# D1.2: Reference architecture description

Revision: v.1.0

| | |
|---|---|
| **Work package** | WP 1 |
| **Task** | Task 1.3 |
| **Due date** | 30/06/2024 |
| **Submission date** | 28/06/2024 |
| **Deliverable lead** | i2CAT |
| **Version** | 1.0 |
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| **Abstract** | This deliverable contains comprehensive documentation of the architecture used by the 6G-XR experimental infrastructure. It addresses system, software and hardware aspects as well as the associated interfaces, considering the implications on extensibility, replicability, modularity, interoperability and adoption. |
| **Keywords** | Reference Architecture, User Devices, Applications, Radio Access Network, Core Network, Edge, Cloud, Network Management, Orchestration, Interfaces, APIs |

Co-funded by the European Union

6GSNS

WWW.6G-XR.EU

Grant Agreement No.: 101096838
Call: HORIZON-JU-SNS-2022

Topic: HORIZON-JU-SNS-2022-STREAM-C-01-01
Type of action: HORIZON-JU-RIA

**Document Revision History**

| **Version** | **Date** | **Description of change** | **List of contributor(s)** |
|---|---|---|---|
| V0.1 | 08/11/2023 | Initial table of contents | i2CAT, VTT |
| V0.2 | 07/02/2024 | Updated table of contents | i2CAT, VTT |
| V0.3 | 22/02/2024 | Updated reference architecture figures | i2CAT, VTT |
| V0.4 | 24/05/2024 | Full draft for external review | All WP1 partners |
| V0.5 | 11/06/2024 | Updated full draft for TM review | All WP1 partners |
| V1.0 | 28/06/2024 | Finalised version for submission | i2CAT, VTT |

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Project funded by

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
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Swiss Confederation

Federal Department of Economic Affairs, Education and Research EAER
State Secretariat for Education, Research and Innovation SERI

The 6G-XR (*6G eXperimental Research infrastructure to enable next-generation XR services*) project has received funding from the **Smart Networks and Services Joint Undertaking (SNS JU)** under the European Union's **Horizon Europe research and innovation programme** under Grant Agreement No 101096838. This work has received funding from the **Swiss State Secretariat for Education, Research, and Innovation (SERI)**



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* R: Document, report (excluding the periodic and final reports)

DEM: Demonstrator, pilot, prototype, plan designs

DEC: Websites, patents filing, press & media actions, videos, etc.

DATA: Data sets, microdata, etc.

DMP: Data management plan

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# EXECUTIVE SUMMARY

The aim of the 6G-XR reference architecture description is to provide a project-wide view into the architectural enablers required to support the deployment of the 6G-XR use cases on top of a mobile network infrastructure. The project use cases driving the development of these architectural enablers cover several of the user and application trends listed in the International Telecommunication Union's (ITU) recommendation document for the international mobile telecommunications (IMT) for 2030 and beyond (IMT-2030). These trends include immersive multimedia and multi-sensory interactions, digital twins and virtual worlds, and sustainability. The published IMT-2030 framework and objectives will guide the development and standardisation work of the 6th generation (6G) mobile networks in the coming years.

Even though the reference architecture is presented as a superset of features required to meet the needs of all 6G-XR use cases, the reference architecture is deployed as two separate subsets of the overall functionality at the 6G-XR experimentation sites in Spain and Finland. These deployed architecture subsets are used to validate some of the use cases at each site, providing also possibilities for further extensions in both the deployed architectural enablers and use cases in the future. This is achieved with a modular design of the 6G-XR architecture components and extensive use of open and standardised interfaces.

The reference architecture domains covered by the 6G-XR project innovations on new enablers cover the user devices and applications, network components, edge platforms, cloud services, management and orchestration as well as network interfaces and application programming interfaces (API). Each architecture domain has a number of technology and service enablers identified from the point of view of use case requirements. These enablers include hardware/software components, interfaces, functionality related to extended reality (XR) content capture and presentation, XR application functions (both on the client and network side), radio access network, core network, end-to-end (E2E) energy consumption measurement and optimisation, artificial intelligence (AI) and machine learning (ML) algorithms for network management, three dimensional (3D) digital twins, XR and edge resource orchestration, remote experimentation control, and network resource and capability exposure.

The 6G-XR reference architecture is also designed to support the project's Open Calls. The 3rd parties funded from the Open Calls can either extend or exploit the reference architecture functionality develop in the project and deployed at the experimentation sites.

 

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# ABBREVIATIONS

| | |
|---|---|
| 2D | Two Dimensional |
| 3D | Three Dimensional |
| 3GPP | 3rd Generation Partnership Project |
| 5G | 5th Generation |
| 5G-A | 5G-Advanced |
| 5GC | 5G Core Network |
| 6G | 6th Generation |
| AC | Alternating Current |
| AF | Application Function |
| AI | Artificial Intelligence |
| API | Application Programming Interface |
| AR | Augmented Reality |
| BWP | Bandwidth Part |
| CDF | Congestion Detection and Control Function |
| CEN | European Committee for Standardisation |
| CENELEC | European Committee for Electrotechnical Standardisation |
| CP | Control Plane |
| CPU | Central Processing Unit |
| CSP | Communication Service Provider |
| DC | Direct Current |
| DESS | Distributed Energy Storage System |
| DL | Downlink |
| DNN | Data Network Name |
| DoF | Depth of Field |
| DRL | Deep Reinforcement Learning |
| DSO | Distribution System Operator |
| E2E | End-to-end |
| E2SM | E2 Service Model |
| eMBB | Enhanced Mobile Broadband |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| EPC | Evolved Packet Core |
| ESO | European Standardisation Organisation |
| ETSI | European Telecommunications Standards Institute |
| EWBI | East-Westbound Interface |
| FMI | Finnish Meteorological Institute |
| FR | Frequency Range |
| GPU | Graphics Processing Unit |
| GRI | Global Reporting Initiative |
| IMS | IP Multimedia Subsystem |
| IMSDC | IMS Data Channel |
| IMT | International Mobile Telecommunications |
| IMT-2030 | IMT for 2030 and Beyond |
| IoT | Internet of Things |
| IP | Internet Protocol |
| ISAC | Integrated Sensing and Communication |
| ITU | International Telecommunication Union |
| ITU-R | ITU Radiocommunication Sector |
| KPI | Key Performance Indicator |

| | |
|---|---|
| KPM | Key Performance Measurement |
| LCM | Lifecycle Management |
| LOD | Level of Detail |
| MAC | Medium Access Control |
| MCU | Multi-point Control Unit |
| MEC | Multi-access Edge Computing |
| MEF | MEC Federator |
| MEPS | MetCoOp Ensemble Prediction System |
| MID | Measuring Instruments Directive |
| ML | Machine Learning |
| MLA | Micro Lens Array |
| MLO | Multi-link Operation |
| mMTC | Massive Machine Type Communications |
| MNO | Mobile Network Operator |
| MQTT | Message Queuing Telemetry Transport |
| MTSI | Multimedia Telephony Service for IMS |
| NaaS | Network as a Service |
| NEF | Network Exposure Function |
| NF | Network Function |
| NFV | Network Function Virtualisation |
| NG-RAN | Next Generation RAN |
| NLF | New Legislative Framework |
| NR | New Radio |
| NSA | Non-Standalone |
| NST | Network Slice Template |
| O-CU | Open Centralised Unit |
| O-DU | Open Distributed Unit |
| O-RAN | Open RAN |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| OPG | Operator Platform Group |
| OS | Operating System |
| QoD | Quality on Demand |
| QoS | Quality of Service |
| PCF | Policy Control Function |
| PDU | Packet Data Unit |
| PMD | Power Metering and Monitoring Device |
| PoP | Point of Purchase |
| PRB | Physical Resource Block |
| PV | Photovoltaic |
| RAN | Radio Access Network |
| RC | RAN Control |
| RIC | RAN Intelligent Controller |
| RIS | Reflective Intelligent Surface |
| RRM | Radio Resource Management |
| RT | Real Time |
| S-NSSAI | Single Network Slice Selection Assistance Information |
| SA | Standalone |
| SFU | Selective Forwarding Unit |
| SNS JU | Smart Networks and Services Joint Undertaking |
| SSD | Solid State Drive |
| TAC | Tracking Area Code |

| | |
|---|---|
| TSN | Time Sensitive Networking |
| TSO | Transmission System Operator |
| TWT | Time Wake Time |
| UE | User Equipment |
| UL | Uplink |
| UP | User Plane |
| URLLC | Ultra Reliable Low Latency Communication |
| VNF | Virtual Network Function |
| VOD | Video on Demand |
| VR | Virtual Reality |
| XR | Extended Reality |

# 1 INTRODUCTION

This document describes the 6G-XR reference architecture. The reference architecture description provides a high-level overview of the architectural components and interfaces needed to support the deployment of the 6G-XR use cases on a mobile network infrastructure. The architecture design is based on the key principles of modularity, interoperability, and maximisation of adoption. The aim of the design is to facilitate and increase 3rd party contributions through the Open Calls during the project's lifetime. The architecture will be able to evolve along with the 6th generation (6G) mobile networks roadmap and accommodate different types of telecom infrastructures through future extensions.

This chapter provides a brief overview of the 6G-XR use cases and 6G technology development avenues addressed by the project R&D activities. Analysis on the potential impact of the ongoing regulation and standardisation related to artificial intelligence (AI) / machine learning (ML) and cybersecurity is also provided from the point of view of experimental research infrastructures in Europe and experimental research performed in the later phases of the Smart Networks and Services Joint Undertaking (SNS JU).

The project use cases driving the development of these architectural enablers cover several of the user and application trends listed in the recommendation document for the international mobile telecommunications (IMT) for 2030 and beyond (IMT-2030) that was recently published by the International Telecommunication Union's (ITU) Radiocommunication Sector (ITU-R) [1]. These trends include immersive multimedia and multi-sensory interactions, digital twins and virtual worlds, and sustainability. The published IMT-2030 framework and objectives will guide the development and standardisation work of 6G in the coming years.

Different 6G technology development avenues in the 6G-XR reference architecture are addressed with varying deployment approaches as some of the utilised technologies are evolution of the current state-of-the-art while some of them are more disruptive in nature. The evolution of the current state-of-the-art technologies based on the 3rd Generation Partnership Project (3GPP) specifications s are expected to offer both indoor and outdoor coverage in live network settings. As an extension to the current state-of-the-art, open-source and open RAN (O-RAN) solutions are expected to offer indoor coverage and lab-based experimentation opportunities with added flexibility. The disruptive 6G technologies are expected to be in a proof of concept (PoC) stage and will only offer lab-based experimentations.

The reference architecture presented in this document, including the technology enablers related to the 6G development avenues, will be deployed as two separate subsets of the overall functionality at the two 6G-XR experimentation sites: The South Node in Spain and North Node in Finland. These architecture subsets will be used to validate some of the use cases at each site, providing also possibilities for further extensions in both the deployed architectural enablers and use cases in the future.

## 1.1 6G-XR USE CASES

The following shortly discuss the 6G-XR use cases and their initial requirements identified earlier and reported in 6G-XR deliverable D1.1 [2]. The motive is providing some insights into why current 5G networks are incapable of supporting the XR applications utilised in the use cases, in a way that is both scalable and future-proof.

### 1.1.1 South Node use cases

Out of the three application areas defined within the 6G-XR project, the South Node experimental infrastructure will be used to test real-time holographic communications. The application areas comprise three distinct use cases that will be developed and validated in parallel:

- UC1 – Resolution Adaptation or Quality on Demand (QoD)
- UC2 – Routing to the Best Edge
- UC3 – Control Plane Optimisations

The main need for beyond 5G (B5G) network performance and functionality in real-time holographic communications is the high amounts of data transferred over the air interface especially in the uplink direction, E2E application latency, and flexibility of the network architecture to support the client devices in extended reality (XR) -related processing tasks in a variety of service deployment scenarios.

A short overview of the South Node use cases is provided below. More detailed descriptions are available in 6G-XR deliverable D1.1 [2].

#### 1.1.1.1 Resolution Adaptation or Quality on Demand (QoD)

In the first 6G-XR use case (UC1), the network detects congestion in a cell serving an XR user equipment (UE) device. Upon congestion detection one of two actions can be taken to remedy the situation, namely, decreasing resolution of XR media from UEs or invoking CAMARA QoD application programming interfaces (APIs) to prioritise XR flow(s) in the cell.

#### 1.1.1.2 Routing to the Best Edge

In the second 6G-XR use case (UC2), a holographic communications application can make use of different edge nodes for XR processing offloading or for managing multi-user communications. The idea is to enable the service to select and make use of the most appropriate edge platform based on specific goals, like minimising delays by selecting a closer edge processing location for the user plane traffic.

#### 1.1.1.3 Control Plane Optimisations

In the third 6G-XR use case (UC3), a holographic call session manager is designed relying on the network control plane so that holographic communications can be integrated smoothly into a dialler app as an evolved communication service in 6G beyond voice. Moreover, the approach aims to maximise the robustness and scale of the solution by relying on the network functionality for session management aspects.

### 1.1.2 North Node use cases

Out of the three application areas defined within the 6G-XR project, two are allocated for the North Node. There are two use cases developed and validated in the North Node, one per application area:

- UC4 – Collaborative 3D Digital Twin-like Environment
- UC5 – Energy Measurement Framework for Energy Sustainability

The main need for B5G network performance and functionality in the collaborative 3D digital twins and end-to-end (E2E) energy efficiency is related to the high amounts of data transferred over the air interface, low and bounded latency for immersive virtual reality (VR), remote controlling tasks, and support for dynamic network reconfigurations for energy-aware resource optimisation.

A short overview of the North Node use cases is provided below. More detailed descriptions are available in 6G-XR deliverable D1.1 [2].

