D6.1: Holographic Use case integration and validation and KPVI assessment

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Abstract	The 6G-XR project is dedicated to building an advanced infrastructure for eXtended Reality (XR) services, including the use cases of Augmented Reality (AR) exploiting network control plane and Virtual Reality (VR) based on network user plane. This deliverable D6.1 describes mainly the adaptations made in the XR applications and network components, the deployed infrastructure and the validation results of those AR and VR use cases.
Keywords	5G/6G, Augmented Reality (AR), Virtual Reality (VR), Holographic Communications, User Plane, Control Plane, Multimedia Functions, Media Synchronization

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DATA: Data sets, microdata, etc.

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EXECUTIVE SUMMARY

This document presents the architecture, validation methodology and execution for validating the next-generation holographic use cases defined for the South Node of 6G-XR. The document highlights the integration and adaptation of network and application enablers developed in the project into the experimentation facilities. The final aim is to demonstrate the operation of XR use cases over a platform including enhanced RAN, Edge and Core networks, showing low latency and high-performance result, as well as paying attention to perceived user experience and societal impact.

Some of the integrated enablers are:

- The Holo Orchestrator that manages the sessions in i2CAT's Holographic application.
- A Remote Renderer that processes the reconstruction image for visualization by an end user.
- Edge Orchestrator features to achieve the closest Edge discovery and selection.
- CAMARA-based and NEF APIs which allow to request the network to locate a user, to change the QoS of a slice or to associate a user with a specific slice.
- The IMS Data Channel Server, which makes possible for a user to access MATSUKO's Holographic application just by calling a service number with the phone's native dialler.

Two different architectures have been implemented in the South Node. One that relies on the 5G Core User Plane Function (UPF) for handling data traffic. In this case the XR applications run on Edge platforms. And a second that leverages the latest innovations of the IMS platform to offer media applications. For this option, an XR application is deployed in the IMS Data Channel Server.

The Key Performance Indicator validation methodology is based on a structured test case approach that ensures reproducible and comparable validation across partners and scenarios. The results show that the use case traffic demands are met by the enhanced 5G network. The XR services benefit from the dynamic adaptation of the network on demand and the selection of the closest Edge to further reduce the latency. In the IMS Data Channel test cases, the sessions are successfully established through the IMS platform, which paves another path for offering added value services leveraging the secure environment of the Telco operator.

The user feedback collected by Key Value Indicator questionnaires is positive. The participants believe there is potential in XR technologies in combination with future mobile networks to enhance the remote real-time communication experience. Most of the responses are also optimistic that these services can reduce travel and raise new learning and business opportunities.

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ABBREVIATIONS

2D	2-dimensional
3D	3-dimensional
3GPP	3rd Generation Partnership Project
5G	Fifth Generation Mobile Network
5GC	5G Core
6DoF	6 Degrees of Freedom
AF	Application Function
API	Application Programming Interface
AR	Augmented Reality
AS	Application Server
CM	Clock Manager
ConM	Index / Connection Manager
CP	Control Plane
CPU	Central Processing Unit
CUDA	Compute Unified Device Architecture
DASH	Dynamic Adaptive Streaming over HTTP
DCSF	Data Channel Signalling Function
DMA	Direct Memory Access
DNS	Domain Name System
DPE	Device Packaging Entity
E2E	End-to-End
EC	European Commission
EU	European Union
FoV	Field of View
fps	Frames Per Second
GPS	Global Positioning System
GPU	Graphics Processing Unit
GUI	Graphical User Interface
HTTP	Hypertext Transfer Protocol
ICE	Interactive Connectivity Establishment
IDE	Integrated Development Environment
IMS	IP Multimedia Subsystem
IMSDC	IMS Data Channel
IMSDCS	IMSDC Server
IMSI	International Mobile Subscriber Identity
IP	Internet Protocol
IPU	Image Processing Unit
KPI	Key Performance Indicator
LF-SDK	Light-Field SDK
LoD	Level of Detail
LTS	Long Term Support
MEC	Multi-Access Edge Computing
MCU	Multipoint Control Unit
mDNS	multicast DNS
ML	Machine Learning
MLA	Microlens Array
MMTEL	Multimedia Telephony
MNO	Mobile Network Operator

MPD	Media Presentation Description
MU	Media Unit
NaaS	Network-as-a-Service
NBI	Northbound Interface
NEF	Network Exposure Function
NTP	Network Time Protocol
NWDAF	Network Data Analytics Function
OS	Operating System
PC	Personal Computer
PCC	Policy and Charging Control
PCF	Policy Control Function
PDU	Protocol Data Unit
PTP	Precision Time Protocol
QER	QoS Enforcement Rule
QoE	Quality of Experience
QoS	Quality of Service
RAM	Random Access Memory
RAN	Radio Access Network
RGBD	Red Green Blue Depth
RoI	Region of Interest
RTCP	Real-time Transport Control Protocol
RTP	Real-time Transport Protocol
SDK	Software Development Kit
SDP	Session Description Protocol
SfM	Structure from Motion
SFU	Selective Forward Unit
SM	Session Manager
SMF	Session Management Function
SNS	Smart Networks and Services
SRTP	Secure RTP
SUCI	Subscription Concealed Identifier
TC	Trial Controller
TCP	Transmission Control Protocol
TSN	Time-Sensitive Networking
UC	Use Case
UDP	User Datagram Protocol
UE	User Equipment
UHD	Ultra High Definition
UM	User Manager
UP	User Plane
UPF	User Plane Function
URSP	UE Route Selection Policy
VM	Virtual Machine
VNF	Virtual Network Function
VR	Virtual Reality
WebRTC	Web Real-Time Communication
WP	Work Package
XR	eXtended Reality
XRM	XR and Media Services

1 INTRODUCTION

The main purpose of D6.1 is to summarize the outcomes of the tasks about the components adaptation, infrastructure deployment and validation efforts related to 6G-XR holographic use cases, namely: UC1 *Congestion Control via Rate Adaptation or Quality on Demand*, UC2 *Routing to the Best Edge*, and UC3 *Control Plane Optimizations*. This work spanned across January 2023 to October 2025 of the project timeline. 6G-XR includes two separate experimentation environments: the North Node in Finland and the South Node in Spain. UC1, UC2 and UC3 were run in 6G-XR's South Node, which is distributed along 5TONIC lab at Madrid and i2CAT premises at Barcelona.

