D4.1: State-of-the-art analysis and initial design of beyond 5G RAN, core, and open-source networks, disruptive RAN technologies and trial controller

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Abstract	The 6G-XR project aims at developing and testing an innovative infrastructure for Extended Reality (XR) services, and deliverable D4.1 outlines the 3GPP XR enablers, O-RAN XR enablers, Disruptive XR enablers for beyond 5G RAN, core, and open-source network. The

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	project aims to conduct trials using trial controller presented and designed in D4.1.
Keywords	Extended Reality (XR), 5G/6G, Holographic Communications, 3D Digital Twin, Energy optimization, Network Slicing, Resolution adaptation, Control plane optimization, O-RAN, disruptive RAN, Trial controller, Network controlled repeaters, Reconfigurable intelligent surfaces, ATSSS.

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V0.1	17/08/2023	1st version of the ToC for comments	I2CAT

DISCLAIMER

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DATA: Data sets, microdata, etc.

DMP: Data management plan

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EXECUTIVE SUMMARY

The 6G-XR project aims to create a cutting-edge experimental infrastructure that will pave the way for next-generation XR services. The project will focus on developing an evolvable infrastructure that can demonstrate the performance of key Beyond 5G/6G candidate technologies, components, and architectures. This infrastructure will remain valid not only in the short-term but also in the mid-term and long-term.

This is the first deliverable of Work Package 4 (WP4) – "Experimental RAN infrastructure". WP4 focuses on the deployment of 6G-XR beyond 5G cellular network infrastructure. The deliverable D4.1 covers the tasks T4.1, T4.2, T4.3 and T4.4 and aims to identify innovative XR enabler technologies. The XR enabler technologies are categories into three main categories: (1) 3GPP XR, (2) OPEN-RAN (O-RAN) XR, and (3) 6G DISRUPTIVE XR. In addition to the initial design and proposed methodology of each innovative enabler technology, a proposed list of KPIs is defined to validate/measure the performance of the proposed solution. Those enablers are to be tested at the project's north node (UOULU 5GTN and VTT 5GTN) and south node (5GBarcelona and 5TONIC) described explicitly in D1.1. Furthermore, the initial design of an XR trial controller is provided to ease the automatic deployment of XR-related experimentations from a GUI on the project nodes.

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ABBREVIATIONS

3GPP Release X	Rx
6G	6th generation mobile network
5G	5th generation mobile network
5GTN	5G Test Network
3D	3 Dimensional
3GPP	Third Generation Partnership Project
ADC	Analog to Digital Converter
AF	Application Function
AMC	Adaptive Modulation and Coding
ANBR	Access Network Bitrate Recommendation
API	Application Programable Interface
AS	Application Server
ATSSS	Adaptive Traffic Switching Steering Splitting
BLER	Block Error Rate
BSoTA	Beyond-state-of- the-art
SoTA	State of the art
CAD	Computer Aided Design
CCC	Cell Configuration and Control
CDF	Congestion Detection Function
CG	Cloud Gaming
C-Link	Control Link
CNC	Computerized Numerical Control
CO2	Carbon Dioxide
COTS	Commercial Off-the-Shelf
CP	Control Plane
CPU	Central Processing Unit

CSS Cascading Style Sheets

CU Central Unit

DAC Digital to Analog Converter

DC Data Channel

DCS Data Channel Server

DDPG Deep Deterministic Policy Gradient

DF Decode and Forward

DL Downlink

DNN Deep Neural Network

DRL Deep Reinforcement Learning

DRX Discontinuous Reception

DSP Digital Signal Processing

DT Digital Twin

DTX Discontinuous Transmission

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

FoV Field of View

FMI Finnish Meteorological Institute

FPS Framerate Per Second

FRx Frequency Range x

gNB 5G NodeB

GPU Graphics Processing Unit

GUI Graphical User Interface

HMD Head-Mounted Display

HW Hardware

IAB Integrated Access and Backhaul

IF Intermediate Frequency

InH Indoor Hotspot

ISAC Integrated Sensing and Communications

KPI Key Performance Indicator

KPM Key Performance Measurements

L1/L2 Layer 1/Layer 2

LO Local Oscillator

LoS Line of Sight

MBB Mobile Broadband

ML Machine Learning

mmWave Millimeter-wave

MR Mixed Reality

NCR Network Controlled Repeater

NCR-Fwd NCR Forwarding

NCR-MT NCR Mobile Termination

NG-RAN Next Generation Radio Access Network

NI Network Interface

NN North Node

NR New Radio

O2I Outdoor-to-Indoor

O-CU O-RAN Central Unit

O-DU O-RAN Distributed Unit

O-RAN	Open Radio Access Network
O-RU	O-RAN Radio Unit
PAPR	Peak to Average Power Ratio
PRB	Physical Resource Block
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RB	Resource Block
RC	RAN Control
RF	Radio Frequency
RI	Research Infrastructure
RIC	RAN Intelligent Controller
RIS	Reconfigurable Intelligent Surface
RL	Reinforcement Learning
RMSE	Root Mean Squared Error
RRH	Remote Radio Head
RRM	Radio Resource Management
RT	Real Time
RU	Radio Unit
SC-FDE	Single-Carrier Frequency Domain Equalization
SDR	Software-Defined Radio
SINR	Signal-to-Interference plus Noise Ratio
SMO	Service Management and Orchestration
SN	South Node
SNR	Signal-to-Noise Ratio
SW	Software
T	Task

TDD	Time Division Duplexing
THz	Terahertz
TRX	Transmit-Receive
UE	User Equipment
UI	User Interface
UL	Uplink
UMa	Urban Macro
UP	User Plane
UPF	User Plane Function
uRLLC	ultra-Reliable and Low Latency Communications
VR	Virtual Reality
WP	Work Package
XR	Extended Reality
XRM	XR and Media Services

1 INTRODUCTION

XR is an umbrella term that covers Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). It provides immersive experiences from a blend of the virtual and real worlds and finds applications in several emerging use cases across different domains and sectors. XR requires performance enablers that can support stringent requirements with respect to low latency, high capacity, low power consumption and high reliability, among other KPIs [1].

The scope of D4.1 is to cover the outcomes of the first, second, third and fourth technical Tasks (T), T4.1, T4.2, T4.3 and T4.4 from Work Package 4 (WP4) of the “6G Experimental Research infrastructure to enable next-generation XR services” (6G-XR) project. T4.1 “Deployment of beyond 5G radio and core networks” describes the 3GPP XR enablers SoTA and proposed initial design for innovative enablers. T4.2 “Deployment of open-source devices and software” focuses on describing O-RAN XR enablers SoTA and initial design. While T4.3 “6G RAN disruptive technologies” focuses on disruptive XR enablers and their initial design. T4.4 “Deployment of trial controller, APIs and novel orchestration” explicitly focuses on the design, requirements, implementation, components, Interfaces and APIs for the experimental trial engine.

1.1 OBJECTIVE OF THE DELIVERABLE

This deliverable has four main objectives (1) adopt 3GPP XR enablers evolutions beyond 5G, (2) innovation of O-RAN XR enablers for radio network architecture and software, (3) develop disruptive 6G for XR applications, and (4) develop a sophisticated trial controller to deploy XR trials from a GUI Portal over the multi-site beyond 5G network. This deliverable shall cover the SoTA for the four objectives and the initial design for those solutions paving the way for full detailed design in the coming deliverables of WP4.

1.2 STRUCTURE OF THE DELIVERABLE

The 6G-XR project aims in demonstrating technological feasibility of innovative radio spectrum technologies of beyond 5G and 6G spectrum and validate an end-to-end beyond 5G architecture including end-to-end service provisioning with slicing capabilities, and at cloud implementation level (Open RAN). Therefore, the deliverable D4.1 is covering the state of the art for RAN, beyond 5G RAN, core, and open-source networks, disruptive RAN XR enabling technologies. Those technologies are categorized into 3GPP XR enablers, O-RAN XR enablers, and 6G DISRUPTIVE XR enablers and the initial design for those technologies and their proposed KPIs for evaluation are presented in this deliverable in an easy-to-read style. The deliverable D4.1 is structured as follows:

- Chapter 2 details the 3GPP extensions for XR support in R17 and R18, describing the SoTA, the initial design and the KPIs for the 3GPP XR enablers such as Network-Controlled Repeaters, Network assisted Rate Control API for XR services, ATSSS based capacity enhancement for XR services, Upgrade, and evaluation of experimental RAN infrastructure in SN and NN to support XR services, and energy efficient XR services.

- Chapter 3 focuses on O-RAN mechanisms for XR services and the proposed O-RAN XR enablers. It details the SoTA, the initial design and KPIs for O-RAN enablers such as Congestion aware load balancing, Energy-aware E2E resource management for XR services, Slice-aware resource allocation in O-RAN for XR services.

- Chapter 4 discusses the SoTA and initial design for the proposed disruptive XR enablers such as High-Frequency Transceivers at 140 GHz and 300 GHz, Baseband implementation for THz-RIS and ISAC based on SC-FDE, and Deep Reinforcement Learning for THz-RIS.

- Chapter 5 describes the trial controller initial design and its requirements. It explicitly details the interfaces, functions, components, and APIs for the development of the trial controller.

- Chapter 6 concludes 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 public.

2 3GPP XR ENABLERS

2.1 OVERVIEW OF 3GPP EXTENSIONS FOR XR SUPPORT IN R17 AND R18

With respect to standardization, the support for XR was introduced in R15, and later in R16 with additional features. In fact, R16 served as the introduction of XR in 5G New Radio (NR). It presented the baseline XR use cases and services, core enablers and network interfaces, as well as the description of its media functions, formats, and features, among others. As a sequel, and through several study and work items, R17 presented several further enhancements on XR in NR via different enablers and features. These enablers and features are in the areas of traffic modelling, network-controlled interactive services, edge computing for XR use cases and deployment scenarios, as well as performance evaluation methodologies for capacity, coverage, mobility, power consumption and overall system performance. Further enhancements in XR enablers and features have been recently also introduced in R18. These enhancements include areas such as tactile, multi-modal, and immersive real-time communication services, architectural enhancements for XR and media services, smart tethering XR glasses, real-time transport protocol configurations, XR audio services and Quality of Experience (QoE) metrics and evaluation methodologies. These features will be further enhanced in R19 and beyond. Table 2-1. XR features and enablers in R17, R18 and R19. presents some XR features and enablers in R17 and R18.

Table 2-1. XR features and enablers in R17, R18 and R19.

3GPP Release (R)	Work Group (WG)	Technology Enablers	Features	Reference Document	Relation to 6G-XR
R17	System and Services Aspects (SA) Work Group (WG) WG1 - Services	Study item on Network Controlled Interactive Services (NCIS)	XR and Cloud Gaming use cases	TR 22.842, TS 22.261	
R17	SA WG2 – System Architecture and Services	Work item on 5G System Enhancement for Advanced Interactive Services	Introduces new 5QIs to identify the requirements on traffic from SA1 NCIS	SP-190564 (TS 23.501, TS 23.502, TS 23.503)	The network exposure enabler described in section 2.2.2, and the ATSSS enabler described in section 2.2.3 relate to this group

R17	SA WG6 – Application Enablement and Critical Communication	Study on application architecture for enabling Edge Application	Edge Computing to enable XR and Cloud Gaming	TR 23.758, TR 23.748	
R17	Radio Access Network (RAN) - RAN1	Study on XR Enhancements for NR	Traffic models, deployment scenarios, XR capacity evaluation (capacity results and potential enhancements), XR UE power consumption evaluation (results and potential enhancements), XR coverage evaluation, XR mobility evaluation.	TR 38.838	Performance enhancement of capacity and UE power consumption of 5G NR for XR and CG applications.
R18	SA WG1 - Services	Study on tactile and multi-modality communication services		TR 22.847, TS 22.261	
R18	SA WG2 – System Architecture and Services	Study on XR and media services	Advanced media services, enhancement for multi-modality, network exposure, QoS and policy enhancements for XR service and media service transmission, potential enhancements of	TR23.700-60	The energy management enabler described in section 2.2.4 relates to this group.

			power management considering traffic pattern of media		
R18	RAN1 – Radio Layer 1 (Physical Layer); RAN2 – Radio Layer 2 and Radio Layer 3 Radio Resource Control	Study on XR enhancements for NR	Power saving and capacity enhancement for XR and XR-awareness in NR	TR 38.835	XR awareness, for example using ISAC; Performance enhancement of capacity and UE power consumption of 5G NR for XR and CG applications. The energy management enabler described in section 2.2.4 relates to this group.
R18	SA2	Work item on Architecture Enhancements for XR and media services (XRM)	Introduction of specification enhancements for support of policy control enhancements, 5GS information exposure, QoS handling, uplink (UL)-downlink (DL) transmission coordination, jitter minimization, enhancements to UE power savings, and trade-off of QoE and power saving requirements.	Work-item description :SP-230092 TSs enhanced: 23.501 23.502 23.503 23.288	

R18	RAN1 RAN2 RAN3 – UTRAN/E-UTRAN/NG-RAN Architecture and Related Network Interfaces	Work item on XR Enhancements for NR	Introduction of specification enhancements related to power saving, capacity, and XR awareness	Work-item description: RP-232778 TSs enhanced: 38.300 38.321 38.322 38.323 38.331 38.306 38.211 38.212 38.213 38.214 38.413 38.415 38.423 38.425 38.473 37.483 38.410 38.420 38.470	Performance enhancement of capacity and UE power consumption of 5G NR for XR and CG applications. Awareness and optimized treatment of XR-application specifics on NR Radio Layers 2-3.
R18	R1	Study on network energy savings for NR	Overview of RAN energy saving methods in time-, frequency-, spatial-, and power-domains, currently considered for standardization with initial assessment.	TR 38.864	The energy management enabler described in section 2.2.4 relates to this group.
R19	SA2	Study on Architecture enhancement for XRM Ph2	Enhancement for PDU Set based QoS handling; QoS handling enhancement for XRM services; Further enhancement to	Study-item description: SP-231198	Further enhancements of 3GPP 5GS to support XR services

			support XR based on non-3GPP access; Network exposure:	TR23.700-60	

In the following section, we present five different technical enablers that are being currently studied in 3GPP that can support and enhance XR. The five enablers are: (i) network-controlled repeaters (NCRs), (ii) XR rate adaptation assisted by 3GPP network, (iii) ATSSS-based UL capacity enhancement, (iv) 3GPP enablers for energy-efficient XR services, and (v) upgrade and evaluation of experimental RAN infrastructure to support XR services.

2.2 3GPP XR PROPOSED ENABLERS

2.2.1 Network-Controlled Repeaters in indoor environment

2.2.1.1 Targeted XR gap

R17 and R18 on XR deployments feature several scenarios such as: (i) Urban Macro (UMa), (ii) Dense Urban, and (ii) Indoor Hotspot (InH) scenarios [1]. For example, the InH scenario is illustrated in Figure 1 where XR users are supported via a NCR for reliable connectivity. The NCR is an in-band Radio Frequency (RF) Amplify and Forward (AF) repeater with beamforming capabilities, under the control of the next-Generation Node B (gNodeB). The use of NCR enables advanced beamforming that avoids blockage, enhances signal quality, extends coverage, and improves the users' QoE. Representative scenarios for indoor deployment include the 3GPP XR Conference/XR meeting use case (i.e., use case 15 in 3GPP TR 26.928) with both physical and virtual participants. Other use cases include XR gaming where users are having gaming parties and call center service agents offering remote expert assistance through virtual reality connections like the Fab lab use case of 6G-XR, among others.

For indoor deployment scenarios, coverage and blockage are among the principal challenges due to indoor blockages from objects, high Outdoor-to-Indoor (O2I) penetration losses as well as the high path losses from the outdoor serving gNodeB. Therefore, new network nodes that can extend coverage and enable reliable communication are required between the outdoor gNodeB and the indoor XR users. The coverage and blockage challenges are more accentuated at Frequency Range 2 (FR2) bands. This is because the high frequency FR2 bands are more prone to blockage than Frequency Range 1 (FR1) bands. FR2 bands also have higher path losses than FR1 and thus require the amplify and forward operation of the NCR for enhanced signal quality.

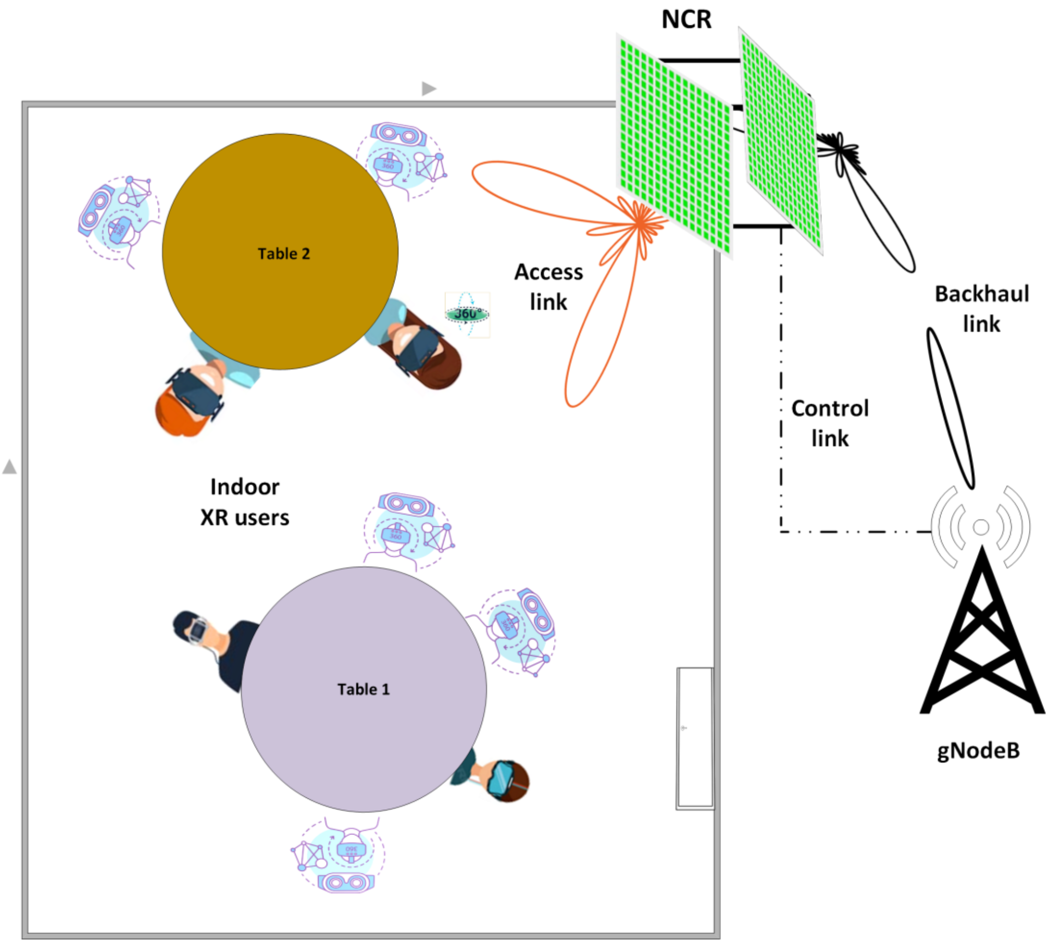

Figure 1. Deployment scenario for indoor XR applications with NCR

Coverage is a fundamental aspect of cellular network deployments. Over the different network generations (2G-5G), several network nodes have been explored in different standardization releases for coverage extension, with some deployed by mobile network operators. The choice of node depends on different factors such as economic viability, backhaul availability, complexity, and flexibility, among others. Over time, some of the relaying nodes that have been explored for coverage extension include full-stack small cells, regular R17 and R18 AF repeaters, and the Decode and Forward (DF) Integrated Access and Backhaul (IAB) nodes.

The IAB was introduced in 3GPP R16 and enhanced in R17 to support enhanced throughput and coverage. It is being further enhanced in R18 to support mobility. Although the IAB has extensive coverage, it is very complex. On the other hand, the RF repeaters, which simply amplify and forward received signal, have lower complexity but lack the beamforming capability that is required for FR2. In R17 3GPP has further specified requirements for RF repeaters for NR targeting both FR1 and FR2 [2].

Despite the prospects of the RF repeater as a cost-effective means of extending network coverage, it has its limitations. The RF repeater operating as an relay does not consider performance-enhancing features such as dynamic DL/UL configuration, adaptive spatial beamforming, ON-OFF status, among others. In response to these limitations, NCRs have evolved as nodes that can provide advanced capabilities over conventional RF repeaters. The NCR can process the side control information it receives from the network, enabling it to mitigate unnecessary noise amplification as well as transmit and receive with better spatial directivity through beamforming, in addition to the primary operations [2].

3GPP launched a study item in Release 18 and followed it with a work item on NCR as a valid candidate for network coverage extension for both FR1 and FR2, and particularly for FR2 operations. The goal is to counteract the large path and penetration losses at FR2/millimeter-wave (mmWave) frequencies. The NCR is preferred for indoor, corridor-like streets and roads because it can provide coverage to such narrow spaces. This is because the NCR is well suited for spaces with limited field of view (FoV), and with signal amplification, they enable high capacity and signal-to-noise ratio (SNR). For FR2 deployments, both outdoor and O2I scenarios are prioritized.

In terms of setup, NCR consists of two analog arrays of antennas, one oriented towards the base station (BS)/gNode (for the backhaul link) and the other towards the user equipment (UE) (for the access link), as shown in Figure 2 [3]. NCRs also have a control link between the NCR and gNodeB as the former are logically under the control of the latter for all management operations. NCRs are only currently single-hop repeaters and maintain both the backhaul and access links concurrently. They are also simpler than the gNodeB because they do not have advanced digital transmit and receive chains.

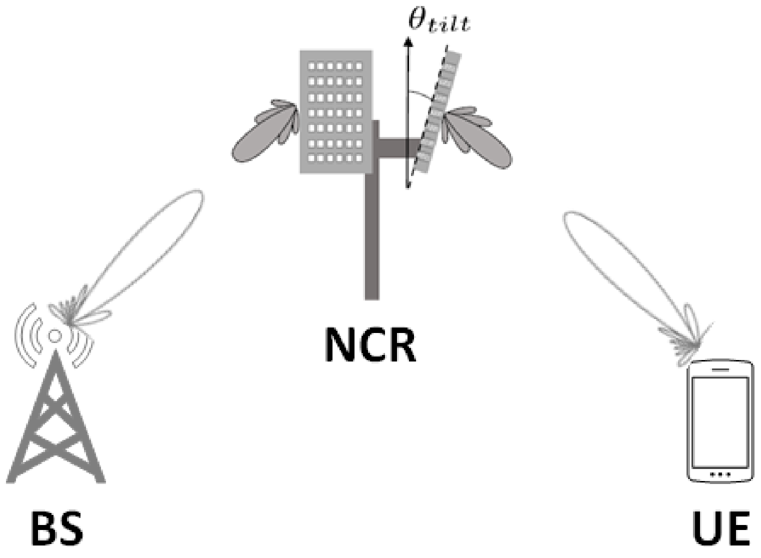

Figure 2. NCR-assisted network setup (Adapted from [3])

The NCR signalling is shown in Figure 3, showing the mobile termination (NCR-MT) and forwarding (NCR-Fwd) links. The NCR-MT is the function entity that communicates with the gNodeB via the Control link (C-link) to enable exchange of control information (e.g., side control information at least for the control of NCR-Fwd). The C-link is based on NR Uu interface. On the other hand, the NCR-Fwd is the function entity that performs the AFforward operation of UL/DL RF signals between gNodeB and UE via backhaul link and access link. The behaviour of the NCR-Fwd is controlled according to the received side control information from gNodeB. The NCR also has a control link that allows the sending of side control information to the repeater for beamforming and timing configurations, among others.