#### 1.1.2.1 Collaborative 3D Digital Twin-like Environment

In the fourth 6G-XR use case (UC4), a pre-created 3D object is collaboratively reviewed in a digital twin environment of a laboratory. After an accepted review, 3D-printing of the object in the real-world laboratory is remotely started from the digital twin environment. The printing process can be monitored in the digital twin environment through a remotely operable camera that is attached to a robot arm in the physical laboratory space. The status and movements of the assets in the digital twin environment and physical laboratory space are synchronised.

#### 1.1.2.2 Energy Measurement Framework for Energy Sustainability

In the fifth 6G-XR use case (UC5), a variety of innovative energy measurement solutions are integrated into the communications and renewable energy production infrastructure of the North Node experimentation site. The accurate energy measurement data collected from the site is utilised to optimise the E2E energy consumption and runtime sustainability of the test network.

## 1.2 6G DEVELOPMENT AVENUES

The following subsections provide a brief overview of the technology focus areas of the 6G-XR experimentation sites. The detailed descriptions of the deployed assets at both sites are included into 6G-XR deliverable D1.3 [3].

### 1.2.1 South Node experimentation site

6G-XR South Node consists of two interconnected test facilities located in two different cities in Spain. The test facilities are 5GBarcelona in Barcelona and 5TONIC in Madrid. The two sites are interconnected and able to share resources and federate edge platform functionalities between them.

The architecture enablers deployed across the South Node test facilities focus on XR capture and presentation hardware, and XR application functionality in the user devices domain. In radio access network (RAN), the focus is on 3GPP based technology evolution and O-RAN whereas the core network enablers are focused on the network exposure function (NEF) and IMS data channel (IMSDC). The deployed edge platform enablers focus on the network side XR application functionality and in the management and orchestration domain, the key enablers are XR and edge orchestration functions. The utilisation of open and standardised interfaces in the South Node is focused on the CAMARA, congestion detection and control, IMSDC, and NEF APIs.

### 1.2.2 North Node experimentation site

6G-XR North node consists of two different but interconnected test facilities in the city of Oulu in Finland. These test facilities are University of Oulu 5G Test Network (UOULU 5GTN) and VTT Oulu 5G Test Network (VTT 5GTN). The two test facilities can share resources and energy related monitoring data between them.

 

The architecture enablers deployed across the North Node test facilities focus on XR presentation hardware in the user devices domain, whereas the available RAN enablers cover 3GPP technology evolution, open source and O-RAN network components, disruptive 6G technologies in the form of sub-THz transceivers, and Wi-Fi time sensitive networking (TSN). In the core network, the focus is on network slice management. The deployed enablers at the edge platform include the energy optimisation framework, AI/ML algorithms for network resource management, and 3D digital twin engine. Connected cloud services provide open data related to cost and $CO_2$ counters of the energy consumed in the network. The utilisation of open and standardised interfaces in the North Node is focused on O-RAN specified and vendor specific APIs.

## 1.3 AI/ML AND CYBERSECURITY REGULATION AND STANDARDISATION

In the context of the 6G-XR project and especially in the context of testbed activities during the later phases of the SNS JU, the future AI and ML related requirements to be introduced by the European AI Act (with a draft being available [4]) need to be considered. Same is true also for the cybersecurity related requirements to be introduced by the upcoming Cyber Resilience Act (with a draft being available [5]) and the newly activated Articles 3(3)(d/e/f) of the Radio Equipment Directive [6]. However, the EU AI Act [4] and Cyber Resilience Act [5] are not yet officially approved and listed in the EU Official Journal. Once this listing will happen, it is expected that a transition period will be granted such that stakeholders can prepare for meeting the new conformity requirements, typically 1-2 years. Concerning the Radio Equipment Directive, new Cybersecurity and Privacy related Articles 3(3)(d/e/f) were activity through a Delegated Regulation [7]. The so-called date of applicability of the new Radio Equipment Directive Delegated Regulation requirements is the 1st of August 2025, this is when the corresponding transition period expires. Once the requirements are fully applicable, they need to be met by manufacturers to place products onto the European Union Single Market. Non-compliance will lead to loss of market access.

Although the requirements are not immediately applicable, the future consequences for the activities of 6G-XR, and other similar Research Infrastructures (RI), should be analysed. Likewise, it will be of interest for the users of the 6G-XR and other European testbeds to know which novel requirements will be required to maintain market access in the European Union Single Market. Concerning research activities, the latest available draft of the EU AI Act [4] includes the following statement:

*"(25) This Regulation should support innovation, respect freedom of science, and should not undermine research and development activity. It is therefore necessary to exclude from its scope AI systems and models specifically developed and put into service for the sole purpose of scientific research and development. Moreover, it is necessary to ensure that this Regulation does not otherwise affect scientific research and development activity on AI systems or models prior to being placed on the market or put into service. As regards product oriented research, testing and development activity regarding AI systems or models, the provisions of this Regulation should also not apply prior to those systems and models being put into service or placed on the market. That exclusion is without prejudice to the obligation to comply with this Regulation where an AI system falling into the scope of this Regulation is placed on the market or put into service as a result of such research and development activity and to the application of provisions on regulatory sandboxes and testing in real world conditions. Furthermore, without prejudice to exclusion regarding AI systems specifically developed and put into service for the sole purpose of scientific research and development, any other AI system that may be used for the conduct of any research and development activity should remain subject to the provisions of this Regulation. In any event, any research and development activity should be carried out in accordance with recognised ethical and professional standards for scientific research and should be conducted in accordance with applicable Union law."*

 

It is indeed important for the scientific community to conduct research without additional barriers. It is thus appreciative to learn that "*AI systems and models specifically developed and put into service for the sole purpose of scientific research and development*" [4] are planned to be excluded from the scope of the EU AI Act. Consequently, it is understood that the work of 6G-XR and related proof-of-concept activities for the sole purpose of research will not need to comply with the requirements of the future EU AI Act. However, it may still be of high interest to the relevant stakeholders to test EU AI Act related functionalities which may need to be implemented in future products to meet conformity requirements and thus market access conditions.

In particular, the draft EU AI Act includes a list of so-called "High Risk" AI Systems (see Annex III of the draft EU AI Act [4]) for which a series of detailed technical requirements is introduced. Each product falling under the "High Risk" AI Systems category will be required to comply with those requirements to maintain access to European Union Single Market. It will thus be of high interest to the community to have access to testbeds for validating the implementation of related functionalities.

Similarly, the draft Cyber Resilience Act [5] mentions the following:

*"(10) In order not to hamper innovation or research, free and open-source software developed or supplied outside the course of a commercial activity should not be covered by this Regulation…"*

Again, it can be understood that the work of 6G-XR and related proof-of-concept activities for the sole purpose of research will not need to comply with the requirements of the future EU Cyber Resilience Act. Similarly, as in the case of the EU AI Act, it may still be of high interest to the stakeholders to test EU Cyber Resilience related functionalities which may need to be implemented in future products to meet conformity requirements and thus market access conditions. This is especially true since the scope of the EU Cyber Resilience Act is extremely broad addressing all "products with digital elements" being defined as follows in Article 3 of the draft EU Cyber Resilience Act [5]:

*"(1) 'product with digital elements' means any software or hardware product and its remote data processing solutions, including software or hardware components to be placed on the market separately;"*

The breadth of the definition is such that almost any data processing product is under scope. Also, the EU Cyber Resilience Act will not only introduce requirements to be met for the placement onto the market (as it is, e.g., the case for the Radio Equipment Directive) but will require manufacturers to ensure continued compliance over the lifetime of the product with a limit of 5 years.

Similarly, the Radio Equipment Directive [6] states that

*"(25) For the purpose of promotion of research and demonstration activities it should be possible, in the context of trade fairs, exhibitions and similar events, to display radio equipment which does not comply with this Directive and cannot be placed on the market, on the condition that exhibitors ensure that sufficient information is provided to the visiting public."*

Still, the newly activated Articles 3(3)(d/e/f) relating to Cybersecurity and Privacy requirements will be applicable soon, starting on the 1st of August 2025. From this date on, manufacturers will need to comply with the novel requirements or otherwise access to the European Union Single Market will be lost. It is thus of high interest to stakeholders to have access to testbeds which allow to validate implementation solutions of some or all of the newly introduced requirements.

The upper framework is further supported by the European standardisation organisations (ESOs), i.e., European Telecommunications Standards Institute (ETSI), European Committee For Electrotechnical

 

Standardisation (CENELEC), and European Committee for Standardisation (CEN). Under the European New Legislative Framework (NLF), the ESOs are authorised to support the European Commission in the implementation of the regulation activities. This is indeed a brilliant opportunity for the stakeholders such as industry, academia, and SMEs, to contribute to the implementation of European regulations and to ensure that the interests of the European industry are met while fulfilling the requirements of the regulation. The European Commission has issued a related standardisation requests on the EU AI Act and the Radio Equipment Directive to CEN/CENELEC, while the related standardisation request for the Cyber Resilience Act is still pending. It is thus recommended to all stakeholders to engage into the process and to support the drafting of the related standards.

# 2 6G-XR REFERENCE ARCHITECTURE

In this chapter, a high-level overview of the 6G-XR reference architecture is presented. The reference architecture comprises the key enablers required to support the 6G-XR use cases and requirements defined in D1.1 [2]. Both the required network functions and services as well as the related interfaces and APIs are included. Each of these reference architecture components and interfaces are defined in more detail in the following Chapters 3 and 4, respectively.

The collection of the key network and service enablers as well as the architectural domains where they are deployed are shown in the layered view of the 6G-XR reference architecture in Figure 1. The layered view also serves as a logical representation of the project's research topics, i.e., 6G-XR innovation areas. The use case enablers where the project is actively developing new capabilities beyond the current state-of-the-art are highlighted with purple blocks. The existing enablers extended and applied by the project into the specific needs of the 6G-XR use cases are shown with dark blue blocks. Each purple and dark blue block contains several individual enablers, which are introduced here and discussed more in Chapter 3. More specifically, the enablers related to user devices are covered in 3.1, enablers related to network components in 3.2, enablers related to edge platforms in 3.3, enablers related to cloud services in 3.4, and enablers related to network and service management and orchestration in 3.5.

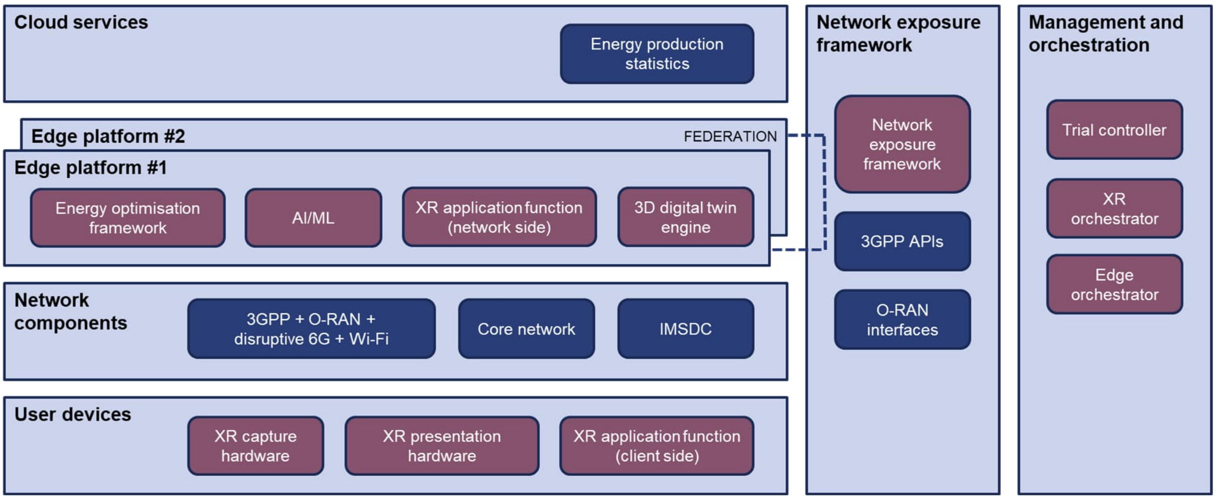


*Figure 1. 6G-XR reference architecture – Layered view.*

A detailed technical view into the 6G-XR reference architecture is provided by the interconnected view shown in Figure 2. Compared to the layered view presented in Figure 1, the interconnected view breaks down some of the high-level functionalities into several individual functional blocks to highlight the distributed deployment approach of those reference architecture enablers. It also shows the placement of the 6G-XR use case applications in the overall architecture with orange blocks and highlights the access of the two key experimentation actors, i.e., the external experimenter and 6G-XR test facility owner, into the 6G-XR experimentation sites with yellow blocks. Moreover, the interconnected view introduces into the reference architecture visualisation also the essential data and control connections, which will be discussed further in Chapter 4. The enablers related to interfaces and APIs in the 6G-XR reference architecture are discussed from the point of the developed 6G-XR network exposure framework in 4.1, enablers related to existing 3GPP based APIs in 4.2 and enablers related to existing O-RAN interfaces in 4.3.