1.1 OBJECTIVES OF THE DELIVERABLE

The objectives of D6.1 are to:

- Describe the adaptation of the holographic communication services (AR platform by MATSUKO and VR platform by i2CAT) for the proposed 6G-XR architecture, adopting network and application technological enablers developed in the project.
- Present the resulting 6G-XR infrastructure after the deployments and configurations performed to support the holographic communication applications on the experimentation facilities.
- Report the testing and validation of holographic communication applications on the 6G-XR infrastructure with the aim to prove that:
    - the 6G Comms control plane of the 6G Network is an enabler to create, through APIs, XR services that can scale and be interconnected with other services and service providers,
    - the modular and adaptive developed XR media enablers are efficiently allocated, deployed and bridged on top of the network and Edge platforms to optimize latency and adapt the use of resources to provide an excellent user experience,
    - the developed Trial Controller (TC) can ease the setup of experiments by instantiating apps on the closest Edge or applying traffic policies.

1.2 STRUCTURE OF THE DELIVERABLE

D6.1 is structured as follows:

- Section 2 starts with an overview of the VR-based use cases (UC1 and UC2) scope and their architecture, to provide context about the end-to-end service for the end user. Next, it dives into the work done for adapting application components and infrastructure to hold those use cases, highlighting the 6G-XR enablers involved in them.
- Section 3 details the same information as the previous chapter, but in this case for the AR-based use case (UC3).
- Section 4 elaborates on the validation test plan and execution to verify the readiness of the 6G-XR infrastructure to run the South Node use cases.

- Finally, Section 5 summarizes the deliverable.

1.3 TARGET AUDIENCE OF THE DELIVERABLE

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

2 USER PLANE OPTIMIZATIONS FOR HOLOGRAPHIC COMMUNICATIONS: UC1 AND UC2

This section reports the adaptations done to enablers described in WP2 D2.3 [1], WP3 D3.2 [2] and WP4 D4.3 [3] for running two Use Cases (UC1 and UC2, defined in detail in D1.1 [4]). Those UCs are targeted at improving the reliability and performance of real-time holographic communication services thanks to user plane innovations.

2.1 OVERVIEW OF UC1 AND UC2

UC1 Congestion Control via Rate Adaptation or Quality on Demand

Holographic communication services bring stringent bandwidth requirements, in the order of few tens of Mbps per holographic stream or even higher. However, the available capacity and whole amount of active traffic in 5G cells largely varies over time due to the dynamic user traffic demands, mobility and interference, thus potentially impacting the Quality of Service (QoS) and Quality of Experience (QoE) in such real-time services. 6G-XR has implemented an innovative Congestion Detection Function (CDF), which continuously monitors real-time radio and traffic indicators in the serving 5G cell to detect emerging congestion conditions. Based on these measurements, if congestion is detected, the CDF (developed in WP4) in collaboration with the XR (Holo) Orchestrator (developed in WP3) can enforce two different mitigation actions with recommended transmission rates for each active client, reflecting the current network load and cell utilization. When congestion is detected, the CDF notifies the XR Orchestrator, which can react in two ways: (i) recommending to the user plane media functions, like client applications or Remote Renderers, to adapt their data rate; (ii) triggering a Quality-on-Demand (QoD) request through the CAMARA QoD API to the 5G network, ensuring prioritized treatment for XR specific streams.

UC2 Routing to the best Edge

The end-to-end holographic communication platform can leverage Edge processing to deploy and run diverse user plane media functions, like Selective Forward Unit (SFU) and Remote Renderers. 6G-XR has developed innovative network APIs between the Holo Orchestrator (developed in WP3) and the Edge Orchestrator (developed in WP2) to be able to use different federated Edge nodes for XR processing offloading e.g., cloudlet selection within different Edge orchestrators in multiple domains (both Barcelona and Madrid 6G-XR testbeds). Optimal Edge allocation will take place based on specific goals like minimizing delays by selecting the closest Edge to the end user, selecting the servers with the most appropriate resources, or even managing mobility patterns.

2.2 ARCHITECTURE OF UC1 AND UC2

Figure 1 provides a high-level overview of the end-to-end holographic communication platform built using enablers developed/evolved in the project within WP3.