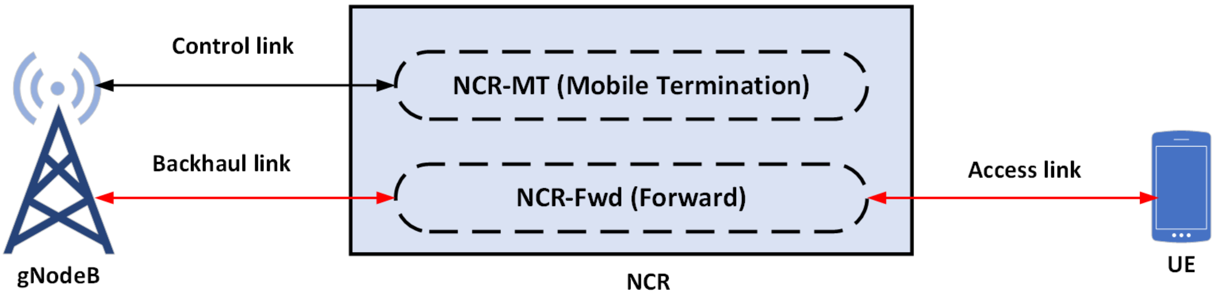

Figure 3. Signalling model of network-controlled repeater (Taken from [2])

The NR NCR side control information include beamforming information, timing information, information on UL-DL time division duplexing (TDD) configuration, ON-OFF information and power control information, as well as the corresponding layer 1 (L1)/layer 2 (L2) signalling (including its configuration) to carry the side control information [2]. For the backhaul link and control link, both fixed beam and adaptive beam are considered at NCR, where the fixed beam refers to the case that the beam at NCR for both C-link and backhaul-link cannot be changed. In case that the adaptive beams are adopted for C-link and backhaul link, the indication and determination of beams of backhaul link can be achieved by a new signalling. The new signalling is dynamic signalling and/or semi-static signalling (e.g., RRC signalling/ MAC CE) indicating beam(s) from the set of beams of the C-link. This does not imply that the beam of backhaul link is always indicated by the new signalling, or determined by a pre-defined rule, e.g., in slots/symbols with simultaneous DL receptions/UL transmissions in both C-link and backhaul link, the beam of backhaul link is the same as the beam of C-link. Otherwise, the beam of backhaul link follows one of the beams of the C link [2], [4].

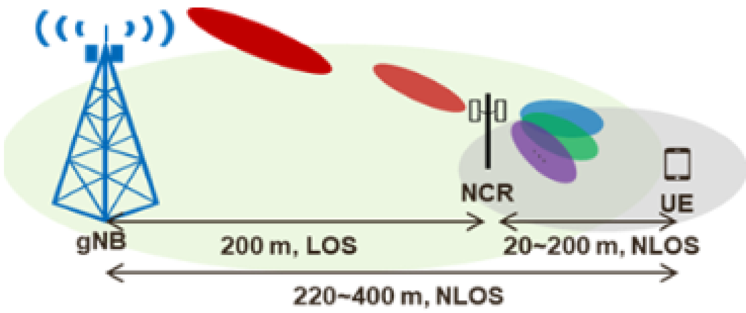

Figure 4: NCR setup for FR1 (Taken from [4])

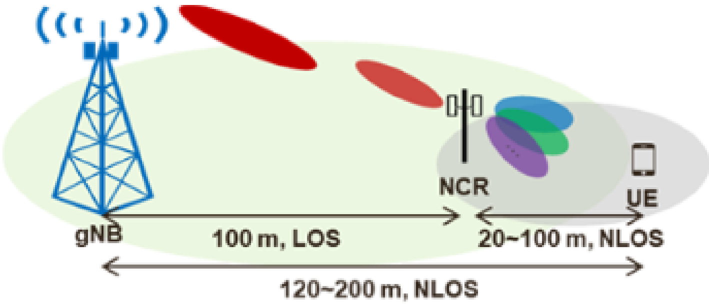

Figure 5. NCR setup for FR2 (Taken from [4])

For the access link, from the perspective of signalling design, both dynamic beam indication and semi-static beam indication are recommended. The semi-static beam indication includes the semi-persistent indication. The time at which the NCR applies an access link beam indication should be considered. As for the time-domain granularity of the access link beam indication and determination, both slot-level and symbol-level granularity are recommended. The typical setups, showing representative ranges for line-of-sight (LOS) and non-LOS (NLOS) are shown in Figure 4 and Figure 5 for FR1 and FR2, respectively [2], [4]. In addition to the beam indication, selection and tracking, the angular separation between the two NCR panels is also a parameter for performance optimization. This is illustrated in Figure 6.

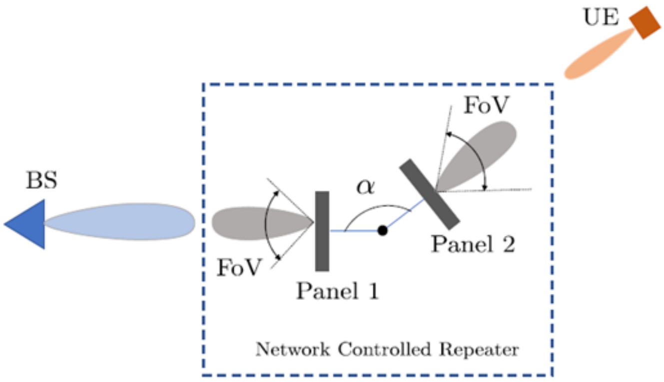

Figure 6. Illustration of angular separation between NCR panels (Taken from [3])

2.2.1.2 Initial solution design and evaluation methodology

2.2.1.2.1 Initial design

Figure 7 shows the NCR-assisted building blocks of the architecture for the XR application scenario illustrated in Figure 1In it , where the blocks that will be newly introduced/enhanced are coloured in brown. The architecture has three principal modules, described as follows:

(i) Node deployment module that parameterizes the gNodeB, NCR and UE in terms of deployment layouts, mobility pattern and radio interface configurations (such as operational frequency, bandwidth, waveform and frame structure, transmission mode and power, array configurations and gains).

(ii) Channel and traffic generator where the gNodeB-NCR and NCR-UE channels as well as the XR traffic are generated. The channel models feature all channel components such as LoS probability, path loss, shadow fading, wall/penetration losses as well as the small-scale losses. The traffic generator uses the trace generated from WP3 XR application scenarios to model XR traffic using traffic features such as frame rate, packet size, packet inter-arrival period, packet delay budget, jitter, etc.

(iii) The radio resource scheduling and performance evaluation module uses the generated channel and traffic as inputs for scheduling, beamforming, link quality and link performance evaluations. Here, Resource blocks (RBs) are allocated based on the channel quality indicator, precoding matrix indicator, and rank indicator feedback (i.e., using the closed loop system approach). The resulting signal to interference plus noise ratio (SINR) vector for each UE is then compressed to a single effective SINR value using mutual information effective signal-to-noise ratio mapping. The effective SINR is then combined with the applied modulation and coding scheme to predict the block error rate of the received transport block. The resulting throughput of each user is evaluated by means of adaptive modulation and coding over the channel.

In particular, the work in this enabler will focus on:

- Modelling the XR traffic using the application traces from WP3.
- Modelling the gNodeB-NCR and NCR-user channels.
- Developing beamforming algorithms and codebooks for beam selection, tracking and optimization.
- Optimizing the angular separation between the two NCR panels for enhanced system performance.

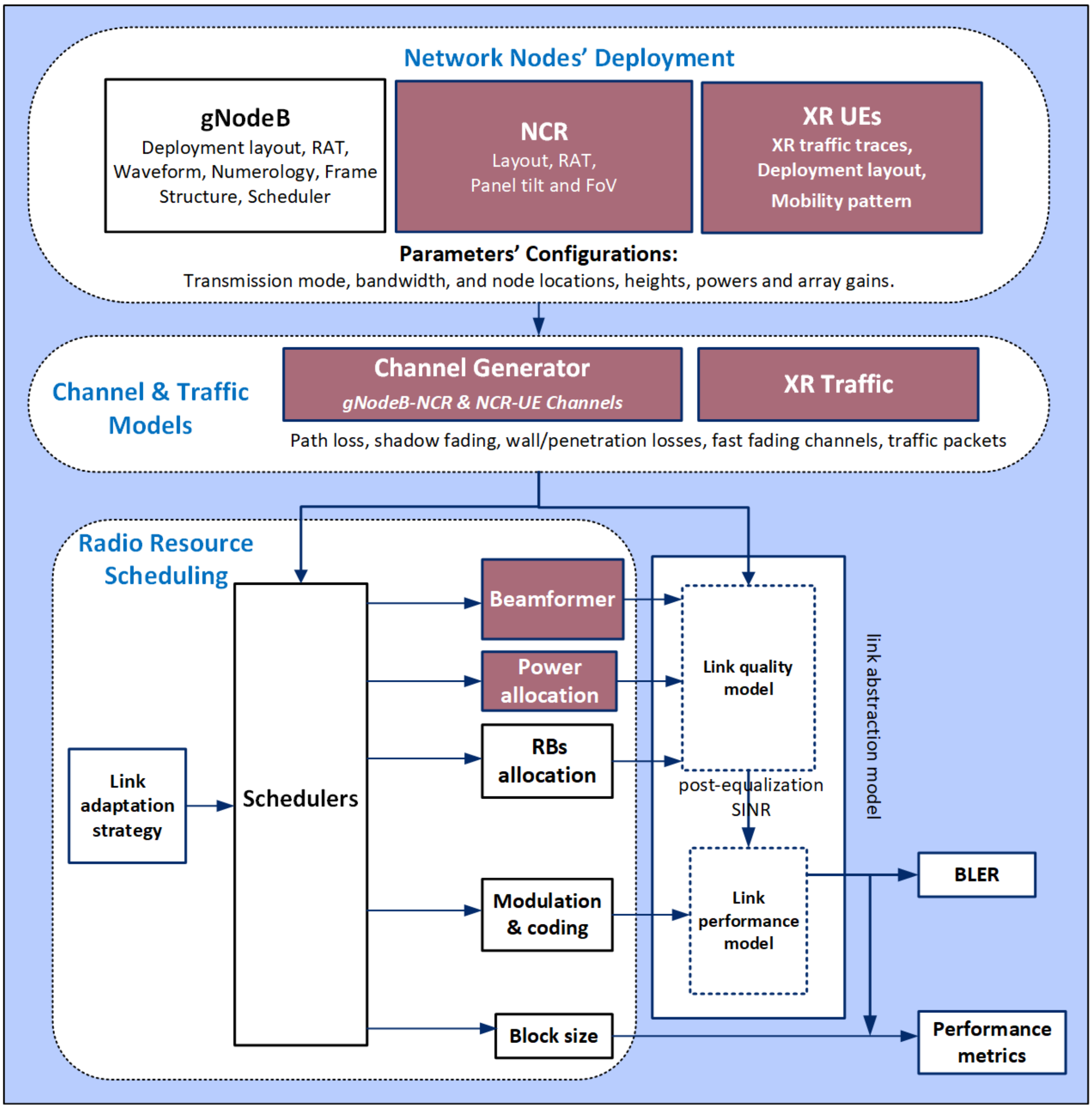

Figure 7. NCR-assisted network architecture for XR

2.2.1.2.2 *Proposed methodology*

System level simulations will be exploited to evaluate the performance of the NCR-assisted network deployment for XR. The UEs are indoor XR users while the gNodeB is either a tri-sectored base station or lamppost-mounted access point (AP), with particular focus on FR2. The system-level simulations will incorporate the real XR traffic and follow the evaluation framework illustrated in Figure 7. This will not only consider the impacts of the physical parameters (e.g., the angular separation between panels for NCR) but also the environmental (mapped area) and network parameters such as the beam information. The performance evaluation metrics include throughput, latency, coverage probability, beam alignment errors, etc.

Also, the simulations will follow the 3GPP evaluation methodology and will be benchmarked with SoTA baselines and compared against predecessor technologies such as conventional relays and RF repeaters. Beam selection design (codebook-based and non-codebook-based) will be explored for both the access and backhaul links. Also, the angular separation optimization of the NCR panels will be explored for enhanced system performance.

2.2.1.2.3 Target KPIs

Table 2-2. KPIs for NCR-assisted network for XR presents the target KPIs for the NCR-assisted network for indoor XR use case.

Table 2-2. KPIs for NCR-assisted network for XR.

KPI name	**KPI description**	**Target Value**
Throughput	Bits per second in UL and DL measured for each XR user	Per-user throughput of 50 Mbps (UL) and 200 Mbps (DL) will be targeted for video, above the 3GPP values of 20 Mbps and 60 Mbps for UL and DL, respectively. Also, an XR conference/meeting of 10 users is targeted, thus amounting to 2 Gbps DL support (DL) for a single session.
Latency	Packet transmission latency (ms)	A 5 ms latency is targeted, below the 10 ms 3GPP target. Latency will be tested under the same network conditions defined for the throughput.
XR UE satisfaction	XR UE is declared satisfied if more than X % of application layer packets are successfully transmitted within a given latency constraint.	95% successful packet delivery per user is targeted.
Coverage probability	Probability that each UE achieves the minimum SNR threshold of 5 dB.	95% coverage probability with 5 dB SNR threshold.

2.2.2 Network assisted Rate Control API

2.2.2.1 Targeted XR gap

XR Extended reality applications such as the holoportation service considered in 6GXR use case 1 [5], are expected to transmit huge amounts of data both in the uplink and downlink directions. This may lead to congestion in current public cellular networks where radio resources are to be shared with Internet users. To cope with the varying radio capacity, XR services today relay on over-the-top (OTT) estimations of available capacity, which are used to adapt the data-rate of the media flows. For example, the Dynamic Adaptive Streaming over HTTP (DASH) streaming protocol relays on measurements of occupancy in the playback buffer of the receiver to tune the transmit rate in the media origin [6]. Although these rate adaptation mechanisms are efficient in streaming services, they may not be useful in interactive XR services where the amount of buffering should be kept at a minimum level. Therefore, new mechanisms are required to allow the media origins to tune rate for the media flow. Specifically, these mechanisms should be based on information provided by the network to the media application function, as is recognized by the Server and Network Assisted DASH (SAND) architecture [7].

3GPP has embraced the vision that the network should behave as a platform offering APIs that can enhance the performance of applications. This has been realized in the 5GCore with the Network Exposure Function (NEF) as a fundamental enabler and is being further developed in SA6 with the development of transversal and vertical oriented application enablers. Outside 3GPP, major Mobile Network Operators, such as Deutsche Telekom, Telefonica, Orange and Vodafone, launched the CAMARA project [8] that develops APIs designed to offer added value to specific applications. An example relevant to XR services is the CAMARA Quality on Demand (QoD) API [9]. Following the API trend, this 6GXR enable the network assisted rate control enabler will investigate the design of new APIs that can add value to XR services, focusing on the 6GXR holoportation service.

Figure 8 depicts the reference usage scenario for the network assisted rate control API enabler. We can see a holoportation user that generates data flow both in uplink, from a capture system to the network, and downlink from the network to a Head Mounted Display (HMD). The holoportation user shares the cell with Internet users that introduce a variable load, which may lead to congestion affecting the performance of the holoportation service. As shown in Figure 8, the XR service functions are connected to the Core Network of the public network, both in the user and the control planes. Relevant to this enabler is the interface connecting the control plane of the XR service to the Network Exposure Function (NEF) of the 5G Core. This interface can be used to exchange control information between the network and the application. The focus of this 6GXR enabler is to design and demonstrate an API in this interface that can be used by the application function to select the appropriate rate for the media flow. The goal of this enabler is therefore to reduce instability and stalls in the media flow, by selecting a data-rate for the media flow that is adjusted to the network capacity available in real-time. at each moment

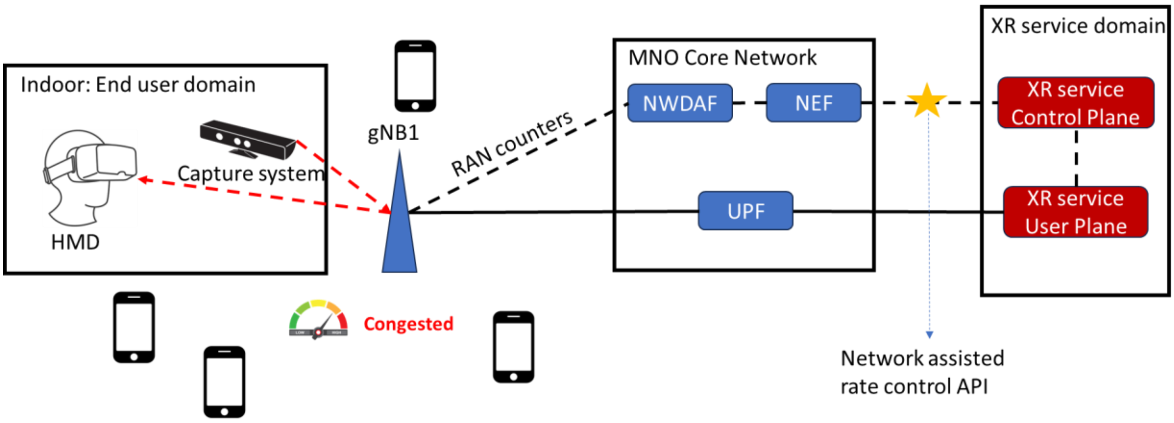

Figure 8. Usage scenario for XR network assisted rate control API enabler

Looking at the state of the art of rate control, the synergy between the network and the application layer to have consistent application data rates has been extensively studied [10]. As an example, the video streaming service having consistent latency leveraging the collaboration between the transport system and the application layer to set the bit rate is studied [11]. However, XR traffic has different unpredictable nature with stringent XR QoS requirements under realistic in highly fluctuating network conditions. In [12], the authors conducted a comprehensive survey on data rate adaptation approaches. Moreover, in [13], throughput (L4S) mechanism standardized by IETF is explored where packets are tagged to identify congestion, aiming at the reduction of the network congestion losses and network queuing latency. The latter mechanism can be adopted for XR traffic. In addition, few XR have considered XR traffic adaptation [14], where rate control strategies for latency reduction is considered. The drawback of such approaches is that they do not allow to have a detailed insight into the 5G configuration and to study the impact of each of the components of 5G RAN on XR traffic characteristics.

2.2.2.2 Initial solution design and evaluation methodology

2.2.2.2.1 Initial design

The Network Assisted Rate Control can be made by two different techniques. First the ANBR (Access Network Bit Rate Recommendation) based where signalling is exchanged between UE modem and RAN. The second mechanism is AF based network assistance where the interaction with NEF and PCF is used [15]. The designed solution for Network Assisted Rate Control API is proposed in 9Figure 9 employing AF based network assistance and close the loop by leveraging the cooperation between the XR aware application on UE and the XR application provider (upper dot lines).

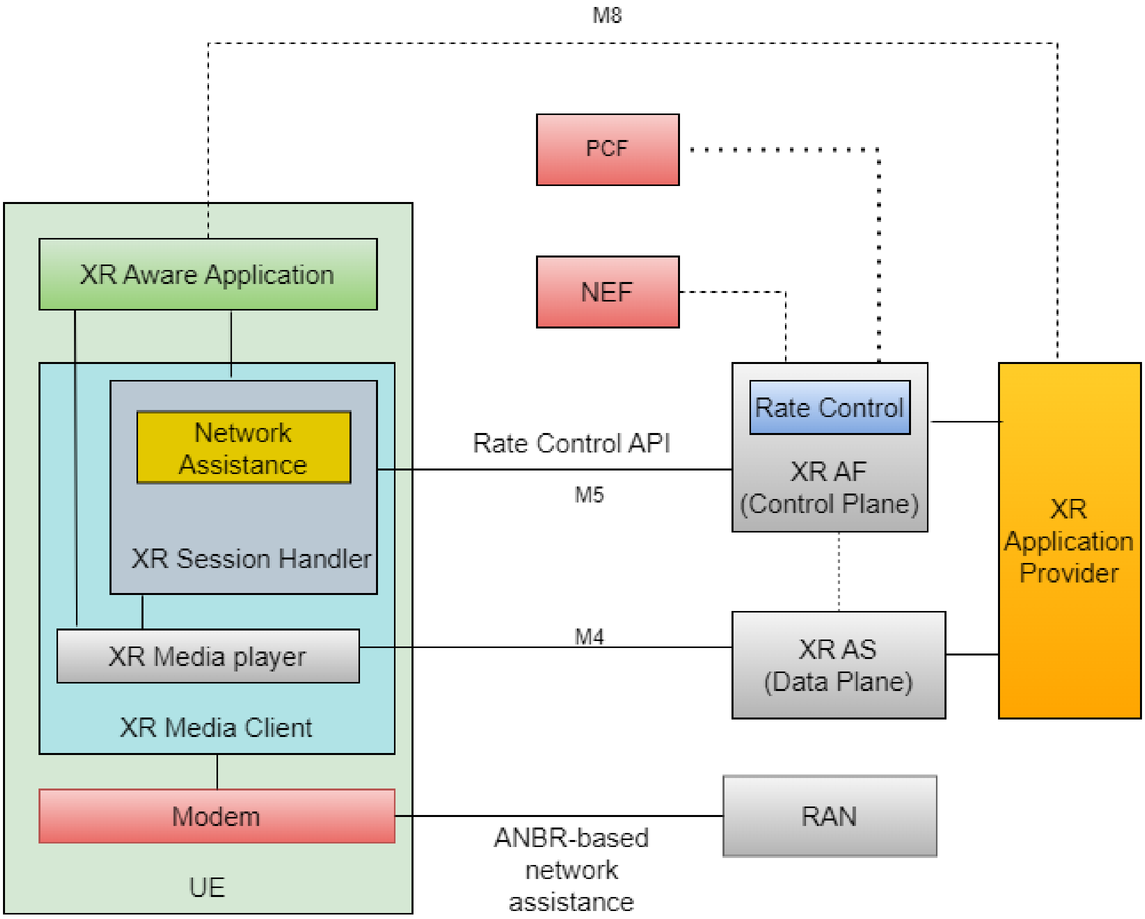

Figure 9. Architecture for the Network assisted Rate Control API.

The XR AF at the network side includes rate control function that currently only uses buffer occupancy and perform rate recommendation that is passed to the XR AS to control the flow of XR UE media player. The solution proposed here is that XR aware application sends XR application related requirements which is passed as another input to the rate control function at XR AF. These requirements are used beside analytics exposed by NEF and KPIs from RAN metric database to generate a rate recommendation. This new rate recommendation together with buffer measurements are used then by XR AF rate control to alter the XR flow rate to meet the required QoS without jeopardizing the network resources. The main component to be developed here is the rate recommendation API that can assist the rate control at XR AF.

2.2.2.2.2 Proposed methodology

The Network assisted Rate Control API will be evaluated. First, ns3 will be used to study the maximum gains achievable by this API when a tight integration between the RAN and our analytics module is possible. Second, simplified version of our API to be tested in the i2CAT laboratory, using a Amarisoft gNB. This step is essential to define the API communication between the network and the holoportation application developed in WP3. In the final step the API and the holoportation application will be integrated and validated in the south node infrastructure described in section 2.2.4.

2.2.2.2.3 Target KPIs

The below Table 2-3 lists the KPIs for Network assisted Rate Control API for XR services.

Table 2-3. KPIs for Network assisted Rate Control API

KPI name	KPI description	Target Value
Per-Session Application Throughput	Bits per second in DL measured between at the client side after the playback buffer	Depends on networks condition but the new API should outperform the traditional OTT
Network overall throughput	Aggregated bits per second in the DL measured between gNode B and each client	Depends on networks condition but the new API should outperform the traditional OTT
Packet loss rate	Number of erroneous packets lost at XR application	Same as above
Media player delay	Time latency between receiving the packet at the UE client media player and being played back	This should be as low as possible to provide smooth playback of the media
Outage	Percentage of time within a simulation run where the playback buffer in a UE is empty	Minimal as possible due to effect of rate adaptation

2.2.3 ATSSS based capacity enhancement

2.2.3.1 Targeted XR gap

As described in D1.1 [5], future XR services are expected to be bandwidth hungry both in UL and DL directions. For example, the holoportation service considered in 6GXR Use Case 1 requires capturing a 3D cloud point of each user, using sensors like Kinect or Raytrix Lightfield cameras [16], which may generate uplink streams of up to 1 Gbps per user. In the downlink, a holoportation service requires to forward to the Head Mounted Display (HMD) a hologram for each participant in the session. Thus, depending on the service implementation, downlink traffic could grow linearly with the number of participants in a holographic session, which may result in significant bandwidth requirements for moderate size holoconference sessions, e.g. a 20 people holoconference with a 50 Mbps bandwidth per hologram would require a 1 Gbps service rate towards the HMD of each user.

XR services like holoportation are expected to be consumed mostly indoors, either at home or in enterprise domains. Thus, solutions are needed that can enhance service uplink and downlink capacity in these scenarios. Wi-Fi is nowadays the main technology used to connect end user devices in indoor environments, such as the HMD or the capture systems required to deliver holoconference services. The latest generation of Wi-Fi, Wi-Fi 7, has incorporated new technologies that allow to increase effective capacity, such as support for 4096 QAM modulation or Multi-Link Operation (MLO), which allows to aggregate capacities of different Wi-Fi ISM bands, namely 2.4GHz, 5GHz and 6GHz. Despite providing higher capacities in ideal conditions, the new Wi-Fi 7 mechanisms can significantly degrade when signal coverage is not ideal, which is common in indoor environments. Thus, 6GXR proposes to complement the indoor capacity provided by Wi-Fi 7 with outdoor capacity provided through public networks featuring 5G-Advanced/6G radio access networks.

