Internet Protocol
ISP	Internet Service Provider
ITU-R	Radiocommunication Sector of International Telecommunication Union
KPI	Key Performance Indicator
KPM	Key Performance Measurement
KVI	Key Value Indicator
LLS	Lower Layer Split
LoD	Level of Detail
LoRa	Long Range
LTE	Long Term Evolution
LTE-M	LTE Machine Type Communication
MCU	Multipoint Control Unit
MEC	Multiaccess Edge Computing
MIMO	Multiple Input and Multiple Output
ML	Machine Learning
mMTC	massive Machine Type Communications
MNO	Mobile Network Operator
MQTT	Message Queuing Telemetry Transport
MR	Mixed Reality
MSE	Mean Squared Error
NAT	Network Address Translation
NB-IoT	Narrow Band IoT
NEF	Network Exposure Function
NG-RAN	Next Generation RAN
NI	Network Interface
NR	New Radio
NSA	Non-Standalone
NWDAF	Network Data Analytics Function
O-FH	Open Fronthaul
OAI	Open Air Interface
PC	Personal Computer
PDU	Protocol Data Unit
PLMN	Public Land Mobile Network
PoC	Proof of Concept
PRB	Physical Resource Block
PSU	Power Supply Unit
PUSCH	Physical Uplink Shared Channel
PV	Photovoltaic
QCI	QoS Class Identifier
QoD	Quality on Demand
QoE	Quality of Experience

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QoS	Quality of Service
RAN	Radio Access Network
RC	RAN Control
RI	Research Infrastructure
RIC	RAN Intelligent Controller
RMSE	Root Mean Squared Error
RRH	Remote Radio Head
RRM	Radio Resource Management
RU	Radio Unit
S-NSSAI	Single Network Slice Selection Assistance Information
SA	Standalone
SDG	Sustainable Development Goals
SDK	Software Development Kit
SDR	Software Defined Radio
SEP	Service Enablement Platform
SFU	Selective Forwarding Unit
SM	Service Model
SME	Small and Medium-sized Enterprise
SMO	Service Management and Orchestration
SNS JU	Smart Networks and Service Joint Undertaking
SoTA	State-of-the-Art
SW	Software
TAC	Tracking Area Code
TSN	Time Sensitive Networking
TSO	Transmission System Operator
TWT	Target Wake Time
UCI	Uplink Control Information
UE	User Equipment
UI	User Interface
UN	United Nations
UP	User Plane
UPF	User Plane Function
uRLLC	ultra-Reliable and Low Latency Communications
URP	Universal Render Pipeline
VNF	Virtual Network Function
VoLTE	Voice over LTE
VoNR	Voice over NR
VR	Virtual Reality
VV	Volumetric Video
XR	Extended Reality

1 INTRODUCTION

The main purpose of D1.1 is to summarize the outcomes of the first and second technical Tasks (T), T1.1, and T1.2 from Work Package 1 (WP1) of the "6G eXperimental Research infrastructure to enable next-generation XR services" (6G-XR) project. T1.1 "Multi-actor use cases, business models and KPI requirements" focuses on describing the project's use cases, defining the requirements for the use cases and business models, and the Key Performance Indicators (KPIs) to be validated. T1.2 "Socio-economic and environmental impact of innovative and existing wireless technologies: KVI requirements" focuses on describing the social, economic, and environmental impacts as well as the Key Value Indicators (KVIs) to be validated. Moreover, a first version of the 6G-XR system architecture is included in this deliverable.

As the first technical output of the 6G-XR project, this document not only provides a concise overview of the project's goals and objectives, but also emphasizes the innovative ideas and aspirations it seeks to accomplish. It delves into the technological advancements that form a crucial part of 6G-XR, aiming to elucidate how the project will leverage existing technologies. Therefore, the deliverable is anticipated to serve as an essential reference guide during the project lifetime.

1.1 OBJECTIVES OF THE DELIVERABLE

The objectives of D1.1 are to:

- Analyze the performance requirements of holographic communication applications and use cases:
    - Describe the use cases, including their deployment architectures, and related requirements.
    - Define the KPIs and KVIs related to holographic applications.
- Analyze the requirements of Three Dimensional (3D) Digital Twin (DT)-like environment use case:
    - Describe the use case, including the deployment architecture with Time Sensitive Network (TSN), and related requirements.
    - Define the KPIs and KVIs related to the DT applications.
- Analyze and design an End to End (E2E) energy optimization platform:
    - Describe the use case with functional and non-functional requirements in terms of mobile network components including the high-level deployment architecture.
    - Define the KPIs and KVIs related to the energy optimization use case in Beyond 5G (B5G) / 6G networks.

1.2 STRUCTURE OF THE DELIVERABLE

As the 6G-XR project combines two different ecosystems, 6G and Extended Reality (XR), it is important to structure the document in a way that allows the reader to get a glimpse of both the systems. The structure of D1.1 is as follows:

- Chapter 2 introduces the key aspects of the 6G-XR project and details the objectives, innovations, impact, different stakeholders and their roles, enabling technologies, and the initial 6G-XR system architecture.
- Chapter 3 focuses on use cases, requirements, and business models, describing example XR use cases and requirements from public sources as well as the project use cases in area of real-time holographic communications, collaborative 3D DT-like environment, and energy measurement framework for energy sustainability.
- Chapter 4 focuses on the definition of the 6G network KPIs and the 6G-XR use cases-specific KPIs.
- Chapter 5 details 6G-XR socio-economic and environmental impact and focuses on the KVIs and their impact.
- Chapter 6 analyzes the three development paths of 6G technologies, i.e., 3GPP evolution path, open source/O-RAN path, and disruptive 6G path.
- Chapter 7 discusses the future prospective of use cases and focuses on Smart Network and Services Joint Undertaking (SNS-JU) stream B projects.
- Finally, the last section, Chapter 8, summarizes the document.

1.3 TARGET AUDIENCE OF THE DELIVERABLE

This deliverable is a public report which targets the project consortium, stakeholders, academic and research organizations, EU commission services, and the general public.

2 6G-XR KEY ASPECTS

2.1 OBJECTIVES, INNOVATIONS, AND IMPACT

6G-XR ambition is to strengthen the European leadership in 6G technologies by enabling next-generation XR services and infrastructures that will provide Beyond State-of-the-Art (BSoTA) capabilities in the run-up to the 6G era.

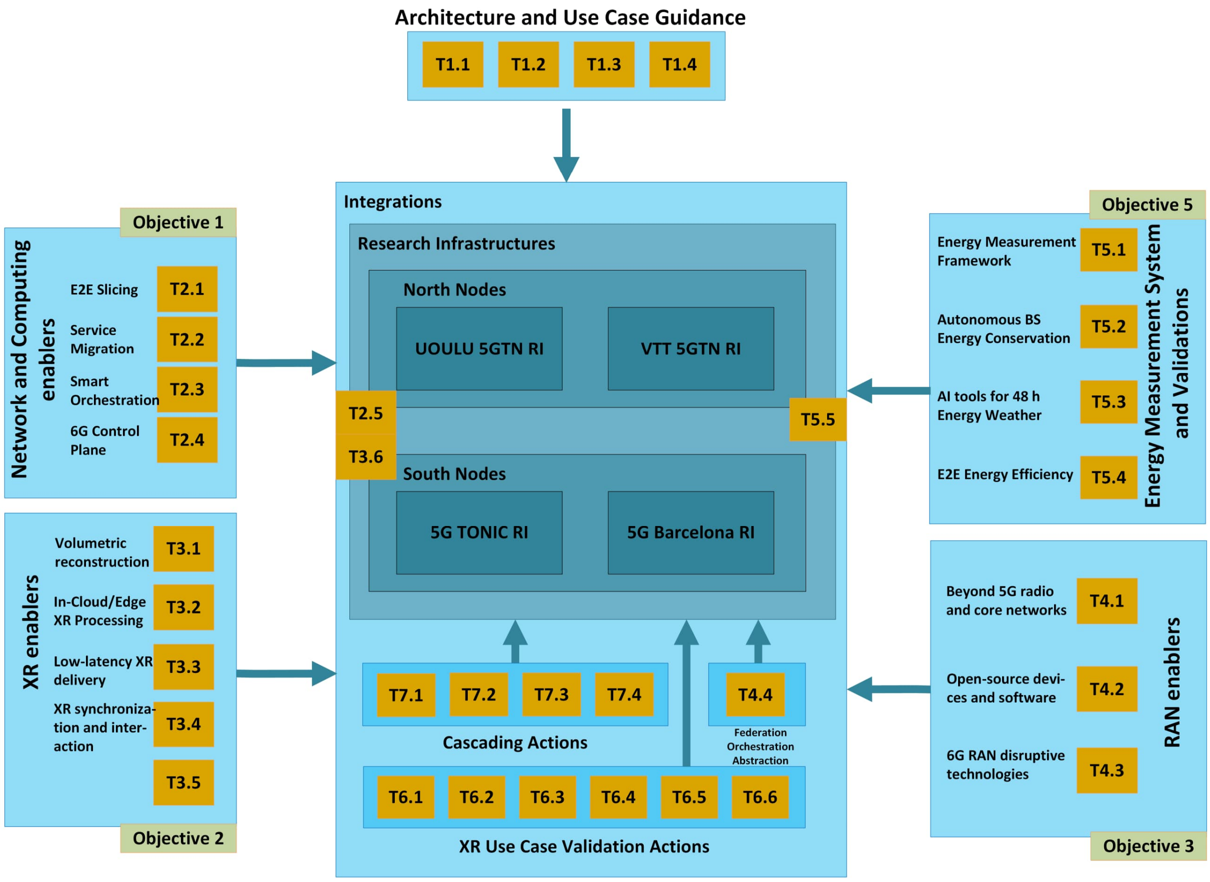

Figure 1. 6G-XR approach, objectives, and innovations.

A high-level overview of the 6G-XR approach is depicted in Figure 1. The project is building its solutions and experiments on top of four State-of-the-Art (SoTA) 5G Research Infrastructures (RIs), namely 5GTN UOULU, 5GTN VTT, 5TONIC, and 5GBarcelona (see APPENDIX 1 – 6G-XR Research Infrastructures (RIs) for more information). These RIs represent the most advanced open environments for communications research in Europe. The 6G-XR project will enhance the capabilities of these RIs to provide BSoTA capabilities towards 6G. It will:

- Develop a multisite RI with the capacity to serve as a validation platform for a wide range of anticipated (extreme) 6G use cases. This involves the development of networking and computing enablers, B5G radio access technologies, XR service enablers with built-in federation capabilities, trial management systems, abstraction tools, and an energy measurement framework.

- Validate Multi-access Edge Computing (MEC) scenarios and their integration into the cloud continuum, support innovative use cases with vertical actors, and support showcasing events.
- Demonstrate and validate the performance of innovative 6G applications with a focus on demanding immersive applications such as holographic communications, Digital Twins (DTs) and Extended Reality (XR) / Virtual Reality (VR).

Expected impacts of the 6G-XR project are as follows:

- Scientific impact: Produce high-quality knowledge on a 6G reference architecture natively supporting common verticals, on efficient mechanisms regarding orchestration (resource allocation, network function placement, etc.) of XR and other services, on cellular/Wi-Fi interworking, on E2E network slicing as well as on operational knowledge on 6G-capable radio, edge, MEC, and data-centric RIs deployment, interconnection and fine-tuning.
- Economic impact: Creation of new markets thanks to the introduced new technology enablers. Enlarge market shares of the European industry and Small and Medium-sized Enterprises (SMEs) thanks to the adoption of 6G-XR results. Lower networks' operational costs thanks to the energy preserving 6G-XR technologies. Users experiencing improved and more reliable services will be willing to pay more for better services. Foster innovation of European businesses through the validation in the experimental infrastructures, reduced time on adoption of new technologies for the products of both established industry and SMEs.
- Societal impact: A better interaction of final users with the 6G technology will cause a faster adoption and deployment of 6G services. Availability of more human-like interactions thanks to the XR-related enhancements will improve the perceived usefulness of 6G technologies. Reduced time to market on products coming out of tested verticals, both targeting individual (e.g., conferencing) or industry (e.g., DTs) customers.
- Environmental impact: Enhanced E2E energy efficiency and lower CO2 emissions during network runtime thanks to 6G-XR proposed technologies. Real-time monitoring of the E2E energy consumption, integration of local renewable energy sources, forecasting of renewable energy availability, and joint adaptation of the network and applications will enable fine tuning of the whole communication path with a common goal to achieve better overall energy efficiency for 6G networks and services.

The development of 6G-XR RIs is based on practical XR-driven use cases. The XR applications that will be used for validation of the deployed technology and service enablers in the project use cases are:

- Real-Time Holographic Communications: Key challenges are addressed to successfully deliver real-time multi-party holographic communication services at scale and over heterogeneous environments. 6G-XR will go beyond SoTA with the goal of increasing the visual resolution of holograms, as well as the performance, scalability, interoperability and efficiency of such services. The envisioned next-generation holographic services will adopt many new features fully compliant with 6G architectural and communication paradigms, and will be expected to contribute to the maturity, robustness, and wide adoption of high-quality, scalable, and affordable holographic communication services.

  - Related use cases: UC1, UC2 and UC3

- Collaborative 3D Digital Twin Environments: The scale of blending digital and physical in VR is still narrow, restricted to simple application areas, and the full potential of XR has not yet been achieved. There are, some SoTA systems that aim to extend the virtual across the XR spectrum, in addition to increasing the intermeshing of the digital and physical worlds. Collaborative 3D DT environments take advantage of existing 3D material for building a mirror world like VR and enhance this environment with remote operation capabilities for robotics and computer mediated collaboration, e.g., using private 5G and emerging B5G/6G devices and networks.
  - Related use case: UC4

- Energy measurement framework for energy sustainability: Investigate solutions for real-time energy consumption measurements in the network infrastructure, maximization of energy usage from local renewable sources, and optimization of energy consumption both at the Radio Access Network (RAN) and E2E.
  - Related use case: UC5.

The use cases UC1-UC5 are described in detail in Chapter 3 of this deliverable.

2.2 INITIAL 6G-XR REFERENCE ARCHITECTURE

Figure 2 provides an initial view into the main components of the 6G-XR reference architecture. The layered structure used to group different enablers and functionalities in the architecture is based on the initial 6G E2E system blueprint provided by the Hexa-X-II project [1].

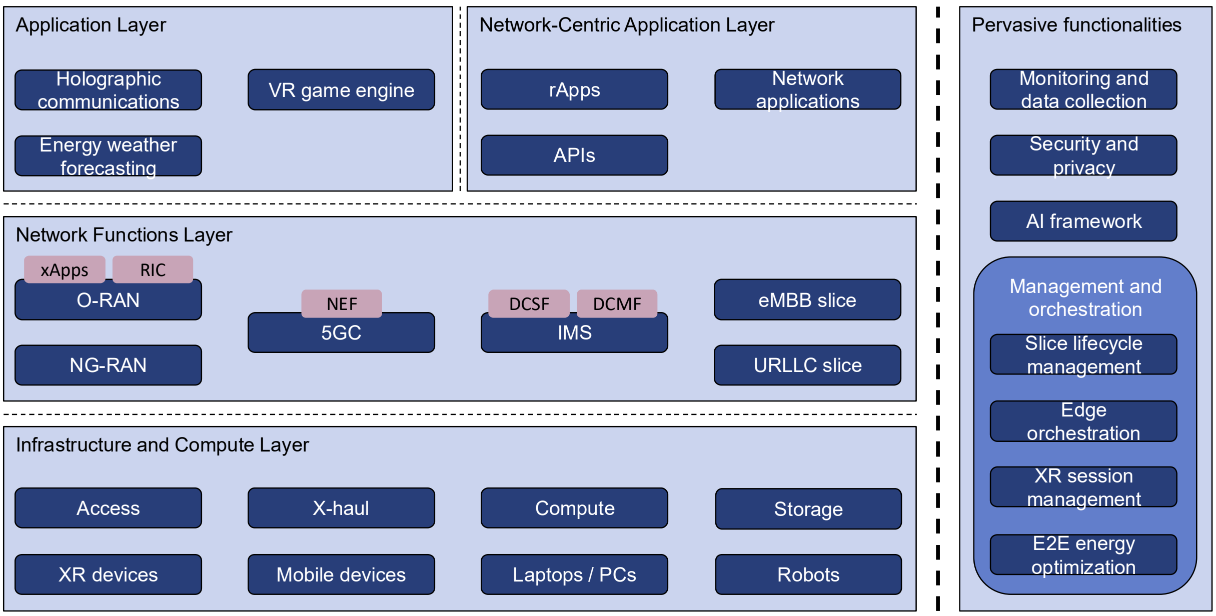

Figure 2. Initial draft of the 6G-XR reference architecture.

The 6G-XR reference architecture will contain the required XR and communication enablers to deploy the use cases introduced in Chapter 3 of this deliverable. The XR enablers developed during the project will mainly reside at the Application Layer (network-based functionality) and Infrastructure and Compute Layer (user applications) of the architecture. The communication enablers, which will be primarily software-based, will reside at the Network Functions Layer (tailored network functions and configurations) and Network-Centric Application Layer (enablers for user-centric network management). In addition, a variety of enablers designed and developed in the project will be placed into the Pervasive Functionalities domain where higher layer functionalities related to overall system optimization and orchestration reside.

The initial draft of the 6G-XR reference architecture provided in Figure 2 is only the starting point of the architecture design work in the project and is subject to change as the work progresses. Dedicated deliverables focusing on the details of the 6G-XR reference architecture (deliverable D1.2) as well as on the implementation details of that architecture on top of the 6G-XR RIs (deliverable D1.3) will provide the final design later in the project.

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3 6G-XR USE CASES, REQUIREMENTS, AND BUSINESS MODELS

3.1 XR IN B5G/6G STANDARDIZATION

B5G and 6G will enrich the capabilities of mobile communications. The upcoming 3GPP standards (from Rel-18 onwards as the 1st 5G-Advanced (5G-A) release is due in 2024, according to the latest 3GPP roadmap[1] depicted in Figure 3) will include new opportunities for immersive XR experiences. It will enable digital-to-physical fusion and energy efficiency optimizations, which is expected to provide an important contribution to the sustainability of future communication networks.

Figure 3. 3GPP standardization roadmap for Releases 18-22.

Extended reality, and media services particularly, require high data rates with strictly bounded latency constraints, typically in the order of 30-100 Mbps at the application layer, with packet delay budgets of 5-15 ms, and with a high packet delivery success rate of 99-99.99%. To achieve a high level of support for XR in B5G and 6G, it is necessary to provide the right Quality of Service (QoS) for the different elements of XR data flows in a way that the network capacity is used efficiently.

Some XR recommendations from the upcoming 3GPP releases [2] include:

- XR application-awareness in RAN and core to better optimize, e.g., Radio Resource Management (RRM) and scheduling decisions.
- Optimized capacity for XR communications in the uplink and sidelink, more flexible utilization of available frequency bands.
- Power optimization for XR devices with adaptive Discontinuous Reception (DRX) to extend device battery-life and reduce network power consumption.

3.2 EXAMPLE XR USE CASES, REQUIREMENTS AND BUSINESS MODELS

XR is seen as one of the driving applications for the further development of 5G as well as for 6G when it comes to ubiquity and scale of XR service deployments for every-day use cases [3]. Consequently, it has also been one of the main use case categories in the Horizon 2020 and Horizon Europe B5G/6G flagship projects Hexa-X [4] and Hexa-X-II [5]. These projects have provided common visions for the development of the B5G and 6G technologies in the 5G-PPP and SNS JU programmes during the past

[1] The 3GPP's system of parallel releases: https://www.3gpp.org/specifications-technologies/releases

years. Therefore, Hexa-X and Hexa-X-II use cases provide an excellent reference point also for 6G-XR to look into the potential future needs of experimental research for XR services over 6G networks. Among the set of six Hexa-X and Hexa-X-II use case categories, telepresence, and more specifically fully merged cyber-physical systems, have been identified as the main areas for further studies.

Moreover, XR has been identified as a key enabling technology for the digital transformation of different vertical domains. For example, University of Oulu's 6G Flagship has defined healthcare as one of the vertical sectors gaining from extensive utilization of XR technologies, in a vision paper for verticals' validation and trials towards 2030 [6]. Another area where XR is seen to have major impact soon is entertainment and online gaming. For example, 3GPP has defined service requirements for VR / Augmented Reality (AR) -based gaming services in [7].

During the past few years, the discussion around XR and its potential future use cases have been dominated by metaverse. Metaverse expands the concept of a XR/VR environment into a network of persistent XR/VR environments with assets, which are synchronized between each other and with the physical world. Compared to the XR use cases listed above, metaverse as a use case introduces additional requirements related to the scalability of the technologies utilized to build it.

The telecom industry has identified a series of use cases and business models for the large-scale deployment of metaverse(s). On a high-level, the use cases can be classified in a few categories depending on the intended user base [8]:

- Industrial metaverse
- Enterprise metaverse
- Consumer metaverse

These high-level categories can be further divided into a variety of specific use cases as in [8] and [9], which have their specific set of key enabling technologies and performance requirements that must be taken into consideration when deploying the use case services. The initial requirements for different use case types have been studied also by 3GPP, and the work will continue as part of Release 19, which is expected to be finalized by the end of 2024 [10].

Table 1 provides some examples of the XR and metaverse use cases discussed above together with related high-level requirements. For the assessment of high-level requirements, a simple classification based on [6], [10], [11] and [12] has been used to group the KPI requirements in Table 1 as follows:

- Data rate: ultra-high (> 20 Gbps), high (1 - 20 Gbps), medium (100 Mbps - 1 Gbps)
- Latency: ultra-low (< 1 ms), low (1 - 10 ms), medium (10 - 100 ms)
- Reliability: ultra-high (> 99.999 %), high (99.9 - 99.999 %), medium (99 - 99.9 %)

Table 1: Examples of XR and metaverse use cases and requirements

	Use cases	Key enabling technologies	KPIs	Scalability
XR	• eHealth	• VR/AR • Haptic communications	• High data rate • Ultra-low latency • Ultra-high reliability	Few simultaneous users
	• Fully merged cyber-physical worlds	• VR/AR • Holographic communications	• Ultra-high data rate • Low latency • High reliability	Tens of simultaneous users
	• Online gaming	• VR/AR • High Performance Computing (HPC)	• High data rate • Medium latency • Medium reliability	Tens to hundreds of simultaneous users
Industrial metaverse	• Remote control • Remote maintenance • Mixed reality workflows • Process simulations	• VR/AR • Haptic communications	• High data rate • Ultra-low latency • Ultra-high reliability	Few simultaneous users
Enterprise metaverse	• Immersive collaboration • Virtual/remote training and group events	• VR/AR • Holographic communications	• Ultra-high data rate • Low latency • High reliability	Tens of simultaneous collaborative users
Consumer metaverse	• Immersive entertainment • Virtual/remote mass events and tourism • Public/shared virtual spaces • E-commerce • E-learning • Telemedicine	• VR/AR • HPC	• High data rate • Low latency • Medium reliability	Tens to hundreds (even thousands) of simultaneous users

Sustainability has become an overarching requirement when the number of users is scaled up. 6G networks must be able to provide everything listed above, i.e., ultra-high data rates, ultra-low latencies, and ultra-high reliability in an energy and resource efficient way. This will make the balancing of the other conflicting KPIs more difficult as minimization of the energy usage will be a critical requirement in all XR and metaverse services offered on a large scale.