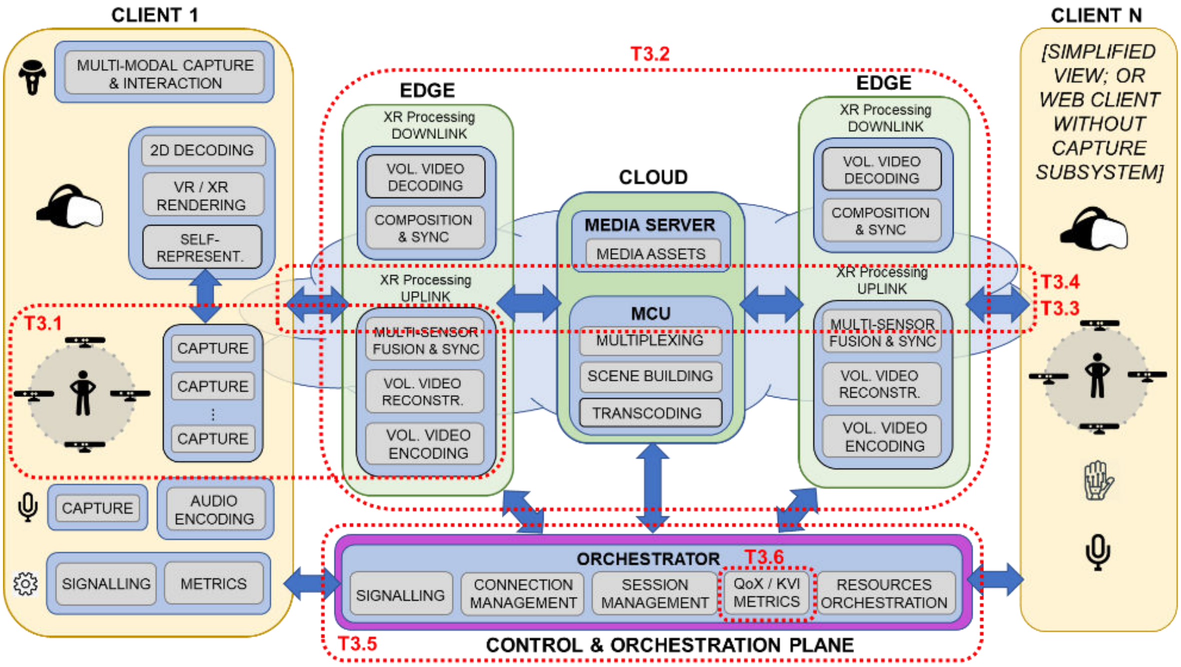


Figure 1: End-to-end holographic communication platform built using WP3 enablers.

T3.1 groups the Volumetric Video Capture and Reconstruction components, T3.2 deals with In-Cloud Processing and Adaptability, T3.3 highlights the Adaptive Low-Latency XR Delivery mechanisms, T3.4 focuses on the Interaction and Synchronization among Edge/Cloud platforms, T3.5 covers the Session Management and XR Orchestration components and T3.6 includes the Cross-layer metrics measurement.

Figure 2 provides a more detailed view of the Volumetric Video Capture and Reconstruction components.

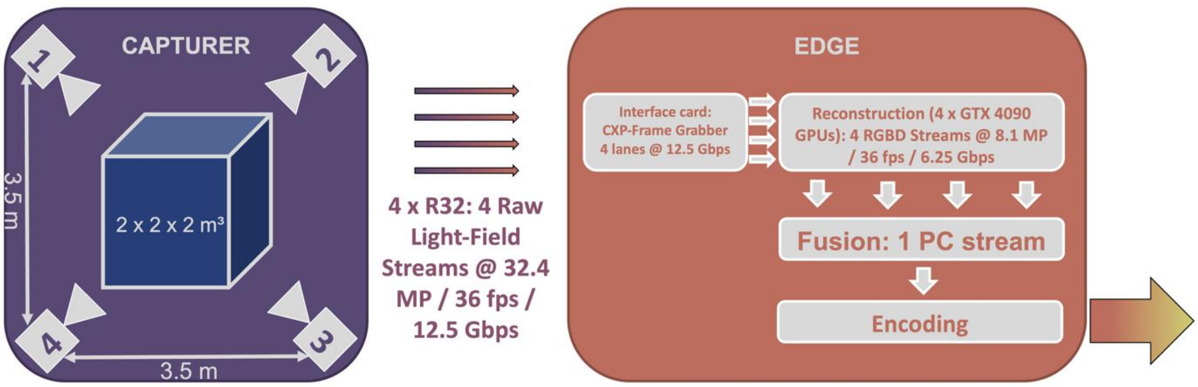


Figure 2: Volumetric Capturer and Edge processing with RAYTRIX and i2CAT components.

The block on the left refers to the Volumetric Capture, comprised of four R32 light-field cameras within a capture zone measuring 2x2x2 cubic meters, and designed for capturing human bodies in real-time. The box on the right refers to the Edge processing, where the data from these cameras is transmitted with a latency lower than 100ms. The light-field streams are transformed at the Edge into Red Green Blue Depth (RGBD) streams. Subsequently, these streams are merged into a unified volumetric stream, encoded, and forwarded for further processing.

The main compute (from WP2) and network (from WP4) enablers developed in the project that are required for UC1 and UC2 implementation are the following (represented in Figure 3):

- The **Congestion Detection Function (CDF)** enabler is a software tool used to detect and report network congestion events. It continuously monitors performance indicators such as cell utilization or throughput to identify overload conditions. The Holo Orchestrator subscribes to the CDF using a specific UE ID, allowing the CDF to locate the user's serving cell and track its congestion status. When congestion is detected, the CDF sends an alarm notification to the Holo Orchestrator, enabling it to take corrective actions such as traffic adaptation, prioritization, or profile adjustment to maintain service quality for the ongoing XR session.

- The **Edge federation enabler** which allows that the machines in Madrid Edge can interact with the machines in Barcelona Edge. As a result, the Madrid Edge orchestrator can see the available resources at Barcelona Edge and decide to deploy applications on it.

- The **NEF APIs** (namely: *Service Parameter*, *UE Location*, *QoS Session* and *Data Collection*) will be called during the use case workflow and will retrieve information or trigger configuration changes in the 5G Core and RAN components. The NEF function is running on a server dedicated to auxiliary tools and is reachable by the other components.

- The **northbound APIs based on CAMARA such as QoD and Simple Edge Discovery** are running on Madrid Edge and they interact with the NEF APIs in the Southbound to get reactions from the 5G network. More specifically, the Quality of Service (QoS) and the User Plane Function (UPF) associated with the UE are dynamically configurable through the QoD API, as described in sections 5.1.2 and 5.1.4 of D2.3 [1] respectively. Furthermore, Simple Edge Discovery – which is a core component of UC2 - identifies the geographically closest Edge to the UE based on end-user network location. This proximity-based selection aims to establish a more efficient connection and improve end to end performance. The functionality of this mechanism was also validated in section 5.1.3 of D2.3 [1].