In Release 16, 3GPP introduced the Adaptive Traffic Switching Steering Splitting (ATSSS) mechanism [[17], which, coupled with the Non-3GPP Interworking Function (N3IWF) [18], allows to aggregate PDU sessions over a 5GNR radio access and a Wi-Fi access that can be located at the user premises. Figure 10. Usage scenario for 6GXR ATSSS enabler

depicts our considered usage scenario, where an end user requests XR services through an HMD and a capture device, generating both uplink and downlink data flows. We consider that both the HMD and the capture system devices embed Wi-Fi and 5GNR interfaces, together with ATSSS capabilities, which allow to aggregate the Wi-Fi and 5GNR data flows into a single multi-access PDU session. On the network side, the Wi-Fi access network is integrated into the 5GCore of a Mobile Network Operator (MNO) through the Non 3GPP Interworking Function (N3IWF) gateway, which in turn delivers user traffic to the User Plane Function (UPF). The UPF is used to anchor traffic addressed towards the two radio access technologies. Hence, the UPF also needs to incorporate ATSSS capabilities to control how traffic is steered through the two technologies. Rel16 ATSSS four steering modes are defined for ATSSS, which include *active-standby*, where only one access (the active) is used until it fails, *smallest delay*, where delay is measured through each access and the smallest is used, *static load balancing*, where a fixed portion of traffic is sent through each access, and *priority-based*, where traffic is sent through the highest priority access unless congestion is detected. In Rel17 ATSSS introduced a new steering mode known as *autonomous steering* where UE and UPF can decide autonomously how to split the traffic based on an implementation-dependent algorithm.

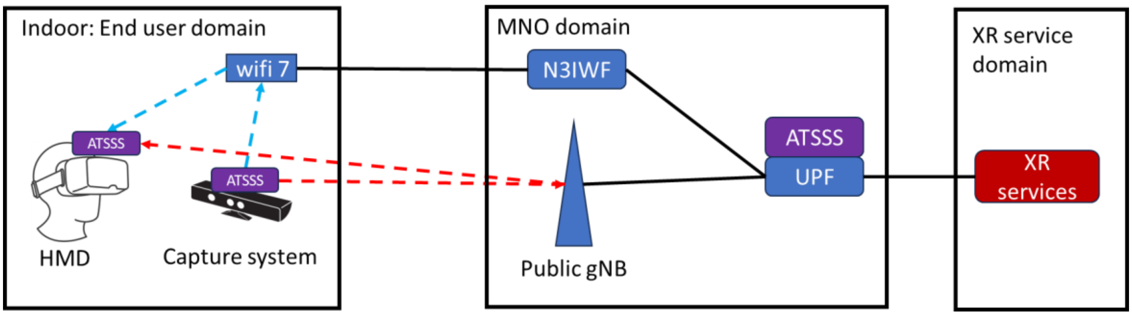

Figure 10. Usage scenario for 6GXR ATSSS enabler

The main research challenge addressed in this 6GXR enabler is the design of a suitable ATSSS forwarding function for XR services. The ATSSS function will be incorporated both in the end user devices and on the network side and shall be able to: i) forward XR traffic at high capacity, and ii) allow MNO to define forwarding policies tailored to the needs of XR services.

Looking at the state of the art in ATSSS design, ATSSS was introduced by 3GPP for IMT-2020 [19], where MPTCP proxy is deployed in 5G User Plane Function (UPF) to facilitate traffic steering via multi-radio access technology [20]. This provides users with low latency and high reliability. In Rel19, the upper layer ATSSS over dual 3GPP access [21] is explored. There are two ways for multipath transport, 1) Above the core and 2) Core centric. In above figure, the multipath transport protocol is deployed at both client and server sides. As an example, for above the core, the work in [22] considers the throughput performance for heterogeneous links including 5G mmWave links. While in [23] multipath on smartphones equipped with mmWave radios are considered and the evaluation of MPTCP's power consumption is provided. In Core-Centric integration, the multipath transport protocol is deployed at the client and in the 5GCore and a single-path transport between the core network and the server [24]. Core Centric integration is a favourable candidate for 5G as it enables more direct control of multi-connectivity within the cellular system.

Looking at concrete ATSSS implementations, it is relevant the work carried out in the 5G-CLARITY project [25], which investigated the use of ATSSS to integrate Li-Fi, Wi-Fi and 5GNR in industrial scenarios. In [25] 5G-CLARITY describes an ATSSS design based on Multi-Path TCP (MPTCP), which supports a round robin scheduler to aggregate capacity and a redundant scheduler to minimize delay. In [25] the 5G-CLARITY consortium reports an experimental performance evaluation in a real factory setup, using a 40 MHz 2x2 5GNR carrier, which is tested with two different TDD configurations, and an 80 MHz Wi-Fi 6 carrier. Under this setting the developed system achieves an aggregated performance close to 600 Mbps in downlink, when a TDD63 setting is considered, and an end-to-end round-trip latency below 10ms even when an 80% of background load is considered in the different wireless access networks. A drawback of the 5G-CLARITY system is that a significant drop of performance is reported when data is generated from a device that is not MPTCP capable, given that in this case 5G-CLARITY employs and proxy to relay split the end-to-end TCP connections.

2.2.3.2 Initial solution design and evaluation methodology

2.2.3.2.1 Initial design

Figure 11 depicts the envisioned architecture of the 6GXR ATSSS enable is depicted in Figure 10. The key function in this system, highlighted in yellow, is the ATSSS user plane (UP) function that aggregates the IP packets coming from the application functions, depicted in purple, and splits them across the indoor Wi-Fi and the public 5G network. In particular, the work in this enabler will focus on:

- Designing the ATSSS UP function, which must be able to relay the packets coming from the application functions, and to balance them across the Wi-Fi and 5G networks. It is an open design decision whether the ATSSS UP function needs to provide reordering, or whether reordering will be left to the transport layer protocol (e. g. TCP). The developed solution will be based either on MultiPath-TCP (MPTCP), which would provide reordering, or on MultiLink-VPN (ML-VPN), which is a multi-path based UDP solution that does not provide reordering. Another critical design aspect is the forwarding agent between the application functions and the multi-path tunnelling solutions, which in previous works has been seen to severely degrade performance [26].

- The Wi-Fi Multi-Link Operation (MLO) system. Wi-Fi 7 MLO allows to aggregate multiple Wi-Fi channels, even channels from different bands, into a single 802 MAC PDU session. Hence, Wi-Fi MLO provides at the MAC layer a functionality equivalent to the one that ATSSS provides at the transport layer. The Wi-Fi MLO system used in 6GXR will be provided by Intel and the impact of the MLO aggregation policies provided by the Intel driver will be analysed.

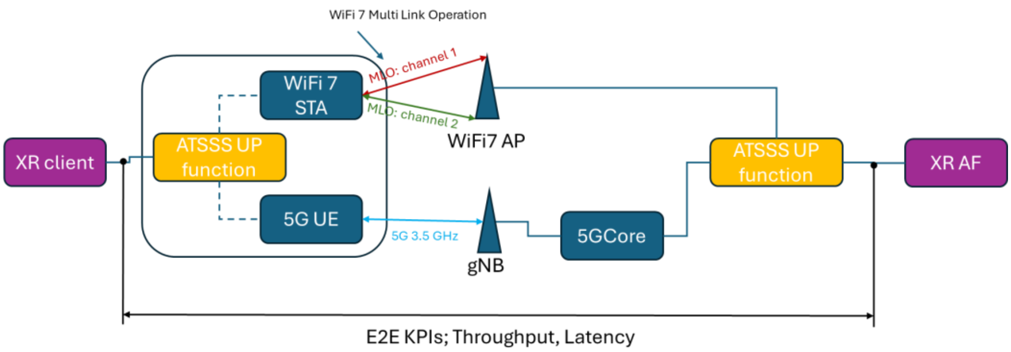

Figure 11. Envisioned architecture for the 6GXR ATSSS enabler

2.2.3.2.2 Proposed methodology

The enabler will be evaluated by means of laboratory-based experimentation. A private 5G network provided by i2CAT, will be complemented with a Wi-Fi 7 AP and station following the architecture depicted in Figure 11. The ATSSS UP function either based on MPTCP or MLVPN, will be deployed on embedded devices or on virtual machines connected to the i2CAT testbed.

To evaluate the efficiency of the developed ATSSS UP function, we will use as baseline the performance of each technology, i.e. Wi-Fi 7 and 5G, when working in isolation. Ideally, the aggregation capacity should equal the sum of the individual capacities but a moderate loss in efficiency is expected.

2.2.3.2.3 Target KPIs

Table 2-4. Target KPIs for 6GXR ATSSS enabler describes the KPIs that will be used to evaluate the performance of this enabler.

Table 2-4. Target KPIs for 6GXR ATSSS enabler

KPI name	KPI description	Target Value
Throughput	Bits per second in UL and DL measured between XR	Depends on underlying network configurations.

	application functions described in Figure 11. Throughput will be measured both for TCP and UDP as transport layer protocols.	Wi-Fi 7 MLO will be tested aggregating different number of channels. 5G will be tested with 50MHz and 100MHZ carriers and with different TDD patterns favoring UL and DL. This KPI will also be measured under different signal conditions, with respect to both the Wi-Fi AP and the 5G base station. Considering a holoconference session of 20 users with 20 Mbps per user, 400 Mbps in DL and 20 Mbps in UL should be supported for a single session.
Round Trip Latency	Round trip latency measured using standard network diagnostic tools such as ping or lagscope [27]	This KPI will be tested under the same network conditions defined for the throughout KPI. Target is to keep the round-trip latency below 20ms.
Number of concurrently supported Holomit users	Number of users that can be connected to the same Holomit call	The number of concurrent users will depend on the capture resolution used in the holographic system. A minimum of 10 concurrent users in a holographic call using a minimum codec rate of 6 Mbps.

2.2.4 Energy and Application aware management of 3GPP infrastructure

2.2.4.1 Targeted XR gap

Reducing the energy consumption of base stations has been a constant target during the past decade. It is well known that the power consumption is not directly proportional to the traffic load because active base stations consume power even without active users. Therefore, the biggest energy savings have been reached by cell and base station sleep modes applicable to network deployments with overlapping cells. In addition to cell sleep modes, energy consumption in RAN has been minimized by techniques such as reduction of the transmission power/bandwidth, adaptation of the number of transmitters, and Discontinuous Transmission (DTX).

These traditional techniques are very generic and application agnostic in their approach to the energy consumption minimization. In the most recent releases, 3GPP has also investigated more XR specific energy efficiency enablers. For example, TR 38.835 [28] studies power optimization for XR devices with adaptive Discontinuous Reception (DRX) to extend device battery-life and reduce network power consumption. These new approaches are based on application awareness in the scheduling process and require more dynamic behavior from the gNBs when carrying out the reconfiguration of the RAN. Hence, the activation time of the above changes in the current SoTA 3GPP-compliant RAN system as well as the effects of the changes to the connected UEs can become a bottleneck in real-life deployments.

To familiarize ourselves with the limitations of the current commercially available carrier grade RAN equipment, a series of network configuration changes related to potential energy saving methods for XR type of data traffic will be tested. The utilized non Real-Time (non-RT) slow control loop running in the network management framework of a 3GPP compliant operator network usually operates in the timeframe of tens of seconds or minutes. The XR applications utilized in tests will be based on 6G-XR use case UC4 – Collaborative 3D Digital Twin-like Environment [5]. In the usage scenario presented in Figure 12 , an XR user changes the utilized application (App1 and App2) which led to different optimal configuration at gNB. A predetermined application specific configuration change is triggered from the network management plane when an application change is detected in the aggregated KPI monitoring data collected from the gNB and 5GC. The time for the changes to take effect in the RAN and their impact on the connected UEs will be recorded. The achievable energy savings will be evaluated using the energy measurement framework deployed in 6G-XR use case UC5 – Energy Measurement Framework for Energy Sustainability [5].

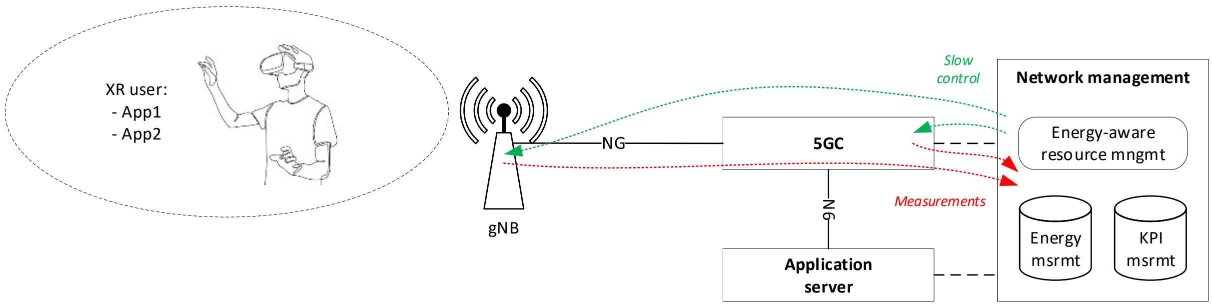

Figure 12. Usage scenario for energy efficient XR services.

2.2.4.2 Initial solution design and evaluation methodology

2.2.4.2.1 Initial design

The first version of the test setup for this enabler will be based on the VTT site 3GPP compliant 5G test network setup at the NN. The network comprises of commercial carrier grade network components. All these components will be utilized without modifications in their baseline functionality. Two 5GNR cells will be formed by using an outdoor macro Radio Unit (RU) as a coverage cell and an indoor pico RU as a capacity cell. This setup will be used so that the energy savings resulting from cell deactivations can be measured together with the network KPIs. COTS UE devices or Keysight UeSIM UE emulator will be used on the UE side. The selection of the utilized UE alternative will be based on the test case requirements, i.e., number of users required to be connected to the 5GNR cell. A simplified representation of the initial test setup is provided in Figure 13 with existing network functionality highlighted in blue and testing tools/configurations highlighted in orange. Wired connections between the depicted modules running in separate physical or virtual machines are drawn with green arrows, wireless connections with red arrows, and connections internal to a single physical or virtual machine with grey arrows. The dashed orange line shows the network components from which the network KPIs are measured and collected using a combination of internal counters of available at the network components and dedicated KPI measurement tools. The planned tests will evaluate both the network KPIs and energy consumption from an E2E perspective.

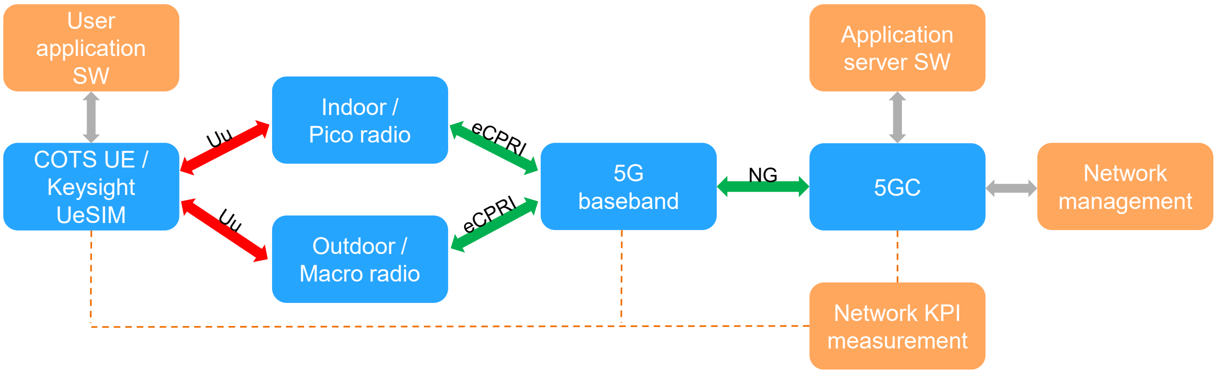

Figure 13. Test setup for non-RT KPI monitoring.

2.2.4.2.2 Proposed methodology

The baseline network performance, energy consumption, and energy optimization measurements will be performed in the carrier grade 5G network at the NN infrastructure. The aim of the first tests is to clarify the granularity and timeliness of the KPI monitoring data collected from the 3GPP 5G network architecture components using functionality provided by the network management plane. The network KPI monitoring data collected by the network management framework is analysed in parallel with the energy measurement data after both have been forwarded a common database for time alignment and further processing. The main topics to be investigated through the baseline measurement are how well the non-RT network KPI measurement data can be synchronized with the near-RT energy consumption measurement data, and in which kinds of usage scenarios this data can be meaningfully used to optimize the network configuration for XR application use without significant service interruptions. Based on the results of the baseline measurements, the most promising UE specific energy optimization methods will be identified for the tested applications.

2.2.4.2.3 Target KPIs

Target KPIs for the baseline measurements in the carrier grade 3GPP compliant 5G network are listed in Table 2-5. Target KPIs for energy efficiency and savings are developed and defined in 6G-XR WP5 and will be introduced into the WP4 measurement campaigns when available.

Table 2-5. Target KPIs for the baseline measurements using a carrier grade 3GPP compliant 5G network.

KPI name	**KPI description**	**Target Value**
KPI monitoring granularity	The time between consecutive KPI measurement results logged into the database.	1 measurement/min
Service interruption time after network re-configuration	The time it takes for the UE to adjust to the network re-configuration.	<1 s

2.2.5 Upgrade and evaluation of experimental RAN infrastructure in SN and NN

2.2.5.1 Targeted XR gap

The 6G-XR project will deploy 3GPP compliant network infrastructure in two different sites, referred to as South -Node (SN) and North Node (NN), which shall be prepared to validate future XR services. Therefore, it is key to identify what are the key 3GPP capabilities that need to be added to the 6G-XR sites. To identify the required 3GPP capabilities, the main challenges of future XR services should be addressed at first.

A first challenge is the availability of lightweight attractive user end devices is key to the success of XR applications. The existence of such devices depends heavily on offloading the computing resources to the Edge. This enables the devices to be smaller, less prone to heating and less energy consuming. The key 3GPP capability to address this challenge is the deployment and configuration of RAN and UPF products that can provide local breakout of the User Plane (UP) traffic needed for the packets to reach the Edge platforms with a low latency.

The compute offload from the devices puts more responsibility on the network to be able to provide the required performance for an acceptable XR user performance. For that matter, the particularities of XR services poses a second challenge in terms of latency and capacity. First, XR services require a low latency with a high reliability. This forces to try to avoid packet loss and retransmissions by being less aggressive in terms of modulation and coding schemes than for a generic MBB service, which however takes a toll in the capacity. In addition, due to the nature of XR traffic, the delays associated with starting to transmit and the retransmissions, there are only fractions of the time that can be effectively used for transmission. This means that at those times the data rate must be much higher than the average XR service rate requirements. Thus, the communication channel must support such higher capacity. Using the FR2 band makes available a large amount of bandwidth to boost capacity both in UL and DL. In particular, the 6G-XR sites will use carrier aggregation of FR1 and FR2 bands to try to take advantage of the better coverage range achieved by mid-bands while benefitting from the higher capacity of mmWave at the same time.

Finally, a third major challenge of future XR-services is to be able to configure a service-optimized QoS treatment from the network, to avoid being impacted by other kinds of traffic crossing the network. Key 3GPP capabilities to provide this customized QoS treatment include Slicing, QoS profiles and Radio Resource Partitioning (RRP) features. On top of 3GPP, novel exposure APIs such as CAMARA Quality on Demand [9] will enable the application to add logic to adapt to the required QoS in real time.

Figure 14. Key 3GPP enhancements to support XR services in 6G-XR depicts the three key 3GPP capabilities that will be added to the 6G-XR sites to address the previously mentioned XR challenges, namely: i) compute offload capabilities, ii) combination of FR1 and FR2 bands, and iii) exposure of network APIs to control service-level QoS treatment.

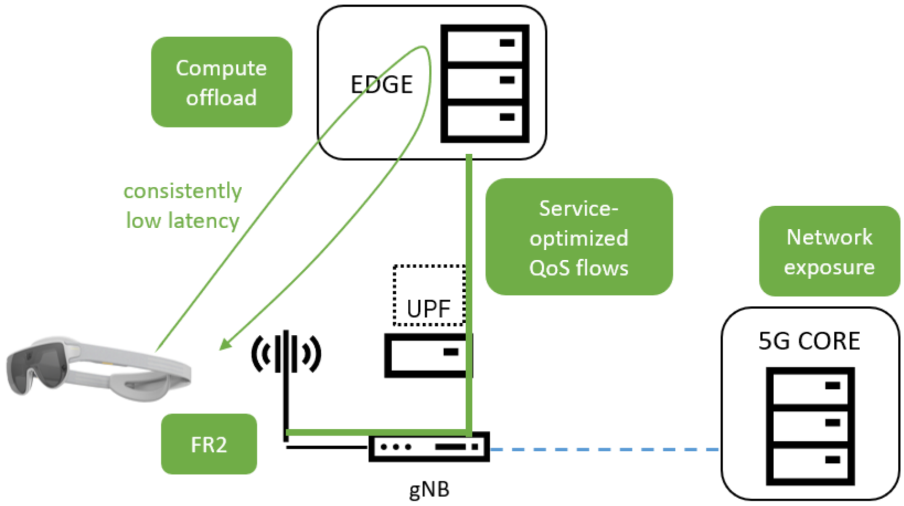

Figure 14. Key 3GPP enhancements to support XR services in 6G-XR sites.

The sources to elaborate this section have been the Ericsson Reports named: Future network requirements for extended reality applications [29], Network evolution to support extended reality applications [30] and XR and 5G: Extended reality at scale with time-critical communication [31] .

2.2.5.2 Initial solution design and evaluation methodology

We discuss in this section the initial RAN and core design for the two 6G-XR sites.

2.2.5.2.1 3GPP SN design

2.2.5.2.1.1 Initial design

The solution designed for the SN connects 5G RAN plus UPF products deployed at i2CAT premises in Barcelona with both the Edge platform located also at i2CAT premises and the 5GC Control Plane (CP) based at 5Tonic lab in Madrid. The 5GC CP controls the registration of the UEs in the network and sets the UP traffic to go through the UPF at i2CAT and reach the applications running at the Edge in i2CAT. The SN will also include an Edge platform provided by Capgemini at 5Tonic to test the service migration between Edges. When the applications are running at 5Tonic's Edge platform, the network will have to adapt to redirect the UP traffic through a UPF at 5Tonic. See Figure 15 for illustration.

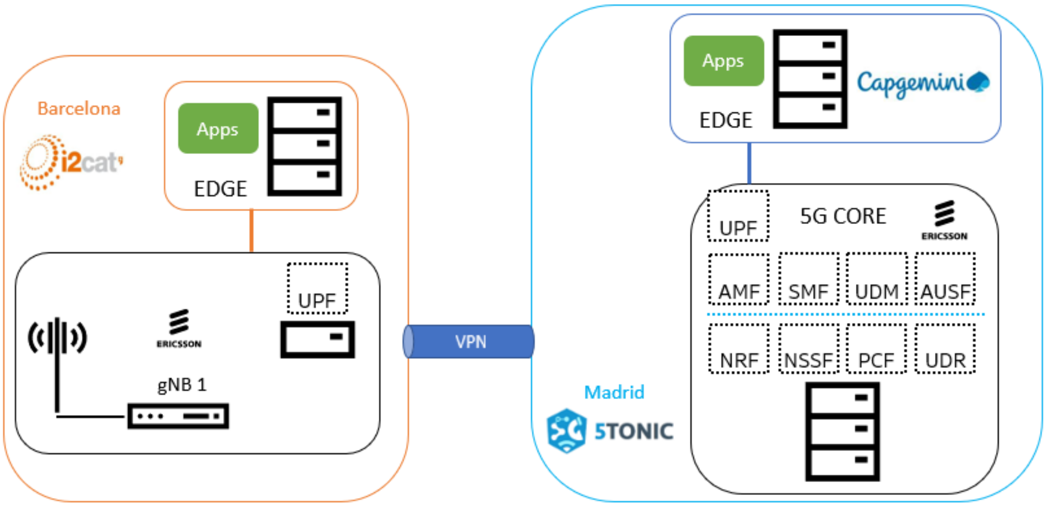

Figure 15. Logical design of 3GPP network in South-Node site, with RAN at i2CAT and Core CP in 5TONIC

The area to cover by the RAN is shown in Figure 16. There will be a mid-band radio installed on i2CAT building's roof (shown in yellow in Figure 16) and mmWaves radios installed on streetlamp poles (shown in red in Figure 16).