The business models related to the examples listed in Table 1 can be divided into Business to Business (B2B) transactions in the eHealth, industrial and enterprise metaverse use cases, and Business to

Consumer (B2C) transactions in the online gaming and consumer metaverse use cases. The fully merged cyber-physical worlds use case can be either B2B or B2C, depending on the specific usage scenario. In the B2B domain, the more traditional business models are still valid as the services related to the use cases are usually bought for the personnel as a whole and not for individual persons. From the more dynamic business models, paid service extensions and tailored subscriptions could play a role in the B2B use cases. However, in the B2C domain, a variety of additional dynamic business models, also including the end user as a provider of services, can range from in-app purchases to community marketplaces. In the future, these different models can become an integral part of the XR and metaverse related business ecosystems in a more flexible way. This potential integration, however, brings about additional requirements for ensuring the security, validity, and traceability of transactions among the diverse stakeholders involved.

3.3 NETWORK SLICING FOR XR

To fully leverage the capabilities of XR, a robust and optimized network infrastructure is paramount. This is where network slicing plays a crucial role. Network slicing enables the virtual partitioning of E2E network resources to create isolated, customizable, and dedicated network instances tailored to specific XR requirements [13], [14]. By allocating and managing network resources dynamically, E2E network slicing ensures optimal performance, reliability, and user experience for XR applications as part of the next generation of 6G mobile systems, namely, 6G-XR.

The relevance of E2E network slicing in 6G-XR lies in the demand for low-latency and high-data-rate connections. 6G-XR applications often require real-time responsiveness and seamless interaction with virtual environments. Network slicing allows for creating dedicated virtual network slice instances, such as enhanced mobile broadband (eMBB) as well as ultra-reliable and low latency communications (URLLC), providing smooth and immersive XR experiences. This is particularly important for XR applications requiring real-time responsiveness such as remote telepresence, remote surgeries, virtual meetings, and real-time collaboration, where any delay or disruption can hinder user engagement and productivity.

Moreover, E2E network slicing enables efficient resource allocation across different network resources. XR applications rely on diverse resources, often involving the core network, edge computing, RAN, cloud services, and network connectivity. By optimizing these resources through network slicing, operators and research infrastructure owners (e.g., 5GTN, i2CAT, and 5TONIC) can ensure efficient utilization of network capacity, reduce congestion, and improve overall network performance for 6G-XR applications. This becomes particularly significant in scenarios involving concurrent execution of multiple 6G-XR applications, each with distinct connectivity demands. Thereby, E2E network slicing facilitates the creation of tailored slices, optimized for each use-case scenario in 6G-XR, such as 3D digital twin and holographic communications.

In the domain of E2E network slicing in 6G-XR, artificial intelligence (AI) also assumes a pivotal role in resource optimization. It is imperative to develop transversal AI / Machine Learning (ML) decision mechanisms that target network optimizations, such as fault tolerance and energy consumption minimization, by leveraging the capabilities of slicing. Since 6G-XR operates in network slices, all optimizations must consider their impact on each slicing. AI in 6G-XR is also expected to utilize both supervised and distributed deep reinforcement learning AI/ML algorithms to optimize resource allocation within the slicing techniques. The focus lies in optimizing virtual network slicing to efficiently utilize E2E resources from the core network, RAN, edge computing, network capacity, performance parameters, and energy consumption within the 5G network, according to the use-case scenario.

Accordingly, E2E network slicing is highly relevant to the 6G-XR project as it enables the creation of dedicated network instances tailored to the specific requirements of 6G-XR use-case scenarios. The combination of network slicing and AI optimization techniques can further enhance the performance, reliability, and resource efficiency of XR experiences. As XR continues to evolve and become more widespread, the role of E2E network slicing in providing seamless, low-latency and high-data-rate connections will become increasingly crucial for unlocking the full potential of 6G-XR use-case scenarios in various domains, where the network infrastructure resources also play an essential role.

3.3.1 5G Recursive Model

The 5G architecture is based on the requirement of recursive structure. One of the requirements in 5G is to be able to create slices where E2E 5G network functionality can be split into multiple separate independent instances. Each of these instances will then offer 5G network capabilities for certain customers or functionalities. Then, it leads to a requirement of recursive structure in the architecture. In the recursive structure the architecture can support several instantiated services of the same Software (SW) block and by that be able to support larger or more complex tasks. In other words, one 5G network can support several slices at the same time in one network. The 5G recursive model architecture is presented in Figure 4.

In the context of 6G-XR use cases, it is required for the network to satisfy the requirements of high throughput and low latency and therefore, two types of slices (eMBB and uRLLC) will be created during the project implementation phase. Considering that, the E2E network slicing is an important part of the 6G-XR architecture, where it ensures the coexistence of the heterogeneous service types with the required QoS for every user.

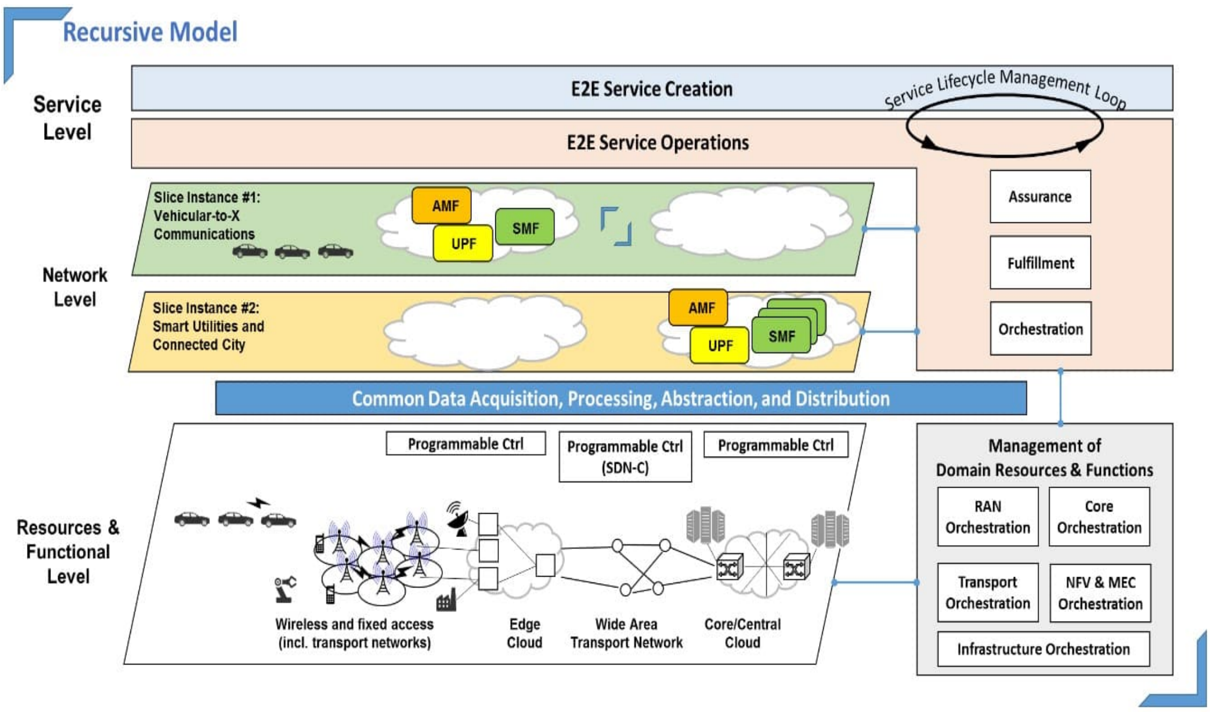

Figure 4. Overall 5G recursive model architecture [15].

Slicing is to be used in both Holographic communications and 3D DT use cases as it is an integral part of the technical tasks and objectives that have been set in 6G-XR. The way the slicing is used in the use cases is elaborated in Chapters 3 and 4 of this deliverable. Requirements that apply for specific slices are presented in the tables below.

Table 2: Slicing user requirements

No.	User Requirement
1	Creation of one E2E network slice of defined type (URLLC or eMBB) must be possible.
2	Creating a second E2E network slice must be enabled. Existence of two simultaneous slices in one 5G network must be enabled. The two slices can be either different slice types or both can be the same type.
3	Re-configuring the active network slice needs to be possible.
4	Deletion of the active slice is to be possible. Each slice is to be deleted separately.
5	Migration of an application / Service from one Edge PoP to another Edge PoP in a different Slice needs to be enabled.

Table 3: Slicing KPIs

No.	Category	Reference point	Performance
1	Slice availability	Number of active E2E slices in each network	2 separate slices
2	Slice instantiation time (same for 1st and 2nd slice)	Max time from sending the start slice command until slice is active	Maximum of 2 min
3	Slice re-configuration time	Max time from sending the re-configuration command until the slice is reconfigured and in active state	30 seconds
4	Slice deletion time	Max time from sending the slice delete command until the slice is removed from the network	20 seconds
5	Slice properties URLLC slice	Max throughput downlink	50 Mbps
		Max throughput uplink	2 Mbps
		Max latency downlink (From Edge server to User Equipment (UE))	8 ms
		Max latency uplink (From UE to Edge server)	10 ms
6	Slice properties eMBB slice	Max throughput downlink	200 Mbps
		Max throughput uplink	10 Mbps
		Max downlink latency (From Edge server to UE)	10 ms
		Max uplink latency (From UE to edge server)	12 ms

7	Application migration	Other KPIs to be considered will be defined in a later phase of the project	The determination of the performance values will be given in a later phase of the project, as these values are subject to governance by both the application and network parameters.

This section, "Network Slicing Requirements," provides a comprehensive overview of the concept and integration advantages of network slicing in the context of 6G-XR. Building upon this foundation, the subsequent subsection outlines the specific use-case scenarios and requirements within the 6G-XR domain. This includes an exploration of network slicing requirements tailored for real-time holographic communications and 3D digital twin services, as key use-case scenarios in the 6G-XR.

3.4 USE CASES AND REQUIREMENTS

The following describes the details of 6G-XR use cases and their respective requirements.

3.4.1 Real-Time Holographic Communications (UC1, UC2, UC3)

3.4.1.1 Use Case Descriptions

Three are three use cases for real-time holographic communications in the South Node. Holographic communications are approached from both AR and VR perspectives, with address different challenges and dimensions:

- User plane optimizations (UC1 and UC2): Addressing hologram processing powered by Edge and enhancements with network QoS and XR enablers.
- Control plane optimizations (UC3): Relying on the control plane evolved from IP Multimedia Subsystem (IMS) to maximize scale and robustness and integrating holographic communications smoothly onto the phone dialler as an evolution of communication services in 6G.

A combination of best-of-breed partner technologies are utilized in two main applications:

- I2CAT holographic communications, together with Ericsson and Capgemini on 5GBarcelona (located at i2CAT premises in Barcelona) and 5Tonic sites (located in Madrid), focusing on XR and User Plane optimizations.
- MATSUKO holographic communications, together with Ericsson and Telefonica on 5Tonic, focusing on XR and Control plane optimizations.

I2CAT Platform (HoloMIT) High-level Description: VR Scenarios, Capture with RGB-D and Light Field Sensors

HoloMIT[2] can provide real-time multiuser holographic communications with realistic and volumetric user (self and others') representations using off-the-shelf XR capture and rendering hardware in XR scenarios, with a key focus on VR. HoloMIT has been assessed and validated in different scenarios, for a set of relevant use cases (see Figure 5), such as collaborative viewing [16], interactive virtual events [17] and virtual meetings [18], obtaining satisfactory and promising results. However, SoTA holographic communication (and Metaverse) technologies and platforms still encounter challenges in terms of:

- Performance (e.g., delays, framerate per second (fps), resolution)
- Resources consumption (e.g., processing, bandwidth)
- Adaptability, interoperability, and scalability

6G-XR will provide relevant XR technologies, computing continuum, and network enablers to effectively overcome such challenges, and to validate their benefits when integrated with HoloMIT.

Figure 5. Examples of holographic communication scenarios using HoloMIT.

HoloMIT Deployment Architecture

HoloMIT is structured into client-based (e.g., multi-sensor capture sub-systems, encoding/decoding, presentation, interaction features) and cloud-based (e.g., Session and Media Managers, etc.) components and modules, which are deployed in traditional client-server architectures, either with usage of Selective Forwarding Units (SFU) or of Multipoint Control Units (MCU) [17], [18], [19], as shown in Figure 6 and Figure 7. Different modular XR enablers can be efficiently orchestrated and

[2] HoloMIT, the 3D holoconferencing solution for a sustainable future: https://i2cat.net/holomit-the-3d-holoconferencing-solution-for-a-sustainable-future/

deployed over the cloud continuum and can be dynamically adapted based on the available resources and/or preferences.

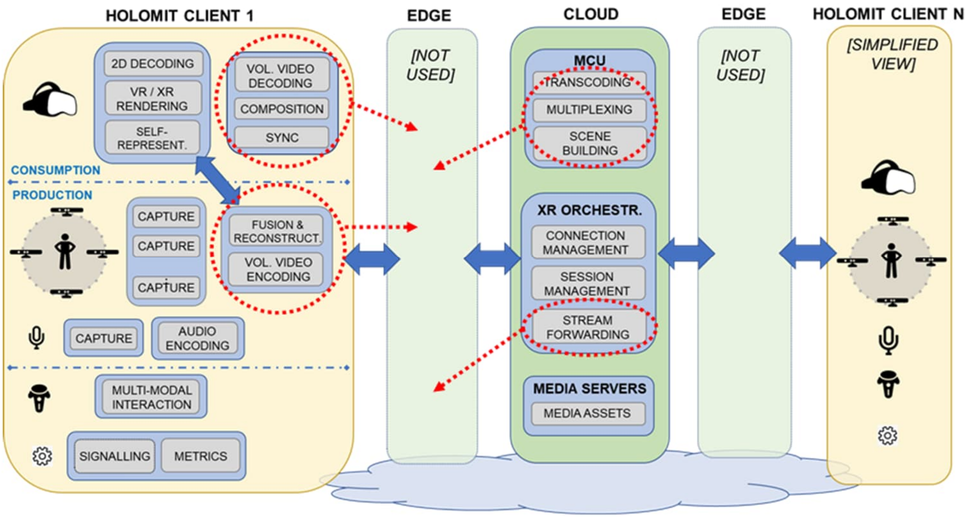

Figure 6. High-level client-server architecture of current HoloMIT implementation (media/network functions that could be deployed on Edge are highlighted with red boxes and arrows).

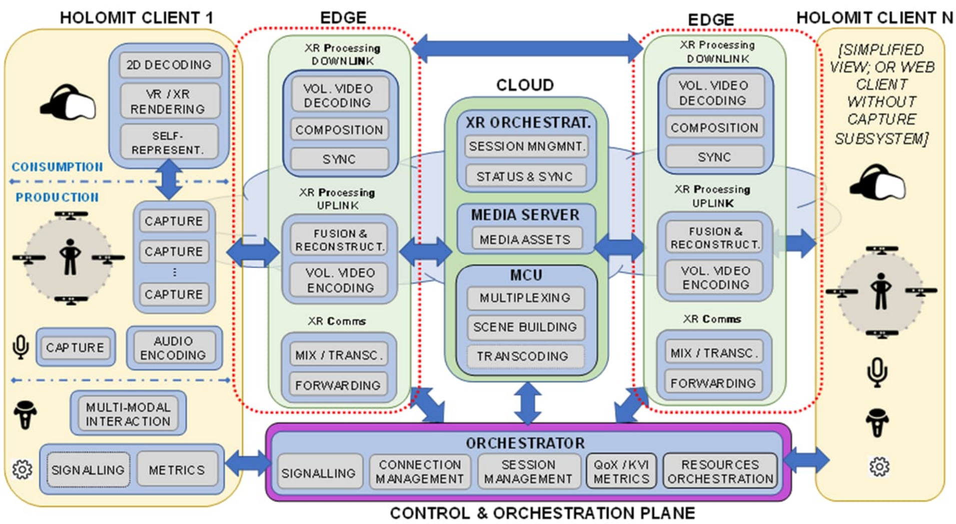

Figure 7. HoloMIT includes modular components deployed over the cloud continuum (clients, Edge, cloud) all tailored to suit the requirements of 6G-XR use cases.

User Plane Optimizations

The user plane optimizations comprise two main use cases:

- Resolution Adaptation or Quality on Demand (QoD) depending on network conditions (UC1)
- Routing to the best Edge (UC2).

For the implementation of these use cases, CAMARA[3] Application Programming Interfaces (APIs) have been chosen. The baseline setup of the user plane optimization approach is shown in Figure 8. This setup assumes the use of i2CAT holographic application (HoloMIT).

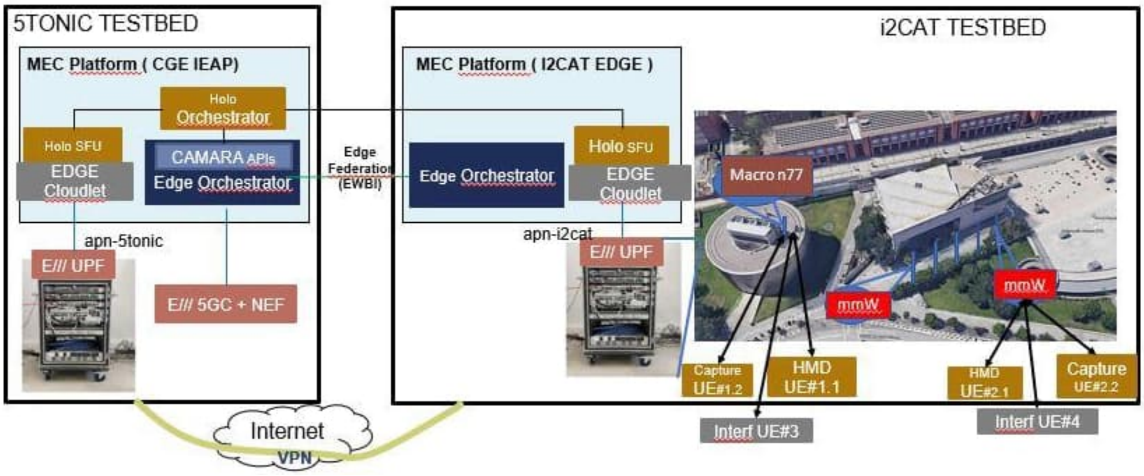

Figure 8. User plane optimization use case setup.

UC1: Resolution Adaptation or Quality on Demand (QoD)

The network detects congestion in a cell where the XR (UE) device is connected. Upon congestion detection one of two actions is taken:

1. Decrease resolution of XR media from UEs.
2. Invoke CAMARA QoD APIs to prioritize XR flow(s).

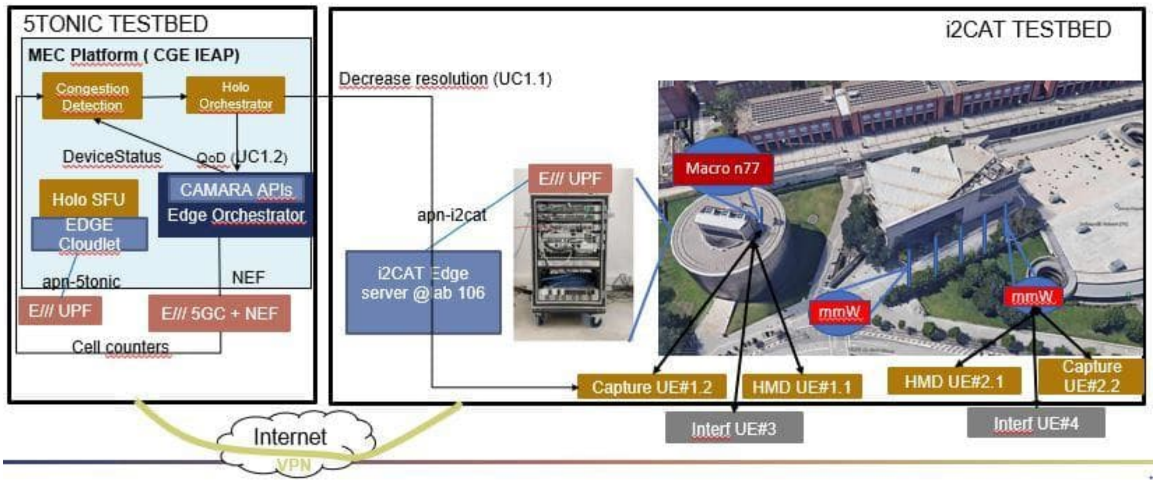

Figure 9. UC1: Resolution adaptation or QoD.

[3] CAMARA is an open-source project within the Linux Foundation to simplify telco complexity making user friendly APIs, thus accelerating technology and commercial development. Website: https://camaraproject.org/

Co-funded by the European Union

UC2: Routing to the Best Edge

The holographic communications application can make use of different Edge nodes for XR processing offloading or for managing the multi-user communications, e.g., cloudlet selection within different edge orchestrators (one Edge server at 5TONIC facilities in Madrid and another Edge server at i2CAT facilities in Barcelona); or cloudlet selection within the same Edge Orchestrator domain (Madrid or Barcelona). The idea is to enable the service to select and make use of the most appropriate Edge based on specific goals, like minimizing delays by selecting the closer Edge by deploying a Selective Forwarding Unit (SFU) component to route the user plane traffic.

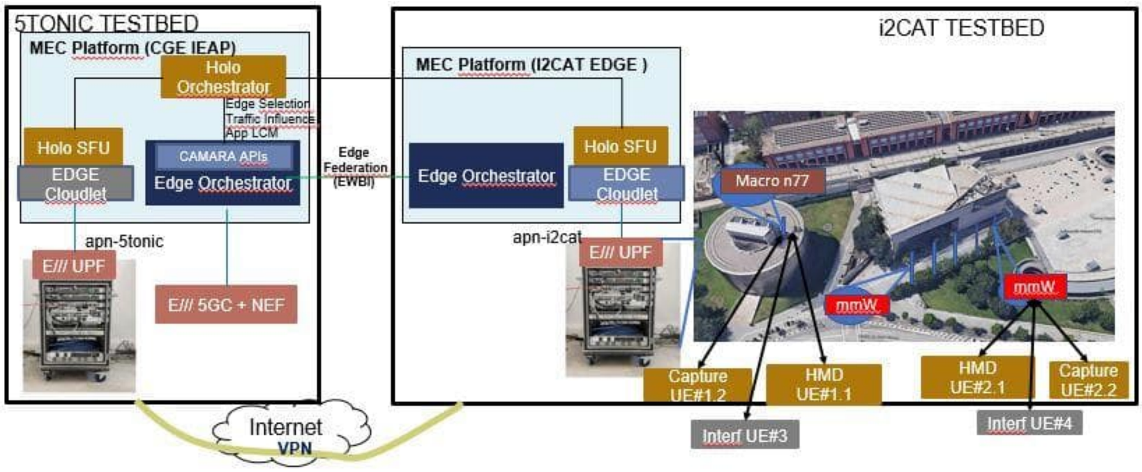

Figure 10. UC2: Routing to best Edge.