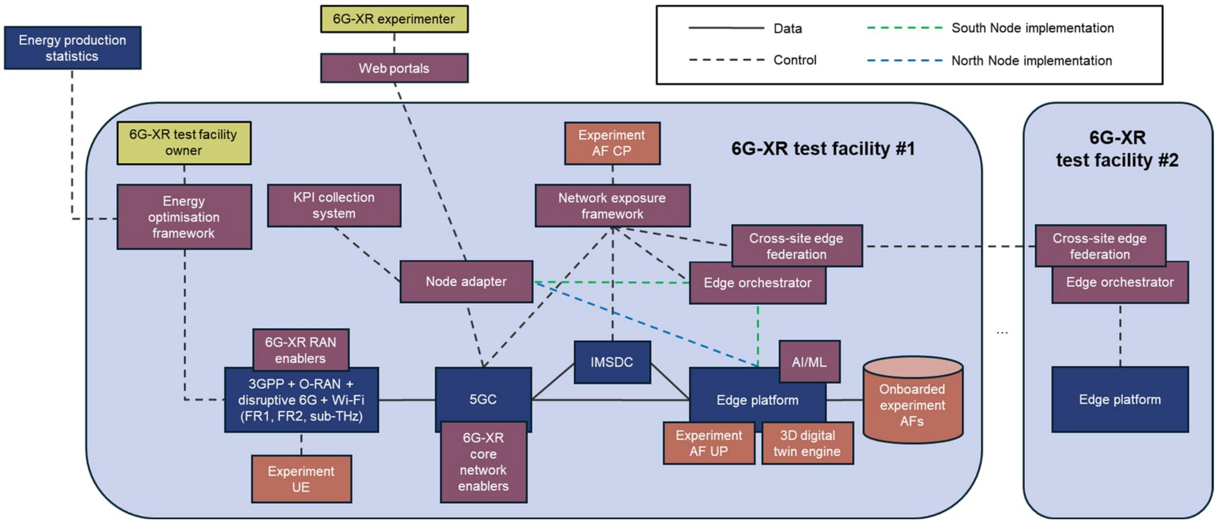


*Figure 2. 6G-XR reference architecture – Interconnected view.*

In Figure 2, the user devices layer is represented with a single block titled "Experiment UE". This block contains all the aspects included in the user devices layer in Figure 1. All the blocks of the network components layer in Figure 1 are also visible in Figure 2. The 6G-XR innovations utilising or complementing the existing RAN and 5G core network (5GC) functionalities (see [8] and [9] for more details) are highlighted in Figure 2 with separate purple blocks in conjunction with the dark blue RAN and 5GC blocks. The blocks of the edge platform layer of Figure 1 are also all present in Figure 2. However, due to the deployment specificities of these blocks, some of them are placed into the interconnected view of the 6G-XR reference architecture a bit differently. For example, the application function's (AF) user plane (UP) is drawn on top of the edge platform whereas the AF control plane (CP) is accessed through the 6G-XR network exposure framework. Similarly, as the energy optimisation framework contains integrations to both the network and energy infrastructure of the experimentation site, it is drawn as a standalone entity in Figure 2 even though the data related to the framework is hosted and accessed at the sites edge platform. The energy optimisation framework is also the only component in the 6G-XR reference architecture directly communicating with the cloud service layer containing external data sources for historical and statistical data related to production of local renewable energy.

The distributed nature of the 6G-XR reference architecture's management and orchestration, and network exposure domains is also more visible in Figure 2. The access to the experimentation site through the 6G-XR trial controller comprised of web portals and node adapter is shown in the interconnected view. As part of the 6G-XR web portal as well as the node adapter functionality is specific to the accessed experimentation site, the differences in the control signalling paths between the South Node and North Node are highlighted in Figure 2 with green and blue dashed lines, respectively. Mode details on the trial controller functionality can be found in 3.5.1. The central role of the orchestration and federation functionalities related to the 6G-XR use case applications and edge platform resources between sites (see [10] for more details) is also visible in Figure 2. Extensive utilisation of the 6G-XR network exposure framework functionalities in these processes are also more evident in the interconnected view compared to the layered view presented in Figure 1. The deployment of the energy optimisation framework as a parallel infrastructure with the communication network components (see [11] for more details) is visualised in Figure 2 with one block that contains all the functionality discussed in 3.3.1 and 3.4.1.

 

The project level representation of the 6G-XR reference architecture provided in this chapter is a superset of functionalities covering all 6G-XR use cases. However, the deployment of the reference architecture functionality is divided between the 6G-XR experimentation sites, i.e., South Node and North Node. Both experimentation sites host different use cases and, hence, implement only subsets of the overall 6G-XR reference architecture functionality needed in their validation tests. The details of the deployed use case validation architectures can be found in D1.3 "Test infrastructure specification" [3].

# 3 KEY COMPONENTS

This chapter describes the network and service functions identified as key enablers in the 6G-XR reference architecture. All these network components are needed to support the five 6G-XR use cases defined in D1.1 “Requirements and use case specifications” [2]. The following subsections shortly describe each of the reference architecture components as well as define the functionality they enable for the project use cases. The structure of the chapter follows the reference architecture layers shown in Figure 1 of Chapter 2.

## 3.1 USER DEVICES AND APPLICATIONS

### 3.1.1 XR capture hardware

#### 3.1.1.1 Cameras

To capture the high-quality video input for the holographic communication in UC1 and UC2, advanced cameras are developed for the specific use case needs as part of the project. For example, the 6G-XR’s R32 light field camera shown in Figure 3 employ the Onsemi XGS 32000 image sensor, providing a lateral resolution of 6560 x 4948 pixels, equivalent to 32.4 megapixels. The effective lateral resolution stands at 3280 x 2474 pixels or 8.1 megapixels. This sensor was chosen to guarantee the optimal lateral resolution that can be transmitted via a single CXP-12 interface, while reaching up to 36 frames per second. The sensor also supports on-camera pixel binning, which, when activated due to bandwidth limitations for level of detail (LOD) adjustment, still deliver UltraHD image resolution.


*Figure 3. 6G-XR R32 light field camera.*

A newly developed low-f-number micro lens array (MLA), which enables the 3D capabilities of light field cameras, is incorporated in the camera. This MLA, designated as L3-D125-A018-VRE-VI, operates on a Galilean multi-focused plenoptic 2.0 light field mode. A novel manufacturing technique and an enhanced iris layer on the MLA have facilitated an aperture of f/1.8 with controllable levels of aberrations (optical errors), a frequent issue in low-f-number optics. The low-f-number increases light transmission through the optical assembly, thus reducing motion blur for moving subjects. The extended depth of field (DoF) provided by the MLA's multi-focus design compensates for the typically shallow DoF that would result from a low-f-number setup.

To accommodate to the low-f-number MLA, which necessitates close proximity to the sensor, a novel process was devised to remove the sensor's cover glass. The power supply is Power over CoaXPress. When combined with a cable length of 30 m, it allows for a flexible, single cable per camera deployment without bandwidth penalties (see 6G-XR deliverable D3.1 [10]section 3 and Appendix 1 for more details).

A Basler OEM Lens, based on the F-S35-2528-45M-S-SD model, was adapted for the 6G-XR UC1 and UC2 needs. The lens possesses a focal length of 24.5 mm and an aperture of f/1.8. The focus range extends from 0.2 to 3.5m. The angle of view spans 55.7° horizontally and 39.1° vertically. A thermal decoupled lens mount was developed to avoid loss of calibration due to thermal variations. The 6G-XR's R32 cameras serve as a versatile 3D sensor suitable for professional environments where high resolution and high frame rates are of paramount importance.

#### 3.1.1.2 Sensors

In addition to special camera setups, VR user plane services in 6G-XR integrate also other volumetric video capture setups, using affordable off-the-shelf sensors, like Azure Kinect. This capture approach is not developed inside the 6G-XR. Instead, 6G-XR applies results from precedent projects, like EU H2020 VR-Together[1] into its use cases and experimental setups.

The required integration efforts for the alternative video capture setup are justified, as they ease planned experimentation activities due to the availability of a limited number of high-end Raytrix light field sensors. The addition of affordable off-the-shelf sensor options facilitates conducting scalability tests in UC1 and UC2. In addition, as Azure Kinect is an affordable and lightweight sensor, it can be easily transported and deployed in different scenarios and locations (even domestic ones for development and testing purposes), which provides more flexibility into the 6G-XR experimentations. Integration of multiple camera and sensor types into the 6G-XR test facilities also enhances the modularity and extendibility of the experimentation sites.

### 3.1.2 XR presentation hardware

#### 3.1.2.1 XR kits

The 6G-XR project uses augmented reality (AR) and VR headsets as XR kits for accessing the VR environments in the project use cases and interacting with them. Several headset models are employed in the project.

Meta Quest 2 XR Kit was first released as Oculus Quest 2, then rebranded as Meta Quest 2 when acquired by Meta. In 6G-XR, it is employed in two different setups. First setup uses USB connectivity where Meta Quest 2 is connected to a laptop with a USB cable. The laptop runs a Unity-based application that provides video to be displayed on the Meta Quest 2 screen. Meta Quest 2 shares the information coming from its sensors to the application running on the laptop. The second setup uses wireless connectivity. In the wireless setup, Meta Quest 2 connects to a WiFi network and opens a Web browser to access a Web application. The Web application provides the content to be displayed and to interact with.

[1] VR-Together website: https://vrtogether.eu/

*Figure 4. Meta Quest 2 headset.*

Meta Quest 3 is the updated version of Oculus Quest 2. The main differences to the older model are higher display resolution of 2064 x 2208 pixels per eye (Quest2: 1832 x 1920 pixels) with better refresh rate and more powerful processing delivering smoother and low latency VR input for users. The hand tracking improvement makes it ideal for reviewing 3D models in VR remote communication. This enhancement allows users to manipulate and explore 3D models with their hands.

*Figure 5. Meta Quest 3 headset.*

Apple Vision Pro is a state-of-the-art advanced AR/VR headset. It features micro-OLED displays with a resolution of 3840 x 2160 pixels per eye, significantly higher than the Quest 3's 2064 x 2208 pixels per eye. The Apple Vision Pro also boasts a higher refresh rate for smoother visuals and is powered by the Apple M2 chip, delivering superior performance and lower latency. The device excels in mixed reality applications, offering precise eye and hand tracking, making it ideal for both AR and VR experiences, including 3D model reviews and immersive remote communication.

*Figure 6. Apple Vision Pro headset.*

In the context of real-time holographic communications, the Meta Quest 2/3 or similar VR Headsets are employed in the South Node for UC1 and UC2. In addition, Meta Quest 3 is utilised in the North Node for the collaborative 3D digital twins UC4. They are employed as end devices for the users that aims to access and interact with the VR scene being generated for these use cases. In addition, Apple

 

Vision Pro AR/VR headsets are used in North Node for the collaborative 3D digital twin usage scenario in UC4. Other VR headsets with similar capabilities to Meta Quest 2/3 and Apple Vision Pro can also be employed in 6G-XR reference architecture to test the developed use case capabilities.

#### 3.1.2.2 Smartphones

The 6G-XR project uses smartphones in real-time holographic communication as capturer and receiver devices. The approach leverages two dimensional (2D) images captured by the sender participant's selfie camera. The employed device models are Samsung Galaxy S22 Ultra, Samsung Galaxy S22+ and iPhone 12 Pro.

The smartphones used for single-camera real-time holographic communication allows streaming of realistic 3D holograms in real-time, creating a sense of presence and connection for the end users. Equipped just with a smartphone camera, people can enter holographic collaborative meetings as their real selves in 3D. This provides a new and immersive way of communication, enabling everyone to enjoy realistic presence in online meetings.

In terms of use cases, smartphones are mostly utilised in the South Node for UC3. An iPhone is used as a sender and a Samsung as a receiver device. The devices are used for holographic call via IMSDC and web rendering implementation. This way, the traditional call can be elevated to a holographic call without the need for a separate holographic communication application.

#### 3.1.2.3 Laptops

In the 6G-XR reference architecture, laptops are employed as user devices running client applications. In the use case deployments, the client applications running on laptops connect to server-side applications deployed on the experimentation site's edge platform even though the processing capabilities can vary from a laptop to another. A few main configurations or profiles have been identified.

For the holographic communications UC1 and UC2 in the South Node, the first configuration option includes a simple laptop without a dedicated graphics processing unit (GPU). These laptops usually have no more than 16 GB of RAM paired with any Intel or AMD central processing unit (CPU). The only available GPU is the basic one embedded within the chosen CPU. This configuration is employed for running lightweight client applications based on Web technologies. It is not employed with the XR kits discussed in 3.1.2.1.

The second configuration option includes a GPU-enabled higher-capacity laptops. These laptops usually have at least 16 GB of RAM paired with a high performant Intel or AMD CPU, and are equipped with a dedicated NVIDIA GPU. These laptops can run heavy processing client applications based on Unity. This configuration is employed jointly with the XR Kits.

The third configuration option is built around a MacBook Pro equipped with a 12 Core Apple M3 Pro chipset and dedicated 18 Core GPU. The laptop is equipped with 18 GB of RAM and 1 TB solid state drive (SSD). This laptop is needed to connect to the Apple Vision Pro headset as the glasses do not work with Linux or Windows operating system (OS).

For the collaborative 3D digital twins UC4 in the North Node, the laptop connected to a XR headset is also connected to a 5G modem. This configuration can be used to provide 5G connectivity for the headset user and enable accurate key performance indicator (KPI) measurements, e.g., between the user device and application servers.

 

For the implementation of the 6G-XR reference architecture and validation tests, laptops are necessary as one type of end user devices for all the project's use cases. This requirement comes from the more flexible possibilities to configure software-based measurement probes in the end user devices when laptops are used instead of commercial XR kits and smartphones. However, it should be noted that laptops are also the main entry point to the VR environments for the users using XR kits.

### 3.1.3 XR application function (client side)

In the context of real-time holographic communications AR user plane for UC3, the client side XR application function on a smartphone can be a WebGL application which supports web browser rendering of 3D content. A holographic call is made by rendering the hologram in 3D in AR mode on a smartphone using WebGL technology. The app can receive data from IMSDCs, process it and render it correctly as a 3D hologram on the smartphone screen. Simplified representation of a holographic call flow with smartphone is shown in Figure 7.