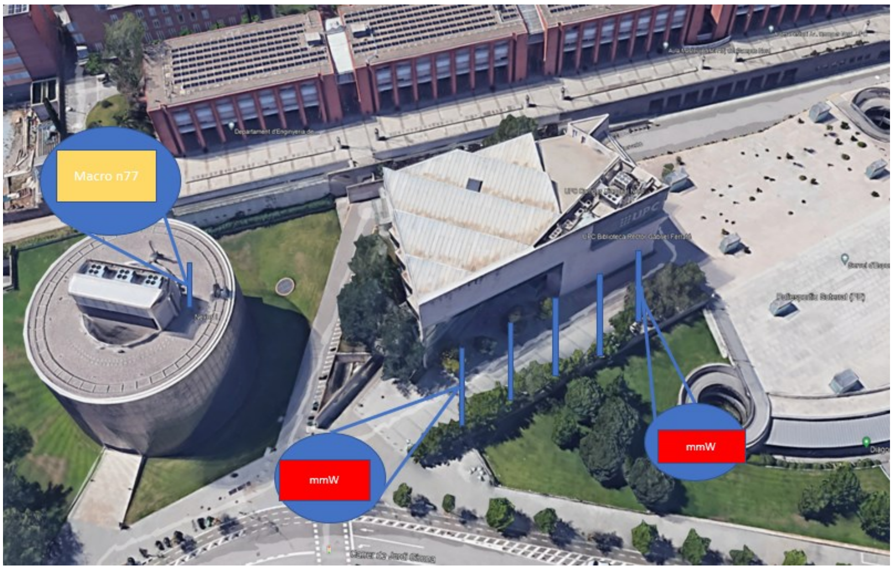

Figure 16. Planned RAN design for south node with FR1 and FR2 nodes.

The RAN and UPF equipment will be installed in a flight rack inside i2CAT building. The diagram represented in Figure 17 depicts the main components. It is worth highlighting some characteristics of the products depicted. The Ericsson's Radio 4408 + antenna 6524 can work in the B42F/B78R band (3420-3600 MHz) and supports a maximum operating bandwidth of 120 MHz. The Ericsson's AIR 5322 can work in the B258 band (24.25-27.5 GHz) and supports a maximum operating bandwidth of 800 MHz. The Ericsson's Baseband 6648 provides connectivity, traffic management and control for the radio units. The Ericsson's Router 6675 provides connectivity among all components and to the outside. It also obtains the clock reference from a GPS signal and servers as PTP synchronization master for the basebands and radios in the network. Finally, there is a Dell PowerEdge R640 server that holds the UPF.

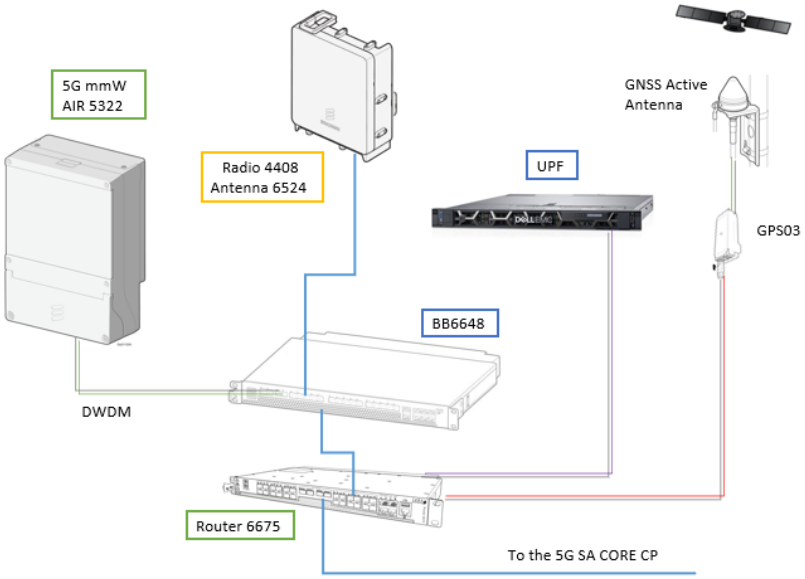

Figure 17. Flight rack design including FR1+FR2 radios and UPF for local breakout.

2.2.5.2.1.2 Proposed methodology

As described in the previous section, this enabler consists of the deployment of an experimental facility in the i2CAT campus network. This facility will be exploited within the 6GXR project in the following way:

- It will integrate the Trial Engine, described in Chapter 5 of this deliverable.
- It will be used to support the demonstration of the holographic communications use case within WP6.
- It will be offered to third parties as part of Open Call 3 in WP7.

2.2.5.2.1.3 Target KPIs

Table 2-6 describes the target KPIs for this enabler.

Table 2-6. KPIs for the south node experimental 3GPP infrastructure enabler.

KPI name	KPI description	Target Value
Per-cell FR2 throughput	Throughput in Mbps or Gbps measured at IP layer in UL and DL supported by an FR2 cell.	Achievable throughput depends on the available carrier BW and on the employed TDD pattern. BWs of 200MHz and 400MHz will be considered, subject to receiving approval from the Spanish regulatory authority.

		Maximum throughput is calculated using tools like iperf. The theoretical figures have been calculated with an online calculator [32] , which is based on the 3GPP TS 38.306 standard, assuming an efficiency of 80% so the goal is to get as close as possible to the following: -with 2x100 MHz BW & TDD pattern 4:1, 2 MIMO layers, 64 QAM: 280 Mbps in UL and 1 Gbps in DL. -with 2x100 MHz BW & TDD pattern 7:3, 2 MIMO layers, 64 QAM: 400 Mbps in UL and 900 Mbps in DL. -with 4x100 MHz BW, TDD pattern 4:1, 2 MIMO layers, 64 QAM: 560 Mbps in UL and 2 Gbps in DL. -with 4x100 MHz BW & TDD pattern 7:3, 2 MIMO layers, 64 QAM: 800 Mbps in UL and 1.8 Gbps in DL.
FR2-FR2 HO latency	This KPI measures the time required to execute a HO between two FR2 cells. This KPI is subject to having overlapping coverage of the two FR2 cells deployed at the i2CAT site. This KPI is measured in milliseconds.	Target value is 20ms. Tools like ping or Qosium and traces will be considered to extract this KPI
User Plane latency (round trip time)	This KPI measures the UP latency between a UE connected to the RAN at the i2CAT site, and an application function deployed in the Madrid or the Barcelona edge sites. This KPI is measured in milliseconds.	Target value is an average of 15 ms in a set of pings when using Barcelona edge, and 20 ms for Madrid edge. This will be measured using ping.

2.2.5.2.2 3GPP NN design

2.2.5.2.2.1 Initial design

6G-XR NN consists of two different but interconnected test networks and architectures: 5GTN of VTT Oulu and 5GTN of the University of Oulu. In this chapter the upgrades and new architecture that is introduced in the 6G-XR or for the 6G-XR are presented. First the 5GTN of the University of Oulu is described and after that the 5GTN VTT Oulu. Only the architecture of the main production network is presented here and the possible other solutions like the Open Source based network enablers are being defined in their own chapter in this document, and in D2.1.

University of Oulu 5GTN is one of the first private 5G Test Networks that were deployed in the world. As such the equipment of the network starts to be quite old as first radios for example are from 2016. In this task, Oulu 5GTN is therefore being renewed with new HW and SW modules and functionalities. All the FR1 5G radios are being replaced with new ones and the amount of the radios is increased to have better radio cell coverage of the University of Oulu campus area. Amount of FR2 radios in the network is increased. Simplified picture of the network is shown in the Figure 18 below.

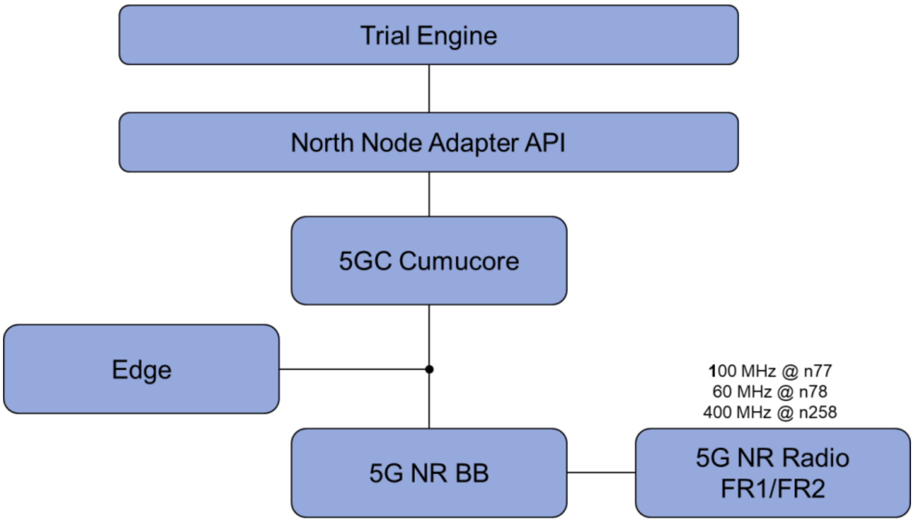

Figure 18. University of Oulu 5GTN

New components of the network are listed below:

- Trial Engine: modified from the 5G!Drones project
- North Node Adapter API: adapts the Trial Engine to the 5GTN
- 5G Core: Cumucore that enables dynamic 5G slicing
- Edge servers: to run for example 3D Digital Twin Use Case 3D engine
- 5G NR BB: New 5G Baseband units
- 5G NR Radio: New radio units for bands n77 and n78 for both indoor and outdoor usage

VTT 5GTN has been deployed in parallel with the University of Oulu infrastructure and is also undergoing an upgrade process for the RAN equipment providing the FR1 outdoor radio coverage at the test facility. In the process, the coverage at the n77 frequency band (with 100 MHz bandwidth) is also extended to offer more capacity alongside the existing n78 frequency band (with 60 MHz bandwidth). In addition, FR2 outdoor radio coverage at the n258 frequency band (with 400 MHz UL and 800 MHz DL bandwidth) will be added as a new access option for even more demanding use cases and experiments. The SW for the upgraded RAN HW is continuously updated throughout the project.

The simplified view of the upgraded network deployment is provided in Figure 19. The Trial Engine and NN Adapter API components are introduced as new enablers by interconnecting them to the test facility in collaboration with the University of Oulu.

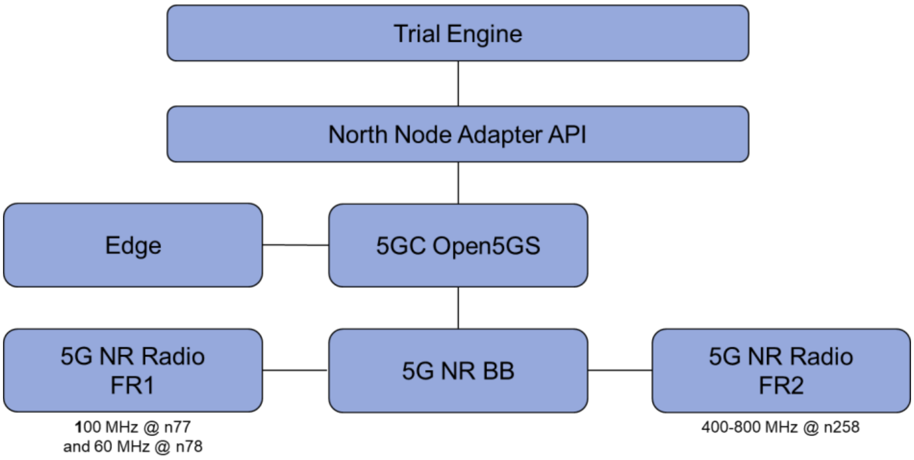

Figure 19. Simplified view of the upgraded VTT 5GTN.

The upgrades specific to the VTT 5GTN test facility are as follows:

- 5GC: Updated Open5GS with enhanced slice configurations.
- Edge: Enhanced GPU support for multimedia and AI applications.
- 5G NR BB: New baseband units with enhanced radio support and energy efficiency optimizations.
- 5G NR radio FR1: Enhanced network capacity on non-overlapping frequency bands.
- 5G NR radio FR2: Totally new network capacity for XR applications and use cases.

Radio coverage of both networks is presented in Figure 20. Cell coverage is not to be seen accurate but more like indicative. The blue colour indicates the upgraded FR1 coverage and red colour FR2 coverage.

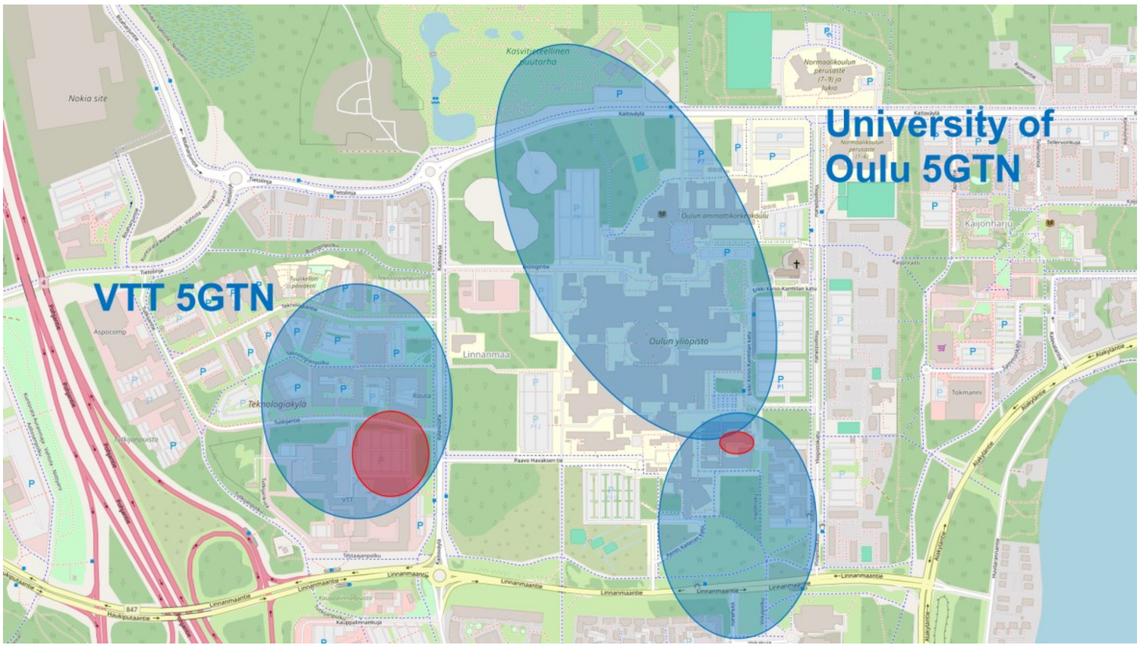

Figure 20. Target 5G Radio coverage in the VTT and University of Oulu Campuses.

2.2.5.2.2.2 Proposed methodology

Architecture of both the University of Oulu 5GTN and VTT 5GTN test facilities were described in the previous subsection. Both networks in their updated fashion are seen as NN enablers for the 6G-XR.

These new enablers will be made available in the following way:

- Trial Engine together with North Node Adapter API will be integrated to the UOulu 5GTN.
- New Core is installed, integrated, configured, tested, and taken into use.
- New Baseband modules are integrated to the new 5G Core.
- New 5G radios are installed, integrate and taken into use in the network.
- New Edge servers are installed to the UOulu 5GTN and existing Edge servers upgraded at the VTT 5GTN.

2.2.5.2.2.3 Target KPIs

Table 2-7 describes the KPIs for the 6G-XR NN.

Table 2-7. KPIs for the north node experimental 3GPP infrastructure enabler.

KPI name	KPI description	Target Value
FR2 throughput	Throughput in Mbps measured for both UL and DL.	Achievable throughput is presented separately for UL and DL. Maximum FR2 UL BW is 400 MHz and maximum DL BW is

		800 MHz. These values are used when testing the throughput. The theoretical figures have been calculated with an online calculator [32] , which is based on the 3GPP TS 38.306 standard, assuming an efficiency of 80%. Used TDD pattern is 4:1. DL target: 4.1 Gbps UL target: 570 Mbps
FR2 User Plane latency	This KPI measures the UP latency between a UE and Edge server in the NN network.	One way latency is measured using Qosium QoS measurement tool. DL target: 5 ms UL target: 7 ms
FR1 throughput	Throughput in Mbps measured for both UL and DL.	Achievable throughput is presented separately for UL and DL. Maximum FR1 BW is 100MHz that is also used when testing the throughput. The theoretical figures have been calculated with an online calculator [32] , which is based on the 3GPP TS 38.306 standard, assuming an efficiency of 80%. Used TDD pattern is 4:1. DL target: 560 Mbps UL target: 150 Mbps
FR1 User Plane latency	This KPI measures the UP latency between a UE and Edge server in the NN network.	One way latency is measured using Qosium QoS measurement tool. DL target: 7 ms UL target: 9 ms

2.2.6 Summary of proposed 3GPP XR enablers

Table 2-8 summarizes the five technical enablers presented in this section, while highlighting their applicability to the 6G-XR use cases described in deliverable D1.1 [5].

Table 2-8. Summary of proposed 6G-XR enablers in the 3GPP path

Proposed 3GPP XR Enabler	Target XR gap	Relation to 6GXR use case
Network-controlled repeaters for coverage extension	Coverage enhancements for indoor UEs	Contributes to UC1 – holoportation, by enhancing the UL and DL capacity that is required for capture and transmission of point clouds
Network assisted rate control API for XR services	Enhance performance of rate control mechanisms used by XR services. Focus is on shifting from OTT estimation mechanisms to network assisted mechanisms.	Contributes to UC1 – holoportation, by allowing the application to control the data rate according to network capacity
ATSSS based capacity enhancements	Combines indoor WiFi with public 5G to enhance capacity of indoor XR users	Contributes to UC1 – holoportation, by enhancing the UL and DL capacity that is required for capture and transmission of point clouds
Energy and application aware management of 3GPP infrastructure	Optimize 3GPP configuration (cells, DRX) according to application needs	Contributes to UC4 – Collaborative 3D Digital Twin-like Environment and UC5 – Energy Measurement Framework for Energy Sustainability: Enhancing energy efficiency of both UEs and network with slow (non-RT) control when XR applications are used.
Upgrade of experimental facilities	Deployment of local breakout, FR1+FR2 and network exposure capabilities in 6G-XR experimental sites	Transversal – applies to all use cases

3 O-RAN XR ENABLERS

3.1 OVERVIEW OF O-RAN MECHANISMS

An introduction to the O-RAN architecture including the role of Non-Real-TimeRIC, the Near-Real-Time RIC, the xApps and the rApps has been provided in D1.1 [5]. In this section an in-depth analysis of how the different work streams developed in the O-RAN Alliance relate to the 6GXR project is provided.

The activity in O-RAN alliance is organized in a set of Working Groups, with a focus on specification-oriented work, and a set of focus and research groups that support transversal and forward-looking activities. The following table details the existent O-RAN groups, highlighting those that carry out activities that are relevant to 6G-XR.

O-RAN Working Groups		
WG name	**Scope**	**Relevance to 6GXR**
WG1: Use Cases and Overall Architecture Work Group	Identifies tasks to be completed within the scope of the Architecture and Use Cases	This group defines application-oriented use cases. Use cases related to RAN slice assurance, congestion prediction, QoE optimization, are already defined that could be applied to XR services.
WG2: The Non-Real-Time RAN Intelligent Controller and A1 Interface Work Group	Supports Non-Real-Time intelligent radio resource management, higher layer procedure optimization, policy optimization in RAN, and providing AI/ML models to Near-RT RIC	The Non-RT RIC hosts rApps, which optimize operation of the RAN using non-real time loops. Interactions between rApps and XR services may be considered to enhance service performance.
WG3: The Near-Real-Time RIC and E2 Interface Work Group	Enables near-real-time control and optimization of RAN elements and resources via fine-grained data collection and actions over E2 interface.	This groups specify the E2 service models, which dictate the information that can be extracted from RAN nodes, as well as the actions that can be enforced on the RAN. Enhancements of existent E2 service models, or definition of new ones, may be considered to optimize XR services.

WG4: The Open Fronthaul Interfaces Work Group	Open fronthaul interfaces, supporting multi-vendor DU-RRU interoperability.	
WG5: The Open F1/W1/E1/X2/Xn Interface Work Group	Provide fully operable multi-vendor profile specifications for 3GPP F1/W1/E1/X2/Xn interfaces.	
WG6: The Cloudification and Orchestration Work Group	Produce technology and reference designs that would allow commodity hardware platforms to be leveraged for all parts of a RAN deployment.	
WG7: The White-box Hardware Work Group	Promotion of open reference design hardware.	
WG8: Stack Reference Design Work Group	Develop the software architecture, design, and release plan for the O-RAN Central Unit (O-CU) and O-RAN Distributed Unit (O-DU) based on O-RAN and 3GPP specifications for the NR protocol stack.	
WG9: Open X-haul Transport Work Group	Transport domain, consisting of transport equipment, physical media and control/management protocols associated with the transport network.	
WG10: OAM Work Group	OAM requirements, OAM architecture and the O1 interface.	O1 interface allows to manage O-RAN nodes. New management options may be considered to optimize XR services.
WG11: Security Work Group	Security aspects of the open RAN ecosystem.	
O-RAN Focus and Research Groups		
SDFG: Standard Development Focus Group	Interface to other Standard Development Organizations (SDOs) that are relevant for O-RAN work	

IEFG: Industry Engagement Focus Group	O-RAN Ecosystem engagement to promote and accelerate O-RAN based technology adoption	
OSFG: Open-Source Focus Group	Planning, preparation, and establishment of an O-RAN Software Community (OSC)	6GXR can benefit from software generated by OSC, as well as contribute to it.
TIFG: Testing and Integration Focus Group	Defines O-RAN's overall approach for testing and integration	
SuFG: Sustainability Focus Group	Focus is to optimize energy consumption, reduce environmental impact, and create more energy-efficient and environmentally friendly mobile networks.	The focus of this group is relevant to the energy efficiency work done by 6GXR in WP5.
nGRG: next Generation Research Group	Focuses on research of open and intelligent RAN principles in 6G and future network standards.	Discussions in this group may be relevant to the disruptive technologies path explored by 6GXR in Task 4.3.

As seen in the previous table, unlike 3GPP, O-RAN is not focusing on specific service enablers like XR. Instead, O-RAN focuses on transversal RAN optimization topics that can be applied to different verticals. Following this transversal approach, **the focus in 6GXR will be to design of rApps and xApps that can be used to enhance performance of XR applications**.

The key O-RAN interface that enables the design of xApps/rApps is the E2 interface, which supports the following service models:

- Key Performance Measurements (KPM) service model: Exposes available measurements at the O-DU, O-CU-CP and O-CU-UP. It supports all counters defined in 3GPP TS28.552 and TS32.425, plus additional counters defined by O-RAN [33]. It allows xApps to subscribe to measurements for a single UE or for multiple UEs. Measurement reports can be based on conditions (e.g. threshold is crossed) or periodic.

- RAN Control (RC) service model: It is used to expose UE context related information. This includes per-UE variables and identifiers at the gNB at the PDCP, RLC, and MAC layers. This service model can also be used to control, among others, bearer setup at the gNB, to control QoS flow to bearer mapping configurations, split bearer setup in multi-connectivity, configure Discontinuous Reception (DRX), semi-persistent scheduling settings, admission control settings, and idle and connected mobility parameters (e.g. conditional handovers).

- Cell Configuration and Control (CCC) service model: It can be used to expose node or cell level configuration parameters to an xApp (e.g. what handover thresholds are configured in a cell). It can also be used to enforce configuration changes from an xApp on a node or cell level. The supported RAN configuration structures are based on those defined in TS28.541, adding some O-RAN customizations. Example of configuration attributes at node level include IDs like

PLMN/SNSSAI at DU, CUUP and CUCP and parameters like the RRMPolicyRatio. Examples at cell level include bandwidth partition (BWP) configuration as well as the RRMPolicyRatio.

- Network Interface (NI) service model: It allows to expose network interfaces to xApps, e. g. N2, Xn, F1, E1. It can be used to report messages received over these interfaces to an xApp. It also enables the xApp to insert messages to a given interface. Could be used for example to have an xApp that brokers interference related Xn messages between two gNBs.