Slicing for User Plane Optimizations

For the Real-Time Holographic Communications use case, optional slicing can be validated as an additional scenario of the UC1 on congestion avoidance. In this scenario, UEs will be requested to adjust media data rate to handle detected congestion situations, potentially originated by interfering data sources.

An alternative approach to address the aforementioned scenario involves leveraging slicing technology to isolate traffic from different stakeholders. By employing slicing techniques (e.g., radio and network slicing), our ability to enhance the uphold Service Level Agreements (SLAs) and maintain Quality of Service (QoS) levels for the holographic communication service is enhanced. This isolation, achieved through slicing, ensures the fulfilment of SLAs and QoS requirements without necessitating adjustments to the data rates of UEs, thereby preserving the quality of the service, regardless of the intensity of interfering data sources.

Additionally, the E2E slicing in UC2 could be tested by creating a slice that allows to reach the application function on the appropriate edge platform and selects the closest User Plane Function (UPF) to that edge platform, or dynamically modifying the slice to reach the application function if the application is migrated from the edge platform and adapting the used UPF accordingly as well.

UC3: Control plane optimizations

Based on MATSUKO holographic solution, the re-design of the holographic session manager relying on the network control plane (IMS and evolutions towards 6G) has two main objectives:

1. User perspective: integrating holographic communications smoothly into the dialler app as an evolved communication service in 6G beyond voice (Voilce over Long Term Evolution (VoLTE) and Voice over New Radio (VoNR)).

2. Technical perspective: looking for maximizing the robustness and scale of the solution by relying on the network for session management aspects. Performance and functional improvements (QoS, roaming, interconnection, and other benefits that IMS brings).

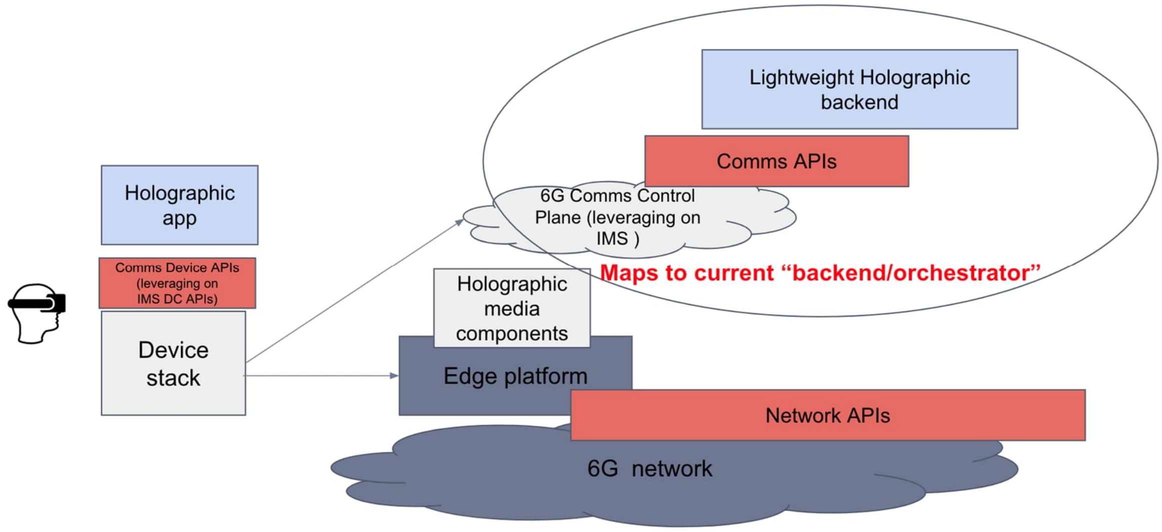

Figure 11. Holographic Edge-IMS communications deployment diagram.

MATSUKO Application High Level Description: AR scenarios, Capture with Smartphones

MATSUKO provides the software-only solution for telepresence - capturing and streaming realistic human holograms in real time. MATSUKO is the creator of the holographic communication system that fills in the missing element in video conferences – human presence. Real people are modelled into three dimensions by algorithms and, at the same time, transferred into real space, in real-time. Using just a simple phone or a computer camera two people can communicate as if they were looking at one another in 3D.

MATSUKO is a standalone app for people to have conversations and meetings with other people, that uses 3D holograms instead of Two Dimensional (2D) video or virtual avatars to represent participants. The MATSUKO App is published on a variety of devices and distributed across the world in app stores. In its simplest form, each participant only requires a smartphone. Other high-end holographic solutions require complex hardware setups and are beyond the technical and financial means of the average customers.

MATSUKO will explore the integration of enablers into the Mobile Network Operator (MNO) standard architecture. The holographic communications services will be connected and integrated with the IMS Data Channel (DC) and 6G XR-Ready Control Plane. This will involve moving media user plane components to the Edge and integrating the identity and session management control functions with the 6G Comms Control Plane APIs (both at device and network side). Establishing an analogy to 5G, it will be a similar concept to IMS DC device-side APIs and Communications Platform as a Service (CPaaS) network APIs on the network-side.

MATSUKO architecture will be adapted to meet 6G-XR requirements in the following ways:

- Integration of IMS Data Channel on both server and client sides
- Adaptation of the MATSUKO signalling service for IMS signalling
- Implementation of the Notification Service to inform Holographic Sender about a new call

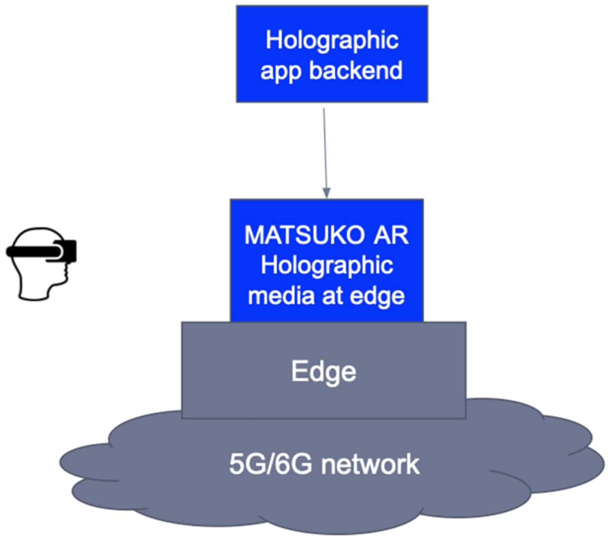

Figure 12. MATSUKO high level vision of network architecture in 6G-XR.

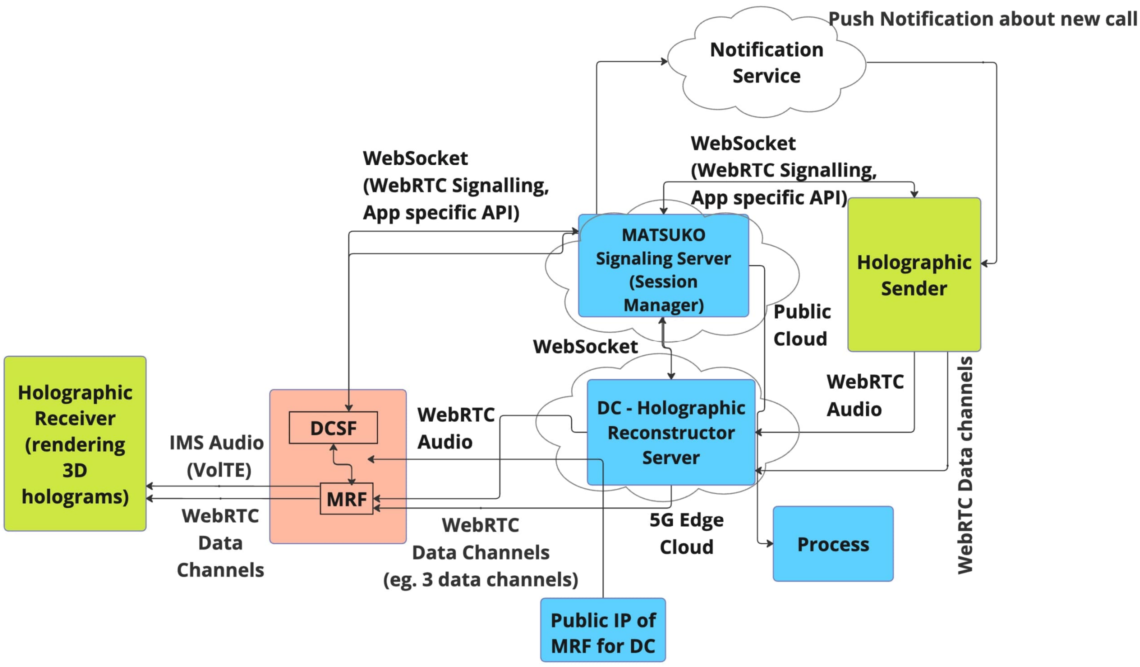

Figure 13. MATSUKO IMS Data channel architecture design.

IMS Data Channel (IMSDC)

The industry vision for Data Channel (DC) in IMS focuses on enhancing interactions and interactivity with information entities beyond the internet or service provider networks. The IMS data channel, as defined in 3GPP TS 26.114 [20], enables the integration of internet and IMS connectivity, providing action-oriented and multi-modal communications.

The IMS data channel brings economic value through the enablement of new innovative services and the optimization of existing business processes. Communication service providers can offer new services, such as screen sharing, which can be monetized through user charges. Additionally, these services improve operational aspects and increase consumer satisfaction, leading to revenue generation, loyalty, churn decrease, and acquisition.

The DC technology used in IMS is based on the WebRTC data channel protocol stack, which allows the flexible transmission of various types of information between User Equipment (UE) and the network.

It leverages dynamically downloaded web pages and JavaScript code to govern the formatting, packing, unpacking, interpretation, and user interaction involved in the data channel. This approach eliminates the need for standardized formats and explicit support in the EU, enabling a wide range of information sharing use cases without further standardization or implementation.

The IMSDC brings significant benefits to voice calls and real-time communications. By leveraging existing investments and functionality, it enables the rapid deployment of new services without the need for individual service standardization.

It establishes real-time communication paths between endpoints, allowing the exchange of any form of data information alongside voice and video or outside a voice session. The format of the information carried across the data channel is transparent to the network, as long as it can be understood by the endpoints involved.

The IMS data channel ecosystem is poised for success by leveraging existing WebRTC standardization, facilitating the adoption of this technology by operators and developers. The data channel functions in 5G are placed in a new IMS logical entity, called the Data Channel Server (DCS).

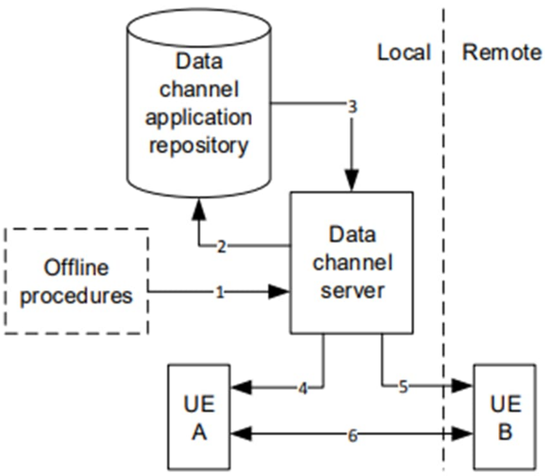

Figure 14. DCS architecture [20].

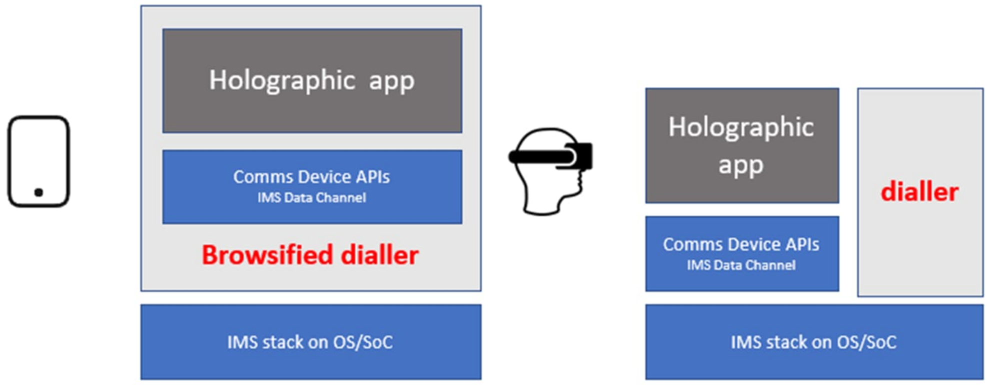

Figure 15. Dialler centric non standalone apps VS standalone apps not associated to a dialler.

The distinctions between applications integrated into the phone's dialler and standalone applications are notable. Applications within the dialler primarily serve telephony-related functions, encompassing call management and contact administration. These embedded apps offer streamlined, uniform user interfaces designed for simplicity and efficiency. Conversely, standalone applications are versatile, capable of addressing an extensive range of needs, from social networking to productivity tools. They provide diverse and customizable user interfaces, offering rich and varied user experiences.

In recent years, all this information has been collected in the standard generated in 3GPP Release 18[4]. This Release will deliver 5G-A, as the mid-point of 5G standardization and augmented reality capabilities is one of the points being discussed in new updates.

IMSDC Call Flow Example

The use case that is going to be tested will be the one in which the caller user generates the hologram with a device. The receiver user will execute web applications (JavaScript, CSS, HTML) downloaded from the IMS network to guarantee the reception of the call. This procedure will be carried out through an application supported by the phone's dialler.

Holographic call in browser-capable dialler – Presentation experience (one way) example is presented in Figure 16:

- Alice initiates a presentation within the Holographic call service by using a room ID or a predefined link. She accesses this service through a native application on her smartphone to begin her presentation.

- Bob initiates a call to the IMSDC-based Holographic service. Then, he downloads the IMS DC App from DCS and an HTML/JS form for room selection is presented to him. Bob enters the ID associated with Alice's presentation as the room number. Upon selection, the IMS-XR Gateway establishes a data channel to Bob and provides a WebRTC stream to project Alice's holographic presentation. The choice of the end-to-end audio path, whether it's VoLTE/VoNR or WebRTC, is yet to be determined for this communication. Optionally, Bob can enhance the experience by connecting his smart glasses, creating an immersive environment. Multiple calls could be established simultaneously to see Alice hologram.

[4] 3GPP Release 18: https://www.3gpp.org/specifications-technologies/releases/release-18

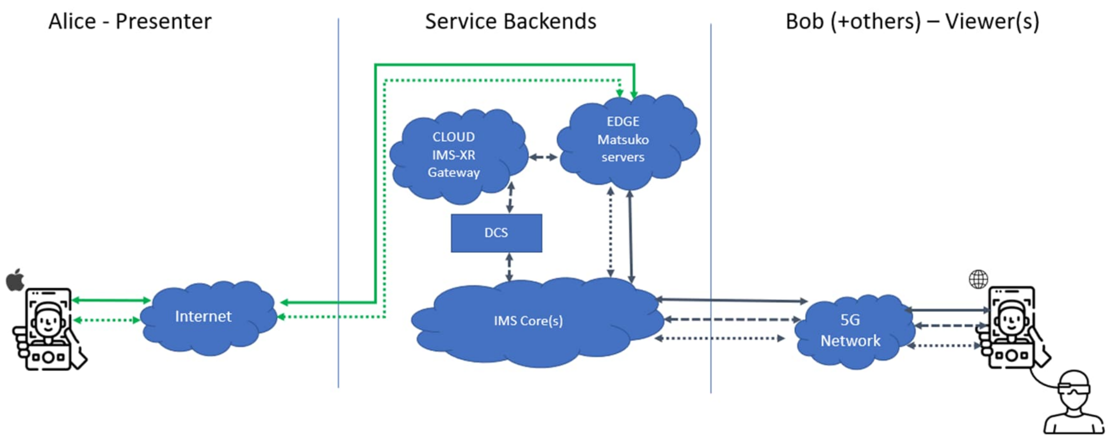

Figure 16. Presentation experience (one way) high level flow.

3.4.1.2 Use Case Requirements

The following tables list the general high-level requirements from use cases UC1, UC2 and UC3.

Table 4: User plane optimizations use case 1 (UC1) requirements

No.	Description
UC1.R1	HoloMIT app able to adjust resolution of hologram.
UC1.R2	An in-cloud module needs to be developed to detect and react to congestion in the network. That would imply that the network needs to be able to expose congestion related counters (RAN or core) to the service.
UC1.R3	Specific media streams would need to be identified and prioritized, in terms of 5-tuple – visible by the application (after Network Address Translation (NAT)).
UC1.R4	Two slices are prepared: One for Holographic Communication service and another one for other services (in this case the interferer service) both in the same network.

Table 5: User plane optimizations use case 2 (UC2) requirements

No.	Description
UC2.R1	Edge onboarding capabilities, which involves being able to deploy a virtualized media function (container-based) on the Edge – renders on behalf of the user. Provide media Virtual Network Function (VNF) access to GPU.
UC2.R2	Edge discovery, which involves that the network provides a subset of Edge locations where service (is/can be made) available.
UC2.R3	Traffic Influence allows UPF (breakout) reconfiguration. UPF selection is decided by the network, but triggered by the service.
UC2.R4	Load mobility: If the service metrics degrade, then an Edge Discovery process is triggered, and a new Edge can be selected. App is re- instantiated with status migration.

Table 6: Control plane optimizations use case requirements

No.	Description
UC3.R1	The holographic service needs to be integrated on the dialler.
UC3.R2	User shall be able to call to another user directly.
UC3.R3	User shall be able to call a room and join an already established manual room selection.
UC3.R4	User shall be able to call a session established in presentation mode.
UC3.R5	The holographic service needs to be integrated with VoNR and IMS.
UC3.R6	The service Ids shall be mapped with IMS Ids.
UC3.R7	Different IMS systems and external Holo users shall be interconnected (room with IMS users and external MATSUKO users).
UC3.R8	The network shall provide E2E QoS across different MNOs through IMS.

Functional and Non-Functional Requirements

A set of functional and non-functional requirements from each of the XR enablers, from media capture to media consumption, that make up the E2E holoportation technology are provided in the tables below.

Table 7: Functional requirements for UC1, UC2 and UC3

No.	Description
UC1-3.FR1	The XR capture modules shall support configurations with a single sensor and with multiple sensors (>=3) for full 3D human body reconstruction.
UC1-3.FR2	The volumetric video capture system shall be able to integrate multiple plenoptic light field sensors.
UC1-3.FR3	The volumetric media processing functions for the capture subsystems (fusion, reconstruction, encoding) shall be integrated, deployed and run locally on the client side.
UC1-3.FR4	The volumetric media processing functions for the capture subsystems (fusion, reconstruction, encoding) shall be integrated, deployed and run on the Edge.
UC1-3.FR5	Streams obtained from volumetric video capture must be precisely aligned, with a synchronization granularity of at least frame level.
UC1-3.FR6	The 6G-XR platform shall support the integration of Edge-assisted Volumetric Video (VV) processing elements, performing at least multiplexing and transcoding features, as typically Multipoint Control Unit (MCU) do.
UC1-3.FR7	The Volumetric Video Multipoint Control Unit (VV-MCU) shall support the processing of multiple incoming VV streams, from at least RGB-D sensors.
UC1-3.FR8	The Volumetric Video Multipoint Control Unit (VV-MCU) shall support the advances VV processing features, like viewport-aware processing, Level of Detail (LoD) adjustment, and caching.
UC1-3.FR9	To obtain the volumetric video, the media processing functions shall be executed with a latency <=100ms.
UC1-3.FR10	The Edge Renderer will adapt the Point Cloud / RGB-D projection depending on the viewpoint.
UC1-3.FR11	The 6G-XR platform shall support the dynamic instantiation and deployment of Selective Forwarding Units (SFU) along the Cloud Continuum for given media sessions.

UC1-3.FR12	The 6G-XR platform shall support the selection of one or multiple SFUs deployed on one or multiple Edges for a given media session.
UC1-3.FR13	The holographic comm platform shall support either a deployment with SFU and/or with in-cloud VV Processing components (e.g., MCU, Remote Rendering).
UC1-3.FR14	The XR streaming protocol should support both one-to-one and one-to-may delivery.
UC1-3.FR15	The XR delivery should consider both low-latency (WebRTC) and scalable (DASH) protocols.
UC1-3.FR16	Media resolution and encoding bitrate should be adapted through the monitored metrics.
UC1-3.FR17	Media encoding/decoding exploits NVIDIA GPU capabilities.
UC1-3.FR18	The native and full-fledged version of the 6G-XR holographic comms client (i2CAT) shall run on Personal Computers (PCs) / laptops and on VR headsets connected to PC via cable, supporting at least Oculus Rift and Oculus Quest.
UC1-3.FR19	A lightweight version of the 6G-XR holographic comms client shall be implemented using web-based components to be run on web browsers.
UC1-3.FR20	Accurate synchronization between cloud processing/streaming and client.
UC1-3.FR21	6G-XR holographic comms client based on web components should provide audio input and interaction capture (6DoF).
UC1-3.FR22	The XR Holo Orchestrator / Session Manager shall be able to provide authentication for user access and session management features to participate in the offered services.
UC1-3.FR23	The XR Holo Orchestrator shall interoperate with an Edge Orchestrator to request the dynamic instantiation/deinstatiation of virtualized networked media functions on the edge and cloud based on demand.
UC1-3.FR24	The XR Holo Orchestrator shall interoperate with a Congestion Detection Function (CDF) to request XR clients to adapt their resolution based on congestion.
UC1-3.FR25	The XR Holo Orchestrator shall be able to request the network to provide Quality on Demand (QoD) for a specific holographic session or to specific XR clients.
UC1-3.FR26	The XR Holo Orchestrator / Session Manager shall manage and orchestrate the lifecycle and status of shared media sessions, including the selection of virtual scenario, the management of the join/leave processes, the user representation formats, capture devices, and user identities (nicknames).

Table 8: Non-functional requirements for UC1, UC2 and UC3

No.	Description
UC1-3.NF1	The latency between the volumetric video capturer and media processing functions (edge) shall be less than 10 ms.
UC1-3.NF2	The light field sensors shall provide at least a resolution of 1920x1080px at a frame rate of 30 fps.
UC1-3.NF3	The XR capture module shall be able to provide, and dynamically switch between, 3 quality levels based on indication from the XR Orchestrator.
UC1-3.NF4	The light field cameras shall provide a bandwidth of at least 10 gigabits per second
UC1-3.NF5	The media processing shall be capable of providing streams with at least the following characteristics: RGB (Color) Resolution >= 1920x1080; Depth Resolution >= 640x576; Frame Rate >=30; Voxels >= 800K.

UC1-3.NF6	The E2E delay for media acquisition, processing and delivery should be less than 500ms.
UC1-3.NF7	The delay between the XR clients and Edge XR Processing nodes in uplink shall be lower than 10ms.
UC1-3.NF8	The XR Holo Orchestrator / Session Manager shall orchestrate and manage all events triggered and status updates (e.g., positions, interactions) in the shared media session and re-distribute them across the involved clients with a latency <=10ms.
UC1-3.NF9	>= 5 Quality of Service (QoS) / resources consumption metrics shall be measured and registers from >4 media processing components along the end-to-end chain.
UC1-3.NF10	Metrics shall be able to be visualized via intuitive and near real-time dashboards (e.g., using Grafana).