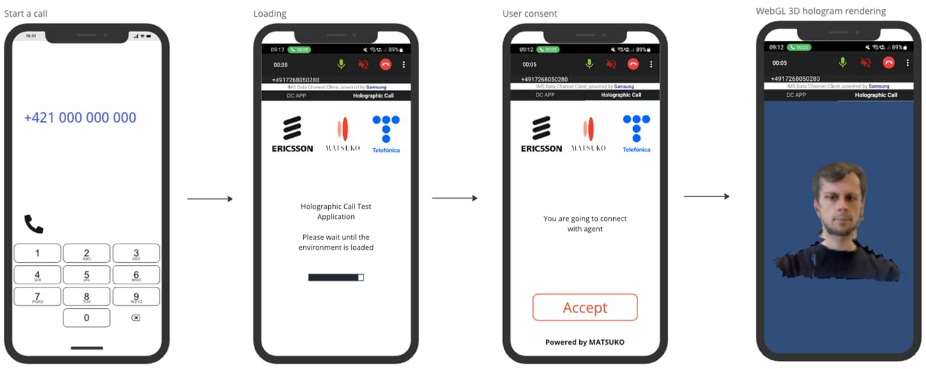


*Figure 7. IMS holographic call on a smartphone.*

In the case of VR user plane for UC1/UC2, two client applications can be employed on a client laptop. The first option is a native player based on Unity framework. This is employed only when running on a GPU-enabled laptop with a XR kit connected though USB cable. The native player has capabilities for both media consumption and media capture / production of volumetric video. The second option is a lightweight Web player. This is employed when the laptop has no GPU. The player is based on Web technologies and uses WebRTC or DASH protocol. In this case, only media consumption capabilities are provided.

When considering the AR user plane (UC3), seamless integration of holographic communications into the smartphone dialler app as an advanced communication service will provide widespread access to the holographic technology. Additionally, leveraging the IMSDC eliminates the necessity for standardised formats and this approach enables a diverse array of information-sharing use cases without requiring further standardisation or implementation efforts. When considering the VR user plane (UC1/UC2), the client application needs to be installed on a laptop only when using the Unity native player. The laptop also needs to be connected to a XR kit. In the case of the lightweight Web player, the only requirement is to have a Web browser to open the Web application. The Web browser could be running either at the laptop or headset, as there is no need to have them working together.

 

## 3.2 NETWORK COMPONENTS

### 3.2.1 Radio access network (RAN)

#### 3.2.1.1 3GPP evolution

When it comes to network capabilities to handle XR application traffic, the evolution of 3GPP standard technologies from 5G-Advanced (5G-A) towards 6G provides the main pathway for enhanced XR support in mobile networks. The introduction of XR specific enhancements to 5G was started already in Releases 15-17 and will continue in the first 5G-A release, i.e., Release 18, which is currently under finalisation. The upcoming releases towards 6G also have numerous XR specific study and work items, which means that there a variety XR-related enhancements coming to the commercial mobile network also in the future. Hence, the 3GPP evolution path is expected to result into the first ubiquitously available communication platform that is able to provide optimised functionality and performance for XR applications in various large-scale use cases and usage environments.

The 5G new radio (NR) air interface can support diverse XR applications. For example, next generation RAN (NG-RAN) supports split rendering by guaranteeing the capacity of tens/hundreds of Mbps and latency of less than 10 ms for XR services, as measured at the transport/application layer. The NG-RAN gNodeB therefore serves as the intermediate node that forwards the XR UE sensor data to the cloud in the uplink (UL) and transports the multimedia data from the cloud XR engines to the XR UE in the downlink (DL). The capacity and latency requirement are stringent. To support XR services' demands, the 3GPP has been exploring several enhancements in the areas of XR awareness, power saving and capacity improvement. The enhancements target 10-30 % gains in power saving and capacity in the 3GPP Release 18 [12].

5G-A at sub-6 GHz frequency bands, i.e., frequency range 1 (FR1), provides the basic connectivity for all 6G-XR use cases. It is the technology that is able to strike a balance between coverage and performance when the utilised XR applications have moderate requirements related to throughput and latency. Due to the extensive usage of FR1 5G in commercial mobile networks, there is a wide availability and a large variety of UEs compatible with it.

5G-A at mmWave frequency bands, i.e., frequency range 2 (FR2), is able to provide enhanced performance with shorter link distances for the XR applications with more demanding throughput and latency requirements. The added performance will be needed in the real-time holographic communications UC1 and UC2 as well as in the collaborative 3D digital twins UC4. The amount of bandwidth available at FR2 frequency bands is much higher than those at FR1. Hence, the impact of the higher bandwidth to the E2E energy efficiency in UC5 is also of interest for the 6G-XR project. However, as FR2 5G is not yet widely used in commercial network deployments, the UE availability and variety for experimentation purposes will be more limited than with FR1 5G.

The 3GPP NG-RAN can be deployed either as a non-standalone (NSA) or standalone (SA) network. In the NSA deployment, the 5G gNodeB relies on 4G eNodeB and evolved packet core (EPC) for its CP signalling. However, a 5G NSA network can use the combined capacity of the connected 5G gNodeB and 4G eNodeB to handle the UP traffic. As 5G NSA is dependent on the 4G CP, it can only support the enhanced mobile broadband (eMBB) service type. In the SA 5G deployment, the 5G gNodeB is connected to the 5GC removing the need to rely on 4G infrastructure. The 5G SA deployment will provide the full functionality of 5G, including support for ultra-reliable low latency communication (URLLC), massive machine type communications (mMTC), and network slicing. 6G-XR use cases and planned experiments rely mainly on 5G SA, but the option to use 5G NSA will also be provided for the experimenters if needed.

 

More details on how technologies from the 3GPP evolution path are utilised in 6G-XR can be found in 6G-XR deliverable D4.1 [8].

#### 3.2.1.2 Open RAN (O-RAN)

The O-RAN architecture, defined by the O-RAN Alliance [13], extends the functionality of the 3GPP NG-RAN. This is done by fully adopting disaggregated approach to base station functionality (called E2 Nodes in the O-RAN terminology), adding new key components for dynamic AI-driven RAN control into the architecture, and introducing open and interoperable interfaces for the exploitation of the added functionality. The aim of the O-RAN architecture extensions is to enhance support for open, intelligent, disaggregated, virtualised, and software-based multi-vendor RAN deployments in the future.

The new key component introduced into the O-RAN architecture is the RAN intelligent controller (RIC). It is a logical RAN management function divided into near-real time RIC (near-RT RIC) and non-real time RIC (non-RT RIC) parts. The RIC is able to reconfigure RAN functionality and resources on the fly in an operational 5G network. The programmable control functionality is implemented through applications called xApps hosted in the near-RT RIC. An xApp can consist of one or more microservices used to collect information and control resources in the E2 Nodes through open APIs available in the near-RT RIC platform. The near-RT RIC interconnects with the E2 Nodes through the E2 interface that is used to carry monitoring information from the E2 nodes to near-RT RIC as well as control signalling from the near-RT RIC to E2 Nodes. The non-RT RIC interconnects with the near-RT RIC through the A1 interface for exchange of information related mainly to the management of long-term RAN optimisation policies and machine learning (ML) model training. A good overview of the O-RAN architecture and interfaces is provided in [14].

ML has been integrated into the O-RAN architecture as a key enabler to facilitate the dynamic control of large amount of RAN parameters and options. There are three types of control loops where ML algorithms can be used in the O-RAN architecture. Those control loops are designed to operate in real time (< 10 ms), near-real time (≥ 10 ms and < 1 s), and non-real time (≥ 1 s) basis [15]. Depending on time scale at which the ML algorithms need to operate, the ML model inference can happen at the non-real time RIC, near-real time RIC or E2 Node level. The training and coordination of the ML models usually happens at the non-real time RIC.

By deploying xApps at the near-RT RIC that utilise the KPI monitoring service provided by the E2 interface (see 4.3.1 for more information), it is possible to directly monitor the selected RAN KPIs in the O-RAN architecture. Moreover, by designing and implementing xApps that control selected E2 Node resources utilising the RAN control service of the E2 interface (see 4.3.2 for more information), it is possible to process the collected KPI monitoring data on top of the near-RT RIC platform and optimise the resource allocations in the RAN in near real-time. This kind of approach can be used for the specific needs of the 6G-XR use cases on real-time holographic communications UC1 and UC2, collaborative 3D digital twins UC4, and E2E energy efficiency UC5 to implement a more dynamic framework, e.g., to manage load balancing, uplink/downlink transmission scheduling, and slice resource allocations with the aim to optimise the either the provided service quality or energy efficiency of the RAN operations.

More details on how technologies from the open source and O-RAN evolution path are planned to be utilised in 6G-XR can be found in 6G-XR deliverable D4.1 [8].

#### 3.2.1.3 Disruptive 6G (terahertz, RIS, and ISAC)

To stimulate the adoption and further development of immersive and realistic XR applications, the utilised communication technologies should support wireless connectivity with extremely high data rates and sensing capabilities. Three disruptive 6G technologies considered foundational for this development by the 6G-XR project are reflective intelligent surfaces (RIS), THz and sub-THz communication links, and integrated sensing and communication (ISAC).

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 its electromagnetic response. This is used especially to overcome the limited propagation distances at very high frequencies due to high free-space losses, high atmospheric absorption, and poor diffraction. THz frequencies comprise the spectrum range 0.1 THz – 10 THz where the wide bandwidths available make it possible to reach data rates of 100 Gbps and beyond. However, the channel is generally sparse at THz frequencies. Therefore, operating RIS at THz frequencies requires new paths that potentially turn the sparse channels into rich scattering channels. This property can be exploited to avoid line of sight blockage and enable 3D beamforming with THz RIS [16].

ISAC is a step forward in the use of wireless communication technologies for radar-like detection of active and passive targets. The joint approach will allow enhanced user experiences to be achieved in everyday situations, benefitting from the environmental awareness that ISAC can provide to better adapt to the surrounding operational environment.

Future XR use case evolution towards large scale metaverse will include extensive use of remote control, remote maintenance, and large group collaboration elements. These kind of extensions to the current 6G-XR use cases will demand ultra-high bandwidths and sensing capabilities discussed above. To enable this, ISAC-capable technologies with very wide bandwidths are required, as currently available in the mmWave and sub-THz spectrums. These disruptive 6G enablers proposed in 6G-XR will focus on an indoor scenario under a few use cases selected from the set of use cases described in 6G-XR deliverable D1.1 [2]. Real-time holographic communications UC1 and UC2 involve 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. While THz can provide the ultra-high bandwidth, RIS and ISAC can significantly boost the added value of the ultra-high frequency links. In addition, collaborative 3D digital twin UC4 is a more advanced use case that demands ultra-high throughput data pipes with very low latency and sensing capabilities. The usage scenario involves bi-directional audio/video for VR equipment, 3D object representation, movement and object interaction, and synchronisation of a camera arm robot motion/position with the virtual environment.

More details on how disruptive technologies are utilised in 6G-XR can be found from 6G-XR deliverable D4.1 [8].

#### 3.2.1.4 Wi-Fi

In many use cases, wireless access based on Wi-Fi, which is widely available indoors worldwide, can provide a complementary solution to cellular based access and cover missing gaps. The evolution of the Wi-Fi standard from 802.11ax to 802.11be and beyond adds new capabilities to improve not only performance, but also determinism and reliability of the wireless connections.

Multi-link operation (MLO) is a new Wi-Fi feature that enables to transmit over different bands, e.g., 2.4 GHz and 5 GHz, simultaneously using a single network interface. Orthogonal frequency division multiple access (OFDMA) and time wake time (TWT) are other two features that provide a framework to implement wireless TSN, where a time-aware scheduler can be implemented to bound the latency of time-critical applications such as XR.

 

Wi-Fi is being integrated in collaborative 3D digital twin UC4, where wireless TSN can protect the transmission of control signals to/from a robot arm from the best effort traffic. In addition, an experimental study on the complementary properties of Wi-Fi 7, with enhanced bandwidth and support for MLO will be evaluated in an indoor scenario related to real-time holographic communication UC1 and UC2. More details on the planned utilisation of Wi-Fi 7 technology capabilities in 6G-XR can be found from 6G-XR deliverable D4.1 [8].

### 3.2.2 Core network

#### 3.2.2.1 5G core network (5GC)

The wireless access points in the 6G-XR reference architecture are connected to the 3GPP specified 5GC. It provides a common core network for all different access technology options listed under 3.2.1. Currently, 5GC can use NG-RAN, O-RAN and Wi-Fi as its wireless access technology, and with its evolution towards 6G, disruptive wireless technologies discussed in 3.2.1.3 are also expected to become part of the supported options.

The 5GC architecture is based on standardised network functions (NFs) which offer specific services to each other to form the desired overall core network functionality. By using NFs and their services as building blocks, 5GC brings flexibility into the deployment process. The network functionality and performance can be tailored to the needs of a specific user group or use case through CP/UP separation and network functions virtualisation (NFV). Deployed 5GC configuration can also be dynamically changed during network runtime to adapt if the original needs change. The key feature in the 5GC to bring this all together is network slicing [17], [18], which allows several different core network configurations to coexist simultaneously as virtual networks on top of a single physical infrastructure.

Network slicing is also utilised in 6G-XR to provide tailored core network deployments to the different project use cases with varying KPI requirements. For example, real-time holographic communications UC1, UC2 and UC3 as well as collaborative 3D digital twins UC4 require core network deployments optimised for eMBB or URLLC type of traffic. Edge computing plays an important role in these deployment scenarios. E2E energy efficiency UC5 will also need to target mMTC service deployments in some usage scenarios.

In addition to the network slicing functionality and tailored core network deployments, 5GC also offers a variety of APIs for network monitoring and configuration purposes. These APIs are used in the 6G-XR use cases to enable intelligent control of various network resources. The exploitation of the services provided by the network exposure function are discussed in more detail in 3.2.2.2. Discussion on the different APIs can be found from 4.2.

More details on the utilisation of core network enablers in 6G-XR use cases and experiments can be found in deliverable D2.1 [9].