Looking at the state of the art, in [34], the authors proposed novel xApp that employs Adaptive Genetic algorithm for optimal user association to gNodeBs, resource allocation (RA) distribution, and power allocation (PA) in the context of 5G. This QoE2F xApp offers QoE gains by enabling both UEs and BSs to achieve their specific needs. Both the user and network are wining situation where the user is getting services at high data rates and quality levels while as for the mobile network, it implies meeting the performance targets indicated in service level agreements while also operating efficiently. In fact, this can be applied to XR where certain level of QoS and QoE should be met. Another interesting work is proposed in [35], where ML framework for jointly optimize the intelligent traffic prediction, flow-split distribution, dynamic user association and radio resource management called "JIFDR" is proposed. The authors developed three dependent rAPPs: traffic prediction, dynamic RAN slicing decision and flow-split distribution at the non-RT RIC and radio resource management xAPP at the near-RT RIC. This work demonstrates maximum throughput at low latency using O-RAN gym simulator which can fit the XR applications. A large-scale ML driven O-RAN xApp for managing and controlling cellular network is presented named ColO-RAN, considered as largescale, experimental O-RAN framework for training and testing ML solutions for next-generation RANs. It combines O-RAN components, software RAN and Colosseum, seen the world's largest, open, and publicly available wireless SDR network emulator [36]. Despite all previous work is not focusing on XR applications but they are concerned with QoE and QoS at low latency which is essential for XR service.

Next, we describe three O-RAN enablers in the form of custom xApps/rApps that will be designed in 6GXR to enhance performance of XR services. For each enabler, we identify the XR gap being addressed, as well as the key O-RAN interfaces and service models that are required.

3.2 O-RAN XR PROPOSED ENABLERS

3.2.1 Congestion aware load balancing

3.2.1.1 Targeted XR gap

As mentioned in the previous section, the holoportation service considered in 6GXR use case 1 [5] imposes significant requirements in terms of capacity both in uplink and downlink. The 6GXR congestion aware load balancing enabler presented in this section, will investigate how O-RAN mechanisms can assist in maintaining the level of quality required by the holoportation user in an O-RAN enabled public network.

Figure 21 depicts the usage scenario considered for this technical enabler. We can see how an O-RAN enabled public network, featuring gNBs and a near real-time RIC is used to server both holoportation users, typically residing indoors, as well as other best effort users doing Internet traffic. We can see in Figure 21 how the public network is composed of different cells, and how holoportation and best effort users may have access to more than one cell from a given location. By default, cell selection in a mobile network is performed exclusively in terms of signal properties, e.g. RSRP/RSRQ. However, mobility load balancing (MLB) procedures can also be implemented that assist in steering users away from congested cells. Figure 21 represents a situation where the holoportation user is connected to a cell that is congested due to the presence of other terminals performing Internet traffic, while another cell where the holoportation user could connect to appears to have a lower congestion.

The goal of the 6GXR congestion aware load balancing enabler is to implement an MLB procedure based on O-RAN capabilities, which can be used to assist in maintaining the performance of holoportation services. To this end, we consider the gNBs connected to the near RT RIC component supporting the E2 KPM and the E2 RAN control service models. Based on the E2 KPM service model, a congestion estimation xApp can track overall PRB utilization in the different cells and detect when congestion may impact the performance of the holoportation service. Based on the E2 RAN Control service model a load balancing xApp can initiate a network handover to move the holoportation user towards the less congested cell. Notice that the situation described in Figure 21 only represents a particular example, whereas a fully developed solution should decide on other load balancing configurations affecting both the holoportation and the Internet users on a particular cell.

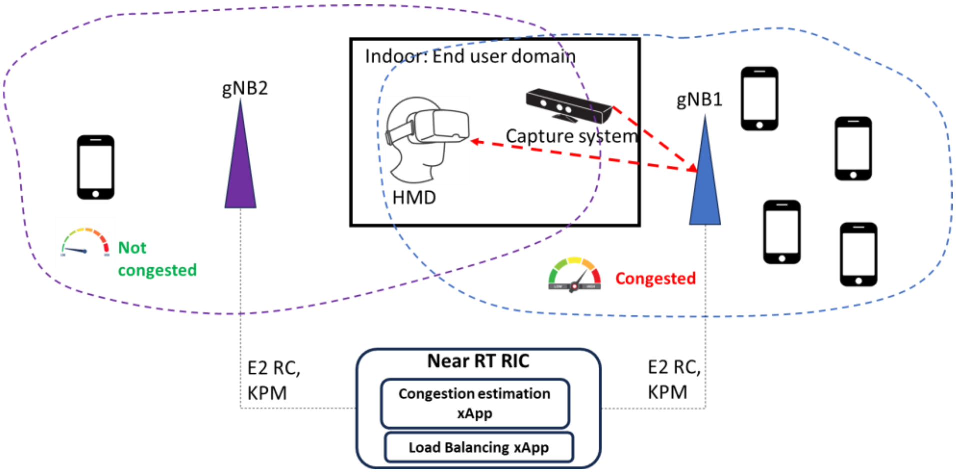

Figure 21. Usage scenario for O-RAN congestion aware load balancing enabler.

By exploring the state of the art, in 5G mobile network the dynamic optimization of the data splitting ratio's utility function among multiple access networks, regardless of application type or the QoS required is explored in *[37]*. Self-optimization employing mobility load balancing status proposed by 3GPP to switch UEs connections from overload cells to underloaded adjacent cells have lower load to improve the overall QoS and network gain capacity. Regarding O-RAN, only traffic steering is proposed *[38] [39]*. Another important problem is that users entering an area can cause a BS to be overloaded, leading to network congestion. Therefore, some work considers mobility load balancing to share network traffic among neighbouring BSs, allowing more efficient allocation of network resources to guarantee QoS for users. In *[40]*, the work proposed load-balanced user association and resource allocation algorithm to compromise both energy conservation and QoS satisfaction. In addition, the load distribution can be improved by adjusting BS parameters such as adjusting handover margin and time to trigger handover incorporating the neighbouring BS available capacity and load *[41]*. Moreover, mobile load balancing can be based on user positions prediction using Bayesian additive regression then forecasts cell load to calculate the cell offset value *[42]*.

3.2.1.2 Initial solution design and evaluation methodology

3.2.1.2.1 Initial design

Figure 22 depicts the envisioned architecture for the 6GXR O-RAN congestion aware load balancing enabler. The designed system will feature four main components highlighted in yellow:

- A load balancing rApp that will interface with the XR application function to identify the target XR user session, as well as its data rate requirements. The rApp will monitor the network conditions and issue non-real time policies about load balancing decisions affecting UEs in RRC_CONNECTED state.

- A load balancing xApp, which will be in charge of interfacing with the gNB through the E2 Radio Control service model in order to execute a concrete load balancing decision, as instructed by the rApp.

- A per-cell telemetry provider, exposing per-cell counters such as PRB-related counters and number of connected UE counters. This is the information required by the rApp to take load balancing decisions.

- A telemetry data lake, which will be implemented using Prometheus [43] that will store time series data about the counters exposed by the gNB.

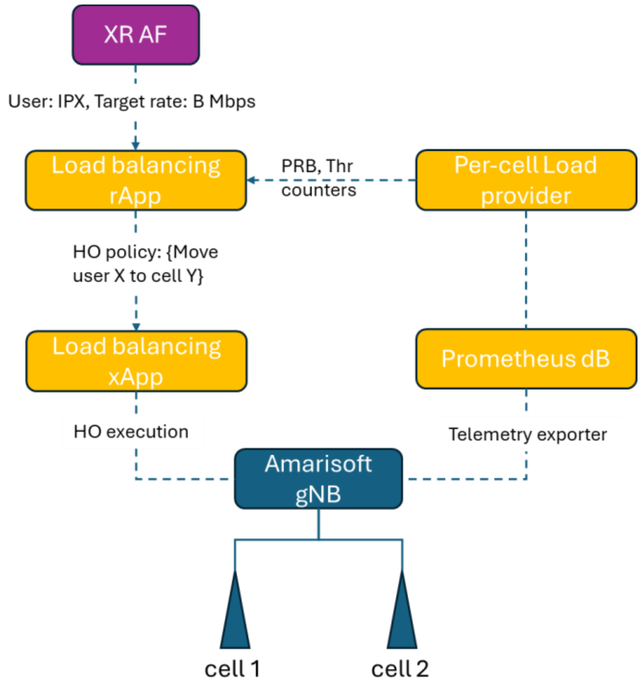

Figure 22. Envisioned architecture for O-RAN congestion aware load balancing enabler.

3.2.1.2.2 Proposed methodology

The applied methodology will be based on laboratory experimentation, which will be hosted by i2CAT. As depicted in Figure 22, an Amarisoft gNB featuring two connected cells will be used as the basis for the testbed. Amarisoft supports an API to control network-based mobility. This API will be used as the basis for the E2 interface between the load balancing xApp and the gNB. Connected to the Amarisoft UE we will consider an XR UE, representing the UE running the XR service that needs to be protected, and a background UE that will generate interfering traffic.

3.2.1.2.3 Target KPIs

Table 3-1 describes the target KPIs for this enabler.

Table 3-1. Target KPIs for 6GXR congestion aware load balancing enabler.

KPI name	**KPI description**	**Target Value**
MLB HO execution time	This KPI will measure the time required from the moment that the rApp issues the HO instruction until the target UE is successfully connected to the target cell. This KPI will be measured in second.	HO execution time should be below 20 ms.

Maximum HO capacity	Given that an rApp may want to execute many load related handovers in a short time, this KPI will measure the maximum number of HOs that the system can support. The number of HOs will be limited for example by the associated signaling load, or the required measurement overhead. This KPI will be measured in terms of HOs per unit of time.	A tentative target value for this KPI is 10 HOs per second. This target value will be reviewed in D4.2.
XR session interruption time	This KPI will measure the impact on a running XR session when a UE is moved from one cell to another. This KPI will be measured in seconds	Seamless – no visible impact on the running XR session

3.2.2 Energy-aware end-to-end resource management

3.2.2.1 Targeted XR gap

In general, XR services have stringent KPI requirements and are resource hungry. However, these requirements can be very different between different XR services and applications. Some services require high data rates (e.g., holographic communications and high-quality content streaming) while others require low latencies and jitter (e.g., interactive VR and haptics). Taking into consideration the varying requirements, the network can cater for the specific needs of the XR services in an energy and resource efficient manner. However, the adaptation at the network side must be able to follow the dynamic changes in the usage patterns of the XR services and network load. With the traditional cellular network resource management approaches this is not possible as adjustments in the network configuration are executed in a timeframe of minutes instead of ≤1 s.

The disaggregated O-RAN architecture and open interfaces are able to provide control loops operating in different time windows at different levels of the architecture hierarchy [44]. The slow or non-RT control loops have a typical time range of >1 s and are running at the non-RT RIC or at the Service Management and Orchestration (SMO) framework. The fast control loops run closer to the network edge. The near-RT control loops run at the near-RT RIC and have a typical time range of less than 1 s, whereas the RT control loops run directly at the E2 Nodes and have a typical time range of less than 10 ms. An E2 Node in the O-RAN architecture comprises of O-CU, O-DU, and O-RU components and is equivalent to a gNB in the 3GPP NG-RAN. In the O-RAN architecture, the different control loops can be utilized to perform RAN resource management with varying granularity, also providing the required enablers for dynamic resource management targeting for energy efficiency in the RAN part of the E2E communication path.

Extending the experimentation of RAN energy efficiency optimization methods executed at the network and gNB/cell level in 3GPP networks (see Section 2.2.4), the near-RT KPI monitoring and dynamic UE specific radio resource management functionality enabled by the O-RAN architecture and interfaces will be tested for different types of XR services present in the 6G-XR use case UC4 – Collaborative 3D Digital Twin-like Environment [5]. In the usage scenario presented in Figure 23, an XR user is changing between two different applications (App1 and App2). Based on the near-RT KPI measurement data collected from the gNB as well as on the historical data provided by the SMO, the energy-aware resource management xApp running in the near-RT RIC will adjust the RAN configuration to better serve the specific needs of the utilized application in an energy efficient manner. In the RAN, the focus will be on the optimization of functionalities such as DTX, DRX, semi-persistent scheduling, and PRB allocations. The achievable energy savings will be evaluated using the energy measurement framework deployed in 6G-XR use case UC5 – Energy Measurement Framework for Energy Sustainability [5].

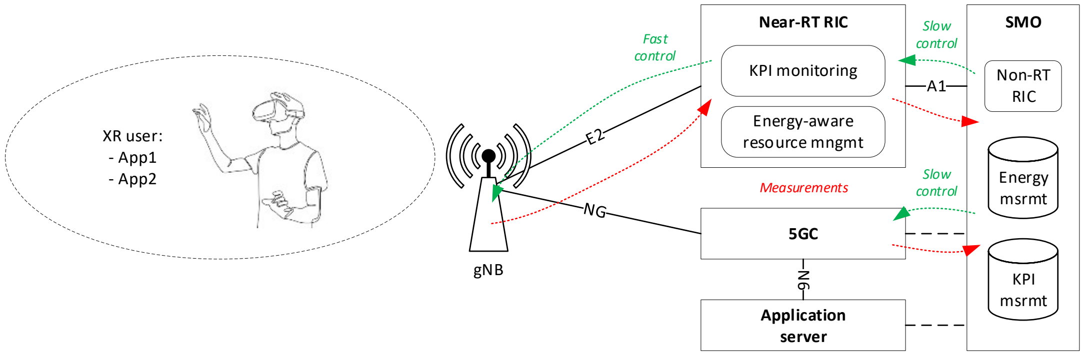

Figure 23. Usage scenario for energy-aware resource management for XR services.

3.2.2.2 Initial solution design and evaluation methodology

3.2.2.2.1 Initial design

The first version of the test setup for this enabler will be based on open-source solutions. A combination of srsRAN gNB [45], FlexRIC [46], and Open5GS [47] will be used. All these components will be utilized without modifications in their baseline functionality. One O-RAN cell will be formed by using a USRP X310 SDR. COTS UE devices (rooted OnePlus 9/10 Pro) or Keysight UeSIM UE emulator will be used on the UE side. The selection of the utilized UE alternative will be based on the test case requirements, i.e., number of users required to be connected to the O-RAN cell. A simplified representation of the initial test setup is provided in Figure 24 with existing network functionality highlighted in blue, testing tools/configurations highlighted in orange, and developed/modified network functionality under test highlighted in yellow. Wired connections between the depicted modules running in separate physical or virtual machines are drawn with green arrows, wireless connections with red arrows, and connections internal to a single physical or virtual machine with grey arrows. Network KPIs are measured and collected through an xApp utilizing the E2SM-KPM service model in the RIC. In addition to the E2E network KPI and energy consumption measurements, the main interface to be tested is the O-RAN E2 interface.

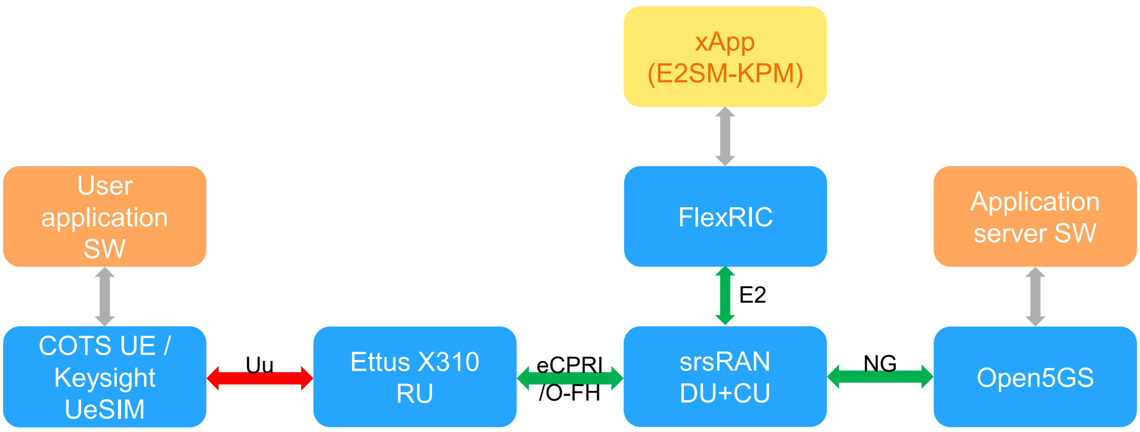

Figure 24. Test setup for near-RT KPI monitoring.

3.2.2.2.2 Proposed methodology

The first step in the implementation of the dynamic resource management functionality on top of the O-RAN architecture will be the testing of the near-RT KPI monitoring capability provided by E2SM-KPM service model. These tests will be performed as lab tests using a short-range O-RAN SDR deployment at the NN infrastructure. The aim of the first tests is to clarify the granularity and timeliness of the KPI monitoring data collected from the O-RAN architecture components using a KPI monitoring xApp running in the near-RT RIC. The network KPI monitoring data collected by the xApp is analyzed in parallel with the energy measurement data after both have been forwarded a common database for time alignment and further processing. The results achieved with the monitoring tools available for the 3GPP carrier grade network infrastructure depicted in section 2.2.4 are used as a baseline and granularity of the monitoring data will be compared between the two setups.

In the second step, one or more radio resource control domains provided by the E2SM-RC service model will be selected for testing. The selection will be based on the results of the baseline measurements depicted above as well as on an analysis of the most promising UE specific energy optimization methods for the tested applications. Depending on the availability of the implemented E2SM-RC control options in different O-RAN platforms (and feasibility of implementing the potentially missing option in the 6G-XR project), the testing will be performed either by extending the functionality of the open-source setup utilized for the initial evaluation of the KPI monitoring capabilities provided by the O-RAN architecture (depicted in Figure 24) or moved on top of a commercial O-RAN platform available at the NN during summer 2024.

3.2.2.2.3 Target KPIs

Target KPIs for the testing of the E2SM-KPM functionality and open-source O-RAN deployment are listed in Table 3-2. Target KPIs for energy efficiency and savings are developed and defined in 6G-XR WP5 and will be introduced into the WP4 measurement campaigns when available.

Table 3-2. Target KPIs for the first version of the energy-aware end-to-end resource management for XR services using an open-source O-RAN deployment.

KPI name	KPI description	Target Value
KPI monitoring granularity	The time between consecutive KPI measurement results logged into the database.	1 measurement/s
Service interruption time after network re-configuration	The time it takes for the UE to adjust to the network re-configuration.	<1 s

3.2.3 Slice-aware resource allocation

3.2.3.1 Targeted XR gap

To address the stringent requirements of XR applications and to enable seamless and realistic interactions between users and virtual environments, the key enabling technology in beyond 5G/6G is called network slicing. A network slice is a logical network comprising of a set of Network Functions (NFs) supporting the communication services for a particular use case deployed on a common physical infrastructure. Those use cases may refer to different applications with different requirements, like XR, V2X Vehicular-to-Everything (V2X), Internet-of-Things (IoT), enhanced Mobile Broadband (eMBB), etc. [48]. Moreover, in recent research [49], S. Karunarathna et al., emphasized network slicing as a key enabler for metaverse realization. Controlling and managing the resources of different slices are very crucial in the context of network slicing and radio resources are the pivotal elements in a slice. RAN slicing, a part of the E2E network slicing, handles the radio resources of the different slices according to the given SLA.

In the case of slice aware resource allocation in an O-RAN environment, two slices are considered having two different types of SLAs. One is for a normal eMBB user, and another slice is aimed for an XR user. To accomplish the requirements, RAN slicing concept is applied in an O-RAN environment. The resources are allocated in the slices according to the requirements of the eMBB slice and the XR slice. In terms of resource allocation and resource management in different slices, the key components of the O-RAN are [50]:

- Service, Management and Orchestration (SMO):
  - Provides information about slice topology and SLA associated with the slice to the Non-RT RIC
- Non-RT RIC:
  - Retrieves RAN slice SLA target from respective entities such as SMO, NSSMF
  - Long term monitoring of RAN slice subnet performance measurements
  - Training of potential ML models that will be deployed in Near-RT RIC for optimized slice assurance.
  - Supports deployment and update of AI/ML models into Near-RT RIC
  - Sends A1 policies and enrichment information to Near-RT RIC to drive slice assurance.
  - Sends O1 reconfiguration requests to SMO for slow-loop slice assurance.
  - Supports rApps for the RAN optimization.
- Near-RT RIC:
  - Near RT monitoring of slice specific RAN performance measurements
  - Supports deployment and execution of the AI/ML models from Non-RT RIC
  - Supports interpretation and execution of policies from Non-RT RIC
  - Performs optimized RAN (E2) actions to achieve RAN slice subnet requirements based on O1 configuration, A1 policy, and E2 reports.
  - Supports xApps for the RAN optimization.
- E2 Nodes (O-CU-CP, O-CU-UP, O-DU):
  - Supports slice assurance actions such as slice-aware resource allocation, prioritization, etc.
  - Supports slice specific performance measurements through O1.
  - Supports slice specific performance reports through E2.

Figure 25 demonstrates the high-level usage scenario of the proposed method of slice aware resource sharing in an O-RAN environment. A couple of users are considered in this case, one is a usual eMBB user (slice 1) and the other one is an XR user (slice 2) which requires more resources than the slice 1. Based on the E2 reports, the slice aware xApp running in the near-RT RIC adjusts the gNB configuration to fulfil the required SLA for the defined slices. The key focus here is to allocate the PRBs according to the demand. As the XR user needs to have more resources, the xApp should allocate more PRBs to the XR slice and comparatively less resources to the eMBB slice. Figure 26 represents the high-level architecture of the given usage scenario.

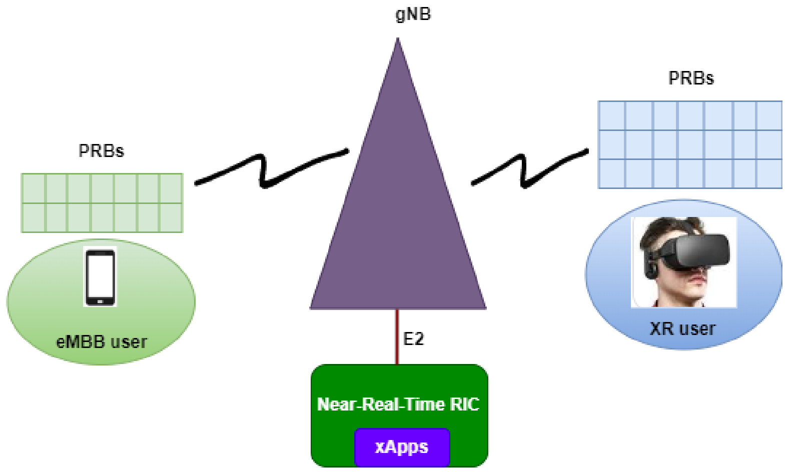

Figure 25. Usage scenario for slice-aware resource allocation for XR services.

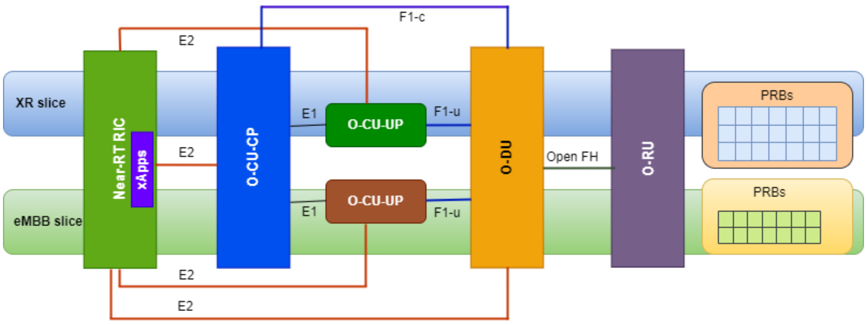

Figure 26. Slice-aware resource allocation high level architecture.

3.2.3.2 Initial solution design and evaluation methodology

3.2.3.2.1 Initial design

Figure 27 depicts the envisioned architecture for the slice -aware resource allocation enabler in O-RAN for XR services. The test setup for this enabler will be based on open-source tools and technologies with the implementation of 6G-XR Open Call 1 (Enabling end-to-end O-RAN slicing in 6G-XR) [45]. As the RAN solution, Open Air Interface (OAI) gNB [46] [51] with split architecture (gNB-CU and gNB-DU) will be used in the setup. As a core network solution, Open5GS-5GC will be used. For RIC purpose, Flexible RIC (FlexRIC) will be used in the design setup. The Ettus and National Instrument (NI) Universal Software Radio Peripheral (USRP) N310 model SDR will be used in the network setup to form the radio interface between the RAN and the UE. As UE, Quectel modem, Google Pixel, and iPhone will be used during the experiment.