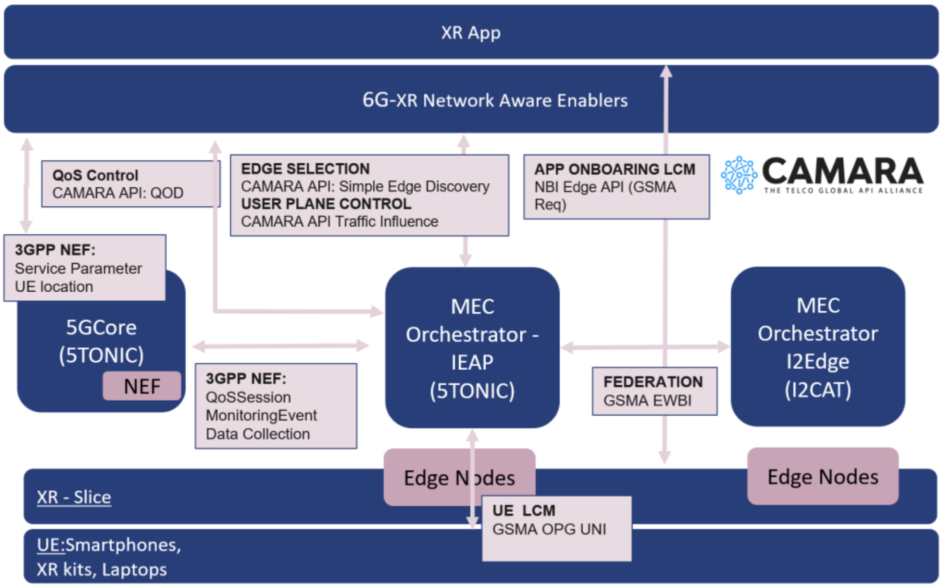


Figure 3: Main 6G-XR Compute and Network Enablers involved in UC2.

2.3 ADAPTATION OF COMPONENTS FOR UC1 AND UC2

UC1 and UC2 adopt a multiuser holographic communication platform for VR/XR environments, called HoloMIT and developed by i2CAT, which has been evolved and adapted within WP3 (details in D3.2 [2]) to: (i) integrate new single- or multi-sensor volumetric video capture setups (T3.1); (ii) interface single or multiple instances of communication servers, with just forwarding functionalities (i.e. SFU) or including in-cloud processing (i.e. Multipoint Control Unit (MCU)), either on public or private cloud servers (T3.2); (iii) integrate Remote Renderers to support lightweight devices (T3.2 and T3.4); and (iv) integrate a new metrics measurement and monitoring sub-system (T3.6).

As anticipated, the above-described WP3 enablers have been extended and adapted to integrate with enablers from WP4 (mainly to support UC1) and WP2 (mainly to support UC2). These adaptations and integrations are briefly detailed next.

2.3.1 6G-XR enablers adaptation to support UC1

To support UC1, three main WP3 enablers (Holo Clients, Holo Orchestrator, Remote Renderer) have been adapted to appropriately interface the CDF and CAMARA QoD API from WP4, via well-defined API and messages, as detailed next and overviewed in Figure 4.

Notification of Congestion Detection: The Holo Orchestrator first subscribes to the CDF API using the User Equipment (UE) ID, prompting the CDF to locate the serving cell associated with that UE and begin tracking its congestion status. When the cell load exceeds a defined threshold (e.g., 80%), the CDF detects a congestion event and returns a notification snapshot to the Holo Orchestrator containing the UE ID, and current congestion status, as illustrated in the API payload example below.


```
{
  "UEs": [
    {
      "UE_ID": "UE12345",
      "Status": "Cell Congested"
    },
    {
      "UE_ID": "UE67890",
      "Status": "Serving Cell Down"
    },
    {
      "UE_ID": "UE54321",
      "Status": "Neighbor Cell Down"
    }
  ]
}
```


Figure 4: Snapshot example of a congestion notification message sent from the CDF to the Holo Orchestrator, including UE ID, serving cell ID, and congestion status.

Rate Recommendation: Once the Holo Orchestrator received the congestion notification from the CDF, it then forwards the message, optionally including specific Uplink or Downlink rate recommendations, to the target/affected UEs.

QoD triggering: Alternatively, to Rate Adaptation, the Holo Orchestrator can invoke a Quality-on-Demand (QoD) procedure through a newly implemented CAMARA-compliant QoD API integrated with the 5G network (see Figure 5). The QoD mechanism operates by dynamically modifying the QoS profile for the connection to the targeted Holo Client, e.g. shifting it from a Low to a High priority level. This profile elevation instructs the 5G core to allocate higher scheduling priority and preferential radio resources to the targeted session. As a result, the affected XR streams can sustain low latency and high throughput even under congestion, while non-critical traffic sources are kept under a best-effort basis.