#### 3.2.2.2 Network exposure function (NEF)

NEF is a 3GPP standardised NF that grants partners and AF access to 5GC using a full set of standard APIs to expose operator's key core network capabilities to their ecosystem partners in a controlled and secure way. Leveraging this, communication service providers (CSP) can easily offer application developers and enterprises a wide set of capabilities to manage and control communications, e.g., to and from their connected Internet of things (IoT) devices. This approach hides the complexity of network systems in the middle and enables new use cases previously unattainable.

 

Several standardised NEF services are applicable to 6G-XR use cases. For real-time holographic communication UC1 focusing on XR resolution adaptation and service quality on demand, *Nnef_EventExposure* service provides support for event exposure, *Nnef_AFsessionWithQoS* service provides support for requesting the network to provide a specific quality of service (QoS) for an AF session, and *Nnef_AnalyticsExposure* service provides support for exposure of network analytics. For real-time holographic communication UC2 focusing on routing to the best edge platform, *Nnef_ServiceParameter* service provides support to provision service specific information.

The 3GPP has standardised NEF APIs for external consumption of core network service by enterprises, app developers, and partners, support among other things the exposure of NF capabilities, events, and analytics securely to 3rd parties, AFs, and edge computing platforms. These APIs for 5G networks offer several network exposure functionalities applicable to the 6G-XR use cases and are discussed more in 4.2.1.

### 3.2.3 IMS data channel (IMSDC)

Multimedia telephony service for IMS (MTSI) is a standardised telephony service utilising IP multimedia subsystem (IMS) capabilities to establish multimedia communications between terminals within and across operator networks. Terminals connect to the IMS via either fixed access networks or 3GPP access networks.

As part of MTSI, IMSDC's contribution to the control plane optimisation in real-time holographic communications UC3 is the capability to facilitate XR holographic calls with the ease of making a regular voice call directly from the mobile dialler application. The user remains unaware of the complex processes occurring internally and can seamlessly receive a holographic service in an Android-based device from the sender's iPhone.

This solution offers also other significant advantages. Firstly, by utilising IMS, it leverages the extensive network capabilities developed over the years for mobile telephony services, such as bandwidth, latency, and throughput. Secondly, by bridging the IMS and XR worlds, it provides a simple integration pathway for developers of such applications, simplifying the incorporation of these advanced services in future services.

More details on the definition of IMS Data Channel can be found in 6G-XR deliverable D1.1 [2] and GSMA white paper [19]. More information about IMS Data Channel implementation can be found in 6G-XR deliverable D2.1 [9] and GSMA white paper [20].

## 3.3 EDGE PLATFORM

### 3.3.1 Energy optimisation framework

#### 3.3.1.1 Energy measurement framework

A comprehensive energy measurement framework is needed to monitor the energy consumption of the deployed 6G-XR reference architecture components at the experimentation site and enable network resource optimisation for E2E energy efficiency. In order to enable communication network resource optimisations that are able take into account also the availability of local renewable energy, the deployed energy measurement framework at the North Node experimentation site covers both the energy consumption (i.e., UEs, RAN, CN, and edge components in Figure 8) and energy production (i.e., PV modules, battery energy storage, and grid power in Figure 8) components of the test facility infrastructures. Facilitating further utilisation of the collected energy consumption and production data by several resource control algorithms, the framework includes functionality for data storing and connections to share the data outside of the measurement framework through a common database. The database can also be used to collect energy related data from external open data sources to complement the locally measured data, e.g., with weather forecasts affecting the predicted availability of PV power or with electricity price information for the grid power. More information on the types of external open data sources utilised in 6G-XR can be found from 3.4.1.

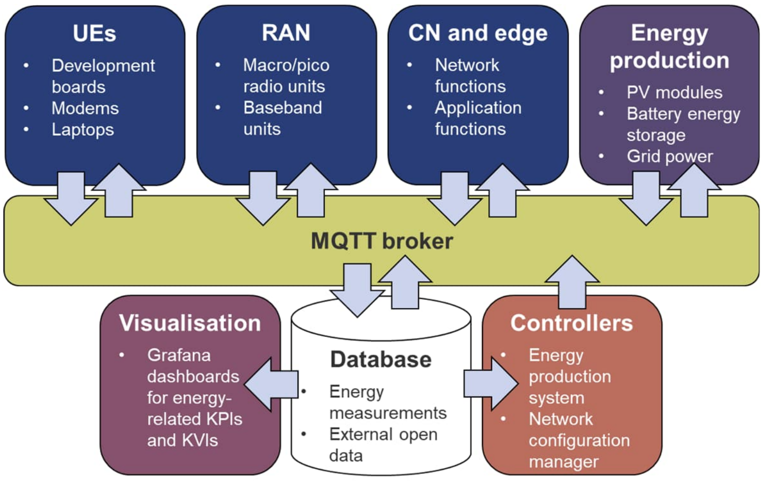


*Figure 8. Main components of the energy measurement framework.*

The energy consumption measurement part of the framework covers the 5G/5G-A network end-to-end, starting from the UEs all the way to the application servers installed to the network edge. All individual network components, i.e., baseband units and radio parts in RAN, and network and application function servers in the CN, are measured separately. The measurement of the network components is mostly based on external professional-level energy meters. When it comes to the measured infrastructure's energy production side, the locally installed PV energy system has internal embedded meters in place.

For both the energy consumption and production domains, the measurement data pipe consists of the individual energy meters and aggregating datalogger units. The measurement data is collected from the datalogger units using message queuing telemetry transport (MQTT) messages though a connected MQTT broker. Other services running in the test facility infrastructure can subscribe to receive the real-time measurement data from the MQTT broker. One of these services is the central database that can then provide both real-time and historical energy measurement data, e.g., to a visualisation dashboard or to a network configuration manager entity, which takes care of controlling the site's energy consumption and production domains conjointly for an E2E optimised end result (see 3.3.1.4 for more details).

The energy measurement framework can provide accurate measurement data of the E2E telecommunication network's energy usage in different operating conditions. This functionality is essential for the E2E energy efficiency pursued in UC5. The energy measurement results, consisting of energy consumption and production data, can be further combined with network KPI measurement data, such as base station resource usage, or video streaming application characteristics to enable coordinated energy optimisation measures between the network and application layers.

More details on the implementation of the 6G-XR North Node energy measurement framework can be found from 6G-XR deliverable D5.1 [11].

Co-funded by the European Union

#### 3.3.1.2 Energy weather forecast

Within the deployed energy measurement framework, the integration of energy weather forecasting for next 66 hours is required for resource optimization, tasks/applications scheduling and load balancing within the 6G-XR reference architecture components. These site-specific forecasts are provided by Finnish Meteorological Institute (FMI) using HARMONIE weather forecast model. These forecasts use MetCoOp ensemble prediction system (MEPS), which provided seven precise estimates instead of one. These sets represent the probability forecasting system using fractals where slightly different forecasts are run simultaneously. Thus, these APIs not only provide forecasting probabilities but an estimate on its uncertainty (see 6G-XR deliverable D5.1 [11] for more details).

Figure 9Figure 9 shows an example of the power outputs and seven fractal estimates based on uncertainty regarding dynamic weather conditions, derived from Finnish Meteorological Institute's (FMI) advanced energy-weather forecasting system. This detailed forecasting is crucial for optimising energy usage, storage management, and grid interactions at gNodeB sites, supporting power-saving measures and efficient energy distribution using the energy measurement framework. These forecasts are integrated inside the energy measurement framework for sustainability experimentation and architecture validation for UC5.

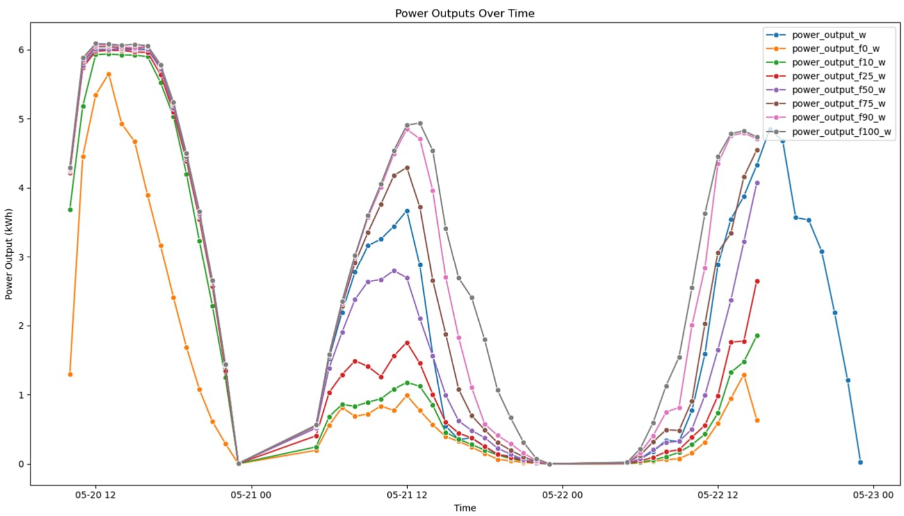


*Figure 9. Example of energy weather forecast for the next 66 hours.*

Figure 10 depicts 66 hours of two temperature forecasts including PV module temperature and air temperature. These forecasts are represented by blue line for PV module which shows the fluctuations that reach up to approximately 35 degrees Celsius, indicating the forecasted temperature of the photovoltaic (PV) module. The air temperature is depicted by the orange line. These predictions provide valuable insights into the expected nominal efficiency of the PV module, as the temperature of the system is a critical factor affecting its performance. Monitoring both system and air temperatures allows for better assessment and optimisation of the PV module's efficiency over time.

 

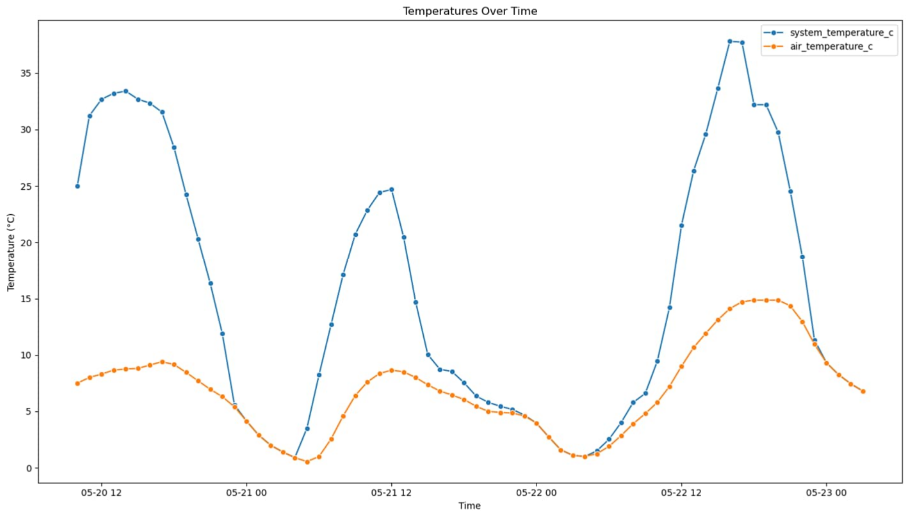


*Figure 10. Example of PV module temperature and air temperature prediction for the next 66 hours.*

Figure 11 illustrates the forecasted total cloud coverage, including high, medium, and low clouds, as a percentage over the next 66 hours. This data is crucial for understanding and predicting the potential impact on solar energy generation, as cloud cover significantly affects the amount of solar radiation reaching the PV modules. The example bar chart shows varying degrees of cloud coverage, with a notable increase beginning around the late hours on the 20th of May 2024.

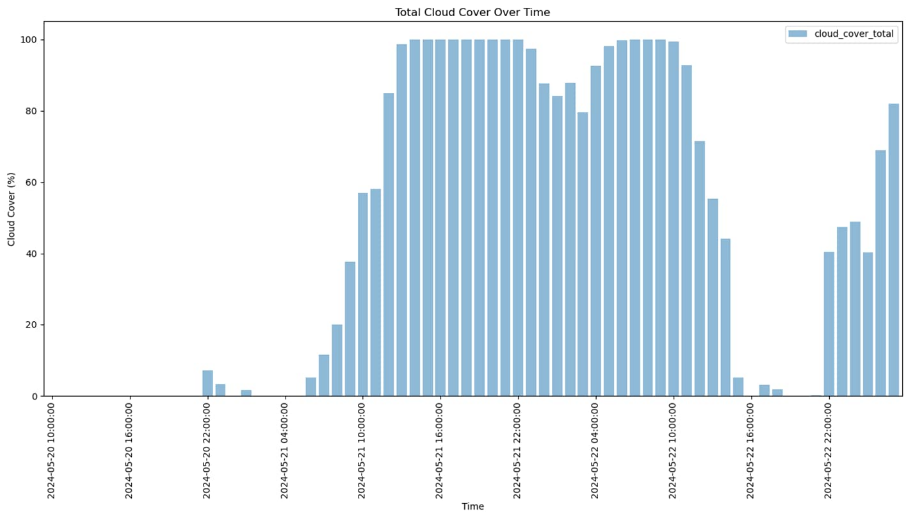


*Figure 11. Example of total cloud coverage prediction for the next 66 hours.*

Figure 12 displays the various radiation values over a span of 66 hours, providing insights into different components of solar radiation impacting the PV module system. The graph includes six metrics, i.e., system radiation global (blue line), system radiation direct (orange line), system radiation diffuse (green line), radiation global (red line), radiation direct (brown line), and radiation diffuse (purple line).