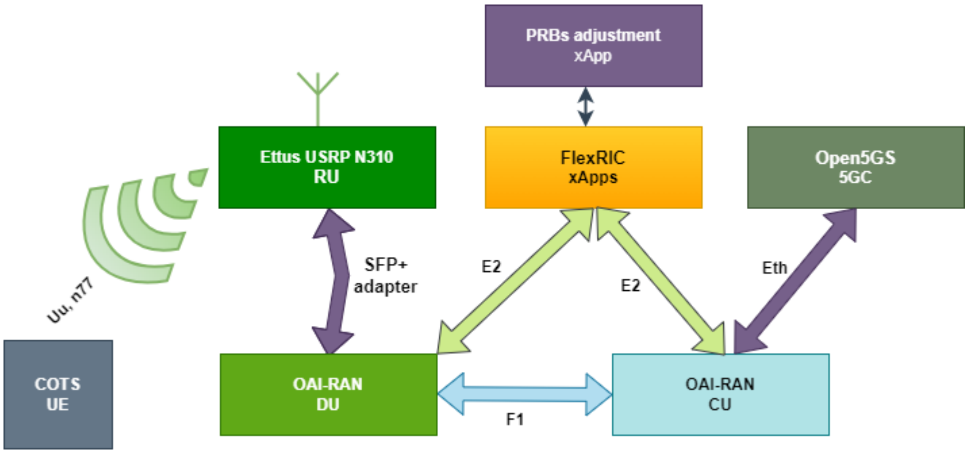

Figure 27. Test setup for slice-aware resource allocation.

3.2.3.2.2 Proposed methodology

The applied methodology will be focused on SDR based in-house laboratory experimentation, which will be hosted by the UOULU 5GTN Research Infrastructure (RI) in the NN infrastructure. According to the OC1 [45], the docker-compose will be used as the orchestrator for the O-CU, O-DU, and RIC. A web-based dashboard will be developed that will work as an abstraction layer to facilitate the use of the 5GTN's OAI based testbed by 6G-XR experimenters. REST APIs will be used which will allow the experimenter to create, update, and delete slices. The dashboard will be used for real-time monitoring and controlling as well as exposes a rich set of real-time network metrics. A couple of slices are considered in the setup. Two xApps will be implemented in the Near-RT RIC using the help of FlexRIC. The 1st xApp will gather all the metrices from the CU and DU of the RAN. Based on the available information (E2 reports), the 2nd xApp will adjust the radio resources (PRBs) to the defined slices. The underlying figure 28 represents the envisioned O-RAN based architecture for slice resource sharing at the 5GTN facility.

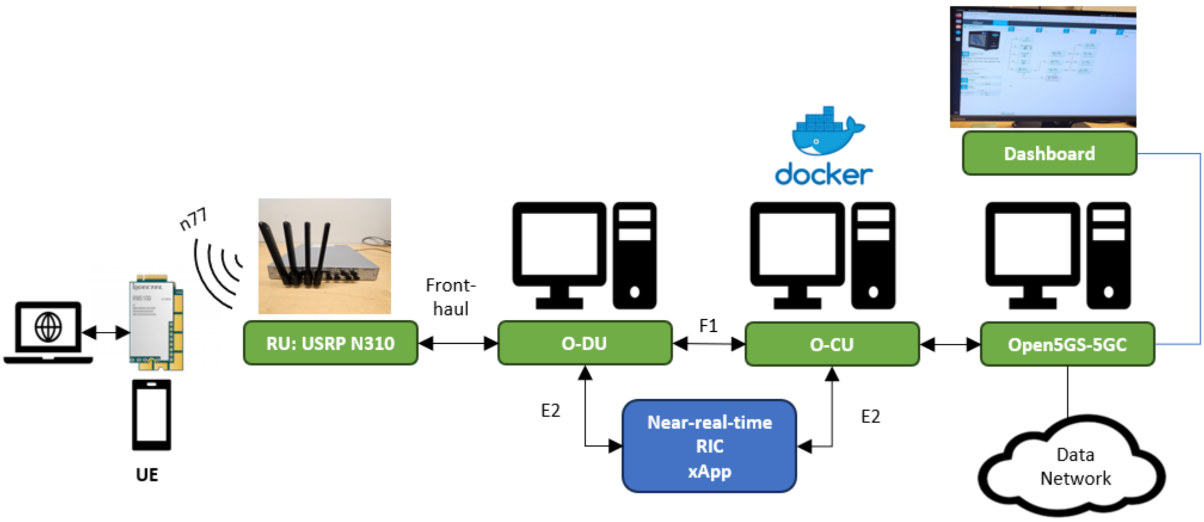

Figure 28. Planned O-RAN architecture to test E2E network slicing and RAN resource sharing in UOULU 5GTN RI [45].

3.2.3.2.3 Target KPIs

The target KPIs for this enabler are defined in Table 3-3 below [47] [5].

Table 3-3. Target KPIs for the slice-aware resource allocation for XR services in an open-source O-RAN deployment.

KPI name	KPI description	Target Value
Slice availability	Number of active E2E slices in the network.	2
Slice resource adjustment time	The time it takes to adjust the resources allocated to each slice.	10 ms – 1 s
DL throughput	Target total DL throughput. Split between the slices.	400 Mbps
UL throughput	Target total UL throughput. Split between the slices	50 Mbps

3.2.4 Summary of proposed O-RAN XR enablers

Table 3-4 summarizes the three technical enablers presented in the O-RAN path, while highlighting their applicability to the 6G-XR use cases described in deliverable D1.1 [5].

Table 3-4. Summary of proposed 6G-XR enablers in the O-RAN path.

Proposed O-RAN XR Enabler	Target XR gap	Relation to 6GXR use case
Network controlled load balancing triggered by XR application	Ensure available of enough radio resources for holoportation services delivered over public networks, where radio resources are shared with Internet users	Contributes to UC1: XR Congestion detection described in D1.1 [5], by providing a new mechanism (load balancing) to react to congestion
XR application-aware joint optimization of QoS and energy efficiency.	Dynamic runtime adjustment of RAN resources based on the changing XR service usage patterns.	Contributes to UC4 – Collaborative 3D Digital Twin-like Environment and UC5 – Energy Measurement Framework for Energy Sustainability: Enhancing energy efficiency of both UEs and network with fast (near-RT) control when XR applications are used.

O-RAN enabled slicing to support XR services	Dynamic adjustment and allocation of RAN resources specifically, PRBs to the slices according to the slice demand	Related to UC4 described in D1.1 [5].

4 6G DISRUPTIVE XR ENABLERS

4.1 OVERVIEW OF KEY 6G DISRUPTIVE TECHNOLOGIES

Three disruptive technologies are considered foundational for 6G-XR: RIS, THz and Sub-THz, and ISAC:):

- RIS is a key candidate technology that has become a hot topic for future wireless networks in the recent years. A RIS is a new network node that can be implemented using an arrangement of scatterer elements (called unit cells) whose properties can be controlled to tailor the electromagnetic response through reflection, refraction, focusing, collimation, modulation, absorption, and combinations of them. Suitable control signalling can be devised to realize these electromagnetic changes on the unit cells. The attractiveness of RIS lies on the fact that it can increase the outreach of other techniques, particularly THz.

- THz frequencies comprise the spectrum range 0.1 THz – 10 THz. While being very broad, some parts of the band are already allocated by ITU-R to, e.g., passive exploration services, imaging, and radar. Other frequencies are also identified for future use in communications but will not receive a formal allocation, until more studies are performed on their usage, protection limits, and coexistence requirements. While fundamentally focused on short ranges when employed in urban environments (up to a few tens of m), other supportive technologies can be applied to reinforce the coverage area and applicability of THz, where RIS stands among the most valuable ones.

- ISAC represents a step forward in the use of wireless technologies for radar-like detection of active and passive targets. Terminology wise, ISAC is different from Joint Sensing and Communication (JSAC or JCS) in that the latter considers joint application of sensing techniques on top of communications (e.g., as an add-on capability), while the former aims to have an integrated design well rooted since its inception. Future 6G networks will leverage ISAC principles in one way or another.

Despite the prospects of these three disruptive technologies independently, their combination comes with additional challenges. Considering the joint THz-RIS for example, the deployment of RIS at THz frequencies increases the network management complexity with respect to controlling/configuring a significant number of RIS elements and the increased associated channels parameters (such as the higher number of subcarriers and resource blocks) from the broadband THz links. Due to the huge scale of the resulting THz-RIS channels, classical model-based and heuristic resource optimisation frameworks become impractical. This, therefore, calls for ML-driven optimisation frameworks. ML exploits operational knowledge obtained from channel/network data to facilitate robust system optimisation. The THz-RIS-ML interplay, for example, can address the problem of channel impairments by intelligently finetuning the incident-reflect cascaded RIS channels as well address the challenge of optimal use of THz spectral resources for XR applications, leading to both improvement in QoS and QoE. The intelligent and dynamic (i.e., ML-driven) optimisation of the THz-RIS networks can enhance the overall system performance for XR use cases and scenarios.

Given the challenges ahead of the three key technologies described, the disruptive XR enablers proposed in 6G-XR will focus on an indoor scenario under two main use cases down selected from the set of use cases described in deliverable D1.1 [5]:

1. Real-Time Holographic Communications. This involves an indoor scenario aimed for virtual meetings, virtual TV shows, virtual visits, gaming/VR films, etc. It can be considered a baseline use case for the three key 6G disruptive technologies involving cameras with a bandwidth of at least 10 Gbps, and media processing units whose delay to/from the XR clients should be below 10 ms [5]. While THz can provide the ultra-high bandwidth, RIS and ISAC can significantly boost the added value of the ultra-high frequency links by:

    a. Improving on the limited coverage and rank of the channel, in addition to enriching the sensing capabilities thanks to the extra angle/delay measurements derived from RIS reflections.

    b. Leveraging the ultra-high spatial resolution of THz and Sub-THz bands for accurate sensing. ISAC information can be beneficial even if the use case does not have sensing demands, e.g., to improve beam management based on the environment.

    An example scenario showing the three underlying technologies (THz, RIS and ISAC), omitting the application cameras, is shown in Figure 29.

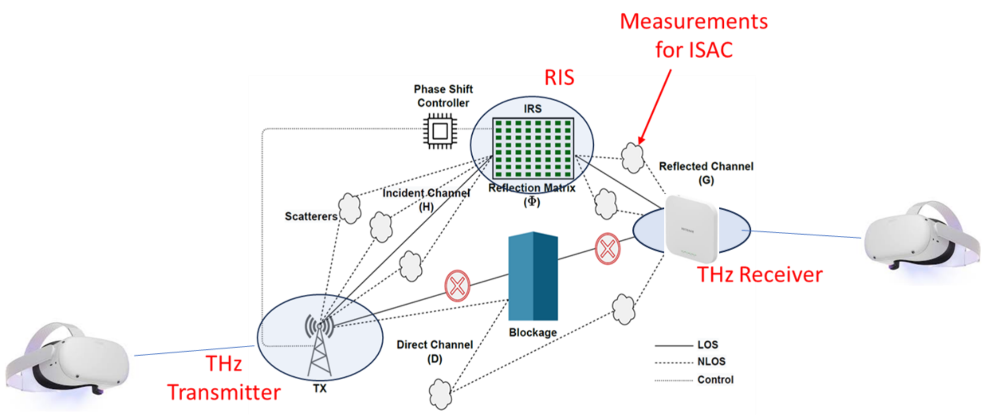

Figure 29. Setup of Real-Time Holographic Communications scenario with THz, RIS and ISAC (re-drawn from [52]) to which a couple of HMD devices are added.

2. Collaborative 3D Digital Twin-like Environment. This is a more advanced use case that demands ultra-high throughput data pipes with very low latency and sensing capabilities, involving: i) Bi-directional audio/video for VR equipment, ii) 3D object representation, iii) Movement and object interaction, and iv) Synchronization of an arm camera robot motion/position with the virtual environment. The example in Figure 29 can be also a valid representation of the underlying technologies in this use case, assuming higher sensing capabilities and accuracies integrated with ultra-high throughput and low-latency communications.

Development of the three key 6G disruptive technologies will rely on the two above-described use cases, starting from the first one to enable a baseline implementation for RT holographic communications, and further progressing towards the second one to enable accurate object representation and interaction with the environment. An example of a baseline implementation that may be suitable for both use cases is shown in Figure 30 comprising two fundamental blocks: the baseband processing stage (FPGA, in charge of performing digital signal processing) and the high-frequency transceiver (in charge of translating baseband signals to the target frequency). This is further illustrated showing the baseband processing stage (FPGA), Intermediate Frequency stage (DAC/ADC + IF/LO) and THz transceiver stage (Radio head TRX). The latter is often split into an Intermediate

Frequency stage (DAC/ADC + IF/LO) and a THz transceiver stage (Radio head TRX). The DAC/ADC and IF/LO blocks are sometimes merged in a single one providing an IF signal (in some cases, a sub-6 GHz RF modulated signal) that drives the Radio head TRX aimed to deliver THz signals. This basic implementation motivates the initial design approaches described in section 4.2.

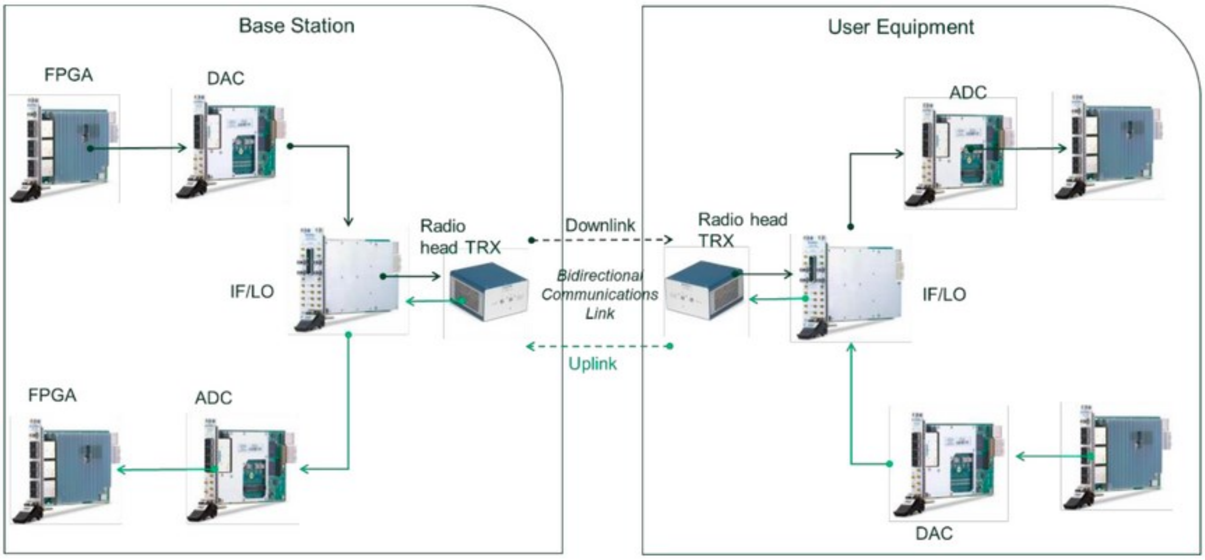

Figure 30. Simplified THz transceiver blocks (taken from [53]).

4.2 6G DISRUPTIVE XR PROPOSED ENABLERS

4.2.1 High-Frequency Transceivers and Baseband implementation for THz-RIS and ISAC

4.2.1.1 Targeted XR gap

To stimulate the adoption and further development of XR applications, XR technologies should support wireless connectivity with extremely high data rates and ISAC capabilities for sensing. This allows close to real-live experiences to be implemented in everyday life environments benefitting from the environmental awareness that ISAC can provide.

The evolution of mobile communications (both cellular and Wi-Fi systems) offers wireless connectivity with increased data throughput, but their capacity is still insufficient to support the envisioned real-live XR experience. XR Metaverse use cases like remote control, remote maintenance, enterprise metaverse, real-time holographic communications, and collaborative 3D digital twin-like environment demand ultra-high bandwidths and sensing capabilities. To enable this, ISAC-capable technologies with very wide bandwidths are required, as currently available in the mm-wave and sub-THz spectrum. The so-called sub-THz regime involves frequencies between 100 GHz and 300 GHz and is considered the most promising range for ultra-high frequencies, where some regulation already exists for communications and active/passive sensing services. Above it, the THz frequency range further extends from 300 GHz up to 10 THz but is less explored due to limited availability of efficient transceiver components.

The D-band (110-170 GHz), the G-band (140-220 GHz) and the H-band (220-330 GHz) are considered as the frequency bands where sufficient spectrum can be allocated for wireless communication with data rates of 100 Gbit/s and beyond. Utilizing these frequency bands comes with substantial challenges. Not only are these bands still unlicensed, but also the development of the electronic circuits and systems operating on these ultra-high frequencies requires disruptive research.

Some of the challenges experienced at sub-THz and THz frequencies are:

- Limited propagation distances due to high free-space losses, high atmospheric absorption, and poor diffraction, at indoor or outdoor environments.
- HW complexity and inefficiencies from increased phase noise, reduced energy efficiency, reduced output power, poor stability of pencil-like beams, and beam squinting effects.
- Need to overcome small environmental obstacles for better tracking of moving users and faster reaction to blockage and obstruction impairments since the communication signal wavelength is in range of 1 mm.
- Channel sparsity, i.e., insufficient multipath richness for spatial multiplexing of signals or users.

Due to the above-described challenges, most of the current approaches at very high frequencies present clear gaps. Firstly, they exhibit very limited communication capabilities, either because of their reduced operating range (motivated by limited output power, excessive phase noise or high noise figure of the receiver), poor stability of the links, and/or lack of environmental awareness to overcome blockage effects. Secondly, ISAC capabilities are generally not present in high-frequency baseband implementations, and sensing is mostly realized through radar-centric techniques with little or no communication capabilities, as, e.g., in automotive radars based on FMCW (Frequency-Modulated Continuous Wave) waveform.

6G-XR will reduce current gaps by developing two innovations: i) 140 GHz and 300 GHz radio front ends for sub-THz communications, and ii) an ISAC-capable baseband design for Sub-THz communications. These two innovations will be integrated in a joint Sub-THz testbed and are described in detail next.

4.2.1.2 Initial solution design and evaluation methodology for Baseband implementation for THz-RIS and ISAC based on SC-FDE

4.2.1.2.1 Initial design

The SoTA in baseband design for sub-THz with ISAC capabilities has traditionally been based on an OFDM waveform, or variations from it (DFT-s-OFDM, etc.), to reuse well-proven baseband design components from lower frequencies (like FFT/IFFT blocks, equalizers, or pilot-based channel estimation). OFDM waveforms however pose multiple challenges when dealing with HW imperfections at very high frequencies (e.g., poor energy efficiency, phase noise, frequency offsets). Some of these drawbacks are partially mitigated by using very wide subcarrier spacing values, but the impaired link budget caused by poor energy efficiency calls for single-carrier waveforms with much better link budget capabilities.

The XR gaps stated in subsection 4.2.1.1 motivate the need of THz baseband implementations with ISAC capabilities (for seamless interplay between sensing and communications). In addition, a HW-friendly waveform with constant envelope will be implemented to partly mitigate the complexity and limited energy efficiency of practical THz transceivers.

Baseband implementation on the THz experimental platform will be based on SC-FDE waveform. Its main building blocks are illustrated in Figure 31. Basic SC-FDE baseband processing chain showing transmitter (top) and receiver (bottom) stages.Figure 31.

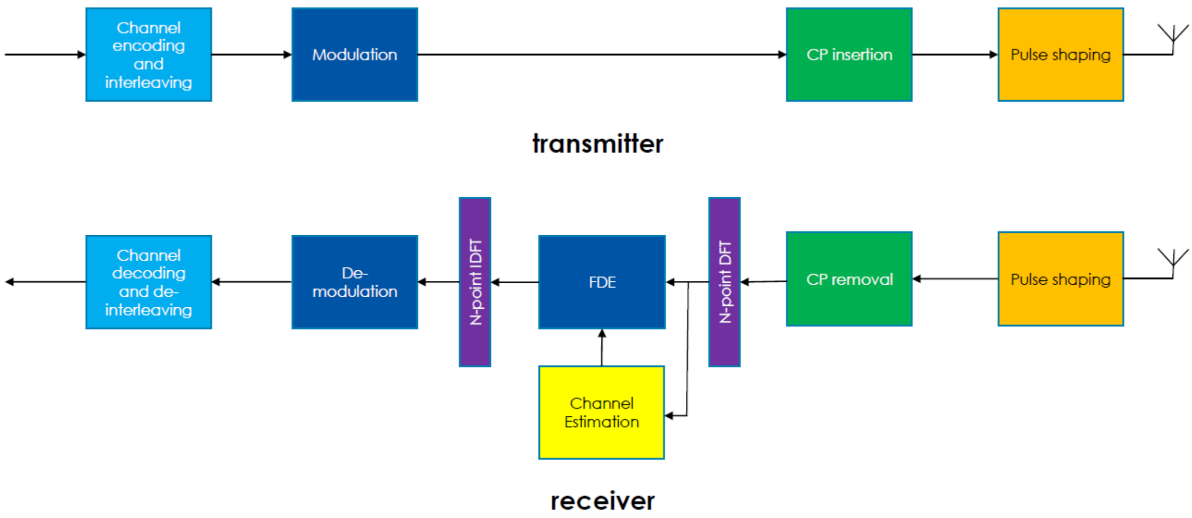

Figure 31. Basic SC-FDE baseband processing chain showing transmitter (top) and receiver (bottom) stages.

Some useful properties of SC-FDE for higher frequencies can be summarized below:

- Better power efficiency than OFDM waveform and its variants thanks to the constant-envelope property (0 dB Peak to Average Power Ratio (PAPR) in the complex baseband domain), although PAPR can be degraded by the prototype filter. SC-FDE is thus susceptible to operating in the non-linear region of the power amplifiers enabling a higher power efficiency.
- Support of 1-tap frequency-domain equalization based on FFTs.
- Challenging to multiplex data/control signals in the frequency domain without degrading PAPR.

ISAC capabilities will be further developed at baseband level leveraging a common RF transceiver frontend and SC-FDE waveform for communications and sensing. The first implementation will be solely based on communications and subsequent refinements will incorporate ISAC technology to, e.g., perform detection of the objects range, speed, location, etc. A bistatic sensing scenario will be considered as a starting point for ISAC implementation due to its higher possibilities for reusing the current communication framework in UL or DL.

Although baseline components already exist for the described building blocks, e.g., in IEEE 802.11ad standard, fitting them to sub-THz frequencies is not yet worked out elsewhere to the best knowledge of the authors.

4.2.1.2.2 Proposed methodology

Some key elements in the proposed methodology for an efficient implementation are described below:

- Waveform transmission will be based on generation of time-domain sampled versions of, e.g., a QPSK modulation with root-raised cosine (RRC) prototype filter, thus simpler than CP-OFDM.

- A cyclic prefix (CP) will be added to the beginning of a group of symbols for DFT-based detection and equalization in frequency selective channels. This is more convenient than time-domain equalization schemes because of the already high maturity of FFT-based receiver implementations. Whereas the CP ensures frequency-domain equalization and inter-symbol interference avoidance, the RRC filter can shape the frequency response of the transmit symbols to, e.g., improve on the spectral confinement of the signal for better coexistence with other signals and/or services in the same band, or an adjacent one.

- FFT receiver processing will rely on some design parameters like, e.g., FFT size (number of samples prepended by the CP and processed upon detection), subcarrier spacing (equal to the inverse of the duration of a block of symbols following the CP), sampling rate, and number of subcarriers allocated to a user or set of users.

- In principle, a 0 dB PAPR prevents from frequency multiplexing the users in the same band unless they are coped with by different power amplifiers, because otherwise the single-carrier characteristic of the resulting waveform is lost. This may be the case when users are addressed by different spatial beams and each beam is transmitted by a different amplifier. The number of beams and transceiver chains in the testbed is still subject to investigation.

Baseband implementations will initially include a simple physical layer transmit-receive chain with an analog output signal driving an RF front-end at D band (around 140 GHz) that will be later extended to 300 GHz. Evaluations of the testbed performance will be first realized with a link-level Matlab simulator based on the Communications Toolbox. Link-level performance figures will be further compared with those measured in the lab testbed, and differences in the channel characteristics will be accounted for in the evaluations.

4.2.1.2.3 Target KPIs

Target KPIs for the High-Frequency Transceivers and Baseband implementation are given in Table 4-1.

Table 4-1. Target KPIs for the High-Frequency Transceivers and Baseband implementation for the Disruptive XR Enablers.