Validating 6G-XR Infrastructure for next-generation 6G use cases

To conduct validation and demonstration tests and confirm the preparedness and advantages of the 6G-XR infrastructure for supporting next-generation 6G use cases, such as multi-party holographic communications, the following steps must be taken (in addition to the requirements outlined in the tables above):

- Define and implement MATSUKO AR scenario.
- Define and implement i2CAT VR scenario.
- Align the validations and evaluations with the defined KPIs and KVIs.
- Execute functional tests and objective performance QoS tests by measuring delays, bandwidth consumption, resources usage, stability, scalability, etc.
- Execute subjective tests involving the participation of users with questionnaires to determine usability, perceived performance, overall Quality of Experience (QoE), etc.
- Provide comprehensive analysis about the obtained results, and their significance.
- Provide recommendations and guidelines on how to deploy and offer next-generation XR services over 6G networks.

Non-mandatory actions for the validation trials that can provide added value are as follows:

- Explore interoperability between different holographic communications solutions relying on the same standards.
- Consider demonstrations to stakeholders and interested agents.

3.4.2 Collaborative 3D Digital Twin-like Environment (UC4)

3.4.2.1 Use Case Description

In the Collaborative 3D digital twin (DT) use case a pre-created 3D object is reviewed by Instructor in a DT environment of University of Oulu Fab Lab and after accepted review the object is 3D-printed in the real-world Fab Lab and delivered to the remote user.

Initially, the virtual Fab Lab room environment is built as 3D DT copy from the real physical Fab Lab room, the Fab Lab instructor and the user join online with VR glasses as its avatars. Also, a 3D printer is made as 3D DT in the virtual Fab Lab room and its functions are synchronized between the VR and physical Fab lab room. The Remote User has two options: they can either create the 3D object file (.obj or .stl) of the desired model for 3D printing or collaborate with the Remote Instructor to develop the model within the DT environment. Subsequently, the instructor evaluates the model in the DT environment to ensure a seamless 3D printing process and to mitigate any potential issues. The instructor's approval is a necessary requirement before the model can be forwarded to the real-world 3D printer. Once the instructor accepts the model, the data file is transmitted to a Fab Lab 3D printer located in the physical world for printing purposes. Throughout the process, the remote user has the capability to monitor the printing status and observe the printed model via an arm camera. This arm camera, equipped with a 6-axis robot, can be positioned, and angled according to the remote user's preferences. The arm robot's movements are synchronized with the DT 3D scene. Finally, the printed object is delivered to a destination specified by the remote user.

To execute this 6G-XR use case, a 3D model of the University of Oulu Fab Lab room, along with all necessary equipment, must be created and placed in a DT world using game engine software platform. Both the instructor and the remote user need to be able to remotely connect to the DT environment and communicate with each other within the virtual world. In order to print a 3D object, a link between the digital and real worlds must be established. While some actions can be executed in the digital world, a real person at the local physical Fab Lab is required to supervise the 3D printing process at the real Fab lab room, then physically send the printed model to the remote user hand.

Figure 17. Overall concept of collaborative 3D DTs.

Digital Twins Environment

In 6G-XR project, the Fab Lab room needs to be replicated as a virtual environment at the same scale as its real-world counterpart. The virtual Fab Lab environment includes a 3D DT copy **of** the 3D printer and its controller (a Windows PC) that are mirrored and synchronized with the functions of their real-world counterparts. A printed 3D model can be created in the virtual environment, or an existing model can be imported. Both the remote user and the instructor can access the virtual Fab Lab room for their meeting using VR glasses. For safety reasons, the instructor, who must physically present in the Fab Lab during the actual printing process, is located in a remote room (dedicated space outside the physical Fab Lab room) with no people or enough space with other local people when using the VR glasses to be in the online VR room together with the Remote User.

The 3D model data for printing can either be made using the virtual mirror Windows PC in the virtual Fab Lab room or by importing the 3D model data file to the Windows PC beforehand. If the remote user creates a 3D model data in the virtual Fab Lab room, they can be avatars and communicate with the instructor and receive instructions in the same immersive VR scene, as if they were working together side by side in a real-life setting.

The 3D model data for printing can be transferred and presented to the VR scene with avatars as a precise representation of its real-world dimensions. Using VR avatars, the remote user and the instructor can touch and move the 3D model in their VR hands, reviewing its size and shape before printing. Additionally, the instructor can provide 3D design tips for any 3D printer-specific issues and offer advice before the physical printing process begins. After reviewing the 3D object design, the remote user can learn from the instructor how to slice the 3D model and set up the 3D printer parameters with appropriate settings for printing. The instructor can provide guidance for these steps within the VR scene.

Throughout the 3D printing process running, both the remote user and the instructor can monitor the printing status using the printer's remote control status information and video stream displayed in the virtual 3D objects in the VR scene.

Time Sensitive Networking

Time Sensitive Networking (TSN) is batch of standards of IEEE802.1. TSN can help to improve the determinism of sensitive traffic, such as machine control signals, even in the presence of heavy best-effort traffic, such as video stream. TSN enables to synchronize machines at finer granularities and establishes a time-aware traffic shaping mechanism to reserve timeslots for different traffic classes. This use case can leverage this feature to enable a safe transmission of control signals of the robotic arm and at the same time transmit the video stream of the mounted camera.

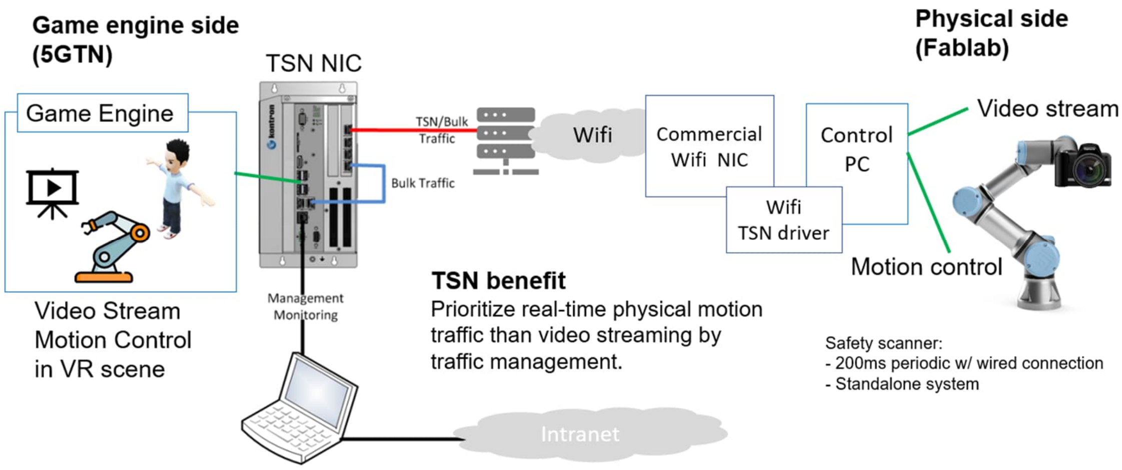

Figure 18. High level diagram of TSN system.

TSN is used in the 3D Digital twin use case (UC4), to guarantee the real time nature of communication for the deterministic communication of robotic arm machine together with video stream. By utilizing TSN, it is possible to prioritize the real time physical motion related network traffic over other traffic.

Slicing in 3D Digital Twin Use Case

5G E2E slicing can be utilized in the 3D DT use case in the wireless communication part as an optional technology that can be used instead of the normal non-sliced 5G network. It is an optional technology that will be tested as an addition to the above-described architecture, but it will not replace the non-sliced main architecture.

There are two instances that use wireless 5G connection in UC4: Remote Instructor and Remote User. Remote Instructor and Remote User are to connect and use different 5G slices of the same test bed, in this case the North Node (5G Test Network of the University of Oulu). Wireless communication related requirements, as well as KPIs and KVIs, must be the same as without usage of the 5G slicing.

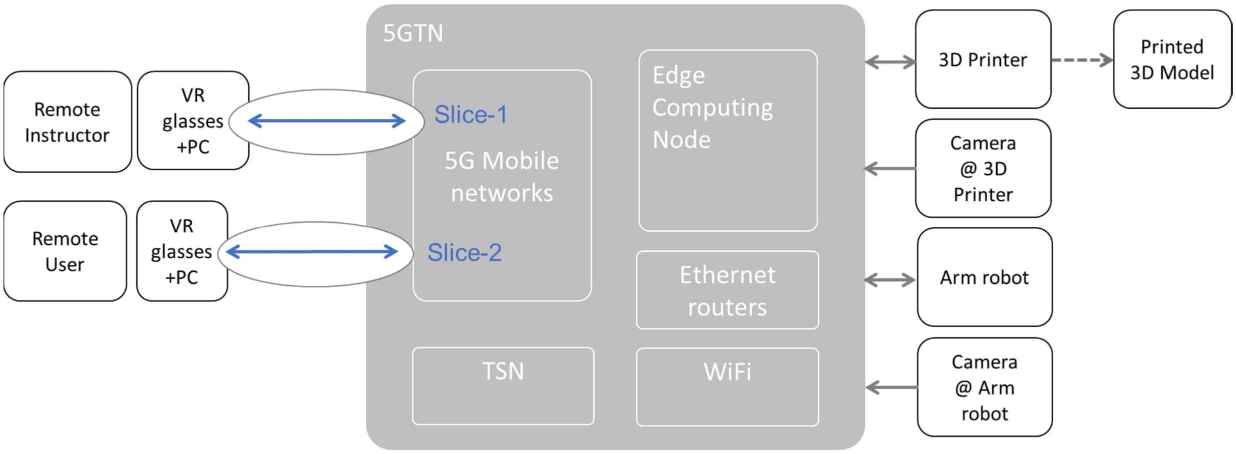

Figure 19. Optional 5G E2E slicing in the local 5G network.

UC4: Collaborative 3D Digital Twin-like Environment

This scenario involves the Fab Lab user remotely printing the 3D model data with the assistance of the instructor who is physically present in the Fab Lab room with the 3D printer, instead of visiting the room in person. High level procedure to review and print the 3D object is listed below:

1. Create 3D model design in VR
2. Review digital 3D model in VR
3. Configure 3D printer in VR
4. Review printed 3D model with arm camera

The Remote User, who may be at home or another location on campus, and the instructor who is physically present in the Fab Lab room have a meeting by joining the VR Fab Lab room using VR glasses. The remote instructor of Fab Lab wears AR glasses to see the physical 3D printer machine and VR components simultaneously.

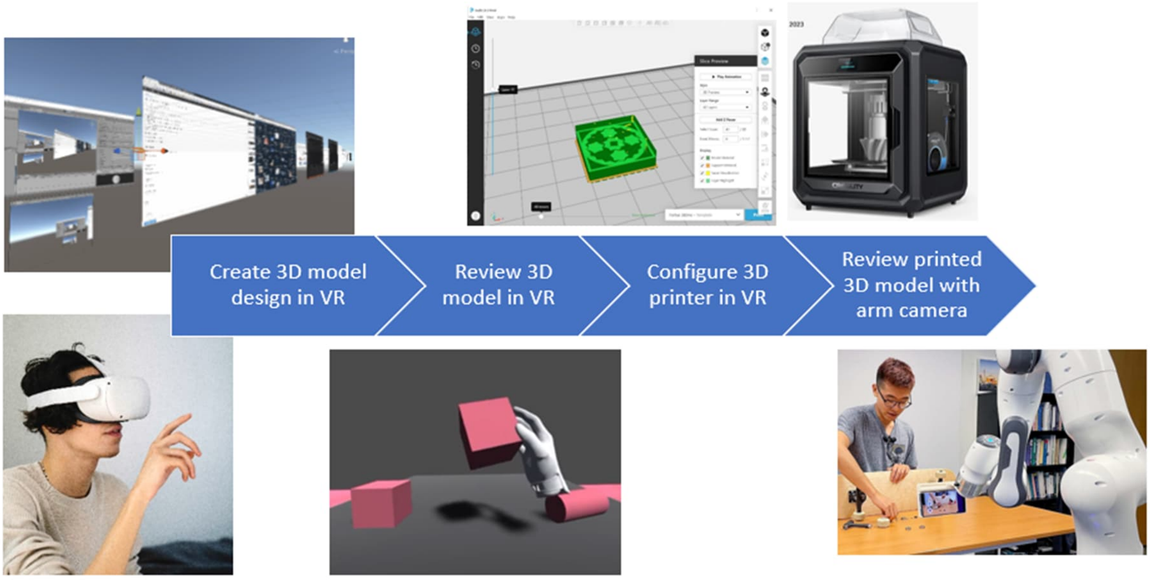

Figure 20. Fab Lab 3D Digital Twin scenario.

Create 3D model design

The virtual Fab Lab room is equipped with a virtual PC that is used for 3D design modelling. The virtual PC is a VR component that mirrors the screen of a Windows PC through an API. The remote user enters the virtual Fab Lab room with VR glasses and then can use the virtual PC equipped with 3D Computer Aided Design (CAD) software to create the 3D design for 3D printing.

As an alternative, pre-defined 3D model can be uploaded to the real-world Windows PC.

Review digital 3D model

The remote user downloads the designed 3D model data from virtual PC to the virtual Fab Lab room scene using Universal Render Pipeline (URP), and then spawns the 3D model into the VR scene. Both the remote user and the instructor can then view the 3D model in VR with any angle and scale using the VR joystick control.

Configure 3D printer

The virtual PC, which has remote access to the 3D printer at the Fab Lab, is also digitally twinned in the virtual Fab Lab scene. The remote user can slice the 3D model data file into G-code for the 3D printer, and then upload it to the 3D printer machine located in the Fab Lab. The 3D printer settings can also be adjusted remotely through the virtual PC's remote access to the 3D printer machine. The remote user can set up the 3D printer parameters with the assistance of the instructor in the immersive VR 3D room environment. The instructor may need to change the 3D printer's nozzle or filament depending on the settings used for the 3D printing process.

The 3D printer machine starts printing based on the command given through the virtual PC's 3D printer settings menu in the VR scene. During the printing process, the status of the 3D printer and a live video stream of the 3D printing are displayed in the virtual Fab Lab room, allowing both the remote user and the instructor to monitor the progress in real time.

Review printed 3D model

When the 3D print is finished, the notification reaches to Remote Instructor and Remote User. The instructor who locates locally in Fab Lab removes the 3D printed object from the machine. Printed 3D model is reviewed. The instructor gives/sends the object to the remote user afterwards.

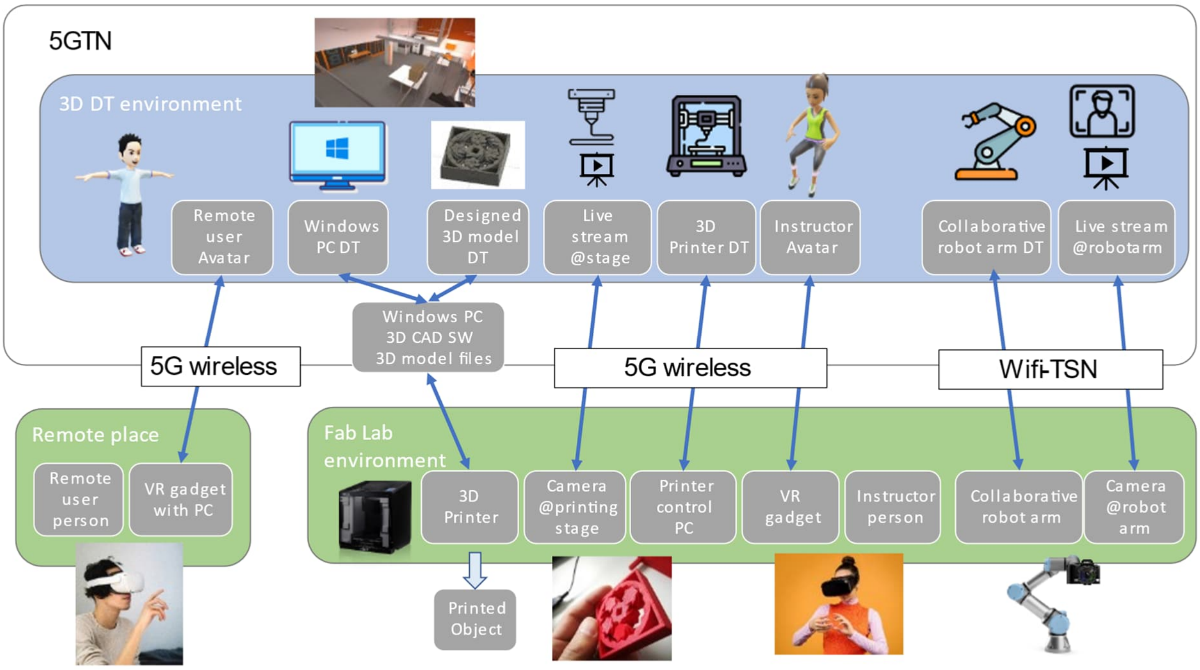

Figure 21. Fab Lab DT system diagram.

3.4.2.2 Use Case Requirements

The following tables list the high-level user and DT requirements from use case UC4.

Table 9: User requirements for UC4

No.	User Requirement	Remote User	Remote Instructor
UC4.R1	Create a 3D object to be reviewed in defined format.	X	
UC4.R2	The Remote User needs to be able to deliver the 3D object in question on-line to a pre-defined location.	X	
UC4.R3	The Remote User is to agree review time with Instructor with pre-defined methods	X	
UC4.R4	The Remote User needs VR equipment compatible with DT environment	X	
UC4.R5	Live 3D environment is delivered to the Remote User 3D glasses	X	
UC4.R6	Bi-directional live audio is delivered between the Remote User and DT environment	X	

UC4.R7	The Remote User needs to be able to interact with DT environment. This includes movement and object interaction	X	
UC4.R8	The Remote User can monitor the progress of the printing process through the virtual User Interface (UI) and live video stream from the physical Fab Lab space	X	
UC4.R9	The Remote Instructor is to agree review time with Remote User with pre-defined methods		X
UC4.R10	The Remote Instructor is to be able to retrieve the delivered 3D object in question from the pre-defined on-line location		X
UC4.R11	The Remote Instructor needs VR equipment compatible with DT environment		X
UC4.R12	Live 3D environment is delivered to Remote Instructor 3D glasses		X
UC4.R13	Bi-directional real-time audio is delivered between the Remote Instructor and DT environment		X
UC4.R14	The Remote Instructor needs to be able to interact with DT environment. This includes movement and object interaction		X
UC4.R15	After approved review process the Remote Instructor starts the printing process		X
UC4.R16	The Remote Instructor needs to be able to re-format the 3D object for printing and upload the re-formatted model to the real world FabLab 3D-printer through the virtual UI		X
UC4.R17	The Remote Instructor needs to be able to set the printing parameters through the virtual UI and starts the actual printing process		X
UC4.R18	The Remote Instructor needs to be able to monitor the progress of the printing process through the virtual UI and live video stream from the physical Fab Lab space		X
UC4.R19	After the printing has been completed, the Remote Instructor notifies the Remote User about that using a pre-defined method.		X
UC4.R20	Lastly, the Remote Instructor needs to send the printed object to the REMOTE USER by post mail		X

Table 10: 3D DT virtual environment requirements for UC4

No.	Requirements for the 3D DT virtual environment
UC4.R21	The environment needs to be an exact replica of the physical Fab Lab space of the University of Oulu
UC4.R22	The environment needs to enable remote online access for two simultaneous users (Remote User and Remote Instructor)
UC4.R23	The environment needs to provide a UI/portal for its users for identity verification and avatar selection
UC4.R24	The environment needs to provide three pre-defined avatars so that the users can select one to use when entering the environment

UC4.R25	The DT needs to support access (virtual UI) to the real-world 3D printer
UC4.R26	The DT needs to be able to receive the live video stream from the 3D printer printing stage
UC4.R27	The DT needs to enable bi-directional real-time audio communication between the Remote User and the Remote Instructor
UC4.R28	The DT needs to be able to access the file system where the 3D models are located
UC4.R29	The DT needs to be able to recreate the 3D object as real scale into the virtual environment
UC4.R30	The DT environment needs to enable Remote User and Remote Instructor interaction with the 3D object
UC4.R31	The DT needs to connect with the arm camera robot at the real Fab Lab via TSN services
UC4.R32	The arm camera robot motion/position is synchronized with virtual environment
UC4.R33	Optional: 5G Network is to support 2 simultaneous URLLC slices

Functional and Non-Functional Requirements

An overview of the UC4 functional components is provided in Figure 22. An initial set of functional requirements for UC4 are provided in Table 11.

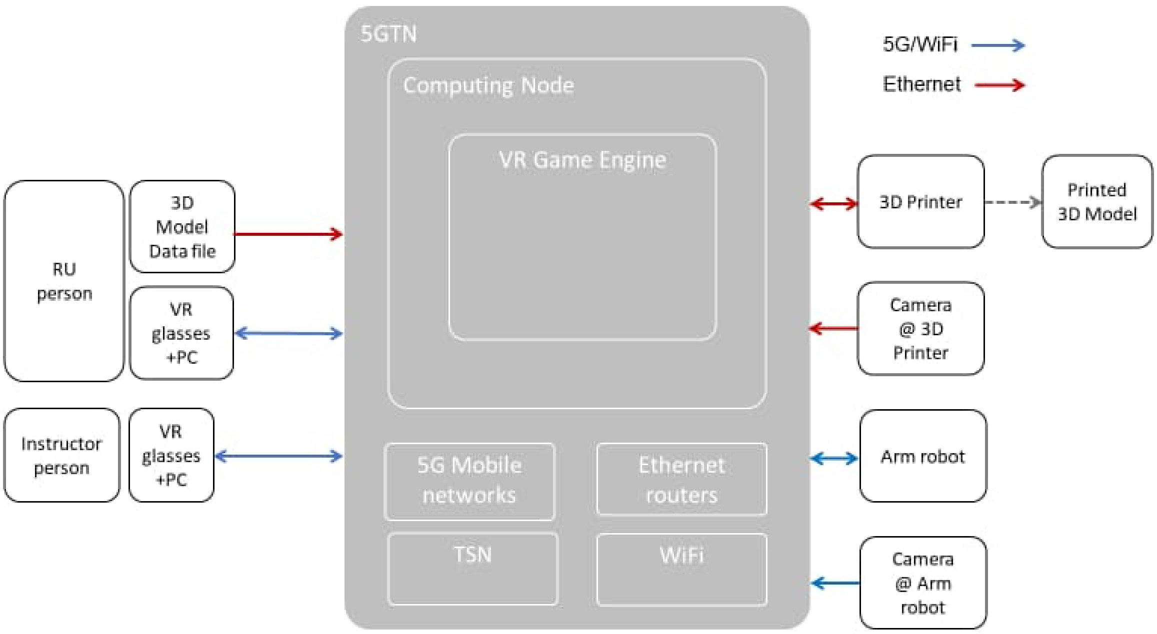

Figure 22. High level diagram of the functional components in UC4.