 

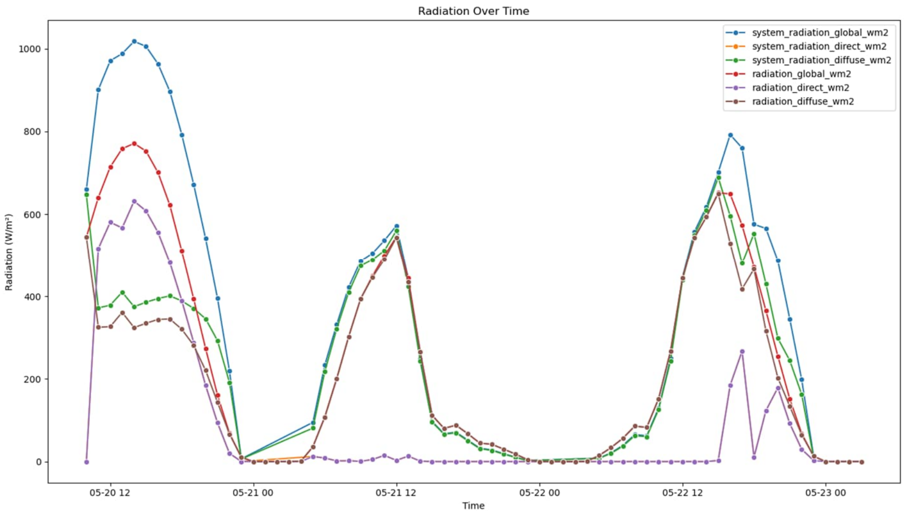


*Figure 12. Example of overall System and diffuse radiation predictions for the next 66 hours.*

The estimated data is curial for E2E energy measurement framework and sustainability experimentation. The cloud and temperature forecasts provide accurate predictions of PV module efficiency and solar energy availability, facilitating the daily energy budget. This is done to obtain maximum efficiency for the PV array placement and orientation angles of the PV modules. In addition to this, the forecast supports dynamic RAN reconfiguration in UC5. This is vital for reducing consumption during low solar radiation periods. Furthermore, it facilitates optimal use of battery storage in the distributed energy storage system (DESS), for efficient energy storage and E2E energy efficiency.

### 3.3.1.3 Energy KPIs

Energy related KPIs are needed to validate the E2E energy efficiency of a communication system. These KPIs can be constructed from the data collected with the energy measurement framework described in 3.3.1.1. In addition to the measurements performed at individual system components, energy meters must also be installed to subsystem (i.e., electricity grid, PV modules, and battery energy storage in Figure 8) boundaries to measure needed energy balances in desired time slots. Additional KPIs interlinking locally measured and external data are also needed to fully assess the overall impact of the energy consumed by the communication system. These external data services are discussed more under 3.4.1.

Active energy consumption (time integral of active power) of a system component is most important KPI to monitor in the E2E energy efficiency UC5. In case a local energy production and battery energy storage subsystem is part of the deployment, this KPI measurement must be bidirectional (2 registers) at the subsystem/grid interface boundary and enable implementation of required calculation principles in a time slot (several methodologies exists for calculating and billing net-energy during one hour). Reliable real-time data is useful for the control systems as well as for the aggregated reporting systems covering communication network or energy production equipment. Active energy (and power) data may originate from the devices' internal sensors and processing systems or external energy meters measuring branches of electricity grid as described in 3.3.1.1 and Figure 8.

Metering devices for the fiscal purposes covering, e.g., datacentres or cell sites offering commercial services, must follow the measuring instruments directive (MID) regulation and standards (implementation of EN 50470-3:2022 [21] is ongoing). Standards for power metering and monitoring devices (PMD) and measurement functions such as voltage/current magnitude, power, and frequency, are covered in EN IEC 61557-12:2022 [22]. Many mobile network operators (MNO) report their aggregated energy consumption in annual sustainability reports according to Global Reporting Initiative's (GRI) reporting index GRI 302: Energy. Thus, it is important that the collected energy consumption data is originating from as comparative metering systems as possible and, if possible, based on standardised methodologies and certified devices.

Energy savings KPI cannot be verified without active energy measurements covering a sufficient time period. Timestamps to measurement datapoints should be derived from a reliable common source when data is combined from several meters, devices, and systems. Common baseline for the energy consumption must also be defined or measured. After that a modified system configuration/state can be measured and investigated, and in the end, compared to the reference state to assess achieved proportional and absolute savings. While assessing system level savings, it is important that the modifications to the trialled configuration are done one parameter at a time. When energy savings are determined in complex live systems and operational environments, the risk of unknown confounding factors always exists. In laboratory and controllable test facility settings, it is easier to standardise and control potential confounding factors and investigate energy impacts of multiple simultaneously activated measures.

Cost counter is a necessary KPI on highly volatile electricity markets. It can be built upon bi-directional active energy counter of the system boundary metering unit by means of recording energy counters' cumulative data on the hourly basis and linking it to the hourly electricity spot-market pricing data available for the coming day. In addition, service costs of distribution system operators' (DSO) relevant cost components can be added to follow operational expenditures as one important performance indicator. This kind of composite KPI requires linking of data from external cost data services to the locally collected data at the experimentation site. The cost counter can also be used to follow the achieved cost savings if it is compared to a common baseline/reference. This may create useful grounding for investment decisions in volatile electricity market conditions where annual monetary savings may differ depending, e.g., on the time of the year.

$CO_2$ counter is a KPI also based on the measured energy transfer data through investigated system boundary (or grid interface) metering unit and emission data from an external data source. For example, in Finland, the transmission system operator (TSO) provides specific emission estimates in the form of $gCO_2$/kWh to consumed average electricity in Finland with a refresh rate of 5 minutes. When this emission data is processed and combined with the measured energy consumption data, absolute indirect emissions related to energy exchange through the grid interface can be estimated. Methodology is similar than in case of the cost counter above.

Following the self-sufficiency proportion of the overall system as a retrospective KPI requires embedded or additional external metering units to the energy production subsystem boundaries. It is important to note that the proportion of locally produced energy from the overall consumption must be calculated for long enough time periods in case battery energy storage and bi-directional energy transfer with the grid is implemented. Measurements can be enabled for the different energy sources periodically or calculated as shares from the continuously monitored overall energy consumption. This requires that all measured devices belong to the same measurement framework.

Energy efficiency of the power supply unit or energy production system, e.g., including the whole PV-hybrid with battery energy storage, is also an KPI worth monitoring in suitable periods of time due to the non-linear nature of losses in the power electronics and battery. Losses increase when temperature rises and may cause activation of power limitations in the inverter/charger units performing direct current (DC) / alternating current (AC) and AC/DC transformation. This KPI can be formulated by means of summing up all cumulative energy yields in the system or by means of measuring the outputs from the PSU system to all connected devices, i.e., total amount of energy transferred for usage in a time slot. This KPI is also useful for better understanding the exact impact of the changes made in the communication or energy production system configurations to the E2E energy efficiency.

Additional energy-related KPI worth considering in hybrid systems such as the one considered in the 6G-XR North Node is the state of health trend of the battery system. By means of long-term degradation trend and other data collected from the system, exact cost of the energy discharged from the battery can be derived. This cost component can impact the optimisation of both the site's battery capacity and daily control patterns.

#### 3.3.1.4 Configuration manager for end-to-end energy efficiency

Configuration manager for E2E energy efficiency is a control entity making dynamic decisions on which configurations are used for RAN, core network, application servers, and mobile devices. These decisions are based on the status and forecasts of energy production and availability, measured and predicted data traffic patterns and KPIs, and flexibility of the used application parameters. Hence, the configuration manager component needs to be able to share data with the energy production system's controller components.

In the context of RAN, the configuration can define the used power saving state for a cell or carrier. A power saving state could, e.g., indicate the cell availability (deep sleep/light sleep/awake), number of used transmitters at the gNodeB, DL transmission power level, and bandwidth part (BWP) size. The task of the configuration manager is then to select the optimal set of cell power saving states for the network given the availability of local green energy, electricity price, and predicted traffic demand.

From the perspective of the applications and servers especially in the context of live or video-on-demand (VOD) streaming, a configuration can also define the application specific parameters. For example, the different states of the application can consist of varying number of video representations with altering bitrates, resolutions or even level of buffering. The application server can be controlled with pre-defined, recommended, and optimum video bitrates for serving the mobile clients to reach the optimum end-to-end energy efficiency depending also on the RAN configuration and availability of local green energy. On the other hand, the server-side controllability can enable client-side energy savings as well, which means that scalability to higher number of UEs can be achieved.

Configuration manager for E2E energy efficiency simplifies the usage and testing of different energy saving methods in UC5. With well-defined (limited) set of configuration options, it is also easier to predict the energy consumption in different operational environments, which could help in dimensioning and optimising the local green energy production at the site. The use of the configuration manager can also organised hierarchically so that higher level system parameters are adjusted more slowly while the local optimisations are done faster. This approach can be deployed, e.g., in the O-RAN architecture using the service management and orchestration (SMO) platform in the cloud for the former and RIC platform at the network edge for the latter level in the hierarchy.

More discussion on the potential energy-aware network resource management approaches can be found from 6G-XR deliverable D4.1 [8].

### 3.3.2 AI/ML algorithms

AI, ML, and deep reinforcement learning (DRL) techniques can facilitate optimal network performance for XR services [23]. They can handle resource scheduling, channel adaptation and traffic management in an intelligent way thereby turning the networks into smart and self-optimising systems. AI/ML/DRL-based techniques, algorithms, protocols, and frameworks can also be applied at all layers of the protocol stack. For example, in wireless network-driven XR setups such as XR use cases aided by RIS and THz communications, AI/ML/DRL can be used for beamforming design, power management, blockage avoidance, and channel and radio resource allocation at the medium access control (MAC) and radio resource management (RRM) layers. At the network layer, AI/ML/DRL can be employed, e.g., for optimising XR traffic clustering and routing, mobility management, and user association. Other enhanced network management tasks at the different layers can also be controlled with AI/ML/DRL [24]. 3GPP Releases 16-18, for example, have considered AI/ML techniques to enhance the air interface, data collection and training operations. 3GPP Release 18 is currently developing AI-based beam management schemes for enhanced network management with the goal of enabling intelligent configuration, maximising capacity, and improving the energy efficiency of the network [25].

DRL algorithms will be employed for an XR meeting session scenario under the real-time holographic communications UC1 and UC2 to facilitate reliable communication via intelligent beamforming and smart allocation of radio resources for THz RIS setups. The DRL-assisted beamforming design will enable beams to adapt to the propagation environment as well as to the user distribution, mobility, and traffic patterns. Extensive system-level simulations will be undertaken to explore the impacts of AI/ML/DRL frameworks on the network management with respect to beamforming, blockage avoidance, XR mobility and overall system capacity enhancement. More details on the planned experiments can be found in the 6G-XR deliverable D4.1 [8].

Radio access resources in general are shared resources that need to be intelligently managed. Network slicing is a technique that enables to reserve such resources to provide QoS guarantees. A static network slicing heuristic would be able to provide QoS guarantees but it would also be wasteful due to the dynamic nature of traffic. AI techniques, such as reinforcement learning (RL), allow to implement a sophisticated dynamic heuristic that adapts to the changing needs, aiming to fulfil the requirements and minimise resource waste. One of the AI-related contributions in 6G-XR, is the design and implementation of an algorithm to manage the radio access across time by deciding the share of time that each network slice will be dedicated. The AI algorithm will be integrated into an experimental network setup at the North Node experimentation site as part of the collaborative 3D digital twins UC4.

### 3.3.3 XR application function (network side)

All available network side AFs employed for the VR holographic communications over the user plane in UC1 and UC2 or for the AR holographic communications over the control plane in UC3 are deployed as virtual network functions (VNFs) on the South Node edge platform infrastructure. There are five network side AFs utilised in the 6G-XR use cases. Selective forwarding unit (SFU) AF is used for the exchange the multimedia information between the clients involved. It only forwards the volumetric video streams without any types of processing. Alternatively, multi-point control unit (MCU) AF provides processing capabilities such as mixing and transcoding of the volumetric video streams. Thus, it enables a more scalable communication between clients. Remote renderer AF is meant for running the rendering of volumetric video stream, when the client is a Web-based lightweight one. Thus, it guarantees a wider access to the VR experience as it enables the access from laptops having no NVIDIA GPU capabilities. XR/holo orchestrator AF oversees managing the media sessions for the holographic communications employing the network user plane. IMS session manager AF oversees managing the media sessions for the holographic communications employing the network control plane, i.e., the IMS signalling and data channel.

 

### 3.3.4 3D digital twin engine

The 3D digital twin utilised in 6G-XR consists of a 3D VR digital copy of a physical fabrication laboratory room. The 3D digital twin has online multiplayer functionality and connectivity with machines residing in the physical space, including a 3D printer and a robotic arm. Babylon.js [26] is used as the 3D game engine platform. It provides the required functionality to create and manage the 3D scenes, upload reviewed 3D models for printing into the 3D scene, and set up online sessions for collaborative interactions between remote users and local instructor. The platform also enables remote VR review and collaboration work function for the 3D model with hand tracking. It also allows the users to monitor the real-time status of the 3D printer located in physical Fab Lab space through a live video stream inside the VR scene. It also enables the user to control the robotic arm residing in the physical Fab Lab space remotely from the VR scene with synchronised moving orientations in the digital twin.

The functionalities of the 3D digital twin engine are extensively used in the collaborative 3D digital twin UC4. More information on the use case flow and building blocks can be found in 6G-XR's D1.1 [2].

## 3.4 CLOUD SERVICES

### 3.4.1 Energy production statistics

#### 3.4.1.1 PV energy forecast data

The 66-hour PV energy forecast provided by FMI is instrumental in estimating the local availability of solar energy as was discussed in 3.3.1.2. Using the interface provided by FMI, the information related to number of panels, nominal output of the PV modules, inverter capacity, orientation and angles of the PV modules can be entered as input to produce accurate energy predictions. The prediction data is offered as input to other energy optimisation framework components using a common interface broker at the North Node experimentation site. The deployed framework leverages MQTT protocol to publish and subscribe to energy-related data, facilitating the data sharing between control mechanisms and energy-saving measures [11].