KPI name	**KPI description**	**Target Value**
Peak BW	Maximum carrier bandwidth	400 MHz (at 120 kHz subcarrier spacing)
Peak throughput	Maximum bits per second in DL	1 – 2 Gbps (depending on the constellation mapping and RRC filter roll-off)
Ranging resolution	Minimum resolvable ranging distance for ISAC	24.4 cm ($\Delta d = \frac{c}{2f_s}$)

4.2.2 Deep Reinforcement Learning for THz-RIS

4.2.2.1 Targeted XR gap

Many XR use cases have been identified by 3GPP in [54]. To motivate the use of RIS, we consider the XR meeting use case (as illustrated in Figure 32), which is aligned with the 6G-XR holoportation use case defined in D1.1 [5]. The XR meeting use case has a mix of physical and virtual participants. The main idea for the virtual participants or remote attendees is to create a virtual, 3D-rendered space where they can meet and interact through their avatars with other people. This 3D-rendered virtual space is a simplified representation of the real conference room, with tables at the same positions as in the real world. Remote participants are equipped with HMD supporting binaural playback. A remote participant can move freely in the virtual conference room and interact with the different subgroups of people depending, for example, on the discussion they are having. A remote participant can speak to other participants in their immediate proximity and obtain a spatial audio rendering of what the other participants are saying. They can hear the real participants from their relative positions in the virtual world, and they can freely walk from one subgroup to another to seamlessly join different conversations that may happen concurrently in the meeting space.

For this demanding use case, the THz spectrum can provide the needed bandwidth to support multi-Gbps or Tbps rates. However, THz channels are generally sparse. It thus becomes necessary to have new paths that potentially turn the sparse channels into rich scattering channels. This property can be exploited to avoid LOS blockage and enable 3D beamforming for the XR users. The RIS can effectively do so, thus enabling the THz-RIS combination that facilitate highly-directive beams directed to the different user locations.

To facilitate reliable communication for the XR meeting session, intelligent beamforming and smart allocation of the spectral resources are required. DRL frameworks can facilitate this intelligent beamforming in real-time in an efficient manner with respect to cost, spectral and energy efficiency. DRL-assisted beamforming design can enable beams to adapt to the propagation environment, user distribution, mobility, and traffic, among others. DRL frameworks enable the discovery of rich knowledge and patterns, and the learning of the mapping functions that facilitate optimal system performance for THz-RIS network to support XR applications. DRL exploits operational knowledge obtained from network data to facilitate robust system optimization. The THz-RIS-DRL interplay for the XR meeting use case is shown in Figure 32.

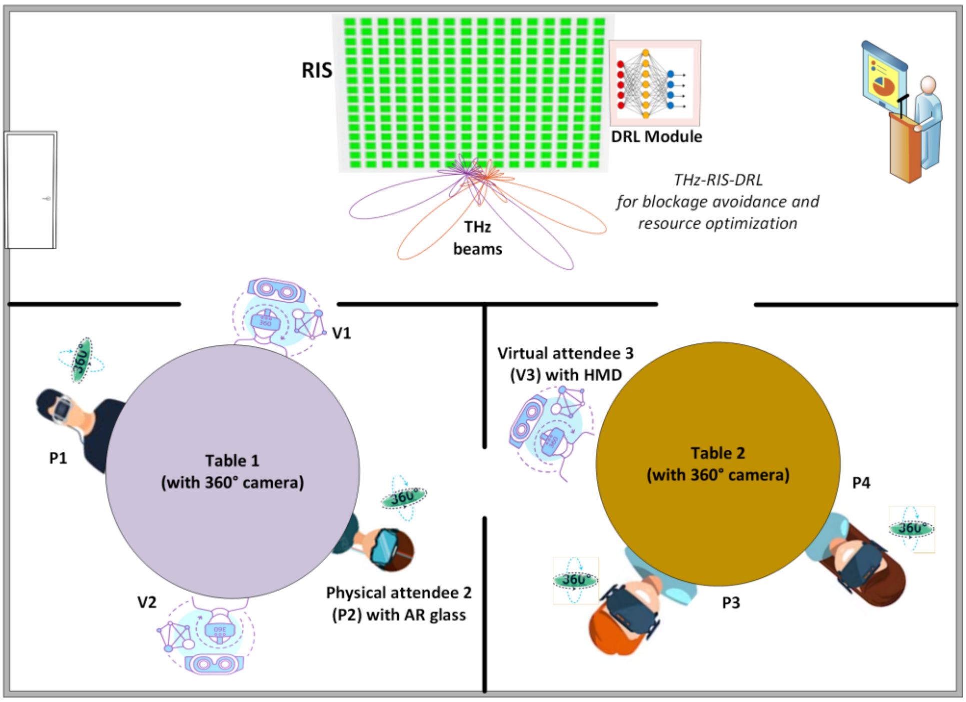

Figure 32. Indoor XR meeting enabled by DRL-aided THz-RIS.

In [55], the authors provided a critical comparison of model-based, heuristic and ML-based optimization approaches for RIS-aided networks. Out of the three approaches, the ML approach provides both the generalizability and robustness to environmental uncertainty capabilities that can be exploited for beamforming designs and frameworks. In recent years, several works have employed DRL for enhancing the performance of RIS-assisted wireless communication systems [56], [57], [58], [59]. Some of the algorithms that have been employed for RIS-assisted networks include: DQN, DDQN, SAC, DDPG, PPO, and TD3, among others.

4.2.2.2 Initial solution design and evaluation methodology

4.2.2.2.1 Initial design

Figure 33 shows the framework design for the DRL-driven THz-RIS network for the indoor XR use case. The design is composed of two principal modules: (i) the THz-RIS environment, and (ii) the DRL module. The THz-RIS environment is shown in Figure 33 while the workflow of the DRL module is shown in Figure 34. Figure 33TheFigure 34, DRL agent observes THz-RIS XR and takes actions in response to the observations. The actions correspond to the configuration of the RIS reflection matrix or phase shifts that enhances the system performance (e.g., SINR). When the action performed matches the agent's goal or progresses towards the agent's goal, rewards are earned, otherwise a penalty is imposed. This process is undertaken autonomously in a loop until system goals are achieved or the termination criterion is reached. The overall system goals include performance metrics such as sum rate, fairness, and energy efficiency.

In particular, the work in this enabler will focus on:

- Set up the THz-RIS environment through the system level simulator described in Section 2.2.1.
- Develop DRL algorithms and agents and integrating the standalone algorithms with the THz-RIS environment from the system-level simulator.
- Evaluate the performance of the integrated DRL-THz-RIS system.

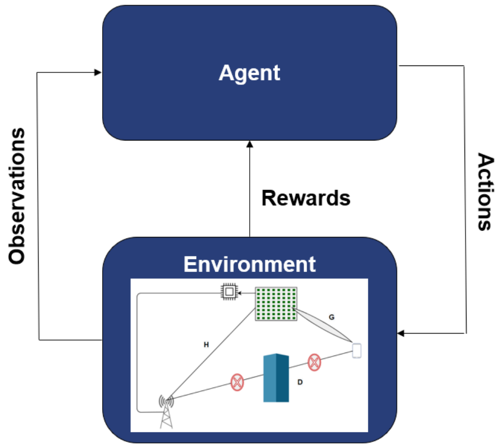

Figure 33. DRL framework for THz-RIS

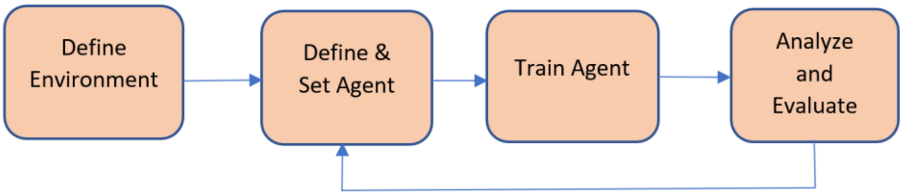

Figure 34. Workflow for DRL

DRL is viable for real-time wireless system optimisation, learning by interacting with the environment without the need for training labels. It is a powerful paradigm that combines deep neural networks (DNN) with reinforcement learning (RL) principles to learn optimal strategies through trial and error. The learning capability of a DRL model exploits learning from the environment and learning from the feedback of UEs, thus mitigating the challenges encountered in conventional RIS-assisted wireless networks. Through continuous training, the DRL solutions can adapt to the dynamic wireless environment of the XR use case.

4.2.2.2.2 Proposed methodology

DRL algorithms will be developed for THz-RIS environment. Preliminary studies show that Deep Deterministic Policy Gradient (DDPG) can maximize RIS system performance [56],[57],[58]. DDPG is a model-free, off-policy, actor-critic DRL algorithm. DRL-based adaptive codebooks will be designed for the gNodeB-RIS-UEs setup for XR. Different variants and hybrids of the DDPG algorithm will also be explored for network optimisation. The performance of the DRL-THz-RIS for indoor XR use case will be evaluated using extensive system-level simulations to explore the impacts of the algorithms on beamforming, blockage avoidance, XR mobility and overall system capacity enhancement.

Further, the performance results will be benchmarked with SoTA baselines such as the gNodeB-UE setups without RIS and gNodeB-RIS-UE setups at FR1 and FR2. Also, the performance results will be compared with alternative solutions to RIS such as the NCR and relays. For the DRL algorithms, various technical robustness tests will be carried out to ensure that the algorithms indeed learn adaptively and are not overfitted to a particular environment and continue to reach the desired efficiency and confidence thresholds. These tests, among others, include random seeding, hyperparameter tuning, addition of random Gaussian noise to the channels, etc.

4.2.2.2.3 Target KPIs

Table 4-2 presents the KPIs for the DRL-based THz-RIS network for XR use case.

Table 4-2. KPIs for DRL-based THz-RIS network for XR

KPI name	KPI description	Target Value
Throughput	Bits per second in UL and DL measured for each XR user	Per-user throughput of 50 Mbps (UL) and 200 Mbps (DL) will be targeted for video, above the 3GPP values of 20 Mbps and 60 Mbps for UL and DL, respectively. Also, an XR conference/meeting of 10 users is targeted, thus amounting to 2 Gbps support for a single session.
XR UE satisfaction	XR UE is declared satisfied if more than X % of application layer packets are successfully transmitted within a given latency constraint.	95% successful packet delivery per user is targeted.

4.2.3 Summary of proposed Disruptive XR enablers

Table 4-3 summarizes the two technical enablers presented in this section, highlighting their applicability to the 6G-XR use cases described in deliverable D1.1 [5].

Table 4-3. Summary of proposed 6G-XR enablers in the disruptive path.

Proposed disruptive XR Enabler	Target XR gap	Relation to 6GXR use case
D-band transceiver and baseband	Ensure enough radio capacity is available for holoportation and 3D Digital Twin-like services enriched with ISAC	Contributes to UC1 – holoportation, by enhancing the UL and DL capacity that is required for capture and transmission of point clouds; and UC4 – Collaborative 3D Digital Twin-like Environment, by incorporating ISAC enablers that complement cameras for

		3D modelling of real-world representations
DRL-based optimization of THz-RIS network	Reliability and Capacity enhancement support for XR	Indoor XR meeting sessions – aligned with 6G-XR holoportation use case. RIS will enhance coverage and capacity in indoor environments

5 THE 6G-XR TRIAL CONTROLLER

5.1 TRIAL CONTROLLER

This section presents an initial review of the SoTA and definition of Trial Controller architecture to place 6G-XR use cases over the 6G-XR facilities from the north and south nodes. The specific elaborated and the document trial

In these regards, we can consider as objectives of the present section are the following:

- Review of the state-the-art of Trial Controller used in the previous 5GPPP project.
- Identify initial requirements of the 6G-XR Trial Controller according to the use case scenarios and the 6G-XR facilities from the north and south nodes.
- Propose an initial design of the software layer architecture for execution and control of the trials on the top of the selected 6G-XR facility from the north or south node.
- Provide a high-level description of the foundation trial flow calls from 6G-XR Trial Controller.

5.1.1 Motivating the need for a Trial Controller in the 6G-XR testbed

This software component of the Trial Controller is composed of several software components running in a central or distributed manner. It is typically implemented using cloud-native architecture, which makes it scalable and flexible. The Trial Controller communicates and interacts with other components of the 5G/6G infrastructure, such as the network slicing controller, the manager or orchestrator, the radio resource controller, and the computing resource controller.

The primary actors for the Trial Controller include: 1) the experimenter with, 2) Experimental facility. We can consider the following features of the Trial Controller as essential for managing trials and experimentation in 5G/6G infrastructures. These features include:

- **Efficient resource management: t**he trial Controller plays a crucial role in providing management and orchestration of 5G infrastructure resources during experimentation. This comprises allocating and controlling resources to experiments, de-allocating resources from experiments that have finished as well as monitoring the usage of resources and performance metrics of the 5G/6G network. Trial Controller ensures the optimal utilization of the network infrastructure, network slice orchestration, and software components involved in the trials. This leads to conduct experiments with precision, scalability, and reliability.
- **Experimentation control and test scenario management:** the Trial Controller provides a way for experimenters to interact abstractly with 5G/6G infrastructures and to control the experiments. This includes scheduling, starting, and stopping experiments, and monitoring the status of experiments. Trial Controller offers the ability to define and manage complex test scenarios, allowing for customization and configuration based on specific project requirements.

- **Data collection and analysis:** Trial Controller streamlines the collection and analysis of diverse data sets generated during the trials, enabling comprehensive evaluation and insightful of the project's performance and outcomes.

- **Integration and interoperability:** Trial Controller provides seamless integration with various tools, frameworks, and platforms, promoting interoperability and compatibility with existing project infrastructures.

- **Streamlines trial activities:** One of the main assets of Trial Controller in several project is its ability to streamline trial activities. It acts as a central hub, allowing researchers, experimenters, use-case owners, and stakeholders to define and manage complex test scenarios tailored to project requirements. With Trial Controller, the execution of trials become more efficient by abstracting resource management, saving time, resources, and manual work.

- **Security:** Trial Controller provides security features to protect the 5G/6G infrastructure from unauthorized access. This embraces authentication, authorization, and encryption.

5.1.2 State-of-the-art review of Trial controllers used in previous 5GPPP projects

The emergence of 5G technology has opened a wide range of opportunities and challenges in the telecommunications and networking fields. As part of the 5G Infrastructure Public Private Partnership (5GPPP) initiatives, several projects are underway to explore, develop, and validate the potential of 5G/6G networks. In these projects, Trial Controllers emerge as a critical component in ensuring the efficiency and success of the trials conducted over 5G and beyond infrastructures. In this context, the Trial Controller plays a key role in the following ICT17 and ICT19 projects:

- **5GROWTH**: This project developed the Experiment Orchestrator that collaborates with the Network Slicing Manager to efficiently manage resources, such as network slices and processing power, across various testbeds as detailed in D2.4 [59] and D3.5 [60]. Together, they create dedicated and secure performance spaces within the 5G network, enabling researchers to optimize resource allocation and maintain ideal conditions for their experiments. Thereby, the Trial Controller version developed by 5GROWTH is built upon a vertical slicer and service orchestrator to control the resource layer.

- **SLICENET**: This project focuses on developing a framework for slicing 5G networks. The Trial Controller developed by SLICENET is integrated with the slicing framework and provided a way for experimenters to create and manage network slices. The SLICENET control plane dynamically manages network slices, offering isolated and secure environments for running experiments with dedicated resources D4.1 [61]. The SLICENET MEC platform provides edge computing capabilities at network borders, enabling low-latency and real-time data processing crucial for controlling and analysing experimental data D3.1 [62].
- **5GEVE**: The experimentation portal of 5G-EVE provides researchers with a user-friendly interface to oversee their 5G trials, customize settings, and monitor data, serving as a central hub for experiment orchestration D4.6 [63]. Additionally, the testing and validation tools within 5G-EVE offer a strong framework for defining protocols, validating functionality, and verifying experiment results, enhancing the control and reliability of research D4.6 [63]. Together, these components empower researchers to effectively manage and oversee their experiments within the 5G-EVE platform effectively. The experimentation portal and

validation tools from the 5G-EVE project provide an initial version of Trial Controller which was used as basis in several projects as 5G!Drones.

- **5G-COMPLETE:** This project implemented a complete 5G trial infrastructure that can be used for various applications. They developed a kind of trial controller able to interoperate with other trial controllers and to support a variety of 5G use-case scenarios as detailed in D6.1 [64].
- **5GCROCO**: This project used an orchestration platform to manage the deployment and execution of trials. This orchestration platform is responsible for some of the tasks that a trial controller would typically perform, such as provisioning and configuring resources for trials, deploying trial applications, monitoring the execution of trials, collecting, and analysing trial data. The project used the Service Orchestrator and the Multi-domain Orchestrator to manage the deployment and execution of E2E trials across multiple domains as detailed in D2.2 [65] and D3.2 [66]. The project used the Edge Dynamic Map database to store and manage real-time information about the deployment of trial applications and resources D4.2 [67]. They used an Event Broker to manage communication between the different orchestration components [68]. The 5GCROCO features are relevant for 6G-XR Trial Controller because it shows a different and useful path to manage the E2E trials and store related information in a dynamic database.
- **5G-VINNI**: The open-source trial controller of 5G-VINNI efficiently manages resources such as network slices and computing power to execute and oversee experiments across diverse testbeds, enabling in-depth exploration of 5G features. In tandem with this, the dedicated and secure 5G testbed environments at facility sites in locations like Norway and Greece serve as the stage for refining experiments and analysing results with accuracy. Together, these components provide the control and adaptability needed to conduct insightful experiments within the 5G-VINNI ecosystem D3.1 [69] and D4.4 [70]. The control and adaptability performed by the components from 5G-VINNI provide an example for the 6G-XR Trial Controller to consider for further implementations and capabilities during experiments across different testbeds or research infrastructures.
- **5G-ZORRO**: This project developed a 5G trial infrastructure for zero-trust networks. The 5G-ZORRO project incorporates two key components, namely Zero Touch Automation with Trust, Security, and AI, and Evolved 5G Service layer with 5G distributed ledger technology and distributed AI D3.3 [71] and D4.3 [72]. Despite not being explicitly termed as a "Trial Controller," these components provide robust tools for automating, securing, and managing experiments within the 5G-ZORRO project. By utilizing these resources, researchers can enhance their control and confidence in conducting 5G experiment.
- **5G!Drones:** This project implemented a Trial Controller in [60] [61] [62] for 5G-enabled drones use-case scenarios to run experiments and trials over several 5G infrastructures. The Trial Controller developed by 5G!Drones is responsible for managing the resources of the 5G trial infrastructure for drones, such as network slicing, radio resources, computing resources, and drone-related adaptations. The Trial Controller provided a way for experimenters to interact abstractly with 5G infrastructures and control the experiments. We are confident that the Trial Controller from 5G!Drones provides a strong foundation and framework for integrating the 6G-XR Trial Controller, thanks to its open-source components, thorough documentation, and harmonization with comparable project resources, requirements, and features.

The Trial Controller and its associated components, as proposed in ICT17 and ICT19 projects, such as the 5G!Drones, play a crucial role in facilitating efficient trials across various infrastructures within their respective project domains. These components serve to demonstrate the advancements and capabilities of 5G and beyond networks, showcasing their potential impact and effectiveness for experimentation.

5.2 REQUIREMENTS AND INITIAL DESIGN FOR THE 6G-XR TRIAL CONTROLLER

This section aims to outline the key components essential for conducting effective trials within the context of 6G-XR. This includes specific requirements for the following items:

- The Experimenter, who plays a crucial role in designing and managing the trials, ensuring their integrity and validity.
- The Trial Controller serves as the core operational component, responsible for providing abstraction, experimenter interface, orchestration of the trial activities and facility resources as well as maintaining synchronization with various subsystems and 6G-XR facilities.
- The 6G-XR facilities, which serve as the foundation for use-case scenarios and enable cutting-edge research and experimentation.

5.2.1 6G-XR Trial Controller requirements

Relying on the technical description of T4.4 and on the well-defined and available components of the Trial Controller from the 5G!Drones project and ICT17 and ICT19 projects, we identified the following requirements as the foundation for the initial design of the 6G-XR Trial Controller:

A. Experimenters' requirements:

ER01: The experimenters shall be able to access a public and secure subdomain of a Trial Controller dashboard in the 6G-XR domain.

ER02: The experimenter shall be able to authenticate and log in the Trial Controller dashboard at the public subdomain of the 6G-XR domain.

ER03: The experimenter shall be able to schedule/create trial(s), validate trial status, activate related KPIs measurement and stop the trial through a unified Trial Controller dashboard.

ER04: In case the facility has artifacts, the experimenter shall be allowed to onboard artifacts related to the application functions that compose the experiment to be run. Onboarding may be done offline, with the support of the facility owner.

ER05: In case the facility has more than one edge, the experimenter shall be allowed to select the edge resource in the 6G-XR facility where the experiment application function needs to be instantiated.

ER06: The experimenter shall be able to select the network slice or slices according to the facility/node capabilities, which provide access to the experiment application functions.

ER07: The experimenter shall be able to configure the slice parameters, such as slice service type, slice subnet (network slice descriptor and virtual network function (VNF)), virtual link domain, QoS, e.g., guaranteed bit rate (GBR), Non-GBR, 5G QoS identifier (5QI), or QoS Class Identifier (QCI), to generate the Network Slice Template (NST) related to the selected network slice and facility/node capabilities.

ER08: The experimenter shall be allowed to select network KPIs (e.g., throughput, latency) to collect related to the execution of the experiment. Note: Service level KPIs are assumed to be collected by the application functions provided by the experimenter.

ER09: The experimenter should be allowed to browse the 6G-XR enablers available in the facility and select the ones that are required for the experiment and potentially to the use case.

B. Trial Controller's requirements:

TCR01: The Trial Controller shall expose a dashboard containing instruments and controls for planning, scheduling, and creating trials based on the network slice capabilities in each facility/node.

TCR02: The Trial Controller shall manage the life cycle of trials during its planning, execution, and termination. When the time for the trial is approaching, it shall be able to validate 5G resources availability and manage the trial execution until it is finished.

TCR03: The Trial Controller shall store the planned trials, trial parameters, times, dates, status, and related information in a common database for trials.

TCR04: The Trial Controller shall allow execution and automation of the trials as well as monitoring for the trial status in each 6G-XR facility or node.

TCR05: The Trial Controller shall enable configurations of the network slice parameters. Due to different level of support of slicing functionalities between facilities, each node or facility shall have its own dashboard or web portal.

TCR06: As part of the Trial Controller components, each facility or node shall have a dashboard or web portal as a configuration interface for the experimenters configure the network slice type and related parameters according to each node, facility, and network capabilities.

TCR07: Using the inputs provided by the experimenter, the Trial Controller shall be able to create the NST that may include details such as slice service type, slice subnet (network slice descriptor and VNF), virtual link domain, QoS based on the selected network slice and facility/node capabilities.

TCR08: The Trial Controller through the specific dashboard or web portal shall be placed in each facility/node and published in a subdomain to enable access to the experimenters for parameter configuration of the network slice instance(s).

TCR09: The Trial Controller shall enable network KPI list input to collect them at each facility/node during the trials according to its capabilities. We assume each facility shall have its own measurement tool for network KPI collection.

TCR10: Based on the KPI list chosen by the experimenter, the Trial Controller shall be able to manage the process to start and end network KPI measurements in each facility/node after creating and ending the trial and network slice.

TCR11: Each facility/node shall be responsible to measure network KPIs, but potential service KPIs shall be responsibility of the experimenter.

C. 6G-XR Facilities requirements:

FR01: The facilities shall expose APIs to the Trial Controller for life cycle management of network slices by processing the NST according to each facility/node capabilities.

FR02: The facilities shall expose APIs to the Trial Controller to enable lifecycle management of experiment application functions provided by the experimenter.

FR03: The facilities shall expose APIs to enable experimenters to onboard application related artifacts. The onboarding process will be done offline (not through the Trial Controller). Each 6G-XR facility should declare in advance the type of application artifacts supported (e.g., Helm charts, Open-Source MANO, Cumucore's solution, or NFV network service descriptors).

FR04: The facilities shall expose APIs to create the measurement job by creating, updating, listing, and deleting them and enabling KPI collection at each 6G-XR facility/node.

FR05: The facilities shall be connected to the Trial Controller using standard security mechanisms, such as VPNs and SSLs.

FR06: If multiple edge sites are supported in a facility, these edge sites shall be exposed to the Trial Controller so that experimenters can select the edge where their application functions should be instantiated.

FR07: The facilities shall define what types of UE are allowed to connect to the facility. Determining the appropriate UE for an experiment shall be done offline between the facility owners and the 6G-XR experimenter.

FR08: The facilities shall define the network KPIs that can be collected according to their measurement tools capabilities in each 6G-XR facility and use case purposes.