Table 11: Functional requirements for UC4

No.	Requirements	Priority	Justification	Description	Related Components
UC4.FR1	DT Environment set up	Essential	Use case driven	Remote Instructor needs to be able to launch the VR game engine loading the DT environment of Fab Lab room replica.	Game engine, windows host PC, 3D printer, arm camera robot
UC4.FR2	Mirror Windows PC	Essential	Use case driven	Remote User and Remote Instructor shall be able to see the mirror Windows PC mirror 3D object in VR scene.	Game engine, windows host PC, 3D printer
UC4.FR3	Review 3D model in VR	Essential	Use case driven	Remote User is to create 3D model data file (.obj).	Game engine
UC4.FR4	Configure 3D printer	Essential	Use case driven	Remote User and Remote Instructor shall be able to see the mirror Windows PC mirror 3D object in VR scene.	Game engine, 3D printer, PC for 3D printer
UC4.FR5	Review printed model with robot arm camera	Essential	Use case driven	Remote User and Remote Instructor shall be able to see the physical replica of arm camera robot and the video stream 3D objects in VR scene.	Game engine, robot arm with camera
UC4.FR6	Network slicing for 3D DT service	Essential	Use case driven	Provides the network slicing function into the 5G mobile networks related Core network and base stations. Two slices are prepared in the 5G network communications. One for the Remote User (remote area) and second the Remote Instructor (the Fab Lab room) in the same local network.	5G Mobile networks core and BTSs.

3.4.3 Energy Measurement Framework for Energy Sustainability (UC5)

3.4.3.1 Use Case Description

The energy measurement framework for energy sustainability use case aims to leverage the innovative energy measurement solutions integrated into the North Node RI of the 6G-XR project. The accurate energy measurement data is utilized to optimize the end-to-end energy consumption in the test networks. The objectives of the use case are as follows:

- Enhance energy measurement solutions for energy forecasting, production, storing and consumption, using ML / Deep Learning (DL) algorithms to predict network and energy resources for achieving E2E energy efficiency and self-sustainability in next-generation mobile networks.

- Investigate ML/DL methods and other energy efficiency techniques for saving energy (and adapting to energy availability) for different components of the base station, OpenRAN, service run-time environments and other key components of the network. These mechanisms may have positive impact even to battery-duration in the end-devices.

- Introduction of measurement solution being able to identify energy-consumption per network element.

UC5: Energy Measurement Framework for Energy Sustainability

The energy measurement framework is planned to be implemented at the North node, specifically at the VTT and UOULU sites. This framework's architecture will involve deploying a communication module as the central controller. This controller will facilitate the exchange of data between various components, including solar energy systems (Photovoltaic (PV) modules), system power supply units (PSUs), the base station system module, and remote radio heads (RRHs). Within this setup, energy measurement devices like Carlo Gavazzi meters will be connected to the power outlets. These devices will have the capability to measure energy consumption for different purposes, including:

1. Radio Access and Core Network System: The framework will gauge energy usage within the radio access and core network system.

2. Edge/Media Server Energy Consumption: It will also monitor the energy consumption of the edge/Media server.

3. Solar Energy System: PV modules, on-site sensors etc.

This approach aims to provide comprehensive insights into energy consumption across various network components, enhancing its manageability and sustainability.

As represented in Figure 23, the 5G Node B (gNB) site is equipped with PV production facilities and on-site sensors that have been collecting historical data over a period of two years. This historical data will serve as the foundation for training the proposed innovative energy measurement solution.

The OAIBOX serves the purpose of facilitating the 5GTN deployment for implementing ML/DL algorithms and offering an open-source testing environment. In this context, ML/DL algorithms leverage energy and traffic forecasts to dynamically adjust base station parameters through the Network Exposure Function (NEF). Within the energy measurement framework, NEF is implemented within 5GTN. This framework employs traffic-based, data-driven decision-making to fine-tune network resources. Moreover, power-saving measures will be enacted using the energy weather forecast and backup battery management. These measures come into play when the battery's state of charge falls below the predefined "survival" level. For instance, in the case of a PV-system battery operating according to its planned daily round-cycle, aggregation of forecasting errors is possible. This aggregated information proves valuable for load management. Flexibility can also be derived from Heating, Ventilation, and Air Conditioning (HVAC) systems, connected servers, and other site components, in addition to the RAN components. This approach enhances the project's ability to optimize power consumption and ensure efficient resource utilization.

Energy Production and Forecasting

North node resources and assets for real-time energy tracking include a setup of photovoltaic (PV) modules, on-site sensors, energy measurement devices, and access to seven Finnish Meteorological Institute (FMI) site-specific energy-weather forecasts for next 48 hours. Additionally, an API monitoring system is in place for measuring overall power consumption of 5G base station with the interval of every 5 minutes.

High Level Architecture

The use case requires the following components for deployment:

- 5GTN network
    - 5G Standalone (SA) network
    - PSUs and system modules
    - 5G core
    - Switch
    - RRHs
    - OAIBOX
    - OpenEdge, Service Enablement Platform (SEP) + xApps
    - Computing Resources
    - User Terminals
- Energy measurement framework
- Data measurement framework
- Energy production infrastructure
- Energy storage infrastructure

Figure 23 depicts the high-level deployment architecture for the energy measurement framework and end-to-end energy optimization use case, including the main service and communication network components.

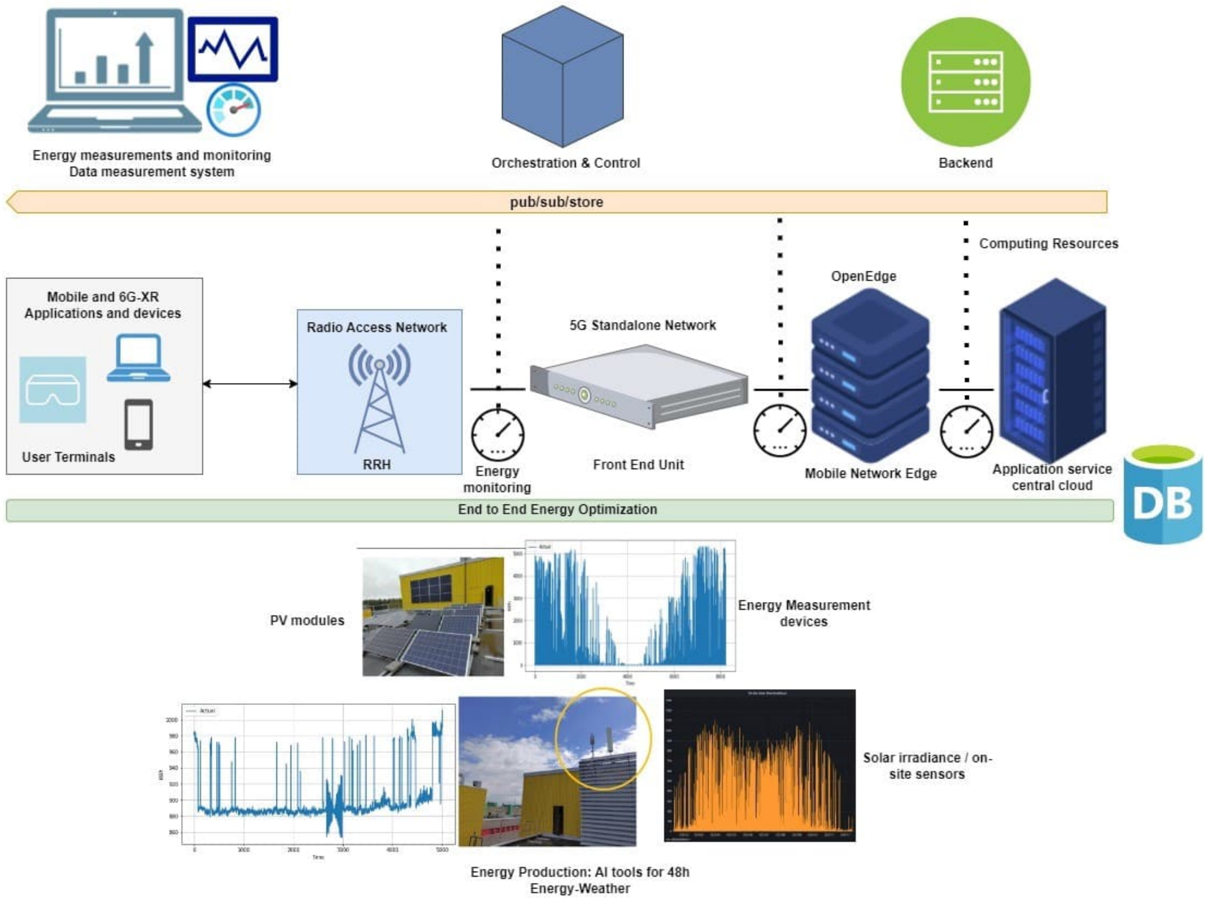

Figure 23. High-level deployment architecture for UC5.

3.4.3.2 Use Case Requirements

The functional and non-functional for the energy measurement framework and end-to-end energy optimization use case are defined. The functional requirements describe what the system should do and how it should behave. The non-functional requirements describe what are the general properties of the system needed to enable the functionalities defined in the functional requirements.

Table 12: Functional requirements for UC5

No.	Requirements	Priority	Justification	Description	Related Components
UC5.FR1	Systems internal resource usage	Essential	Use case driven	The radio access and core network systems shall send reports of their internal resource usage to a central database.	5GTN, energy measurement framework, central database

UC5.FR2	Overall energy consumption data	Essential	Use case driven	The overall energy consumption data of the radio access and core network systems shall be sent to a central database by the external meters.	5G core, RHHs, PSUs and system modules, energy measurement devices
UC5.FR3	Dynamic operational parameters	Essential	Use case driven	The radio access and core network systems shall be able change their operational parameters on the fly based on control commands received from a central network resource management entity.	Central controller, data measurement framework, energy production infrastructure, energy storage infrastructure
UC5.FR4	Reports of their internal energy usage	Essential	Use case driven	The radio access and core network components should send reports of their internal energy usage to a central database.	Central database, energy measurement framework
UC5.FR5	ML/DL algorithms for energy optimization	Essential	Use case driven	ML/DL algorithms shall be deployed for energy optimization trained over historical energy and on-site sensor data.	ML/DL algorithms, on-site sensors, energy production infrastructure, energy weather forecast

Table 13: Non-functional requirements for UC5

ID	Description
UC5.NF1	The radio access and core network systems shall offer open interfaces for the collection of resource usage reports from the system's internal counters.
UC5.NF2	The radio access and core network systems shall support dynamic reconfigurations without service interruptions.
UC5.NF3	The overall energy consumption of the radio access and core network systems shall be measurable with external meters.
UC5.NF4	The mobile network shall be able to utilize local renewable energy sources.
UC5.NF5	The mobile network shall be able to utilize energy from the local battery storage.
UC5.NF6	The mobile network shall be able to utilize energy from the power grid.
UC5.NF7	The base station site shall have on-site sensors such as solar irradiation, module temperature, and ambient temperature.
UC5.NF8	The mobile network shall be able to utilize energy weather forecast for next 48hours from FMI APIs.

UC5.NF9	The NEF (Network Exposure Function) shall be deployed to facilitate the seamless exchange of information of the radio access and core network systems.
UC5.NF10	The OAIBOX shall be able utilized for facilitating the deployment of a 5G testing environment for the implementation of ML/DL algorithms.
UC5.NF11	The mobile network shall be able to implement time-based/traffic based triggers to activate power saving measures in the identified network components.
UC5.NF12	The mobile network shall implement energy optimization balance (1/d before planning) based on data from energy balance forecasts.
UC5.NF13	The system shall enable the initiation of power saving measures when battery levels are lowered than planned state of charge.

4 6G KEY PERFORMANCE INDICATORS (KPIS)

The aim of the 6G-XR project is to provide a multi-site validation platform for the various foreseen 6G use cases, which are based on extensive utilization of XR applications and services. The project will take a focused experimentation driven approach to the development of such use cases and the required technology enablers, which has a direct effect also on the definition, measurement, and verification of the most essential 6G network KPIs related to these use cases. As the project is mainly interested in the measurement of the network performance in a variety of use case specific network configurations, practical measurements in dynamic but controlled live networks will be favored instead of aiming for theoretical maximum performance and optimal test conditions for all target KPIs. The repeatability of the 6G-XR experiments will be guaranteed, as far as it is possible in live wireless communication networks, with full control of test infrastructures when it comes to the network configuration and data traffic.

Using the KPI definitions and recommendations provided in the 5G PPP Test, Measurement and KPIs Validation Working Group (TMV WG) white paper[21] as a reference, the project has identified the basic KPIs listed below to be in the key role when validating XR application and services on top of the 6G-XR test sites. To validate the performance of a variety of XR use cases on top of the utilized RIs, the generic definition used for these KPIs and means for their assessment in the 6G-XR project are as follows:

- **Peak data rate:** Maximum achievable data rate in bps measured in good network conditions (i.e., line-of-sight link in an otherwise empty cell) while using the use case specific network configuration.
- **User experienced data rate:** Average user throughput in bps in good network conditions (i.e., line-of-sight link in an otherwise empty cell) while using the application/service under test.
- **User plane latency:** Time between when the source node sends a user data packet to when the destination node receives it in ms. The measurement is performed at Layer 3.
- **Jitter:** The latency variance between two consecutive successfully delivered data packets in ms.
- **Control plane latency:** Time between when the source node sends a control data packet to when the destination node receives it in ms. The measurement is performed at Layer 3.
- **Application layer latency:** Time between when the source application sends a data packet to when the destination application receives it in ms.
- **XR User Equipment (UE) satisfaction:** An XR UE is declared satisfied if more than X % of application layer packets are successfully transmitted within a given latency constraint.

4.1 GENERIC 6G NETWORK KPIS

The current view of the generic 5G/B5G KPI target values from [21], which are based mainly on Radiocommunication Sector of International Telecommunication Union's (ITU-R) IMT-2020 requirements [22] and are most relevant to the 6G-XR use case experiments, are summarized in Table 14. These values are provided by the 5G PPP TMW WG and will be updated in the future for 6G based on the ongoing ITU-R efforts and results of the ongoing 5G PPP and SNS JU projects. In 6G-XR, these generic KPI target values are only used when assessing the baseline performance of the test sites in different experimentation configurations. For use case validation purposes, the more realistic real-life KPI targets from the point of view of the project use cases and utilized XR solutions are listed and discussed in the following subsections.

Table 14: Generic 5G/B5G KPI target values

KPI	Target value	Original source
User experienced data rate	Downlink: 100 Mbps Uplink: 50 Mbps	ITU-R M.2410-0 (11/2017) [22]
User plane latency	eMBB: 4 ms URLLC: 1 ms	ITU-R M.2410-0 (11/2017) [22]
Control plane latency	20 ms	ITU-R M.2410-0 (11/2017) [22]

The 3GPP 5G/5G-A requirements and targets for XR with respect to XR traffic streams are given in Table 15. The different values depend on whether the application is AR, VR or cloud gaming (CG), and are based on [2] and [23]. The jitter is modelled as a truncated Gaussian process with zero mean and 2ms standard deviation.

Table 15: 3GPP Traffic Model Requirements for XR

KPI	Video (Downlink)	Motion/Control (Uplink)	Audio + Data (Downlink + Uplink)
Packet rate (fps)	[30, 60, 90, 120]	[60, 250]	100
Average data rate (Mbps)	[8, 30, 45, 60]	[0.2, 10, 20]	[0.756, 1.12]
Jitter (ms)	[0 – 4]	[0 – 4]	[0 – 4]
Packet delay budget (ms)	[10, 15, 30]	10	30

In addition to the 6G performance KPIs that are most essential from the point of view of XR applications and services, energy efficiency of the network components utilized at the 6G-XR test sites and, especially, end-to-end energy efficiency of the whole communication path utilized by the XR services through the test sites infrastructures are of interest to the project. The energy efficiency KPIs are discussed more in section 4.2.3 of this deliverable.

During the 6G-XR project, the need to validate also other aspects of the 6G network functionality and performance, e.g., related to reliability, compute, and scalability, can arise in the 3rd party experiments funded through the 6G-XR Open Calls. For these needs, the 6G-XR partners are prepared to define, in collaboration with the 3rd party experimenters, additional 6G KPIs that can be measured with the tools available at the project's test sites.

4.2 USE CASE SPECIFIC 6G NETWORK KPIS

4.2.1 Real-Time Holographic Communications (UC1, UC2, UC3)

Real time holographic communication will be monitored by bandwidth, FPS (framerate per second), image resolution, jitter, latency, packet loss. Good network conditions are a crucial prerequisite for high quality holographic communication.

Table 16 lists the initial target KPIs for UC1 and UC2. The values are based on previous development efforts [16]-[19], adopted hardware specifications and from project ambitions.

Table 16: Target KPIs for UC1 and UC2

No	Category	Requirement	Value
1	XR Hologram Capture system	# of capturing sensors	1 frontal view capture >3 for full 3D body capture
		Frame granularity	>= 30 fps
		Refresh rate	>= 50 Hz
		Cameras resolution	>= 1920*1080
		Multi-sensor synchronization accuracy	frame level accuracy
		RGB-D encoding	>= 1920x1080
		Depth	>= 640x576
		Point Cloud encoding	>= 800K
		Voxels	15-30 fps
		Bandwidth	6-70Mbps (for RGB-D sensors)
		Latency from XR client to Edge	<= 10ms
		Media quality levels from XR capturers (exact levels to be decided upon tests)	>=3
		Volumetric Reconstruction and Encoding delay	<= 50ms
2	Remote Rendering	Latency from Edge to lightweight XR clients	<=100ms (depending on scenario)
		Remote Rendering	>= 100 passive users >4 interactive users
		Media quality levels from Remote Rendering modules for passive consumers	>=2
		Round trip delay (RTT) between Edge Renderers and interactive XR clients	<= 100ms

3	Edge-assisted Communications	Capability	>1 SFU in a single shared session
		# of concurrent users per session	>=6 concurrent users per session
		E2E delays with SFU	<=100ms (high-speed network)
		E2E delays with cloud processing	<=200ms (high-speed network)

Table 17 lists the initial target KPIs for UC3. The KPIs below are the starting values and will be iteratively updated during ongoing experiments. In the table we provide the metrics for different stages of hologram resolution, which have been measured during multiple tests of the application on 4G and 5G networks.

Metrics are divided into three categories to measure results from:

- Participant Sender: device on which the person is captured for the hologram (column 1)
- Backend: server where holograms are being rendered, where 2D image is processed into 3D hologram (column 2)
- Participant Receiver: device where hologram is viewed (column 3)

The focus will be mainly on validation of the figures for high hologram resolution (below in bold).

Table 17: Target KPIs for UC3

Participant Sender			Backend				Participant Receiver		
		Capture Device (iPhone) (color/depth)	**Connectivity (upload) (closest node)**		**Inter-MNO networking**	**Backend /Reconstructor (Color/depth)**	**Connectivity (download) (access leg)**		**Viewer device (number of vertices)**
			FPS:15	FPS:30			FPS:15	FPS:30	
Hologram Resolution Data Rate ranges are controlled via WebRTC bitrate controller (minimum requirement)	low	(128 x 96) / (128 x 96)	2-3 Mb/s	4-5 Mb/s		(128 x 160) / (128 x 160)	3-4 Mb/s	6-8 Mb/s	15k-20k
	mid	(256 x 192) / (256 x 192)	3-4 Mb/s	6-8 Mb/s		(256 x 320) / (256 x 320)	4-6 Mb/s	8-12 Mb/s	50k-80k
	high	**(1024 x 768) / (256 x 192)**	**4-6 Mb/s**	**8-12 Mb/s**		**(1024 x 1280) / (256 x 320)**	**5-7 Mb/s**	**10-14 Mb/s**	**50k-80k**

Latency (Expected) (High Resolution)	4G (Cloud)	(256 x 192) / (256 x 192)	20 ms	40 ms	25 ms	30 ms	20 ms	40 ms	
	5G (Cloud)	(1024 x 768) / (256 x 192)	5 ms	5 ms	20 ms	30 ms	10 ms	10 ms	
	5G (Edge)	(1024 x 768) / (256 x 192)	5 ms	5 ms	10 ms	30 ms	5 ms	5 ms	
	Wifi (Edge)	(1024 x 768) / (256 x 192)	5 ms	5 ms	10 ms	30 ms	5 ms	5 ms	

4.2.2 Collaborative 3D Digital Twin-like Environment (UC4)

In Table 18, UC4 related KPI's are presented. Each KPI is numbered and its category, reference point and performance are presented. Performance requirements are based on the analysis of the use case components and presented as fixed, maximum or minimum figure, based on the case.

Table 18: Target KPIs for UC4

No.	Category	Reference point	Performance
1	VR glasses Link Data Rate: Link Capability in Gbps	3D printer monitoring video	2 Mbps
		VR glasses (3D data + audio + control)	1 Mbps
		3D printer virtual UI (remote desktop)	1 Mbps
		Wi-Fi towards the VR glasses (wireless uplink and downlink)	400 Mbps
		Wi-iFi traffic towards 5GTN (wired)	10 Gbps
		5G downlink	400 Mbps
		5G uplink	50 Mbps
2	Latency: End-to-end in ms for both 5G and Wi-Fi	Downlink (from VR glasses to game engine)	10ms
		Uplink (from game engine to VR glasses)	14ms
		Game engine processing time:	16.6 ms (60 fps)
3	Reliability: Percentage of packets delivered within the target latency KPI		99.99 %
4	Mobility	Users are located indoor	Low
5	Density	Users are located indoor rooms	10/m2
6	Energy efficiency		Nominal
7	Wifi-TSN between VR and arm robot (PC on the lab and robot connected to a PC with a W-TSN NIC)	Time Synchronization Accuracy	~10 µsec
		Bounded Latency for 200 ms cyclic signal from robot	10 – 1 msec
		Video payload	1M bps (30fps) with lower resolution, optionally higher data rate with the capability of traffic shaping limitation.
8	Slicing (optional)	Wireless connectivity	Two separate slices are to exist. Users can connect to separate slices.

4.2.3 Energy Measurement Framework for Energy Sustainability (UC5)

The 6G-XR project aims to deploy an extensive energy measurement framework for the test sites as well as to introduce the required intelligence and functionality into the network components so that the energy consumption data can be utilized to optimize the end-to-end energy consumption and use of local renewable energy for variety of different XR related applications. As the project has a holistic approach to energy efficiency through coordinated adaptation of applications, user devices, and network components in the optimization process, it will be impossible to define meaningful numerical targets for energy efficiency before the test setup is up and running, and the achievable overall gains in the energy efficiency are verified with experiments. The numerical KPI targets are dependent on the use case, network configuration, and in some cases, on the selected baseline against which to compare the optimized performance. Hence, the project will re-visit them towards the end of its lifetime. In the beginning of the project, the main target for the energy efficiency use case is to maximize self-sufficiency of the utilized test network configuration, i.e., to maximize the ratio for the network uptime when the required energy is coming from renewable sources.