This efficient energy utilization of gNodeB is achievable using energy weather forecasts as a tool to activate/deactivate power saving measures. This approach supports optimised energy production and consumption based on energy forecasts, supporting the dynamic reconfiguration of RAN resources and effective use of DESS with batteries. This functionality is integral part of enhancing energy sustainability for gNodeB sites in the North Node E2E energy efficiency UC5.

#### 3.4.1.2 PV yield data

The PV yield data is crucial to energy measurement framework as it provides basis to train the ML/DL algorithms. The PV yield data is collected from the 24 PV modules located at the North Node gNB sites. These panels are connected to a smart Solaredge inverter which not only converts PV yield into AC energy but also provides detail insights of the PV production data. The PV production data is accessible using secure APIs which provide real-time monitoring of the PV modules collectively and individually.

Figure 13 provides a time series dataset for daily solar energy production at the North Node gNB site for 24 PV modules. The blue spikes represent the daily PV yield with seasonal variations significantly visible as the summer months in Nordic regions reach the energy positive months and the winter months shows less PV yield. These data logs are published through the MQTT broker in the energy measurement framework. This comprehensive dataset lays the foundation to train the optimisation of energy production forecasts, facilitates better decision-making for energy sustainability and provides training data for ML/DL algorithms.

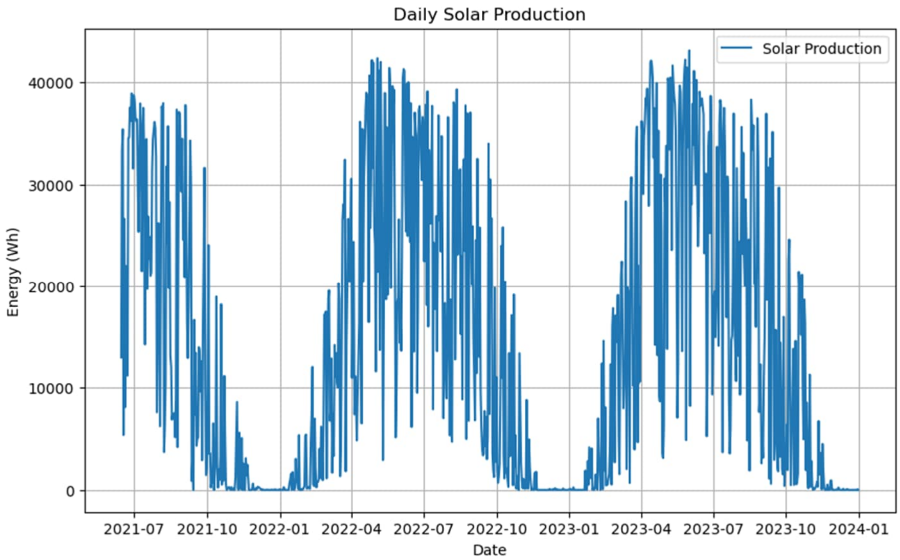


*Figure 13. PV yield dataset for North Node covering the past three years.*

The real-time and historical PV yield data, sampled every 15 minutes as shown in Figure 13 , is essential for the E2E energy efficiency UC5, particularly for enhanced analysis and better understanding of KPI measurement data related to active energy consumption counters.

### 3.4.1.3 $CO_2$ and cost counters

The North Node energy measurement framework is able to produce accurate data about the energy consumed in the mobile network infrastructure. However, electricity is a finite product and thus it has a market price. Complex production systems create external impacts which are not typically considered in market pricing mechanism or internalised by regulation. Groundings to save electricity or improve energy efficiency depend often on its indirect impacts like costs or $CO_2$ emissions. In addition to absolute energy consumption, this kind of information may be interesting also to MNOs and their customers if linked to the delivered billing information. In smart energy monitoring system, multiple perspectives can be followed by means of emerging trends generated from the near real-time data.

As discussed in 3.3.1.3, a cost counter may be necessary when operating on highly volatile electricity markets. By combining the energy consumption data and forecasts from the energy optimisation framework to the hourly day-ahead electricity spot-market pricing data (e.g., from European Network of Transmission System Operators for Electricity's (ENTSO-E) transparency platform [27]) and service costs of DSO, it is possible to follow and estimate operational expenditures as an important performance indicator. The same data can also be used to follow realised cost savings over specific time periods when compared to a common reference. Figure 14 provides an example view from the Grafana [28] dashboard, where the available electricity spot price data has been taken as one element of the multidimensional energy monitoring system.


*Figure 14. Example of the 1-day ahead electricity spot prices (hourly prices for the next day are automatically added to the dataset between 2:00-4:00 pm each day).*

Similarly to the cost counter, a $CO_2$ counter can also be created by combining the energy consumption data from the energy optimisation framework to emission data from an external source as described in 3.3.1.3. When this emission data (see Figure 15 for an example) is processed and combined with the site consumption data, absolute indirect emissions related to energy consumed from the grid can be estimated. When estimating the $CO_2$ emission reductions achieved by using local renewable energy at the site, the methodology is similar to the one used in the relative energy savings monitoring, i.e., a common reference or baseline for the emissions must first be defined.


*Figure 15. Example of the specific emission factor of consumed electricity in $gCO_2/kWh$ available through the FINGRID's API [29].*

In practice, hourly day-ahead costs may activate flexibility measures in those systems which are capable to adapt their systems or behaviour to volatile electricity prices. This may have impact, e.g., on optimal battery or inverter/charger usage by changing power transfers direction and scheduling. Similarly, mitigation of cumulative $CO_2$ emissions as an objective may change the targeted consumption patterns but not necessarily to the same direction as in the cost-based optimisation, e.g., due to the regulation of hydropower during winter consumption peaks. However, seasonal fluctuation and decreasing trend in the long-term emission levels of grid power production systems as well as PV-yield's hourly profile are all necessary things to consider when cost efficiency analysis is made about the $CO_2$ emissions of the local substitute energy sources available at the site. These aspects are considered in the E2E energy efficiency UC5 using the data available from external cloud services.

## 3.5 MANAGEMENT AND ORCHESTRATION

### 3.5.1 Trial controller

6G-XR trial controller is based on an existing 5G!Drones[2] trial controller implementation. The architecture of 5G!Drones trial controller implementation has been simplified for the needs of 6G-XR experimentation plans to avoid unnecessary complexity in the system. 6G-XR trial controller is based on i) two web portals (unified web portal and node-specific web portal) used by the experimenter to access and configure the resources of either one of the 6G-XR experimentation sites, and ii) node adapters that perform the actual test facility configurations based on the selections the experimenter has made in the node-specific web portal. The streamlined 6G-XR trial controller architecture is presented in Figure 16.

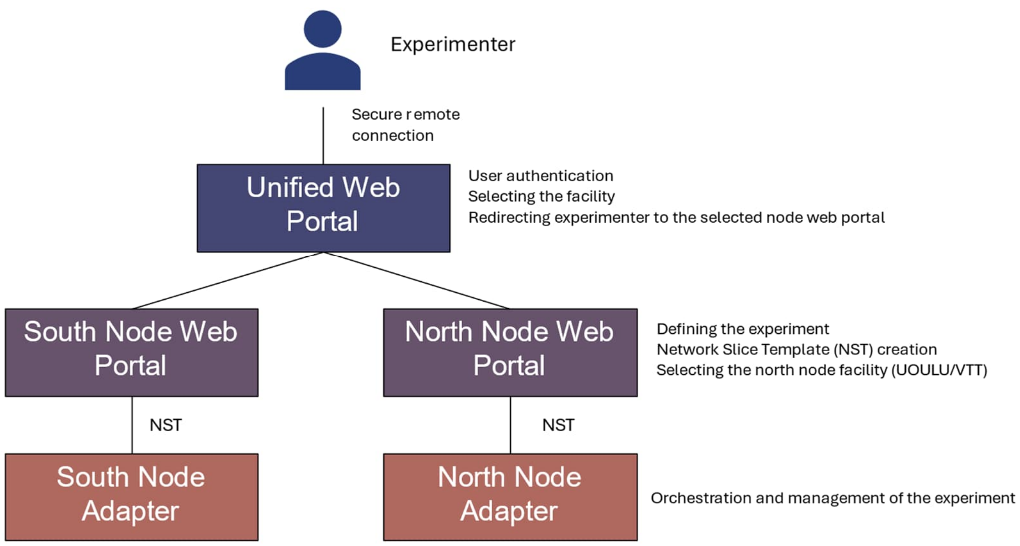


*Figure 16. 6G-XR trial controller architecture with example workflow for the 6G-XR North Node.*

#### 3.5.1.1 Web portals

The 6G-XR trial controller provides a unified user interface for the experimenters to access the 6G-XR experimentation sites. The first part in this user interface is the unified web portal, which acts as the initial point of contact towards the test facilities. The unified web portal is responsible for offering a secure remote connection for the experimenter, providing user authentication, and selecting the correct node-specific web portal for the planned experiment. After the selection, the unified web portal redirects the experimenter forward to the node specific web portal to make the necessary experiment configurations. The 6G-XR unified web portal also provides functionality to perform user self-management activities such as changing the password, adding a telephone number to the experimenter contact information, and completely remove the account if it is no longer needed.

[2] 5G!Drones website: https://5gdrones.eu/

The 6G-XR node-specific web portal provides the functionality for defining the experiment configurations, creation of the network slice template (NST) based on the defined experiment configuration, and selection of the correct test facility in the 6G-XR experimentation site in question.

The unified web portal and node specific web portals are used to enable remote access to and remote configuration of the 6G-XR South Node and North Node experimentation site resources. Consequently, they act as enablers for all use case experiments performed by 6G-XR project partners as well as by third parties entering the project through 6G-XR Open Calls.

#### 3.5.1.2 Node adapter

The node adapter is a 6G-XR experimentation site-specific component that enables the experiment configuration data received from the node-specific web portal to be deployed at the test facility's network infrastructure. Consequently, the South and North Node adapters act as enablers for all use case experiments performed by the 6G-XR project partners on top of the experimentation sites as well as by third parties entering the project through 6G-XR Open Calls. The node-specific adapter has different responsibilities in South and North Nodes.

North Node adapter is responsible for:

- Management and orchestration of the experiment
- Configuring the facility components according to NST
- Starting the experiment
- Transferring the measurement parameters from Cumucore and Qosium measurement system to AI during the experiment
- Transferring the reconfiguration parameters from AI to Cumucore and Qosium during the experiment
- Recording experiment configurations to a log file
- Stopping the experiment

South Node Adapter is responsible for:

- Configuration of the experiments
- Splitting the NST to be understandable by the MEC orchestrator and 5GC NEF
- Calling the related APIs for network function configuration and monitoring
- Configuring the Qosium measurement system for KPI collection
- Launching each experiment in the infrastructure

More information on the experimentation site specific node adapter deployments can be found from the 6G-XR deliverable D1.3 [3].

### 3.5.2 XR orchestrator

The XR orchestrator plays a key role in the execution of the real-time holographic communication UC1 and UC2 at the South Node experimentation site. The XR or Holo Orchestrator is a virtualizable in-cloud component in charge of session management features and interfacing the Edge Orchestration components for the envisioned multi-user holographic communication services. It is composed of different modules, managers, and services to allow the establishment, appropriate configuration, and lifecycle management of multi-user holographic communication sessions.

The user manager module is in charge of registering, managing and offering information/data from registered clients, scenarios and other in-cloud components. The session manager takes care of managing the lifecycle of multi-user sessions (i.e., creating, joining, leaving and eliminating sessions) for each involved user/client and for each selected virtual scenario. Session manager is also in charge of interfacing the other services of the of the XR orchestrator to be able to select the most appropriate in-cloud media functions (i.e., SFU, MCU or remote renderer) to handle the communications for each session, the in-cloud servers where to instantiate them, and then communicate this information to the involved clients. The clock manager ensures a coherent notion of time to all involved entities in the media session. It can act as a clock source against which synchronise to. The index/connection manager is in charge of interfacing the edge orchestration platform for selecting the most appropriate location where to deploy in-cloud VNF for media processing and communication, and to manage their lifecycle. This module will also be an endpoint for the envisioned network-as-a-service (NaaS) APIs for enhanced XR services, like network-assisted rate control in UC1 and edge-cloud APIs in UC2.

The XR orchestrator is used in the VR user plane related usage scenarios in in the South Node. It is the interface for XR clients/UEs for creating/joining/eliminating sessions, receiving the endpoints of the in-cloud VNFs to which to connect, and receiving recommendations for enhancing the performance or stability of an ongoing media session, e.g., through rate control, among other relevant functionalities.

### 3.5.3 Edge orchestrator

The edge orchestrator is a multi-access edge computing (MEC) orchestrator instance (compliant with ETSI MEC specifications) that is in charge of the lifecycle management (onboarding, instantiation, monitoring and termination) of applications over the edge compute infrastructure. The edge orchestrator offers to application developers cloud-computing capabilities and an IT service environment at the edge of the network. The edge orchestrator interfaces with 5GC, specifically through NEF, to manage QoS provided for each application and to be able to optimise application edge compute placement location based on multiple network information, such as UE location or traffic congestion. In addition, the edge orchestrator exposes Northbound APIs to ease the access to network capabilities by the application layer.

The edge orchestrator performs several functionalities for the different 6G-XR use cases under the real-time holographic communications topic.

For the XR resolution adaptation and QoD functionality in UC1, the edge orchestrator exposes an API by which the QoS can be easily requested or changed by the application layer (see further details on QoD API in 4.1.1). Upon a request to change QoS by the application on an existing UE connection the edge orchestrator will launch a session with specific QoS into the NEF using the 3GPP 5GC API (see further details on NEF exposure API in 4.2.1) to create a new subscription for that specific device connection.