5.2.2 6G-XR Trial Controller initial design

With the aim to meet the above requirements, we carried out an initial review of the Trial Controller component. We consider the Trial Controller from 5G!Drones as a basis for the implementation of the 6G-XR Trial Controller because it has open-source components, extensive documentation, as well as similar project resources, requirements and features. The Trial Controller from 5G!Drones is composed of the Web Portal 1, Facility Web Portal or Web Portal 2, Trial Repository, LCM (Life Cycle Manager), Trial Validator, and Trial Enforcement for managing the life cycle of trials, network slicing and measurement jobs in different 5G facilities during UAV-related experimentations. Two additional relevant components outside of the Trial Controller are the Abstraction Layer and the specific Facility Adapter. The first one is responsible to, which route requests from the Trial Controller components to specific Facility Adapter API. Meanwhile, the Facility Adapter is an API responsible for managing the life cycle of the network slice(s) at the facility level and thus translating the Trial Controller requests to the specific facility technologies (e.g., OSM). The components from the Trial Controller, Abstraction Layer and specific Facility Adapter implemented in 5G!Drones may require re-factorization of the SW code and further analysis in T4.4 to integrate them as part of the 6G-XR Trial Controller and fulfil the requirements detailed in subsection 5.2. In regard to this initial analysis of the Trial Controller components from 5G!Drones, we consider the most relevant ones to meet the subsection 5.2

requirements at this early stage. This initial analysis aims to build a 6G-XR Trial Controller to manage the life cycle of trials, E2E network slices and KPI measurement jobs in the 6G-XR facilities for experimentation of use cases related to 3D DT and real-time holographic communications. After the initial analysis, we propose the following initial architecture design for the 6G-XR Trial Controller and related components to fulfil above aims and subsection 5.2.1 requirements.

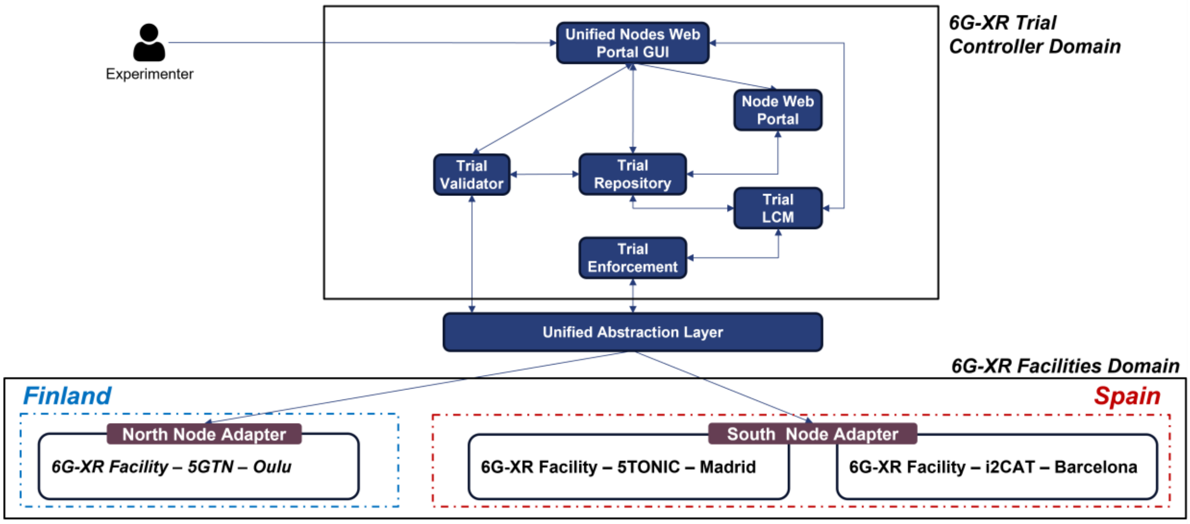

Figure 35. Initial Architecture Design of 6G-XR Trial Controller

In the initial design architecture depicted in Figure 35 for the 6G-XR Trial Controller components, we provide a comprehensive and potential approach for managing the trials, E2E network slices, and KPI measurement jobs with each component playing a vital role in the overall functionality and performance of the system. The Trial Controller interacts with the experimenter to describe the scenario to evaluate, along with the technical description of network slices in the trials. As shown in Figure 35, the Trial Controller domain is broken up into five main and functional components, which are: i) Unified Nodes Web Portal GUI, ii) dedicated Node Web Portal, iii) Trial Repository, iv) Trial LCM and v) Trial Enforcement. There is one more component called Trial Validator that is still under evaluation to be included in the 6G-XR Trial Controller. According to this evaluation, it will be defined the complete or partial development of Trial Validator. The architecture of the 6G-XR Trial Controller consists of the following key components working together with the aim to manage the life cycle of trials, E2E network slices, and KPI measurement jobs according to each 6G-XR facility capabilities, resources, and own requirements:

- **Unified Nodes Web Portal:** Is the main GUI used by the experimenter(s) to access the functionalities of the Trial Controller. It acts as an interface, providing a user-friendly dashboard platform for browsing, planning, scheduling, and management of trials or experiments related to specific use-case scenarios. It allows experimenters to create, modify, and monitor trials according to the specific requirements of the experimenter and to attend to the use-case requirements. This component will rely on the 5G!Drones Web Portal 1.

- **Node Web Portal:** Serves as a specific dashboard component that enables the Experimenter to define and configure network slice parameters according to each 6G-XR facility. North and South facilities have their own Node Web Portal because of the specific capabilities and technologies in each one. We consider at the initial stage that the Node Web Portal can also include a module to map the trial requirements given by the experimenter to the required components in terms of 6G-XR facilities and potentially specific use-case scenarios. The necessary information for the trial is provided in the form of a Blueprint through the specific Node Web Portal, which creates for example the NST, RAN information, KPI list, application artifact and potentially other use-case-related application description used as an input for slice creation in each specific 6G-XR facility. The Node Web Portal component will be based on the structure, workflow, functionality and evolution of the Web Portal 2 implementation from the 5G!Drones project.

- **Trial Repository:** Serves as a central persistence storage database to store all trial-related information, configurations, metadata, network KPIs requested and the specific facility NST request associated with the specific trial. The repository is planned to contain information about underlying 6G-XR facilities. This information includes 6G-XR facility per component, network slice capabilities and templates, and KPIs (available to measure in each platform). This component will be built upon the foundation of the 5G!Drones Trial Repository.

- **Trial Validator:** Is the component responsible to perform alternative validations from relevant trial components, such as trial status validation, KPIs comparison and use case related validation, and to treat the use of validation requests of the 6G-XR facility resources (e.g., network slice) and potentially the use case-specific plan. It is active from the moment the validation is requested until the start of the trial deployment. It will stop if validation fails or is cancelled, or the validated plan is withdrawn. In case of failures, it should give back the information about the errors to ease implementing corrective actions. The trial validator shall be in charge of checking if the targeted 6G-XR facility is ready to host the trial. This is done through the Unified Abstraction Layer and Node Adapter at the 6G-XR Facilities domain. Furthermore, in case of use case validations, there shall be one more component potentially liable for use case plan validation that shall be done via a use case Adapter API. Once the status (i.e., accepted or rejected) of the validation plan is known, the Trial Validator updates the Trial Repository, after that the Unified Nodes Web Portal and Trial LCM can update their information about the status of the plan accordingly. This component is still under evaluation to be part of 6G-XR Trial Controller.

- **Trial Life Cycle Manager (LCM):** As the core component of the Trial Controller, it is responsible for handling the life cycle operations of trials during their execution, including validation, management, instantiation, and termination process of the trial, network slice and KPI measurements according to the facility/node. The LCM validates changes during the trial. The LCM is also considered for facility validation capabilities with a gate check mechanism of simple rules which would decide if the trial can be performed or not. In simple words, the output of the trial validation will be Go (green light) or No Go (red light). The following versions of the validation feature could include specific use-case availability to enable green or red light for the trial. The Trial LCM will validate inputs received from the Trial Repository. This component will rely on the LCM implemented in 5G!Drones.

- **Trial Enforcement:** is the component responsible for the execution and automation of the trials as well as for providing monitoring of the trial status on the facility/node side. For this purpose, it includes interfaces for the management of network slice and measurement jobs at the facilities that will be developed that will activate when arrives a request from the Trial LCM. Then it will contact the underlying 6G-XR facility using the Unified Abstraction Layer component and specific Node Adapter to run the predefined trial scenario through sequential steps. Trial Enforcement will be composed of one sub-module, Configuration and Deployment.

During the pre-trial stage, it is liable for the preparation of the trial with actions such as network slice creation and potentially network service deployment. During the trial phase, the Trial Enforcement will have as a primary function the runtime configuration and monitoring of the trial progress. This refers to the steps, status, and result of trials executed but not the data generated during it. It is also liable to run the test scenarios linked to the trial. The module will be also responsible for providing an interface for the 6G-XR facility owners and potentially verticals, to show the monitoring results. To perform runtime configuration and collect the measurements, the module will have to communicate with the Node Adapter from a specific 6G-XR facility via the Unified Abstraction Layer. This component will rely on the Trial Enforcement implemented in 5G!Drones.

Among the additional but key complement components for tandem working between the Trial Controller domain and the 6G-XR Facilities Domain, we identified the following:

- **Unified Abstraction Layer:** Acts as an intermediary between the Trial Controller components and the underlying infrastructure, providing an API gateway to route the Trial Controller requests to specific 6G-XR facility and Node Adapter.

- **Node Adapter:** Is an essential API that facilitates the setup and management of network slices and KPIs collection in each facility, communicating with the specific underlying 6G-XR facility resources and orchestration technologies. In this case, the Facility Adapter is the keystone for the Node Adapter API functionality.

All the interactions with the different 6G-XR facilities go through the Unified Abstraction Layer and specific Node Adapter API. The Unified Abstraction Layer provides a gateway to each Node Adapter API (i.e., NN Adapter or SN Adapter) for life cycle management of network slices (e.g., instantiation and deletion) during the trial and the KPI measurement job in each 6G-XR facility. In practice, the Unified Abstraction Layer routes the Trial Controller requests to the specific Node Adapter API. Each Node Adapter API communicate such requests to underlying 6G-XR facility technologies for managing and orchestrating specific facility components (e.g., Helm charts, OSM, Cumucore's solution, or NFV network service descriptors). It is hereby ensuring a consistent operation of the Trial Controller across various 6G-XR facility technologies. Under the refactorization umbrella of Trial Controller components, we will also consider the adjustments in the configuration of the Unified Abstraction Layer and implementation of dedicated Node Adapter in each 6G-XR facility, tailored to their specific capabilities.

Furthermore, we are carefully considering the requirements for additional configurations to ensure smooth operations between the Trial Controller components, Unified Abstraction Layer, and each Node Adapter API, specifically tailored for each 6G-XR facility. Some of the key configurations we are currently examining include:

- The specific Node Web Portal from NN and SN publishes and enables access from a subdomain to the experimenters for planning the trials and then configuring the required QoS parameters inside the NST for network slice creation at each specific 6G-XR facility.

- The Unified Abstraction Layer provides secure and seamless communication between the centralized 6G-XR Trial Controller components and the specific 6G-XR facilities through the Node Adapter API by using a Virtual Private Network (VPN) or SSL connection.

- The Trial Controller components provide encrypted authentication and authorization.

- The Unified Abstraction Layer provides an API gateway to route upper requests from the Trial Controller to the specific 6G-XR Facility and vice versa.

5.2.3 Foundation Trial Flow Calls – 6G-XR Trial Controller

This subsection serves as an introduction to the foundational flow of calls of trial operations in the Trial Controller, providing essential insights into their functionality. The focus lies on detailing key operations, including trial creation and network slice deployment, measurement job creation and KPI collection, as well as the deletion process for trials, measurement jobs, and network slices. This comprehensive overview aims to enhance understanding of the interactions of pivotal element within the Trial Controller after an in-depth initial analysis.

5.2.3.1 Trial Creation and Network Slice Deployment

Figure 36 illustrates the prospective workflow to create a trial and deploy the network slice through the Trial Controller. The first step corresponds to the experimenter's entry by login and authentication to the GUI dashboard of the Unified Nodes Web Portal for the trial planning phase. In step 2, the Unified Nodes Web Portal registries the new trial at the Trial Repository, which gets as a response a Trial ID that uniquely identifies a trial. Then in step 3a, the experimenter is redirected to the Node Web Portal to create the NST. Since each facility uses a different NST due to different network slicing capabilities, then two Node Web Portals exist. According to the selected 6G-XR facility to deploy a trial, the Unified Nodes Web Portal redirects the experimenter to the appropriate Node Web Portal (step 3a). An HTTP redirection is used, including the Trial ID as a basic input parameter. The Node Web Portal creates the NST using additional experimenter's input parameters according to the network slice capabilities on each 6G-XR facility. Then, the Node Web Portal stores the NST in the Trial Repository using the Trial ID as a discriminator (step 3b). Thereafter, the experimenter back to the Unified Nodes Web Portal to start the execution of the trial validation process there (step 4a), by sending a request to the Trial Validator, including the specific 6G-XR facility name to run the trial and potentially a use case-specific plan (if there is specific use case information). Trial validation is performed as an independent parallel task based on the validation of the required resource availability at the 6G-XR facility (4b). Based on the response obtained in step 4b, the Trial Validator updates the trial status (step 5) at the Trial Repository.

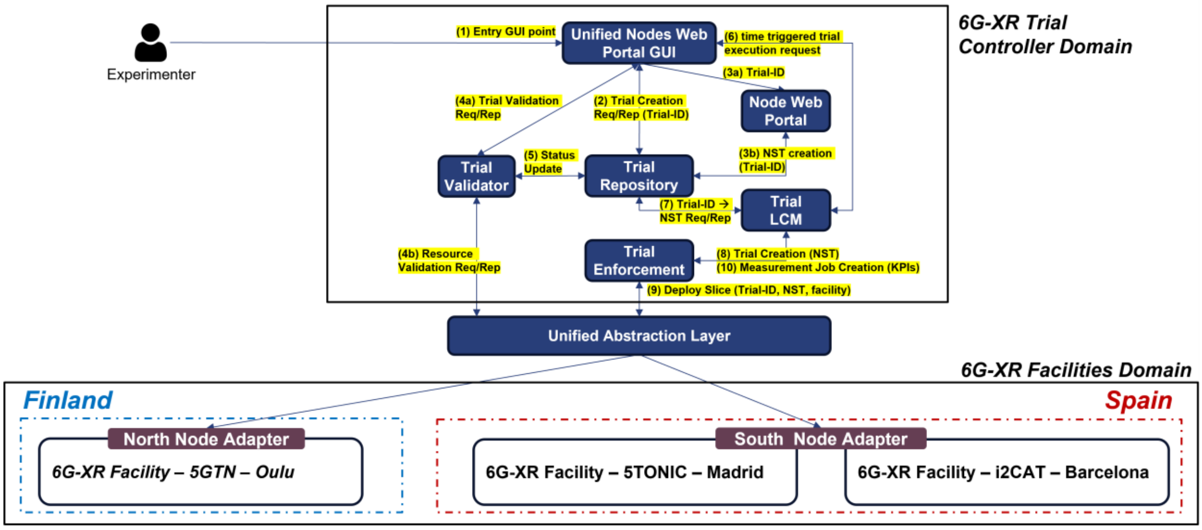

Figure 36. Trial Creation and Network Slice Deployment.

After the trial status update is approved at the Unified Nodes Web Portal and as the trial time is approaching, there are two options as part of step 6. Option 1: a timer triggers the trial execution request to create the network slice by the Trial LCM to start the trial implementation. Option 2: the experimenter manually initiates the trial execution at Trial LCM through the Unified Nodes Web Portal (step 6) to also start the trial implementation when required. After the trial execution starts, disregarding which of the two Option is selected, the Trial LCM fetches the NST of the trial from the Trial Repository (step 7) using the Trial ID to request the creation and deployment of the network slice to run the trial at the targeted 6G-XR facility using the Trial Enforcement (step 8). In its turn, the Trial Enforcement modules send the request to the specific Node Adapter through the Unified Abstraction Layer to deploy the network slice (step 9) using the Trial-ID, NST and specific 6G-XR facility name as input parameters. The Trial Enforcement procedure returns the Slice-ID to the Trial LCM for life cycle procedures that is useful to then create the measurement job for KPI collection at the facility level.

5.2.3.2 KPI Measurement Job Creation

Figure 37 illustrates the workflow to create and execute KPI measurement jobs. The first step (1) represents the experimenter's login to the Unified Nodes Web Portal during the trial definition phase (as described in section 5.2.5.1). After the trial definition and configuration, the experimenter is redirected to the specific Node Web Portal (step 2) to configure the network slice and then define the network KPI list (e.g., throughput, delay, jitter, and packet loss). The experimenter decides which KPIs from the available list according to the specific 6G-XR facility will be measured during the Trial and this information is updated in the Trial Repository (step 3). At the Unified Nodes Web Portal, the experimenter can fetch the corresponding trial configuration information alongside the available KPI list (step 4). In Step 5, the time triggers the trial execution request to create the measurement job by the Trial LCM just after the network slice is created. At step 6, the Trial LCM fetches related trial information (Trial-ID, Facility, Slice-ID, and KPI list) from the Trial Repository to create the measurement job. Then, the Trial LCM sends the request with the information from Step 6 to the Trial Enforcement to create the measurement job (step 7). Next, the Trial Enforcement sends the measurement job creation request (Trial-ID, Facility, Slice-ID and KPI list) to the specific Node Adapter of 6G-XR facilities through the Unified Abstraction Layer. After successful measurement job creation, the specific Node Adapter responds with an ID of the measurement job that is spread to Trial Enforcement, Trial LCM and Trial Repository. In parallel, the KPI measurements data stream is potentially collected, stored, monitored, and depicted by the specific measurement tool at each 6G-XR facility (this is still an open topic under review so far).

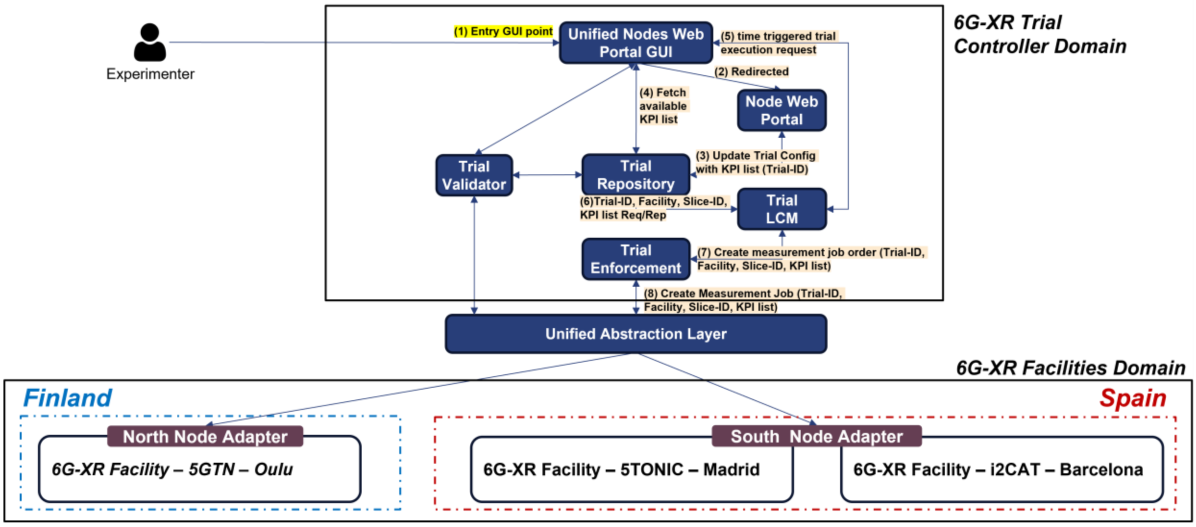

Figure 37. Measurement Job Creation and KPI Collection.

5.2.3.3 Deletion Process of the Trial, Measurement Job, and Network Slice

The trial deletion can be performed by the experimenter at any time by logging into the Unified Nodes Web Portal and deleting (i.e., marking it as deleted) the trial instance from the Trial Repository. No more action is required to be performed with a trial that has not been set up yet (i.e., instantiated). Such a deleted trial would not be instantiated. The trial configuration will also be removed from the specific 6G-XR facility after the trial execution completion (i.e., end time of the trial). This process is depicted in Figure 38. As part of Step 2, there are two cases that can trigger the close service and release resources request. The first one is the trial end time managed by the Trial LCM and the second one is the trial deletion request sent by the Experimenter from the Unified Nodes Web Portal. In any case, the action triggers the close service and release resource process managed by the Trial LCM. In the next step, the Trial LCM sends the stop and delete measurement job order to the Trial Enforcement (step 3a), which sends the respective request to the specific Node Adapter through the Unified Abstraction Layer (step 3b). Then, the Trial LCM sends the request to the Trial Enforcement to release the 6G-XR facility resources (step 4a). Thereafter, the delete slice request is sent by Trial Enforcement to the specific Node Adapter (step 4b) for slice decommissioning. Next, the specific Node Adapter sends confirmation of the network slice deletion to the Trial Enforcement, which sends the related response to the Trial LCM. The appropriate status of the trial (i.e., finished) is also updated in the Trial Repository (step 5) as part of the trial life cycle.

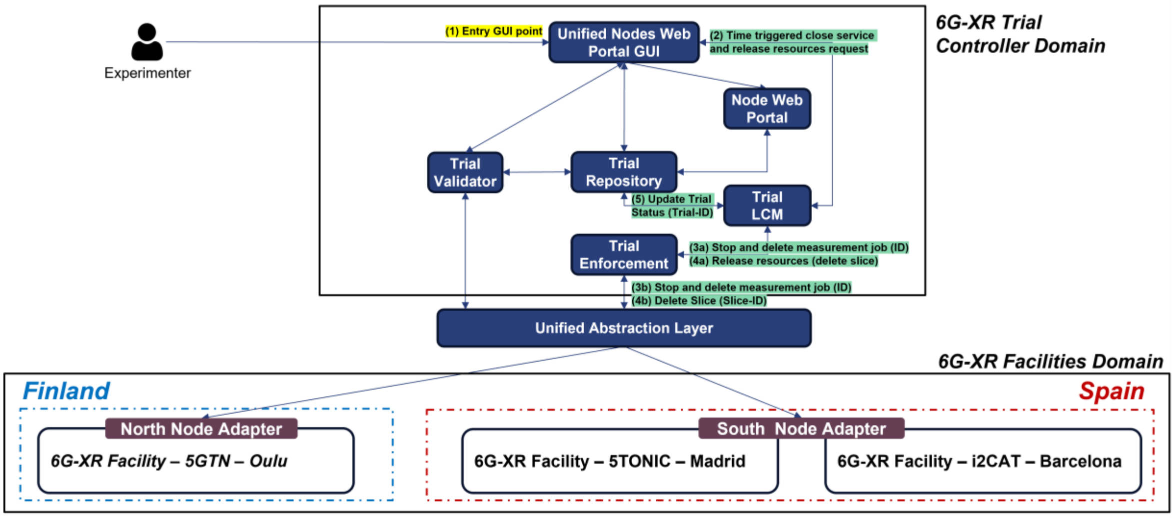

Figure 38. Deletion Process of Trial, Measurement Job, and Network Slice.

6 SUMMARY

This deliverable presents the XR enabler technologies that will be developed, deployed, and verified on 6G-XR distributed nodes including the NN (UOULU 5GTN and VTT 5GTN) and the SN (5GBarcelona and 5TONIC). The XR enablers are categorized based on three main pillars: (1) 3GPP XR Enablers, (2) O-RAN XR Enablers and (3) 6G DISRUPTIVE XR Enablers. After the analysis of the SoTA per each XR enabler category and the target gap, the enablers per category are identified as

(1) 3GPP XR Enablers:
- Network-Controlled Repeaters.
- Network assisted Rate Control API.
- ATSSS based capacity enhancement.
- 3GPP enablers for energy efficient XR services.
- Upgrade and evaluation of experimental RAN infrastructure in SN and NN.

(2) O-RAN XR Enablers
- Congestion aware load balancing.
- Energy-aware end-to-end resource management.
- Slice-aware resource allocation.

(3) 6G DISRUPTIVE XR Enablers
- High-Frequency Transceivers at 140 GHz and 300 GHz.
- Baseband implementation for THz-RIS and ISAC based on SC-FDE.
- Deep Reinforcement Learning for THz-RIS.

This report is paving the way for the coming deliverables in WP4 by providing the Initial design, the method of evaluation and the target KPIs for all abovementioned XR enablers. In addition, an XR trial controller is proposed to deploy XR trials from a GUI Portal over the multi-site beyond 5G network. This deliverable presents the Initial design, Components, Functions, Interfaces and APIs of the proposed trail controller and identified the requirements.

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