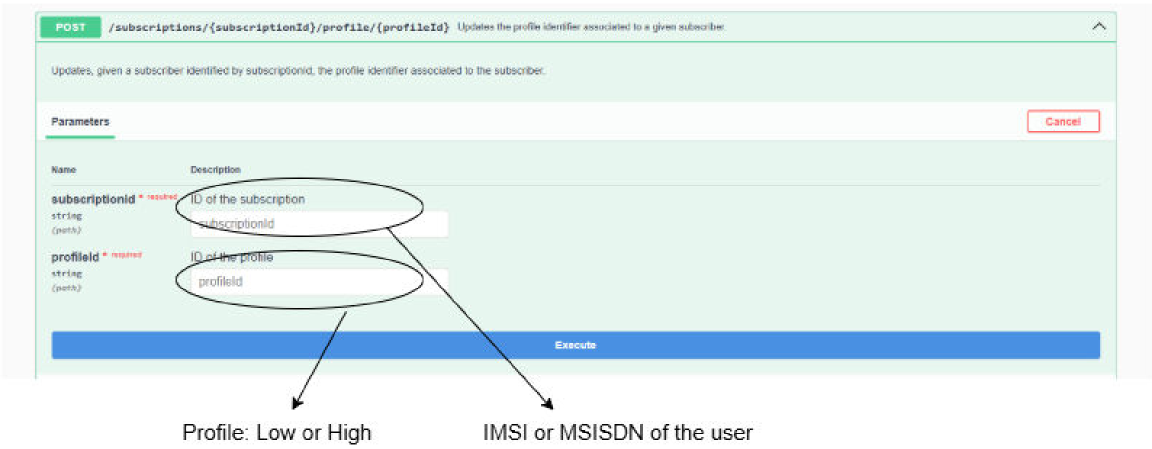


Figure 5: QoD API call showing user identification (IMSI/MSISDN) and requested profile level ("High" or "Low").

The end-to-end workflow from congestion detection to mitigation action, integrating enablers from WP2, WP3 and WP4 is illustrated in Figure 6.

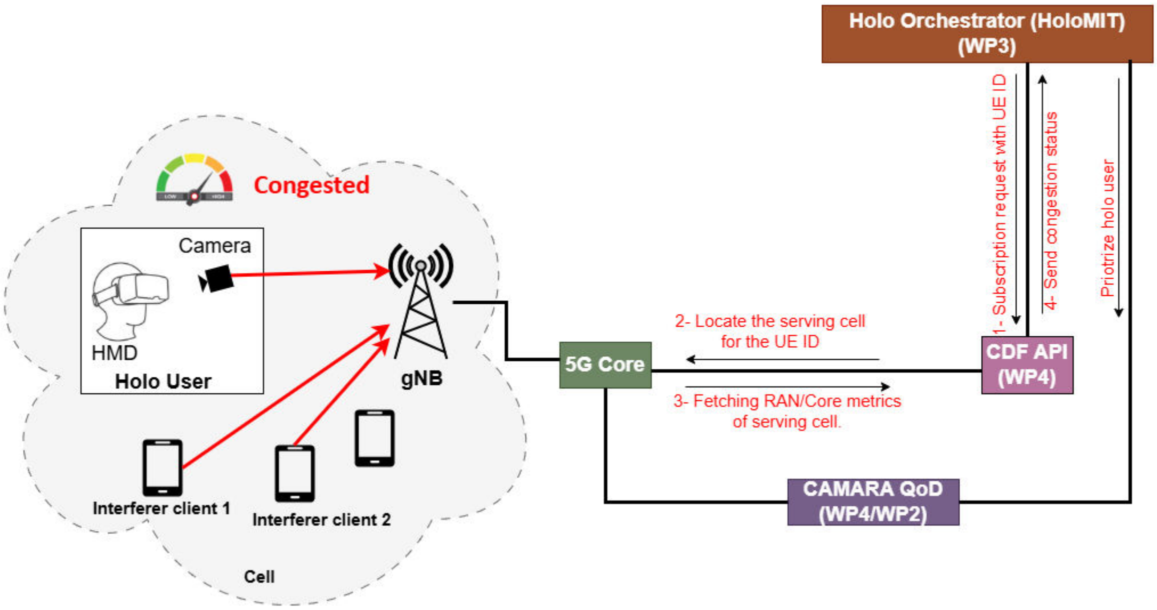


Figure 6: Conceptual interaction flow between Holo Client/User (WP3), Holo Orchestrator (WP3), Congestion Detection Function (CDF) (WP4), and CAMARA QoD API (WP4/WP2) within a 5G network to support UC1.

2.3.2 6G-XR enablers adaptation to support UC2

In order to support UC2, three main WP3 enablers (Holo Clients, Holo Orchestrator, Remote Renderer) have been adapted to appropriately interface the Edge/MEC Orchestrator from WP2 to achieve the following functionalities: (i) Edge discovery, so that the Holo Orchestrator can identify the available Edge server where to run a specific user plane WP3 enabler (e.g., SFU, MCU, Remote Renderer); (ii) Edge selection, so that the specific media function can be onboarded and/or run as part of a holographic communication session; and (iii) app lifecycle management during the service's lifetime.

By leveraging these novel functionalities, the XR application/service will be able to use different federated Edge nodes for XR processing offloading e.g., cloudlet selection within different Edge orchestrators in multiple domains (both Barcelona and Madrid 6G-XR testbeds), even if the end user moves. Optimal Edge allocation takes place based on specific goals, e.g. minimizing delay by selecting the closest Edge to the end user to deploy components to route the user plane traffic.

Next, the main adaptation and interfaces between WP2 and WP3 enablers to support UC2 are represented in the following flow diagram (see Figure 7).