The numerical KPI target for the energy measurement framework are as follows:

- The radio access and core network components should report their internal resource usage once per second.
- The overall energy consumption of the radio access and core network components should be reported once per second by the external meters.

Definition of other potential KPIs to be investigate during the project are provided in Table 19.

Table 19: Potential KPIs for UC5

No.	Category	Reference point
1	Density	Low
2	Active energy counter	The total energy consumed (KWh)
3	Cost counter	The electricity prices to calculate the cost of operating the system
4	CO2 counter	The amount of carbon dioxide (CO2) emissions produced because of energy consumption based on indirect emissions estimates from Transmission System Operator (TSO)
5	Energy savings	The amount of energy saved
6	Self-sufficiency proportion	The proportion of local energy yield per grid intake during a certain follow-up period of time
7	Energy efficiency of power supply unit	Efficiency as a whole

5 SOCIO-ECONOMIC AND ENVIRONMENTAL IMPACT

The future 6G technology is expected to introduce many innovative and exciting technologies and applications on a large scale. As one of those technologies and applications, XR (including VR, AR, and mixed reality (MR)) has the potential to transform both industries and consumer markets. It is important to understand the potential socio-economic and environmental impacts of the 6G-XR use cases, particularly in comparison to current 5G and 5G-A technologies. The 6G-XR initiative is fully aligned with these guiding principles. Within Stream C, its objectives encompass: (i) provide 6G technological foundations in line with Stream B strands. (ii) a network of interconnected experimental facilities characterized by interoperability, replicability, sustainability, and cost-efficiency, (iii) introducing inventive and adaptable technological breakthroughs, to empower the next generation of extended reality (XR) services, highlighted by impactful use cases with economic, societal, and environmental advantages, and (iv) offer access to third-party entities and encourage businesses to test new enablers or verticals. Moreover, 6G-XR goes beyond just showing that it performs better than 5G. It aims at providing very careful and complete ways to evaluate things, clear benchmarks, and plans for strategic testing. Another important aspect is focusing on various Key Value Indicators (KVIs). These are not only based on the SNS Work Programme (WP), but also come from previous efforts in the 5G-PPP and 6G-IA frameworks.

5.1 METHODOLOGY

To analyze the impact of 6G-XR on current and future technologies, we conducted a review of publicly available work and results of different 6G research programs and projects, as well as relevant standardization work and scientific publications. We also considered the visions of where 5G-A and 6G technologies are heading and identified risks and challenges. Furthermore, this study will also review the indirect impact of the 6G-XR often implied to as ICT for sustainability by examining the project use cases and how their advancements and applications contribute to enhance sustainability efforts by reducing the need for physical travel and resource-intensive activities through environmentally responsible practices, thus minimizing its ecological footprint.

The SNS WP aspires to position the European Union (EU) as a frontrunner in shaping the landscape of 6G definition and design. This aims to establish the EU as an innovative hub for novel use cases, services, and applications. The primary emphasis is on harmonizing these efforts with the fundamental aspirations of United Nations (UN) Sustainable Development Goals (SDGs). Among these SDGs, SDG 8's focus on stimulating economic growth, SDG 9's pursuit of robust infrastructure for innovation and efficient industrialization, SDG 11's commitment to inclusive, safe, resilient, and sustainable urban habitats, and SDG 13's drive for impactful climate action, collectively underscore the programme's mission [24]. By aligning with these SDGs, the SNS WP not only envisions a more progressive society but also envisions a bolstered European economy. This, in turn, enhances the region's technological autonomy and global significance in vital technology sectors and supply chains. As we navigate the journey towards 6G, it becomes essential for our community to broaden its horizons beyond mere technical and performance considerations. We must embrace a more holistic perspective that encompasses human well-being, societal impact, and environmental sustainability. This entails adopting a people-centered approach, ensuring fairness, prioritizing safety, and laying emphasis on sustainable practices. Additionally, our focus should be directed towards minimizing carbon emissions and optimizing energy consumption, contributing to a greener and more efficient technological landscape.

The UN SDGs provide a versatile framework for key values as covered by the related three areas of Societal sustainability, Economic sustainability, and Environmental sustainability. 6G-XR will comprehensively and accurately gather, categorize, and register a wide set of value-oriented metrics (KVIs).

5.2 STAKEHOLDERS AND TARGET GROUPS

6G-XR envisioned outcomes aim to bring about substantial societal changes. To achieve these effects, the project has carefully recognized various stakeholders, dividing them into specific target groups. These groups will be the main beneficiary of the innovation and technology enablers provided by the project.

1. Community groups (Research Community, Experimenters' Community).

Community groups are categorized into two distinct groups: the research community, encompassing academic and research center personnel primarily engaged in 6G systems and solutions, and the experimenters' community, seeking to validate 6G technology through the utilization of testing facilities and use cases developed during the 6G-XR project across both North and South Nodes, solely for non-commercial and non-business purposes.

2. Manufactures

This group consists of SMEs and Start-ups. This group needs the improved capacity to assess upcoming 6G technologies, which are vital for their business models, market entry, and aiding larger players. However, they often lack the means and expertise to operate up-to-date internal labs due to resource and personnel skill limitations.

3. Society

This group consists of members of the society and policy makers. This group consists of public representatives, including regulatory bodies and legal experts, responsible for defining and announcing the key features and technologies that will make up 6G. It also includes society's members who lack specific technology expertise or interest. Instead, they are individuals seeking cost-effective, novel, and improved services and applications that can positively impact their daily lives.

4. Business (Industry)

This group comprises technology providers, cloud providers, system integrators, application developers, and equipment vendors, as well as network operators, all of whom are engaged in the development of 6G systems.

5.3 EXPECTED IMPACT ON KEY VALUES

Following the methodology, the main purpose of the KVI analysis shown in Table 20, is to identify potential social and societal value of 6G-XR research and innovation work. The analysis is performed through the project use cases which act as a driver for the technology development work in 6G-XR. The KVs, KVIs and KV enablers, listed in Table 20, offer a user-driven, and in a larger-scale, a society-driven approach for the assessment of the 6G-XR technology design and research development.

Table 20: KVs mapped to use case areas and definitions of related KVIs and enablers

Use case area	KV examples	KVI examples	KV enabler examples
Real-Time Holographic Communications (UC1, UC2, UC3)	**Societal sustainability**	Equal opportunities for accessing holographic communication for everyone with a smartphone. A more inclusive and democratic society.	Smartphones, Low-cost XR capture and display gadgets, Software Development Kits (SDKs) for integrating holographic comms in third-party XR products Easy to use and standardized interfaces
	Environmental sustainability	Reduce travel and associated emissions.	Holographic meeting instead of travel, smartphones. In-cloud processing for reducing overall energy consumption Live validations digitally signed by digital video processing
	Personal freedom	Increase accessibility for people with disabilities or those who are unable to travel.	Holographic meeting, smartphones. Cost reduction. Breaking physical and geographic barriers SDK and functionalities to allow people change the hologram appearance covering potential disabilities Connectivity available in potential remote regions where people are located
	Trust	Facial relief visualization of the people we are interacting with helps in the enhancement of the inter-personal relations. Then, it is increased the level of thrustless, cooperation and understanding.	Holographic meeting, Smart devices SDK to measure the trust level of the people you are interacting
	Time Saving	Virtual meetings contribute to saving time due to unnecessary travels.	Family and work balance Productivity Enhancement of the people focus on their comfort zone SDK standardization of the meeting rooms with the necessary interactive material

	Knowledge	Increased access to live lectures seminars and conferences enabled thanks to holographic communications. Then, real time participation via holographic can foster knowledge sharing and professional/personal development.	Retention of the lectures content via digital recording, training activities, virtual visit to cultural heritage and touristic places, virtual attendance to events Smartphones and virtual attendance to events Access to the knowledge anywhere anytime Database hosting the records of the holographic communications
	Improved quality of life	Reduced travel and immersive experience which improve quality of life by saving time and increasing quality of communication.	Holographic meeting and smartphones
	Training	Enhancements of the training activities using holograms communications avoiding displacements of trainers at the same time it is closed the personal gap between trainer and trainee. In addition, it is possible to integrate users in realistic and interactive XR scenarios for training in a wide variety of scopes and disciplines (e.g., Industry, driving simulators…).	Rapid and effective skills acquisition Knowhow retention within upper organizations Standardization of the pedagogical way to transmit the content SDK which improves the training creation process
	Safety	By using realistic holo-portation, learning, training and visiting activities can be safe, avoiding risky situations in terms of machinery manipulation or dangerous environments.	Costs and risks minimization Increased user confidence Hands on safety collaboration

	Digital inclusion	Easiness to use accessible Hardware (HW) which improve the digital inclusion of the whole society.	Holographic-meeting, smartphones Rapid and effective skills acquisition Budget friendly HW in which holographic communications can be operated Globalization of the compatible HW Easy to use HW Variety of versions to match different society use cases
	Cost Saving	Cost savings associated to travel expenses, accommodation, logistics, time improvement, and other associated cost sources.	Centralized team measuring the cost savings associated to the use of holographic communications
	Industrial improvements	Other industrial improvements associated to the implementation of holographic communications as several industrial gaps could be covered. Remote Collaboration, supply chain optimization, remote inspections, cross functional collaboration, real time interactions and collaboration are examples of gaps covered.	Standardized assets with industrial scalability and application Potential to commercialize assets
Collaborative 3D DT-like Environment (UC4)	**Societal productivity and efficiency**	Remote collaboration enhances societal and team productivity/efficiency. Real collaboration around of a common asset, machine, manufacturing place or environment is enabled thanks to a collaborative 3D DT environment. Key outcome is extracted due to the capabilities of bridge regional disparities and provide equal opportunities regardless of the geographical location. Traditional example of gaps covered is the disparity	Digital presence Rural and industrial equality Telepresence

		between industrial and rural locations.	
	Societal sustainability	Measures productivity and efficiency in remote teamwork. Reduction of regional disparities of rural area.	VR telepresence and remote control
	Environmental sustainability	Measures the reduction of the carbon footprint associated to travels by eliminating the physical meetings within local and global communities, asset logistics and other transportation through the adoption of collaborative DT environments.	VR telepresence and remote control Standardized platform to DT implementation Remote collaboration with enhanced and real time information from 3rd party software Visualization of the information enhancing discussions and decision-making processes
	Digital inclusion	Measures fair opportunity as accessibility and user interface for industrial production by the DT participation. People can use the manufacturing facility even from the regions not locating manufacturing. Increasing the inclusivity of the user interface design by means of a collaborative 3D interface. It enhances and standardises the accessibility of different people with a variety of abilities, skills, background, and culture.	VR telepresence and remote control, VR UI, accessibility Digital accessibility supplementing potential limitations of people interacting with the Digital Twin like hand disabilities (i.e., voice interaction) Telepresence in a common digital environment Accessible immersive UI EAA guidelines (https://ec.europa.eu/social/main.jsp?catId=1202)
	Economical sustainability and innovation	Economical improvements associated to the production and productivity efficiency through the adoption of DT environment. Partially enabled by the ability to differentiate and customize the production, leading to increase economic sustainability and innovation within the processes.	VR telepresence productivity, accessibility Part customization Product previsualization Improve try and error processes Speed up testing phases Telepresence Productivity

			Accessibility
	Data Privacy and security	Measure the effectiveness of the privacy and security of 3D DT environments. Key points to check are user data, privacy and confidentiality as well as other potential security leaks. Virtual interaction needs to comply with general and industry standards.	VR telepresence avatars, edge cloud, E2E communications SDK to implement masks in the communication and video streaming Edge and cloud combination to reduce potential points of attack Encrypted information
	Knowledge sharing	Measure the increase participation and involvement of the local community with knowledge sharing and transfer among global communities. Then it is transferred to the collaborative 3D Digital Twin environment. It is boosted thanks to the cross-cultural collaboration, idea exchange and individual knowhow shared.	Utilization rate of application and usability, accessibility Cultural exchange Amount of content stored in the environment Type of content consumed Number of ideas generated Category of the people using and consuming the collaborative information and environments
	Simplified life	Reduced travel and immersive experience which improve quality of life by saving time and increasing quality of communication	Utilization rate of application and usability, accessibility
	Optimized daily activities	Improvement of the communications and effectiveness of the information shared while people's time is saved as no travel is needed.	Utilization rates of the application Time saved while using the application in comparison with travel Reduction of misunderstandings due to the immersion of the solution Common asset as centre of discussion

	Optimized resources	Resources (material, energy, equipment, supply chain, personal, etc.) optimization due to the decentralized location of the people and assets. Then, the optimal allocation of the resources can be selected according to the restrictions in place or organizational decisions.	Decentralization of the knowhow allowing to access global talent Optimization of the energetical resources consumptions Global vision of the complete environment resource consumption
	Ethical assurance	Ensure the adherence to ethical practices in place in both manufacturing and sociological practices. Having a 3D DT environment helps in the guidance and implementation of corporative, social, or governmental ethical guidelines.	Proof of ethical compliance and channel to introduce potential ethical limitations Register potential deviations of the ethical politics and ensure corrective actions Modules and SDKs to enable ethical assurance standardized
Energy Measurement Framework for Energy Sustainability (UC5)	**EcoMonitor**	Allowing stakeholders to monitor energy usage patterns promptly and make informed decisions to optimize energy efficiency.	Advanced Metering Infrastructure (AMI) and IoT devices
	Energy data sharing	Measures the framework's capability to facilitate sharing of energy data with relevant stakeholders.	Secure data sharing platforms, secure data sharing APIs
	Energy efficiency	Improved energy efficiency by providing accurate and real-time energy measurements and energy balancing as a whole system.	Smart metering and intelligent control and monitoring system using Message Queuing Telemetry Transport (MQTT)
	Affordable and clean Energy	The electricity prices to calculate the cost of operating the system.	Renewable energy sources, such as solar or wind, reducing the reliance on expensive fossil fuels and decreasing monthly energy bills for consumers
	Measurement accuracy	It quantifies the level of precision achieved in measuring E2E energy measurement framework, expressed as a percentage of accuracy.	Root Mean Squared Error (RMSE) and Mean Squared Error (MSE) are commonly used metrics to quantify the accuracy of measurement models ML/DL algorithms can minimize these error metrics, ensuring higher accuracy in energy measurements within the E2E framework
	CarbonCut	Assesses the reduction in greenhouse gas emissions achieved	The amount of carbon dioxide (CO_2) emissions produced

		through the use case, promoting a more sustainable and environmentally friendly energy system.	because of energy consumption based on indirect emissions estimates from TSO

5.4 GENERIC KVIS, IMPACT AND CHALLENGES

In this section, we have analyzed the generic impact of 6G-XR with respect to KVs, possible KVIs and their potential research challenges as presented in Table 21.

Table 21: Generic 6G-XR KVs, impact and potential research challenges

Generic KVs	6G-XR Generic Impact	Research challenges
Enhanced Productivity	6G-XR consortium has been carefully built, by selecting key expert partners in the 5G and towards 6G arena. The integration of Wi-Fi based Time Sensitive Networking enables to enhance digital resilience through diverse access, i.e., communication to end-devices may continue operating even if cellular access is lost	Optimizing seamless handover and resource allocation between cellular and Wi-Fi networks *Likelihood: Medium* *Impact: Medium*
Economic sustainability and innovation	Wi-Fi based access for XR end devices will contribute to economic sustainability and innovation as the new 6 GHz band enables a suite of advanced applications with superwide channels bringing additional capacity. Furthermore, growth in Wi-Fi value for XR end users is powered by the increasing importance of free Wi-Fi. Overall, the 2021 economic value of Wi-Fi in the 27 European Union countries combined is estimated at $457.6 billion and is expected to grow to $637.2 billion by 2025. The global economic value of Wi-Fi is estimated at more than $3.5 trillion USD [25].	Efficient utilization of the new 6 GHz band alongside existing Wi-Fi networks *Likelihood: Medium,* *Impact: Medium*
Improved user experience	Wi-Fi based access of XR services enabled by TSN allows: users to benefit from accessing free Wi-Fi networks in public locations, including libraries, cafés, and even Wi-Fi buses; and Internet Service Providers (ISPs) to offload the traffic and wireless ISP services. The service availability is enhanced through the complementary nature of wireless coverage to cellular access.	Integration with existing networks and efficient spectrum management and coexistence *Likelihood: Medium,* *Impact: Low*

Energy efficiency using TWT	New Wi-Fi features, such as Target Wake Time (TWT) allow to increase a device's sleep time and improves battery life, making Wi-Fi 6 particularly beneficial for battery powered devices, such as patient monitors, infusion pumps, respiratory equipment, and sensors.	Effectively managing and coordinating TWT schedules *Likelihood: Medium, Impact: Medium*
Improved healthcare	Wi-Fi enabled medical devices—as well as patient monitors, streaming cameras for virtual patient engagement, and imaging systems—will work more efficiently and stay consistently connected to provide a better overall patient experience. In telemedicine, higher data rates provided by Wi-Fi 6 allow healthcare providers to move away from in-person consultations to Ultra HD video sessions. Remote video surgery improved data transfer speeds and ultra-low latency enabled by Wi-Fi 6 also mean that healthcare organizations can deploy robotics and AR/VR solutions to remotely carry out surgical procedures and medical training.	Robust network design *Likelihood: Medium, Impact: Medium*
Societal sustainability	Facilitates inclusive access to digital fabrication tools and technologies, promotes collaborative innovation, and enhances resource optimization. It empowers diverse community groups, facilitates skill development, and enables remote collaboration. Moreover, it supports sustainable design practices, reduces material waste, and encourages the adoption of circular economy principles. This approach nurtures social cohesion equitable economic opportunities while promoting environmental stewardship and resilience.	Ensuring equitable access *Likelihood: Medium, Impact: Medium*
Community Empowerment	Increased participation and involvement of the local community with knowledge sharing and transfer among global Fab Lab community.	Collaboration between local communities and the broader global Fab Lab network *Likelihood: Medium, Impact: Medium*

Environmental sustainability	Reduced travel, excess volume production logistics and associated emissions. Remote telepresence of users and remote control of the 3D printer of production device in Fab lab reduce the human travel to the Fab Lab location. Also, 3D printer location production can eliminate the logistical emissions from volume production location to the user. Fab Lab local production eliminates excessive mass production and wasteful inventory in the market by just delivering digital data of manufacturing, the XR telepresence communications enhance its opportunity and efficiency.	Optimal integration of remote telepresence, 3D printer control, and XR telecommunication *Likelihood: Medium, Impact: Medium*
Sustainability and Circular Economy	Integration of sustainable design principles in XR-based fabrication, exploration of eco-friendly materials and manufacturing processes, adoption of circular economy principles in Fab Lab operations	Operational strategies while maintaining performance and usability. *Likelihood: Medium, Impact: Medium*
Real-time synchronization	Synchronization with VR (Virtual Reality) users and physical devices in Fab Lab. Handling large volumes of data in real time. User experience (UX) is measured with XR tools and Fab Lab devices connectivity	Network latency and bandwidth limitations. *Likelihood: Medium, Impact: Medium*
Innovation and Entrepreneurship	Promotion of innovation and ideation through XR-enabled design tools, incubation of entrepreneurial ventures leveraging XR and Fab Lab resources	Effective knowledge dissemination particularly in diverse and underserved communities. *Likelihood: Medium, Impact: Medium*
Scalability and performance	By creating a common platform for Fab Lab, 3D printer and XR gadget and connectivity, the common service can be delivered to global Fab Lab communities more than 2500 worldwide including metropolitans and rural areas	robust and inclusive common platform that seamlessly integrates Fab Lab, 3D printers, and XR gadgets. *Likelihood: Medium, Impact: Medium*

Precision	Quantifying the level of precision achieved in measuring energy consumption, expressed as a percentage of accuracy. These energy consumption aware strategies will also contribute to a better sustainability	Enhancing the accuracy of energy measurements. *Likelihood: Medium, Impact: High*
Affordable and clean Energy	The 6G-XR energy use case offers an energy measurement framework to implement hybrid energy solutions for the next generation of mobile networks, extending even to remote and rural areas. This will enhance the affordability of mobile services, marking a significant stride towards the transformation of these networks into green and sustainable entities	Effectiveness and implementation of the energy measurement framework. *Likelihood: Low, Impact: Medium*

6 ANALYSIS OF THE THREE DEVELOPMENT AVENUES OF 6G

6.1 3GPP EVOLUTION PATH

In 3GPP Next Generation Radio Access Network (NG-RAN), the gNB functionalities are divided into the Central Unit (CU), Distributed Unit (DU), and Radio Unit (RU). The Control Plane (CP) and User Plane (UP) functionalities are also separated allowing different deployment options and approaches to the control for the RAN functions.

Furthermore, the gNB protocol stack functionalities can be split between the CU, DU, and RU in different ways to further optimize and tailor the RAN performance. The Higher Layer Split (HLS) options (e.g., the default HLS Option 2) provide increased flexibility in the implementation and deployment of NG-RANs as a mix of virtual and physical network functions. The Lower Layer Split (LLS) options (e.g., Option 7 or 8) are well suited for deployments requiring extremely high data rates and low latencies, but they are less flexible from the point of view of large-scale deployments.

Simplified representations of the resulting 3GPP NG-RAN architecture are depicted in Figure 24. The different CU-DU-RU configurations and deployment options as well as the additional interfaces interconnecting the different logical entities can be found from the 3GPP Release 15 RAN specifications [26], [27] and from [28].

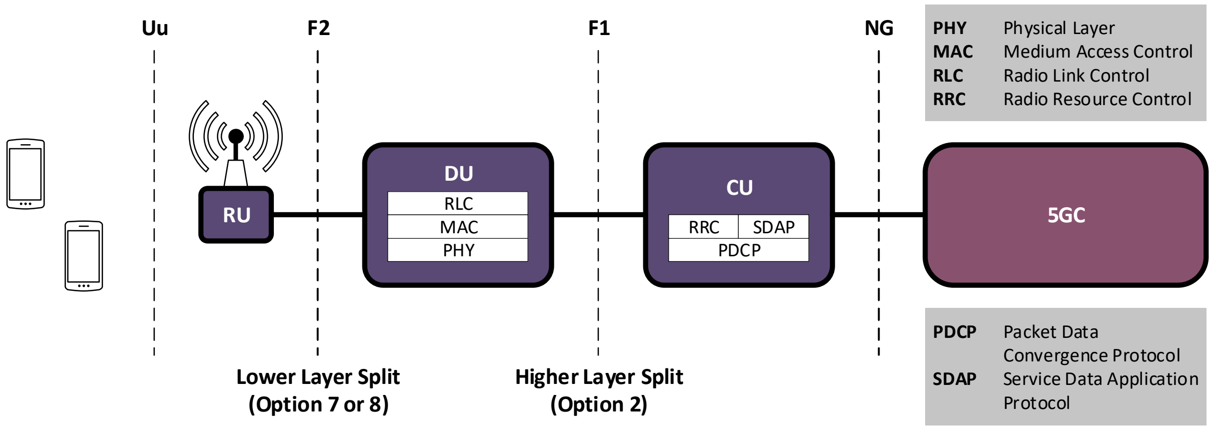

Figure 24. 3GPP NG-RAN architecture.