For the routing to the best edge functionality in UC2, initial application instantiation can be based on business decision, e.g., as part of a point of purchase (PoP) strategy. By means of the edge orchestrator northbound lifecycle management (LCM) API, it is possible to launch the onboarding and deployment of an application on a specific cloudlet location as well as manage its whole lifecycle including retrieving monitoring information. The initial application instantiation is also based on UE location. Upon a request of available edge based on UE location, the edge orchestrator will decide the best cloudlet PoP based on its own criteria considering location or by launching a monitoring event tracking area code (TAC) to NEF (see further details on *Simple Edge Discovery API* in 4.1.1)

Part of the routing to the best edge functionality is also the application re-selection upon a change in UE location within same edge domain. Once the application is running, if a UE location changes, the edge orchestrator will interact with NEF to select new cloudlet to migrate the application optimising minimum delay (see further details on *Traffic Influence API* in 4.1.1). Application re-selection can also be triggered upon a change in UE location from one edge domain to another. In 6G-XR, each edge orchestrator is federated, by means of the East-Westbound interface (EWBI), with another edge orchestrator in different edge domain to enable the deployment of the application in a multidomain environment. The migration of the service based on new UE location as well as optimising minimum delay at a given time, is thus enabled to be done considering also the compute resources in a second federated edge domain.

The 6G-XR South Node experimentation site in Spain consists of two distinct test facilities with dedicated edge locations. One test facility is in Madrid and the other in Barcelona. To demonstrate the edge federation capabilities required in the 6G-XR reference architecture within the project, a design decision has been made that the Barcelona edge can only be accessed through the Madrid edge via federation. To grant this, both test facilities incorporate a MEC federator (MEF) component responsible for establishing and managing the federation between the two edges.

For implementing the edge federation, the project follows recommendations from the GSMA Operator Platform Group (OPG), which advocates for a standardised API for the EWBI. At the time of writing this deliverable, the platform complies with the GSMA OPG EWBI API Version 4.0.

# 4 INTERFACES AND APIS

This chapter describes the interfaces and APIs identified as key enablers in the 6G-XR reference architecture. All these interfaces are needed to support the five 6G-XR use cases defined in 6G-XR D1.1 [2]. The following subsections shortly describe each interfaces/APIs and define the functionality they enable for the project use cases.

## 4.1 NETWORK EXPOSURE FRAMEWORK

### 4.1.1 CAMARA APIs (quality on demand and edge selection)

The edge orchestrator exposes at its Northbound interface several APIs that aim to ease the access to network capabilities by the application layer. In 6G-XR South Node, those APIs are aligned with the API provided by CAMARA Linux Foundation project [30] for that purpose (more details can be found in 6G-XR deliverable D2.1 [9]).

For the XR resolution adaptation and QoD functionality in real-time holographic communications UC1, the edge orchestrator exposes an API by which the QoS can be easily requested or changed by the application layer.

For the routing to the best edge functionality in real-time holographic communications UC2, the edge orchestrator exposes an API aligned with CAMARA simple edge discovery API that enables the best edge cloudlet location for a given UE location. The edge orchestrator also exposes an API aligned with CAMARA traffic influence API that enables the selection of the best edge cloudlet location prioritising the achievement of minimum delay.

### 4.1.2 Congestion detection and control function (CDF)

XR services, especially holographic communications, require transmission of huge amounts of data and thus demand a lot of network resources when those resources are not arranged properly. Users competing for transmission opportunities especially in the uplink direction lead to congestion and thus degradation in performance. To address this issue, a congestion detection and control function (CDF) module is designed specifically to satisfy the needs of the 6G-XR use cases. Its functionality is to first detect congestion in the cell where XR UEs are served and notify the XR AF (i.e., XR/Holo Orchestrator). When congestion is detected, CDF provides data rate recommendations to the XR AF based on load balancing target in the cell. CDF is also able to predict congestion if an existing user requests a data rate increase or if a new user is requesting to be added to the holographic call and notifies the XR AF accordingly.

This module has direct connection to the holographic communications UC1 defined in 6G-XR D1.1 [2] and D4.1 [8] since it detects congestion in the serving cell and proposes corrective actions to the XR AF instead of only alarming about it. The CDF module includes six submodules as shown in Figure 17. Each submodule carries out a specific function.

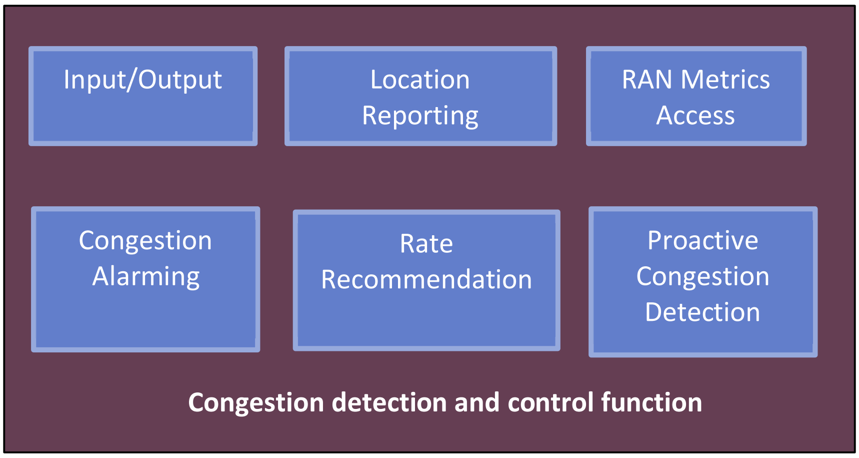


*Figure 17. Congestion detection and control function components.*

The input/output module is the main interface of the CDF towards external entities and coordinator of the overall CDF functionality driving the rest of the components. It handles the input to the function, which is the request from the XR AF with the list of UE internet protocol (IP) addresses that are performing XR services. Its output is sending an alarm back to the XR AF when congestion exists in the cell and/or a data rate recommendation per UE IP address.

The location reporting module is triggered by the input/output module to fetch the cell ID serving each entity on the XR UE list. For this, the module calls the 3GPP event exposure NEF API described in 4.2.1. Upon identifying the cell ID for each XR UE, the input/output module triggers the RAN metrics access module to fetch the corresponding RAN metrics that will be used for load balancing and rate recommendations.

The congestion alarming module is responsible for real-time monitoring of RAN metrics, such as physical resource block (PRB) utilisation, and raises an alarm when any of them crosses a certain threshold. It is called by the input/output module and takes as an input the list of cells that include XR UEs. Upon detection of congestion or receiving a new request for UE data rate increase, the rate recommendation module runs a cell load balancing algorithm that outputs a recommended new data rate per XR UE.

The proactive detection module is responsible for predicting whether an added XR user could cause congestion in the serving cell. In addition, it could predict whether an XR user requesting a data rate upgrade will cause congestion. It will output an alarm if congestion is predicted to happen.

### 4.1.3 IMSDC exposure

For IMSDC exposure, two interfaces are provided for developers who wish to use this service. The first interface is for the control plane (DC4) and handles the preparation of all internal connections between the various network elements involved in the holographic call between the two devices. The second interface is for the media plane (MDC2). Once this connection is established and communication between both devices is secured, MDC2 interface will connect from the MRF to the most optimal reconstruction server capable of rendering the presented hologram. Both interfaces are used as part of the control plane optimisations in the real-time holographic communications UC3.

At the time of this writing, these interfaces are not yet defined in 3GPP Release 18. For that reason, they have been implemented in the project based on the latest updates to the specifications and have started being documented in D2.1 [9].

 

## 4.2 3GPP APIS

### 4.2.1 3GPP NEF APIs

For the XR resolution adaptation and QoD functionality in real-time holographic communications UC1, the 3GPP event exposure API provides the AF with information about the location of the UE. In addition, the 3GPP AF session with QoS API allows the AF to influence the QoS of one or multiple service data flows of an ongoing packet data unit (PDU) session at the UE by providing policy requirements / specific QoS to the corresponding policy control function (PCF), which initiates the PDU session modification. Lastly, the 3GPP analytics exposure API's metrics retrieval functionality provides the AF with congestion analytics information related to a specific area.

For the routing to the best edge functionality in real-time holographic communications UC2, the 3GPP service parameter API allows the AF to request a policy subscription for a UE or a group of UEs to use certain single network slice selection assistance information (S-NSSAI) and data network name (DNN) identifiers for its own application data flows.

The 3GPP NEF APIs utilised in the South Node experimentation site are described in more detail in D2.1 [9].

### 4.2.2 Vendor specific APIs

In addition to the 3GPP standardised APIs provided through NEF, other network APIs specific to the utilised 5GC solutions at the test facilities can be potentially used for additional functionality. Example of such an API in the North Node experimentation site is the Cumucore API for network slice management described in 6G-XR D2.1 [9]. Additional API implementation opportunities can also be pursued with open source 5GC instances, e.g., in Open5GS [31], if necessary. Such approach can become relevant in the context of 6G-XR Open Calls and the need for it will be evaluated case-by-case, taking into consideration the added value to the 6G-XR experimental infrastructure as well as the required implementation resources from the project.

## 4.3 O-RAN INTERFACES

### 4.3.1 Key performance measurement (KPM)

O-RAN architecture provides reporting services through the E2 interface that can be used for RAN KPI monitoring. The E2 service model (E2SM) key performance measurement (KPM) enables continuous or triggered collection of selected KPIs with different granularities [14]. The measurements can be collected for the whole E2 node, single UE or group of UEs. As the KPI data is gathered by an xApp running in the near-RT RIC inside the O-RAN architecture, the process utilises the near-RT control loop, which operates in the ≤ 1 s timeframe. Typical measurement frequency used in the E2SM-KPM is one measurement per second.

E2SM-KPM performs several functionalities related to exposure of the E2 node reports. It exposes cell related performance metrics from the open distributed unit (O-DU), cell/UE/bearer related performance metrics from the open centralised unit (O-CU) and KPI measurement capabilities of the O-DU/O-CU [32]. Based on the KPI measurement configuration selected from the exposed options during the E2 service setup procedures, the E2SM-KPM then performs the reporting of the measurements subscribed to by the xApp running in the near-RT RIC.

 

In the 6G-XR use cases, E2SM-KPM can be used to collect near-RT KPI measurements directly at the network edge. As the KPI monitoring data is collected and processed on top of the same near-RT RIC platform where the control algorithms utilising the same data as input are running, the control loops for RAN resource optimisation are able to perform faster than with the 3GPP APIs described in 4.2. More specifically, UC1, UC2, UC4, and UC5 will benefit from the collection of E2 node level KPI measurements when optimising the resource allocations for QoS assurance and/or energy efficiency. Moreover, UC5 can also utilise KPI measurement data collected for a single UE or group of UEs when fine tuning data transmission scheduling parameters both in UL and DL directions.

More details on how O-RAN architecture's KPI monitoring capabilities are planned to be utilised in 6G-XR use cases and experiments can be found in deliverable D4.1 [8].

### 4.3.2 RAN control (RC)

In addition to reporting services, the E2 interface also provides control services that can be used by xApps running in the near-RT RIC to adjust the functionality and resource allocations in the O-RAN architecture. More specifically, the E2SM RAN control (RC) provides control functionality that can be used to modify resource allocations down to a single UE level [14]. The available control options include methods to dynamically manage radio bearer, radio resource allocation, mobility, admission, dual connectivity, carrier aggregation, and beamforming configurations during network runtime. As the xApps utilising E2SM-RC are running in the O-RAN architecture's near-RT control loop, the timeframe of the related control operations is ≤ 1 s.

On a high level, E2SM-RC is responsible for a handful of functionalities related to the E2 nodes. It exposes RAN control and UE context related information towards the near-RT RIC and xApps, modifies and initiates RAN control related call processes and messages in the O-RAN architecture, and executes policies that may result in changes of RAN control behaviour and resource allocations [32].

In the 6G-XR use cases, E2SM-RC functionality can be used for UE specific and application-aware radio resource management in the E2 Nodes. For example, resource allocations, scheduling decisions and air interface configurations benefitting specific XR applications in UC1-4 or E2E energy efficiency in UC5 all can utilise the control services offered in the E2 interface through E2SM-RC. As the control functionality is implemented as xApps on top of the near-RT RIC platform at the network edge, the KPI measurement data collected through E2SM-KPM as well as information from the application layer can be combined to make better optimisation decisions. Deployment of AI/ML algorithms is natively supported and enables also the historical KPI measurement data to be used in the process.

More details on how O-RAN architecture's RAN control capabilities are planned to be utilised in 6G-XR use cases and experiments can be obtained from deliverable D4.1 [8].

 

# 5 SUMMARY

This deliverable provides an overview of the 6G-XR reference architecture, including components, enablers, interfaces, and APIs.

The introductory Chapter 1 provided short overview of the 6G-XR use cases and 6G technology development avenues addressed at the 6G-XR experimentation sites as a reminder of the requirement setting for the reference architecture design. As the reference architecture utilises AI/ML algorithms for network and service management, and makes use of open interfaces and APIs, analysis on the potential impact of future AI/ML and cybersecurity regulation and standardisation regarding experimental research infrastructures in Europe was also provided.

The overview of the reference architecture was provided in Chapter 2. The layered view of the reference architecture provided a system component or functionality-centric representation whereas the interconnected view provided a more deployment-oriented representation of the reference architecture focusing on the connections between the architectural components. Consequently, both views to the reference architecture highlighted different aspects of the overall system required to support all the 6G-XR use cases.

The key building blocks of the reference architecture were described in more detail in Chapter 3. The described hardware and software components covered the architecture domains of user devices and applications, network components, edge platform, cloud services, and management and orchestration. Each architecture domain included one or more individual enablers that were discussed from the point of view of their basic functionality and why they are needed to enable the 6G-XR use cases.

The interfaces and APIs enabling essential reference architecture functionality were described in Chapter 4. The described interfaces and APIs focused on the exposure of the network resources and capabilities to applications and users as well as on the monitoring and control of selected network components. Discussion on the basic functionality and usage of the interfaces and APIs in the 6G-XR use cases was included in the provided descriptions.

Co-funded by the European Union

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