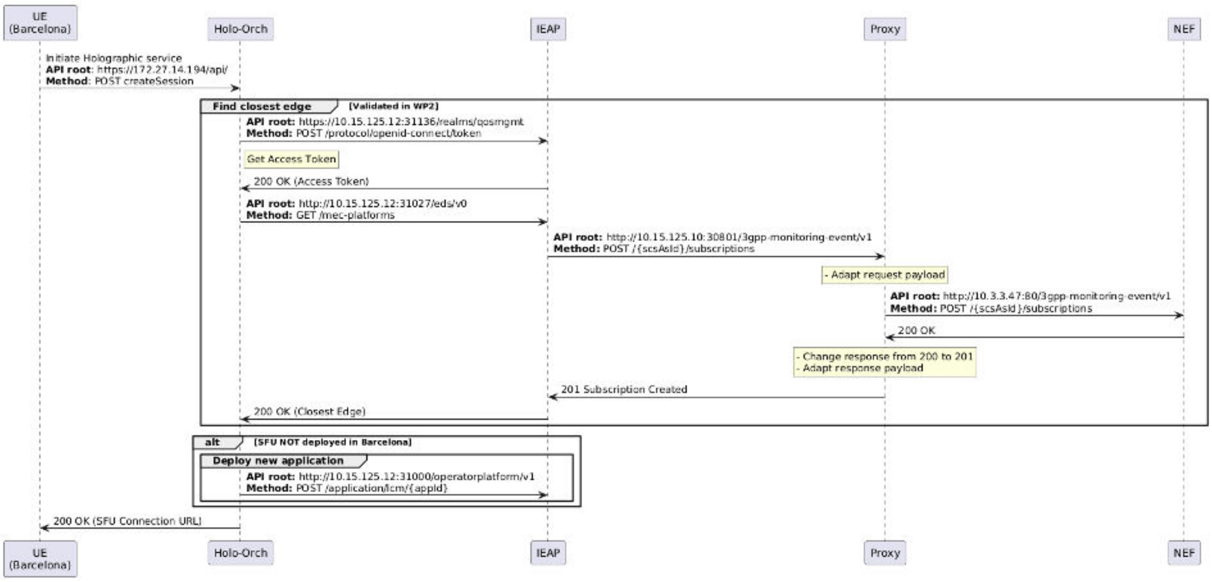


Figure 7: Simple Edge Discovery workflow for UC2.

Upon a request for creating a session, the Holo Orchestrator is requesting the Edge orchestrator (IEAP) for available Edge nodes (MEC platforms). Moreover, the IEAP will be able to find out the most suitable one (the closest Edge) by surveying the NEF network end-user location. Accordingly, the closest Edge will be returned to the Holo Orchestrator, as represented in the workflow in Figure 7. Error handling is managed as defined in the IEAP APIs swagger, and includes invalid tokens, expired tokens, invalid API parameters, server errors due to platform issues and responds accordingly to the Holo Orchestrator.

The XR applications and XR enablers for UC2 have been adapted, typically containerized, to be deployed into the MEC orchestrator by Capgemini (IEAP) at 5TONIC Edge infrastructure. The IEAP platform computing model has been designed to place the computational power in a distributed manner at the Edge of the operator network. This distribution is utilized to enable IEAP Edge device applications to push out the compute-heavy components to Edge datacenters in the form of low latency applications or for other reasons like compute offload and backhaul savings.

As depicted in Figure 8 below, the MEC orchestrator at 5TONIC supports application artifacts to be deployed both over containers (Docker, Kubernetes (K8s)) or virtual machines.

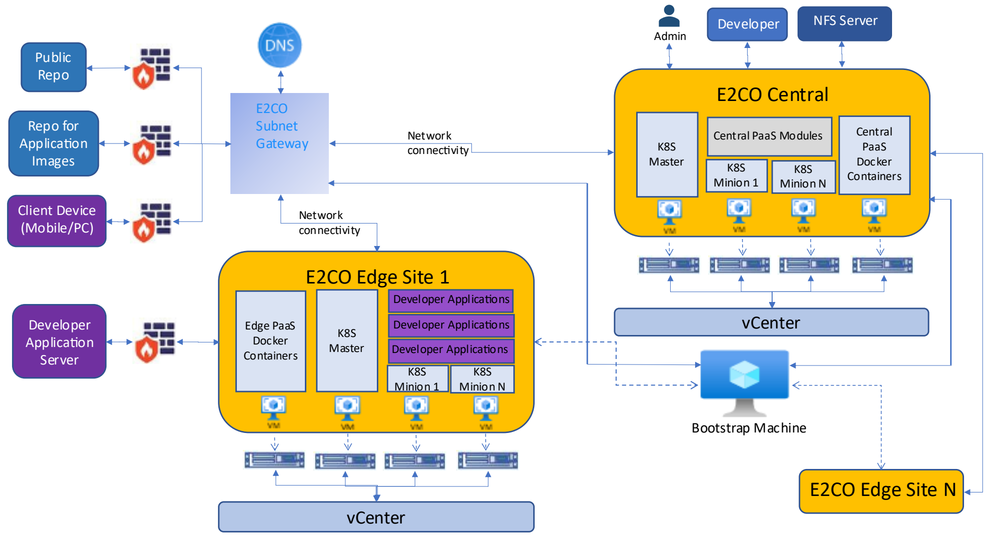


Figure 8: App deployment view with MEC orchestrator at 5TONIC (Madrid) Research Facility.

For the containers virtual type, the artifacts descriptor could be chosen among Helm, Terraform, or other container specification so the app provider can define either a Helmchart or a Terraform script or container spec.

The information needed to be provided in the Component Descriptor for the Helm charts was:

- Name
- No. Of Instances
- OS Architecture
- Distribution
- License
- OS Version

The app provider had to provide also compute resource requirements such as:

- CPU Architecture
- Number of CPUs
- Memory (Megabytes)
- Storage (Gigabytes)

Regarding the application information to be provided this was:

- Name
- Version
- Mobility support
- Description
- Under "category", multiple types can be considered, including gaming, XR, etc.

It was also possible or the app provider to select a QoS Profile indicating:

- Latency Constraints
- Bandwidth (Mbps)

- Maximum number of supported Users

Figure 8 presents the Edge infrastructure deployed in Barcelona. The i2CAT Edge environment comprises several K8s clusters distributed across different locations and centrally managed by i2EDGE, i2CAT's implementation of an Edge Orchestrator.