Enhanced support for XR applications and services in 5G has been studied under several work items for 3GPP Releases 15 and 17, and the work is still ongoing for 5G-Atargeting the future 3GPP Releases 18 and 19. Table 22 contains some examples of the most relevant XR related study items inside 3GPP.

Table 22: Example 3GPP specifications and work items related to XR

3GPP spec./ work item	Brief description	Potential applicability to XR in general and relation to 6G-XR use cases
TR 26.918 / Study on Virtual Reality (FS_VR)	This document describes VR concepts, presents VR use cases (3DoF), lists methods for assessment of QoE of audio and video systems, indicates latency and synchronization requirements, performs gap analysis on 3GPP standardization of VR services. The report concludes that: • VR services using existing 3GPP speech/audio codecs is possible. • A study item on QoE metrics relevant to VR user experience should be initiated (TR 26.929). • Standardization of VR streaming could be based on progressive download, DASH-based streaming, or DASH-over-MBMS delivery • Standardization of 'real-time' VR calls between UEs could be based on MTSI codecs, although encapsulation into RTP and SDP signalling are FFS.	XR relation: Virtual Reality is just one of the types of Extended Reality. 6G-XR use case relation: • VR calls between UEs is addressed in section 5.9 of TR26.918. • DT use case is not contemplated in TR26.918.
TR 26.928 / Study on Extended Reality (XR) on 5G (FS_5GXR)	This document studies the use of 5G networks to deliver XR applications. It describes the types of XR, describes the degrees of freedom that must be supported, identifies the several types of delivery of XR applications, and lists the available types of XR devices. It also presents 26 XR use cases, to add to those identified in TR26.918, and identifies the 3GPP standardization needs to deliver these use cases.	XR relation: This document explains what XR is, it presents an overview of how the 5G networks can deliver different XR use cases and identifies potential standardization needs. 6G-XR use case relation: • TR 26.928 includes use case no. 7 (Real-time 3D communications), which is similar to 6G-XR's "real-time holographic communication" use case. The potential standardization work related to this use case are described in section 5.3.3. and 7.5. • Use cases no.3 (streaming of immersive 6DoF), no. 21 (streaming of immersive 6DoF with social interaction) and no. 13 (3D shared experience), although not identical to 6G-XR's "collaborative 3D digital twin-like environment" use case, share some similarities

		among them. Potential standardization work related to these use cases is described in section 5.4.3 and 5.7.3.
TR 22.842 / Network Controlled Interactive Service (NCIS)	TR 22.842 describes use cases and performance requirements for interactive services, focusing on CG.	XR relation: The requirements for a use case using interactive VR devices are included. 6G-XR use case relation: The performance requirements related to CG could be applicable to use cases where VR models are running at the network edge or in the cloud.
TR 22.847 / Study on Tactile and Multi-Modality Communication Services (FS_TACMM)	TR 22.847 describes tactile and multi-modal use cases and respective performance requirements. By definition tactile internet services combine ultra-low latency with extremely high availability and reliability, while multimodal services combine input from more than one source (e.g. several sensor types) and/or output to more than one destination (e.g. several UEs).	XR relation: The document describes three use cases related to XR, more specifically, related to VR. These use cases are i) immersive multimodal VR application; ii) immersive VR game; iii) virtual factory. 6G-XR use case relation: The initial 6G-XR pilot use cases described in this document do not include tactile internet or multimodality aspect, but it is expected that both could be part of the future prospective use cases from the 6G-XR Open Calls or from the later phases of the SNS JU.
TR 22.856 / Study on Localized Mobile Metaverse Services (FS_Metaverse)	This Release 19 document proposes 28 enhanced-XR use cases, and potential 5G requirements and KPIs.	XR relation: TR 22.856 investigates specific use cases and service requirements for 5GS support of enhanced XR-based services, (as XR-based services are an essential part of "Metaverse" services considered in this study,) as well as potentially other functionality, to offer shared and interactive user experience of local content and services, accessed either by users in the proximity or remotely. 6G-XR use case relation: Section 5.3 presents the use case “collaborative and concurrent engineering in product design using metaverse services”,

		including the typical QoS requirements. This information can be used to configure the 6G-XR use case on "collaborative 3D DT-like environment".
TR 38.838/Study on XR evaluations for NR (FS_NR_XR_eval)	This Release 17 document assesses the performance of 5G RAN for XR applications. More specifically, it: • defines traffic models for diverse XR applications. • defines the evaluation methodologies to assess 5G RAN performance for diverse XR applications deployed in FR1 and FR2 frequency ranges. The metrics considered in the study were network capacity, UE power consumption, coverage, and mobility. • concludes that 5G New Radio (NR) can support XR for the evaluated scenarios, although NR was not designed taking into account the XR specificities. • demonstrated that RAN capacity and UE power consumption can be improved if some suggested RAN enhancements are used. • recommends to further study and enhance at least the capacity and UE power consumption performance of 5G NR for XR applications.	XR relation: This study assesses the performance of 5G NR for diverse XR applications and shows that 5G NR can support them in several scenarios. It also shows that performance (capacity, UE power consumption) can be improved if the RAN improvements suggested by the authors of the study are introduced in 5G NR. However, these improvements were not standardized by 3GPP. 6G-XR use case relation: The study allows to determine what are the performance limits of 5G NR when deploying the 6G-XR use cases. It also suggests some 5G NR improvements that, although not standardized by 3GPP, allow to improve the performance (e.g., capacity, UE power consumption) of 6G-XR use cases.
TR 38.835/Study on XR enhancements for NR (FS_NR_XR_enh)	Following the recommendation of the Release 17 RAN study (TR 38.838), this Release 18 study (TR 38.835) recommends the standardization of a set of RAN enhancements to improve the capacity and UE power consumption of XR applications. In addition, this document also proposes the standardization of a set of enhancements to improve XR awareness in the RAN. To improve the XR awareness in the RAN it is suggested that: • XR packets are aggregated in 'Protocol Data Unit (PDU) sets' and 'Data Bursts' and the	XR relation: This study recommends the standardization of some RAN enhancements, specifically designed to cope with the periodic XR traffic characteristics (i.e., frame rate). 6G-XR use case relation: It is not expected that 6G-XR will be able to implement these RAN enhancements into its experimentation facilities. However, the proposed functionalities could be analyzed in other ways when it comes to potential enhancements to the

	importance/priority of each 'PDU Set' is defined. • the core network provides additional information to the RAN so the downlink scheduling performed at the gNB can be adapted to the time characteristics of XR traffic. • the UE provides additional information to the RAN so the uplink scheduling performed at the gNB can be adapted to XR traffic periodicity. In addition, to improve UE power consumption it is suggested to align DRX periodicity with XR frame rates and to improve the RAN capacity for XR services it is proposed to: • have the possibility of occurring several configured grant Physical Uplink Shared Channel (PUSCH) transmission occasions during the period of a single configured grant PUSCH configuration. • add the Dynamic indication, by the UE, of unused configured grant PUSCH occasion(s) based on Uplink Control Information (UCI). • add Buffer Status Report (BSR) enhancements including at least new buffer size table(s). • Add Delay reporting of buffered data in uplink. • Add the Discard operation of PDU Sets.	identified shortcomings in the capabilities of the currently standardized 3GPP technologies to support the 6G-XR use cases.

6.2 OPEN SOURCE/O-RAN PATH

Like other technologies, 5G is evolving quite rapidly with the open-source principles which are directly contributing to the 6G development. In 6G-XR project, together with all the commercial 5G solutions, several open-source 3GPP compliant 5G-A components will also be used both in north and south nodes of the project. The idea is to complement the functionality of main network deployments at the testing facilities and provide more flexibility for the implementation of the project use cases and scenarios.

In addition to the 3GPP specified network functionality, the testing facilities will investigate the usefulness of O-RAN Alliance specified RAN components and interfaces in the deployment of the 6G-XR use cases. The main novelties introduced by the O-RAN architecture (see Figure 25), as compared to the RAN architecture proposed by 3GPP are the following:

- The introduction of an Open Fronthaul (O-FH) interface between DU and RU, which ensures that DU and RU components provided by different vendors should be interoperable.

- An O1 interface to manage the different elements of the RU, DU and CU components using NETCONF/YANG, where the actual YANG models may be defined by the different vendors.

- A near real-time RAN Intelligent Controller (near rt-RIC), which controls the DU and CU elements through the E2 interface. ORAN specifies different Service Models (SMs) for the E2 interface, which define the interactions between the RIC and the E2 nodes. At the time of this document, E2 Service Models include:

    - E2SM-Key Performance Measurement (E2SM-KPM)

    - E2SM-RAN Control (E2SM-RC)

    - E2SM-Cell Configuration and Control (E2SM-CCC), and

    - E2SM-Network Interfaces (E2SM-NI).

- A key feature offered by the near rt-RIC is the concept of xApps, which are containerized control plane applications that provide customized control logic. The xApps interact with the DU and CU elements through the E2 interface.

- A non-real-time RAN Intelligent Controller (non rt-RIC), which can manage policies for the xApps deployed in the near rt-RIC through the A1 interface. The non rt-RIC can also host customized radio management applications known as rApps. ORAN defines the notion of near real-time to comprise time scales between 1 ms and 1 second, and the notion of non-real-time to comprise time scales above 1 second.

- The Service Management and Orchestration (SMO) component that is used to manage the radio functions through the O1 interface, and the underlaying cloud infrastructure hosting the radio functions through the O2 interface.

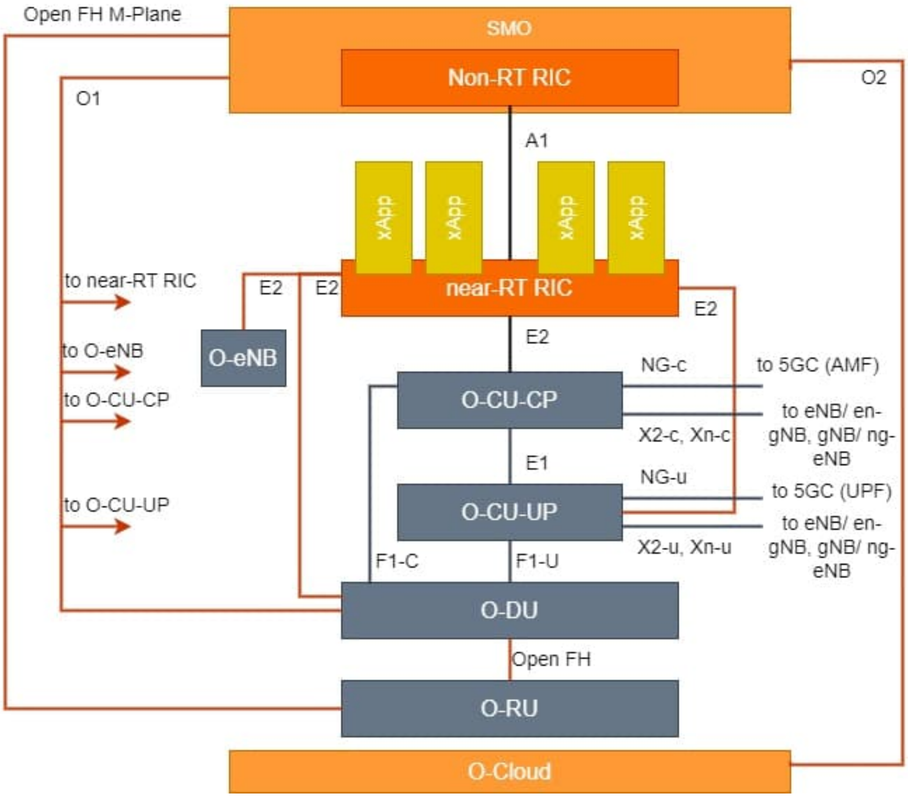

Figure 25. O-RAN architecture [29].

Besides fostering an open ecosystem through the introduction of open interfaces, the main feature of O-RAN is the ability to customize the behaviour of the RAN functions using xApps and rApps. In Table 23, we provide examples of how these customization capabilities could be applied to enhance the performance of XR services, while referring to the 6G-XR use cases when possible. The application of O-RAN capabilities to enhance the performance of the use cases considered in 6G-XR will be studied in detail in WP4.

Table 23: O-RAN features and their relation to XR applications

O-RAN feature	Brief Description	Potential applicability to XR in general and relation to 6GXR use case (if applicable)
Near real-time RIC hosting xApps	xApps can be seen as cloud native applications that sit in the near real time RIC and can monitor and configure E2 nodes through the E2 service models (E2SM) standardized by ORAN.	XR relation: Custom xApps could be designed that enhance some aspect of the XR application performance by making use of E2 service modes. Concrete examples provided later. 6G-XR use case relation: See discussion in E2SM entries.
E2SM-KPM	E2SM Key Performance Measurement (KPM) – provide UE/cell level counters to near-real time RIC with granularity below 1 second.	XR relation: Among others, the high granularity provided by the E2SM-KPM can be used for example to: • Optimize grant configuration for eDRX, thus optimizing the power consumption performance of an XR headset.

		• Map O-CU and O-DU loads to accurate energy consumption data for the creation of energy profiles for different applications and network states. 6G-XR use case relation: E2SM-KPM could be used in the 6G-XR use cases defined in Chapter 3 in the following way: • E2SM-KPM could be used to collect Physical Resource Block (PRB) utilization at cell level with high granularity to feed the congestion detection function specified in the south-node user plane optimizations use case. • The energy profiles based on the E2SM-KPM and energy consumption data could be used for the optimization of the end-to-end energy consumption of XR application and services in the North Node use case developed in WP5.
E2SM-RC	E2SM RAN Control (RC) – Allows xApp to: i) Control radio bearer parameters (e.g. QoS Class Identifier (QCI)), ii) Control resource allocation (PRB) at slice or UE level, iii) Control connected mobility (e.g. command handovers), iv) Control carrier aggregation/dual connectivity parameters.	XR relation: E2SM RC impacts performance experienced by a certain UE and can therefore be directly applied to enhance performance of XR applications. For example: i) an XR UE could be prioritized inside a cell by upgrading the QCI of its bearer, ii) a set of PRBs could be reserved for XR applications, and this reservation could be updated dynamically to avoid wasting resources when XR devices are not active in a cell, iii) control over connected mobility could be used to load balance XR users to a less congested cell in case of congestion, and iv) carrier aggregation or dual connectivity configurations could be used to favour XR users. A challenge associated to all these use cases is how to effectively identify an XR user in the RAN, where xApps only have visibility of RAN Ids. 6G-XR use case relation: E2SM-RC could be used in the following way in the 6G-XR use cases identified in Chapter 3: • South-node user plane optimizations use case: Upon detecting congestion, E2SM-RC could be used to protect the XR devices by, e.g., redirecting them to a less congested cell. Notice that this is complementary to the prioritization mechanisms discussed in the use case, e.g., the CAMARA QoD API. • The E2SM-RC functionality could be used for the UE specific energy-aware resource (scheduling, resource block, resource element) control required by the Nort Node end-to-end energy optimization use case developed in WP5.

E2SM-CCC	E2SM Cell Configuration and Control (CCC) – Allows xApps to configure cell parameters such as: i) membership to RRM policy groups, ii) Public Land Mobile Network (PLMN) ID, Single Network Slice Selection Assistance Information (S-NSSAI) and Access and Mobility Management Function (AMF) lists, iii) configuration of bandwidth parts, and iv) radio related parameters (e.g., Tracking Are Code (TAC), E-UTRA Absolute Radio Frequency Channel Number (EARFCN), etc).	XR relation: E2SM-CCC can be used to optimize configurations at cell level. An example application to optimize XR services consist of an MNO that has deployed a slice dedicated to serve XR users. This XR slice is allocated a given number of PRBs in the different cells where it is present. Given that the presence of XR users connected to these cells will not be constant, an xApp could be designed that uses the E2SM-CCC to adjust the number of PRBs dedicated to the XR slice in the different cells to minimize waste of PRBs while delivering the desired QoE to XR users. 6G-XR use case relation: E2SM-CCC could be used in the following way in the 6G-XR use cases identified in Chapter 3: • The E2SM-CCC functionality could be used for the cell specific energy-aware resource (booster cells/sectors, TX chain, Multiple Input Multiple Output (MIMO) configuration, component carrier) control required by the Nort Node end-to-end energy optimization use case developed in WP5.
non-rt RIC and rApps	The non real time RIC hosts radio Apps (rApps) which can influence RAN behavior by means of: i) issuing policies towards the xApp through the A1 interface, and ii) acting upon the radio and O-Cloud configurations through the O1 and O2 interfaces respectively. The O-RAN External Interface (EI) can be used to inject application-level context to rApps.	XR relation: rApps have access to non-real time RAN information while embedding native ML capabilities. A typical example for an rApp is a predictor rApp that serves predictions to other rApps that can then optimize the network. As a matter of example, in the context of XR applications, a congestion prediction rApp could be used to optimize QoE of an XR session, or a trajectory prediction rApp could be used to customize the handovers of a moving XR device. 6G-XR use case relation: The rApps in the non-rt RIC could be used in the following way in the 6G-XR use cases described in Chapter 3: • South-node user plane optimizations use case: An rApp could be implement that access cell-level counters retrieved by an xApp at high granularity to implement the congestion detection function. This rApp would be integrated with a congestion detection module in the Network Data Analytics Function (NWDAF). • rApps could be used for the collection of long-term resource and energy consumption data as well as for the high-level optimization policies based on the availability of local renewable energy in the Nort Node end-to-end energy optimization use case developed in WP5.

6.3 DISRUPTIVE 6G PATH

The ever-growing need of wireless communication calls for wide bandwidths that is available in the mm-wave and sub-THz spectrum. The D-band (110GHz-170GHz) and G-band (110GHz-300GHz) are seen to be the frequency bands in which sufficient spectrum can be allocated for wireless communication with data rates of 100Gbit/s and beyond.

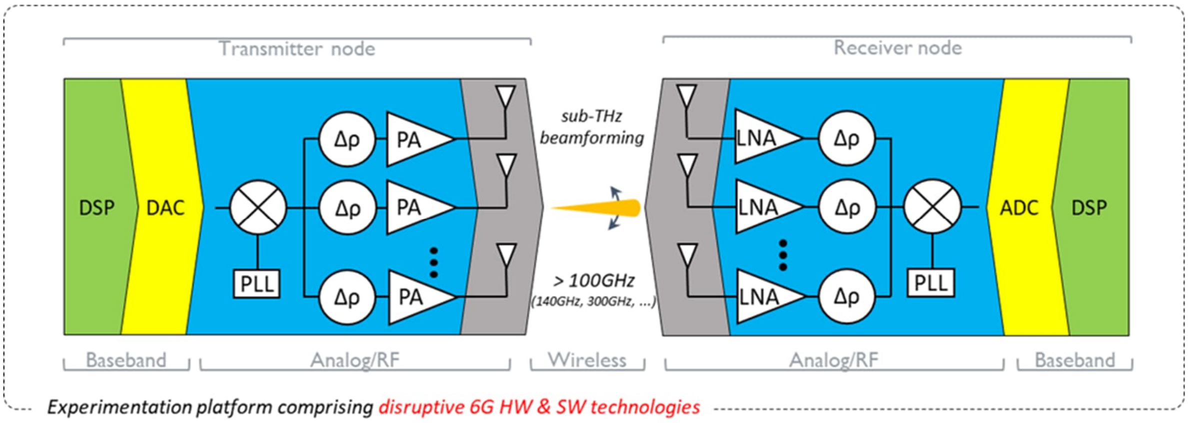

Figure 26. Abstract illustration of the envisioned disruptive 6G platform.

An experimental framework will be developed comprising disruptive technologies which are key in future 6G radios. The framework builds on disruptive sub-THz frequency transceiver technologies of integrated sensing, communication, and localization. An illustration of a possible platform is illustrated in Figure 26.

The transmitter and receiver nodes will comprise disruptive analog/RF hardware components & research prototypes and will implement high-throughput baseband software on commercial data acquisition and processing boards. There will be two parallel radio transceiver development paths in the project. The first transceiver is targeted for 140 GHz operation by IMEC, and the second transceiver is targeted for the 300 GHz band by the University of Oulu. The RF interface towards the radio transceiver can be either radiated or conducted depending on RF chip implementation. The RF-to-baseband interface is an analog interface, and the analog-to-digital (ADC) converters are external components. The radio solution can be tested as a standalone with measurement equipment. The beamforming will be supported with developed radio transceiver key components.

The ADCs can be integrated with the digital signal processing (DSP) functionality which performs digital signal manipulation. The selection of the DPS functionality unit effects the achievable system data rate of the radio demonstrators. The DSP equipment can be connected to the higher layers of the communication network.

The design and performance targets as well as validation results of the 6G radio demonstrators will be documented in the following documents D4.1, D4.2 and D4.3.

7 OUTLOOK FOR FUTURE PROSPECTIVE USE CASES

In addition to the internal pilot use cases described in this document, the RIs developed throughout the project should also be able to serve the needs of the complementary use cases coming from the 6G-XR Open Calls during the project's lifetime as well as the needs of the future prospective use cases developed at the Proof of Concept (PoC) level in the Phase 1 of the SNS JU Stream B projects. In order to assess the potential future needs, this chapter provides some preliminary discussions on the XR related PoCs currently under development in the following projects.

Hexa-X-II[5]: The project has defined an initial set of 7 use cases. Among these, a telepresence use case titled Fully Merged Cyber-Physical Worlds have been chosen as one of the technology-centric use cases to be investigated especially from the point of view of the novel technologies enabling the required new services. The use case will look into the application of mixed reality and holographic telepresence technologies over mobile networks to facilitate remote collaboration between workers and social interactions between people in general. As the telepresence use case in Hexa-X-II has a close resemblance to the Holographic Communications use case in 6G-XR, future large-scale trials on the Fully Merged Cyber-Physical Worlds use case could potentially be run on top of the 6G-XR RIs exploiting the XR and communication enablers developed in the 6G-XR project. Other Hexa-X-II use cases in the domain of DTs, cobots, and sustainability also have some synergies with the 6G-XR use cases, but as the environments to which the Hexa-X-II use cases are focusing on are drastically different than those targeted in the 6G-XR use cases, the potential for the direct utilization of the 6G-XR RIs and enablers is harder to estimate in the early stages of the use cases' development at the time of this writing.

ADROIT-6G[6]: One of the project's three PoCs is called Immersive XR – Holographic Teaching. The PoC is built around a teaching scenario where the teacher is teaching from a remote location (e.g., home or office) and the students are gathered into a classroom to follow the class given by a holographic version of the remote teacher. This scenario has strong synergies with the Holographic Communications use case in 6G-XR which implies that the XR and communication enablers developed in 6G-XR and deployed in the 6G-XR RIs could be utilized to also trial a large-scale use case based on the Immersive XR – Holographic Teaching PoC of the ADROIT-6G project.

DETERMINISTIC6G[7]: The project studies deterministic wireless communications and TSN as technology enablers for XR, manufacturing, and robotics through modelling and simulations. Definition of more focused use cases requiring deterministic communications will be part of the project work in DETERMINISTIC6G, so clear trialling collaboration scenarios have not yet been identified. However, as XR is one of the target vertical domains under investigation, potential trialling needs can emerge as the research progresses. 6G-XR also includes TSN experimentations in its use cases. New communication enablers deployed into the 6G-XR RIs as a result of those experiments could offer trialling capabilities also for the DETERMINISTIC6G use cases when they have been defined in detail.

HORSE[8]: The project focuses on the design and development of the new and novel security solutions for 6G networks and service management. One of the use cases where the developed solutions are to be demonstrated is called Remote Rendering to Power XR Industrial. The use case is built around extensive utilization of XR technologies in critical industrial settings. Even though the HORSE project

[5] Hexa-X-II project website: https://hexa-x-ii.eu/

[6] ADROIT-6G project website: https://adroit6g.eu/

[7] DETERMINISTIC6G project website: https://deterministic6g.eu/

[8] HORSE project website: https://www.horse-6g.eu/

focuses more on the security and service management enablers, potential trialling synergies with 6G-XR project and its RIs could be found in the future based on the XR enablers developed in 6G-XR.

6GTandem[9]: The project studies and develops new radio communication enablers for indoor and environments and crowded pubic areas. One of the foreseen use cases for the developed technologies is titled Immersive Entertainment for Crowds of People (e.g., arenas). The research in the 6GTandem project is very focused on the radio interface, but from the point of view of the potential future trialling needs, the XR and communication enablers developed in 6G-XR and deployed in the 6G-XR RIs could provide possibilities for integration of testing environments or network components for the deployment and large-scale experimentation of the Immersive Entertainment for Crowds of People use case.

6G-SHINE[10]: The project investigates access network deployments in different environments focusing on industrial, in-vehicle, and classroom setting. In these environments, the use case In-Classroom XR Applications for Education contains gaming and entertainment aspects in addition to the utilization of XR application for teaching. Similarly, to the ADROIT-6G project and its use case related to teaching, there could potentially be strong synergies between the 6G-SHINE classroom use case and the 6G-XR use cases on Holographic Communications and Collaborative 3D Digital Twin-like Environment. Both the XR and communication enablers deployed in the 6G-XR RIs could be of use in the future trials based on 6G-SHINE work.

[9] 6GTandem project website: https://horizon-6gtandem.eu/

[10] 6G-SHINE project website: https://6gshine.eu/

8 SUMMARY

This deliverable provided a detailed description of the project's five use cases and different scenarios planned to be trialled during the project regime. It also listed all the requirements as well as all the KPIs and KVIs considering the use cases and scenarios of the 6G-XR project. Since this document is going to be the first technical deliverable of the 6G-XR, an initial reference architecture has also been included in this document for the better understanding of the principal components of the project targeting the use cases.

This deliverable covers all the initial details of the components, methodologies, deployment architectures, etc. for the project use cases and scenarios. Therefore, it shall be used as a foundation for the project's subsequent technical tasks in different work packages during the 6G-XR project lifetime. The work and plans presented in this report will have a direct impact on the following tasks of the project, which will provide more details in their respective deliverables on the XR and communication enablers developed in the project:

- T1.3, to make sure that the 6G-XR reference architecture design supports the target use cases.
- T1.4, to ensure that the experimental infrastructure and testbeds implementing the reference architecture are evolved with the use cases.
- T2.1, to confirm the capabilities of the computing tools and edge computing to support the use cases and scenarios.
- T2.2, so that the AI based orchestrator can optimize the 5G network.
- T2.3, for the E2E network slicing focusing on resource optimization in the slices of the use cases.
- T4.1, to deploy the B5G E2E network to support the target use cases.
- T4.2, to deploy and use the B5G E2E network based on open-source tools and technologies for validating the use cases KPIs.
- T4.4, to ensure that the trial controller, APIs, and orchestration supports trialling the use cases and scenarios of the project.
- T5.1, for ensuring the energy measurement framework to support the 3rd use case of the project.
- T5.4, to make sure that energy efficiency optimization supports the target use cases.
- T6.1, to confirm that the adjustment of the components of holographic application supports the target use case.
- T6.6, targeting the 3D DT use case KPI and KVI validations.

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APPENDIX 1 – 6G-XR RESEARCH INFRASTRUCTURES (RIS)

The RIs providing the starting point for the 6G-XR technology and use case development work as well as the experimentation and validation platform for the project's final use cases are defined in the following subsections. A more detailed description of the RI architectures and configurations to be utilized during the 6G-XR project will be provided in the deliverable D1.3 later on in the project.

6G-XR North Node (UOULU 5GTN and VTT 5GTN)

The **University of Oulu** (UOULU) has 5G Test Network (UOULU 5GTN) with campus-wide-reach small cell, macro-cell and distributed antenna based cellular network to be complemented by NFV based Evolved Packet Core (EPC) and 5G backhauling solution (http://5gtn.fi/).

The Full-scale 5G Test Network in the University of Oulu supports usage of 5G devices, higher frequency bands, cognitive management functionalities, system testing tools for new solutions. The 5G Test Network feature evolution follows 5G research and standardization progress, acting as verification platform for theoretical 5G research. The cellular devices part of the network is composed of 30 Long Term Evolution (LTE) small cells (700 MHz, 2.1, 2.3, 2.6, 3.5 GHz) and 2 macro cells (2.3 GHz). The network has two 5GNR base stations (3.5 GHz) complemented with several tens of User Equipment (UE) from various manufacturers that are easily integrated to any device, and tens of 5G enabled mobile phones from several vendors. The network is currently being complemented by commercial mmW (24-28 GHz) 5G NR base stations with several mmW capable UE's as well as with 36 remote radio head (RRH) based cloud RAN 5G NR devices. The network is controlled by operator grade EPC (Evolved Packet Core), thus making UOULU in practice a network operator with own SIM production for mobile devices. The current operational EPC version is 5G Non-Standalone (NSA) compliant, but for research purposes 5G stand-alone (SA) solution with its own core and macro base station is also available. The network within the campus is complemented by wireless IoT sensor network extension with estimated 2000 different kinds of sensors with wireless connectivity through Narrowband IoT (NB-IoT), LTE Machine Type Communication (LTE-M) and Long Range (LoRa) links. Furthermore, the network has big data computing servers for network data analytics purposes. Some of these servers are distributed as edge servers within the network thus allowing multi-access edge computing (MEC).

On top of the commercial 4G, 5G and mmW solutions also open standard solutions are offered. Several different 4G and 5G core solutions are available for research use. Technologies in use are for example Open5GS core, Open Air Interface (OAI), different kinds of USRP radios, etc.

Several different kinds of test equipment and software is offered to be used. There are for example commercial grade radio parameter measurement equipment and software available. For IP network traffic an extensive Quality of Service (QoS) test software is in use.

VTT Technical Research Centre of Finland Ltd (VTT) is operating a 5G Test Network (VTT 5GTN) with several private 5G network deployments in different locations in Finland including outdoor coverage as well indoor coverage in several buildings and areas (https://www.vttresearch.com/en/technology-infrastructures/secured-connectivity-infrastructure). The main site for 6G-XR experiments is located in Oulu, but all VTT sites are connected via fiber connections for resource sharing, and it is possible to create connections to remote experimentation infrastructures via virtual private network (VPN) or direct fiber links. The current radio coverage is deployed with LTE, 5G NR, Wi-Fi 6 and LoRa technologies. The current deployment includes the following frequency bands: LTE 450MHz (BW:5MHz), 700MHz (BW:10MHz),1800MHz 2100MHz (BW:10MHz), 2300MHz (BW:20 MHz), 2600MHz (BW:10MHz), 5GNR 3500MHz (BW:60MHz), 5GNR mmW band N258 (BW:800MHz).

The network has been designed to support dynamicity in the experimentation. Network configurations (e.g., number of cells, frequency) and antenna setups including transmitting power may be changed towards specific vertical use case requirements. While the network coverage with high frequency 5G NR is typically < 1 km, with cellular IoT technology such as, NB-IoT the coverage will reach above 10 km distances for massive Machine Type Communications (mMTC). In addition to LTE and 5G NR coverage test sites include indoor deployments with Wi-Fi 6 technology. The available user equipment (UE) includes the newest commercial UEs, evaluation boards as well as a software-defined radio (SDR) based UE emulator (Keysight) capable of emulating with current setup up to 1000 LTE and 100 5G NR UEs. For the deployed core networks there are carrier-grade telco cloud and open-source instances available.

Edge processing has been deployed with several edge platform implementations with local data break out following the ETSI multi-access edge computing (MEC) specifications and application development in local/private networks. Edge solutions include general hardware and open-source software as well as commercial proprietary solutions. Deployment includes Nvidia Tesla server platform for AI processing as mobile network edge server, which can be tailored to process application/service data or large telecom data from our carrier-grade cellular network. Fixed backbone includes 40/100 Gb connections on site as well as 10 Gb links towards world-wide internet connection. The test site also includes an off-grid powering system for the cellular network site components including local power production with solar cells. The system is modular and capable of supplying both 48 VDC and 230 VAC for the indoor and outdoor RAN components.

6G-XR North Node Beyond State-of-the-Art

VTT 5GTN and UOULU 5GTN will be upgraded to allow B5G and 6G experimentation and research activity. 3GPP 5G advanced evolution will be supported by upgrading the 5G core software (commercial and open source) and RAN with 3GPP Rel. 16 and 17 base stations and user equipment at 3.5 GHz and 24 GHz to support URLLC as well at lower frequencies such as 450-850MHz for supporting mMTC. Possible new frequency bands and support for both 5G NR TDD and FDD is expected. For non-3GPP technology, Wi-Fi 7 technology will be adopted when it comes available.

The different nodes comprising the experimental facility will adopt Open RAN (O-RAN) architecture and interfaces to study the impact of having virtualized distributed function splits in the RAN. The different RAN functionalities will be managed and monitored by the near-real-time and non-real-time Radio Intelligent Controller (RIC). Both the controlling and monitoring capabilities offered by the O-RAN architecture will facilitate the deployment of AI algorithms for RAN optimizations and energy-efficient RAN control. Virtualized Radio Unit (RU) functionalities will run on SDR platforms providing up to 140 MHz radio links and MIMO schemes.

Atomic clock-based time synchronization will be deployed for accurate and robust indoor time synchronization. Time synchronization plays a key role for the accurate data delivery and measurement timings needed in the various validation cases.

For developing and validation purposes of sustainable and energy-efficient 5G-A, as well upcoming 6G technology, this project will build a validation environment providing E2E energy forecasting system, storing assets and autonomous base station(s) with energy optimization features. The network will be equipped with intelligent off-grid power systems as well to maximize the utilization of renewable and local energy by the network components.

6G-XR South Node (5GBarcelona and 5TONIC)

i2CAT Foundation offers 5GBarcelona, a fully-fledged 5G network for experimentation purposes in the city of Barcelona (https://5gbarcelona.org/). This is a multi-site network distributed in various locations of the Barcelona metropolitan area, mixing indoor and outdoor deployments. Sites are interconnected with dedicated point-to-point fibre links (10 Gbps) to i2CAT's headquarters. 5G Barcelona covers media, health, industry, transport, security, and automation, among other services, ranging from encouraging the adoption and validation of 5G technology, and the transfer of knowledge in 5G, to the creation of business opportunities. Its current equipment can be categorized in the (1) radio, (2) edge and (3) datacentre segments. Under an open and multi-vendor perspective, where the (1) radio infrastructure is composed of three 4G small cells (two in b43 and one in b42, both are with a maximum bandwidth of 20MHz), one 5G small cell (N77 with a maximum bandwidth of 100 MHz and a starting frequency of 3900 MHz), as well as 23 multi-purpose SDRs (each of them with a maximum bandwidth of 50MHz, central frequencies of 100-6000 MHz, and featuring 4G and 5G in NSA/SA modes). The cellular infrastructure is connected to a fully virtualized 5G Core Network (5GC) from different open-source projects (i.e., Open5GS, Free5GC, OpenAirInterface), and all of them support NSA and SA modes. Regarding the non-3GPP radio access, 5GBarcelona has six WIFI nodes (five WIFI 5 and one WIFI 6), that can be used either as access points or as backhaul links. On the (2) edge segment, 5GBarcelona features 3 NUCs with a combined maximum theoretical capacity of ~700 vCPUs and 192 GB of memory. Finally, the (3) datacentre segment consists of 3 servers with a maximum capacity of ~2600 vCPUs and 512 GB of memory. The whole cellular and WIFI infrastructure is managed by a radio controller developed by i2CAT. On top of this, i2CAT's Slicing and Orchestration Engine manages the whole lifecycle of the network slices. 5GBarcelona will be interconnected with 5TONIC with the best available alternative in terms of throughput and latency with the objective of easing the federation of resources across the network slices.

Telefónica/Ericsson/Capgemini Spain operate 5TONIC, an open research and innovation laboratory focusing on 5G technology integration, adoption, and evolution (https://www.5tonic.org/). 5TONIC is an open global environment where members of industry and academia alike can work together on specific research and innovation projects related to 5G technologies with their combined insight allowing them to boost technology and business innovation ventures. Ericsson is the partner that provides the RAN and the 5G core network for the laboratory. The infrastructure supports common 5G Services: (1) enhanced Mobile Broadband (eMBB), (2) massive Machine Type Communications (mMTC), and (3) ultra-Reliable and Low Latency Communications (uRLLC). It provides a 5G NR access network in low, mid, and millimeter wave bands with different bandwidths (20,40,50, 60, 100 MHz) and with the possibility of doing carrier aggregation, to achieve sustained throughput beyond the Gbps and lower latency than LTE networks (as good as 4 milliseconds one-way delay in the access network). The access network also supports MIMO technology, NB-IOT, and Cat-M for testing machine-to-machine use cases, and a dedicated edge data network that is less than 1 millisecond from the access and allows the deployment of vertical applications at the network edge.

5TONIC also provides a full-fledged portable 5G network that can be used for demonstrating use case in the vertical premises or in an event. It allows for exploring and validating a variety of Edge Computing models by keeping the URLLC slice closer to the physical location of the user. The portable network is composed by a RAN and the 5GC user-plane, which are the elements deployed near the users, and allow to connect through a secure connection with the 5TONIC central core for managing the control plane. The portable system supports antennas for providing outdoor (e.g., a 5G MIMO mid-band antenna) and indoor (e.g., Ericsson Dot system) coverage. Such equipment is used to provide 5G coverage in vertical offices or in events.

5TONIC regularly cooperates with 5G handset and CPE manufacturers for their use in E2E validation activities of mutual benefit. WNC, Fivecomm, Xacom and ASKEY are representative manufacturers engaged in 5TONIC activities.

5TONIC also integrates in its site a MEC implementation that offers multiple capabilities, accelerators and frameworks for rapid development of MEC solutions with optimized HW infrastructure resources and increased computing and Input/output Operations per Second (IOPS) performance and reduced network latency. The platform integrates OpenNESS and can reside on micro data centres close to the access network, aggregation points, regional data centres and central offices, as best suited for edge app developers. The platform offers API integrations compliant with GSMA Operator Platform, CAMARA Project API and ETSI MEC.

6G-XR South Node Beyond State-of-the-Art

5GBarcelona and 5TONIC will see upgrades on their equipment and functionality to support the 6G capabilities by addressing four main pillars: (1) AI/ML powered XR service awareness; (2) holistic end to end XR awareness, service migration and continuity, (3) XR-aware eMBB/URLLC; and (4) native XR session control. The infrastructure will be upgraded to meet these capabilities. Firstly, (1) the AI/ML powered XR service awareness aims to integrate decision-making components and algorithms providing the capability to optimize the usage of resources (e.g., XR applications, energy efficient policies) in each segment and keep track of their serving needs across multiple domains. Secondly, (2) the holistic E2E XR awareness, an extension to AI/ML-powered XR service awareness that will require extending the inter-domain and intra-PLMN mechanism and APIs defined by the GSMA and CAMARA Project API, as well as mechanisms for edge federation and PLMN roaming / federation with focus at service migration / continuity. Thirdly, (3) the XR-aware eMBB/URLLC is an evolution of the eMBB/URLLC use case aiming at dealing with superior downlink and uplink bandwidths and, at the same time, minimizing the E2E application delay. In practice, this evolution for XR will require the use of additional carriers or RATs and an optimal selection of edge resources based on load conditions and/or proximity to the end user to reduce latencies. Finally, (4) the Native XR session control will take care of the integration of the XR service control layer (e.g., IMS) with the XR services and ecosystem (e.g., the media session orchestrator), as well as with the holistic XR orchestrators mechanism derived from above mentioned development.

Besides this, the infrastructure will also be upgraded: (i) RAN will be extended to operate in new mid and mmW bands with commercial and open solutions, as well as updating the existing radio infrastructure to 3GPP Release 16 and 17 and Wi-Fi 7. (ii) The edge platform will add new servers, mostly focusing on cores and memory processing (considering both Central Processing Unit (CPU) and Graphics Processing Unit (GPU) resources, e.g., to use with AI workloads). The (iii) data centre will introduce new servers in 5TONIC to achieve full compliance of the 5G core network with 3GPP releases 16 and 17. Finally, (iv) 5GBarcelona will incorporate XR infrastructure, in particular, two volumetric, light field powered, capture sub-systems and four holoportation nodes, including VR headset, VR-ready PCs or laptops, and RBG-D capture sensors.

APPENDIX 2 – UC3 RELATED ADDITIONAL INFORMATION

Matsuko Application High-level Description Additional Information

Real-time holographic communication is especially suitable for hybrid collaborative meetings. Despite the advances in holographic communication, there are different requirements which need to be fulfilled for the high-quality holographic calls such as: sufficient network (e.g., high bandwidth, low latency) and scalable infrastructure. To address these challenges, 6G-XR will provide network enablers that can effectively overcome potential issues.

IP Multimedia Subsystem (IMS) for XR

The IMS solution for XR services is a good alternative for upgrading XR applications. The considerable increase in bandwidth and the complex capacity to transmit these volumes of data and ensure low latency and jitter values means that we need to take advantage of the capabilities that IMS can provide us.

It is possible to apply IMS to any service that:

- Is session oriented.
- Requires establishing one or multiple QoS channels.
- Is E2E across operator network borders.
- Is used across different access networks.
- Works in roaming.
- Relies on carrier grade robustness.

It is possible to rely on IMS session management and routing across access networks and operator boundaries (even in roaming) relying on secure user identities. The QoS is E2E managed instead of, e.g., leg based QoS management (via API). In the same way, the capability of interoperability across devices and network accesses is provided because it's possible to find GSMA profiles for interoperability. The processes and infrastructure are available for VoLTE for accounting, billing, conciliation, interconnection, accounting, etc. The service is provided always with robustness because the topology has been already developed for Volte and VoIP, being able to get a massive scale reliable and distributed service.

APPENDIX 3 – UC4 RELATED ADDITIONAL INFORMATION

High Level Architecture

The collaborative 3D DT represents a transformative convergence of digital and physical worlds, offering unparalleled opportunities for innovation and growth across industries. By leveraging the power of 5G connectivity, extended reality (XR) technologies, and advancements in artificial intelligence and machine learning (AI/ML), we can further enhance the metaverse experience by seamlessly integrating Internet of Things (IoT) and robotics. This fusion of technologies will enable more immersive, interactive, and intelligent virtual environments, unlocking new possibilities for communication, collaboration, and automation, and driving the next frontier of human-machine interaction. Our primary area of interest is exploring how individuals can collaborate with remote peers in the digital space, breaking the limits of distance in real-time using 5G networks. Particularly, we are interested in verifying how people can interact with machine controls and work together as a social community.

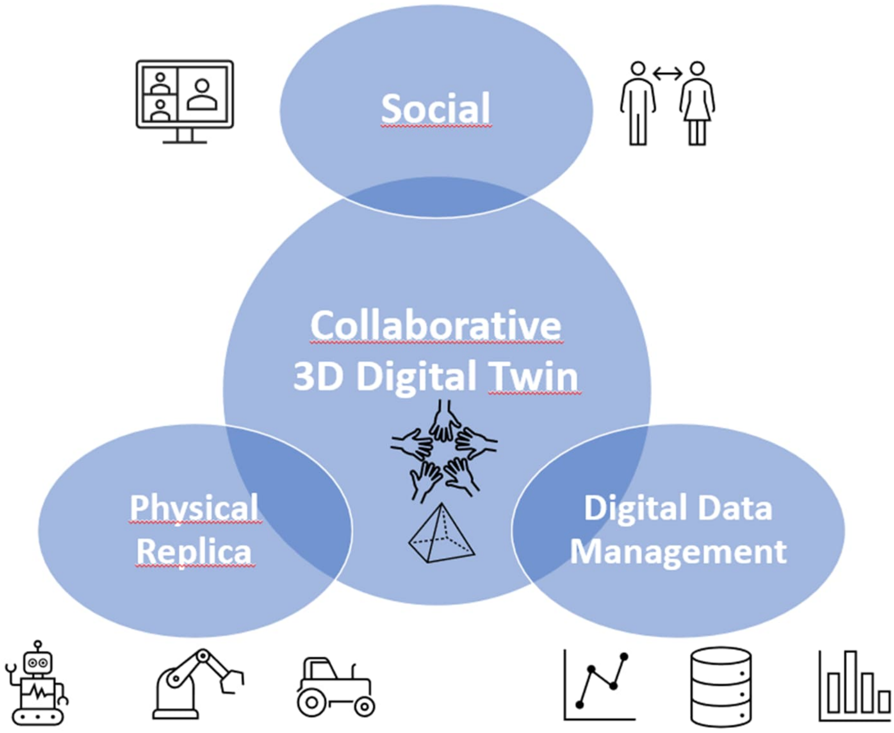

Figure 27. High level architecture of Collaborative 3D DT.

Fab Lab Environment

In 6G-XR project, we use Fab Lab as a use case of human-machine interaction. A Fab Lab, short for "fabrication laboratory", is a small-scale workshop offering digital fabrication tools and resources, enabling individuals to create, learn, and innovate. Founded by Professor Neil Gershenfeld at MIT's Centre for Bits and Atoms in the early 2000s, Fab Labs have since spread across the globe, with a strong community of makers, educators, and entrepreneurs. Common digital fabrication tools found in these labs include 3D printers, laser cutters, Computerized Numerical Control (CNC) machines, and electronics workstations, fostering collaboration and innovation within the global Fab Lab community.

The Fab Lab network includes more than 2,500 centres across 125 countries, including places as remote as northern Norway and as populated as the city centres of Cairo and Barcelona.

Digital fabrication has surpassed the limits of location on a global scale. Designs created in one location can be reproduced in other locations across the world. However, the process of producing physical objects from digital assets using fabrication tools requires communication between the designer and Fab Lab instructor to set up the tools according to the site's specific requirements. For example, when producing a 3D design using a 3D printer, different vendors offer varying machines with different setups at each site. Additionally, depending on the complexity of the 3D design or the condition of the materials, a dedicated setup may be necessary. Communication is limited and difficult to phone calls or video conferences for reviewing physical designs and controlling the machine at the site. If the machine is located locally, the user needs to go to the Fab Lab room to discuss the project with the instructor, review the digital data, and ensure that the machine is set up correctly.

To address the challenges of reviewing 3D designs, setting up machines, and controlling them collaboratively between the remote user and the instruction in the same location, we need a digital space using XR synchronized with machines and human avatars.