The infrastructure integrates heterogeneous cluster setups: the MIA Tower 3 site hosts a bare-metal K8s deployment, whereas the 6G-XR cluster operates within an OpenStack tenant where the K8s environment has been instantiated. Both clusters are orchestrated through i2EDGE, enabling unified management and coordination.

Within the 6G-XR project framework, i2EDGE exposes the available Edge resources through the MEF Manager, which implements the federation interfaces defined by the GSMA OPG (Operator Platform Group) EWBI (East-Westbound Interface) API. In Use Case 2 (UC2), the Barcelona Edge infrastructure is federated with the 5TONIC site, allowing the latter to access computational resources located in Barcelona. This federation mechanism supports remote application onboarding and lifecycle management across geographically distributed Edge infrastructures.

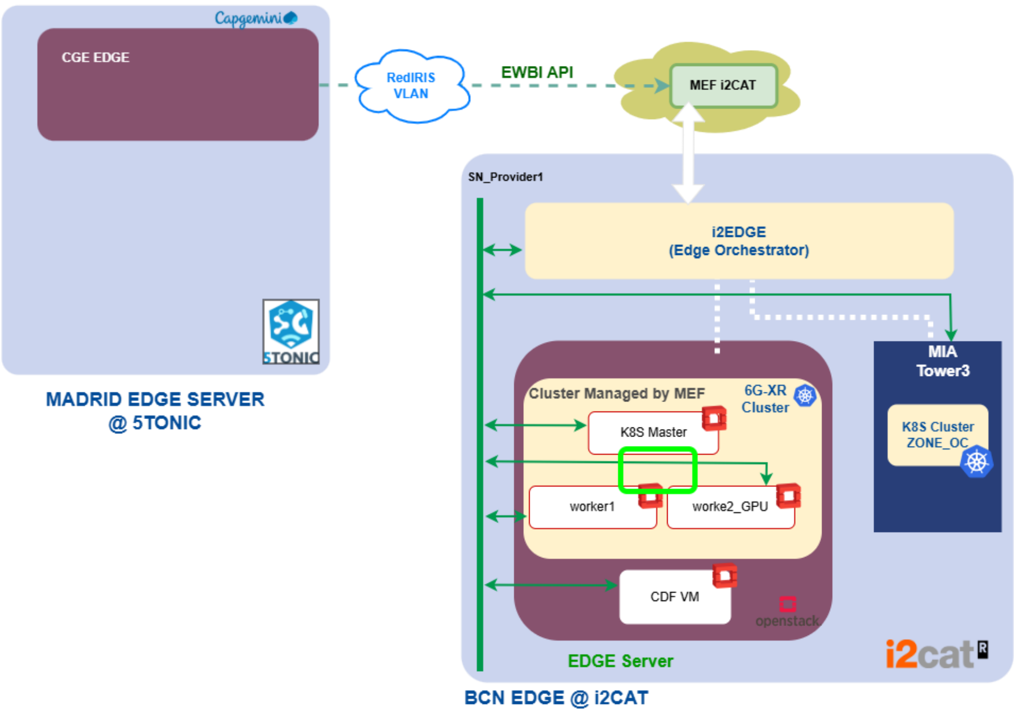


Figure 9: i2CAT´s Edge deployment in Barcelona.

2.4 INFRASTRUCTURE SETUP FOR UC1 AND UC2

The infrastructure required in the South Node for the user plane UCs (UC1 and UC2) is shown in Figure 10. The elements of the infrastructure that have been deployed or enhanced for this project are: (i) the Virtual Private Network (VPN) tunnel required to connect i2CAT and 5TONIC sites; (ii) the 5G Radio Access Network (RAN) and User Plane Function solution provided by Ericsson to cover i2CAT premises in Barcelona; (iii) the i2CAT's Edge platform in Barcelona; (iv) the Capgemini's Edge platform located at 5TONIC (in Madrid); (v) the Network Exposure Function (NEF) within the existing

5G Core at 5TONIC; and (vi) the VPN tunnel required to connect 5TONIC and UOulu sites in order to benefit from the Trial Controller (TC) and the Unified Web Portal (UWP) functionalities.

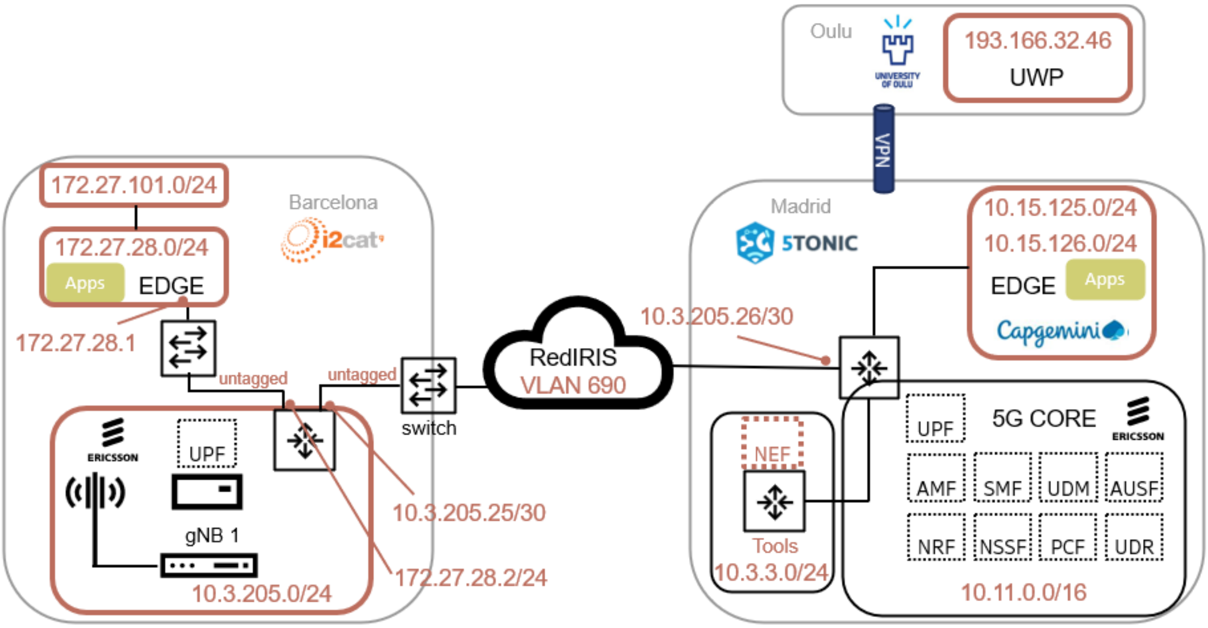


Figure 10: Infrastructure setup for UC1 and UC2.

The connectivity between 5TONIC and i2CAT sites is achieved via RedIris. RedIris[1] is the backbone network among research and academic institutions in Spain, part of the pan-European GÉANT[2] network. It provides a layer 2 VPN connection between sites, so a point-to-point communication is configured within the subnet 10.3.205.24/30. The routing is configured on both sides to guarantee all the IP addresses in the design can interconnect. The inter-site connectivity is a must for the distributed 5G network and for other WP2 enablers to work. For details about WP2 enablers, kindly check D2.3 [1].

To start with, this connectivity grants that the 5G RAN equipment in i2CAT can reach the 5G Core in 5TONIC, and the access of the UEs to the 5G network is managed remotely by the 5G Core control plane. The 5G RAN deployed by Ericsson includes FR1 plus FR2 bands, ensuring high speed data rates for the XR services. Together with the RAN equipment, the solution also includes a User Plane Function (UPF) in i2CAT premises, allowing to select the UPF in Barcelona when the applications are running in Barcelona Edge. The design is thoroughly described in section 2.2.5 of both D4.1 [5] and D4.2 [6]. The components of this piece of the infrastructure are configured with IP addresses in the range of 10.3.205.0/24. The IP addresses that the UEs will get depend on which UPF they are using for user plane traffic and is defined as shown in Table 1.

[1] https://www.rediris.es/lared/index.html.en

[2] https://network.geant.org/

Table 1: IP allocations for UEs in UC1 and UC2.

SIM	Fixed IP for UPF Barcelona	Fixed IP for UPF Madrid
M28	10.3.205.85	10.3.202.117
M35	10.3.205.65	10.3.202.97
M36	10.3.205.69	10.3.202.101
M37	10.3.205.73	10.3.202.105
M38	10.3.205.77	10.3.202.109
M39	10.3.205.81	10.3.202.113

The UPF and the QoS that the service traffic will use are tied to different slice profile names as listed in Table 2 via Service Parameter and QoS Session APIs, each Subscriber Identity Module (SIM) subscriber is associated with a specific slice profile.

Table 2: Slice profile names for UC1 and UC2.

Slice Profile	SST	SD	UPF	QoS
madrid-low	1	1	Madrid	5qi 9
barcelona-low	1	2	Barcelona	5qi 9
madrid-high	1	1	Madrid	5qi 6
barcelona-high	1	2	Barcelona	5qi 6
barcelona-interferer	1	2	Barcelona	5qi 5

Additionally, a VPN was configured over Wireguard to connect 5TONIC to UOulu site. This is needed for the use of the Trial Controller (TC) developed by the project in WP4. As part of the TC operation, the Unified Web Portal (UWP) must contact the South Web portal, which is running on Madrid Edge. For more details on the operation of the TC, kindly check the D4.3 deliverable [3].

3 IMS CONTROL PLANE OPTIMIZATIONS FOR HOLOGRAPHIC COMMUNICATIONS: UC3

The adaptation of the end-to-end (E2E) components of holographic communication services of the AR platform by MATSUKO is required for successful deployment within the envisioned 6G architecture by leveraging technological enablers developed in WP2 and WP3.

Holographic communication services were interfaced and integrated with the IP Multimedia System (IMS) Data Channel (DC), implementing 3GPP Rel-18 standards, and the XR-Ready control plane. This integration involves migrating media user plane components to the Edge and aligning session management control functions with the 6G-XR control plane APIs at both device and network levels.

The E2E components were adapted to measure and register cross-layer Key Performance Indicators (KPIs), such as bandwidth usage, resolution, frame rate, latency, jitter, synchronization levels, packet loss, and resource consumption.

3.1 OVERVIEW OF UC3

Integrating holographic calls directly into a smartphone dialler would allow users to access and utilize this advanced communication technology seamlessly without the need for additional applications.

IMS Data Channel is a cutting-Edge, standards-based technology that enhances existing IMS voice networks, allowing mobile network operators to deliver improved services to millions of users. This technology leverages the inherent strengths of telephony networks, such as Quality of Service (QoS), reliability, seamless mobility, and security, while introducing new capabilities for interactive and immersive communication.

The work in WP6 achieved several significant milestones. Using IMS Data Channel compliant devices, the transmission of a one-way holographic call was demonstrated, where a caller's face and torso can be captured and transmitted as a real-time hologram to the receiver, along with two-way audio between them over IMS channels. The holographic service was seamlessly integrated into native smartphone dialler, eliminating the need for additional applications. Additionally, MATSUKO's advanced holographic service processed and reconstructed the hologram data in the cloud, ensuring high-quality performance.

3.2 ARCHITECTURE OF UC3

Figure 11 identifies the different elements of the network that must be considered when establishing a holographic call between two users in presentation mode, where one agent user will produce a hologram and a viewer user visualizes it during an IMS Data Channel (IMSDC) call with an IMSDC-capable dialler. The boxes in green and blue and the interfaces among them are the components that need adaptation to work on an IMS system.

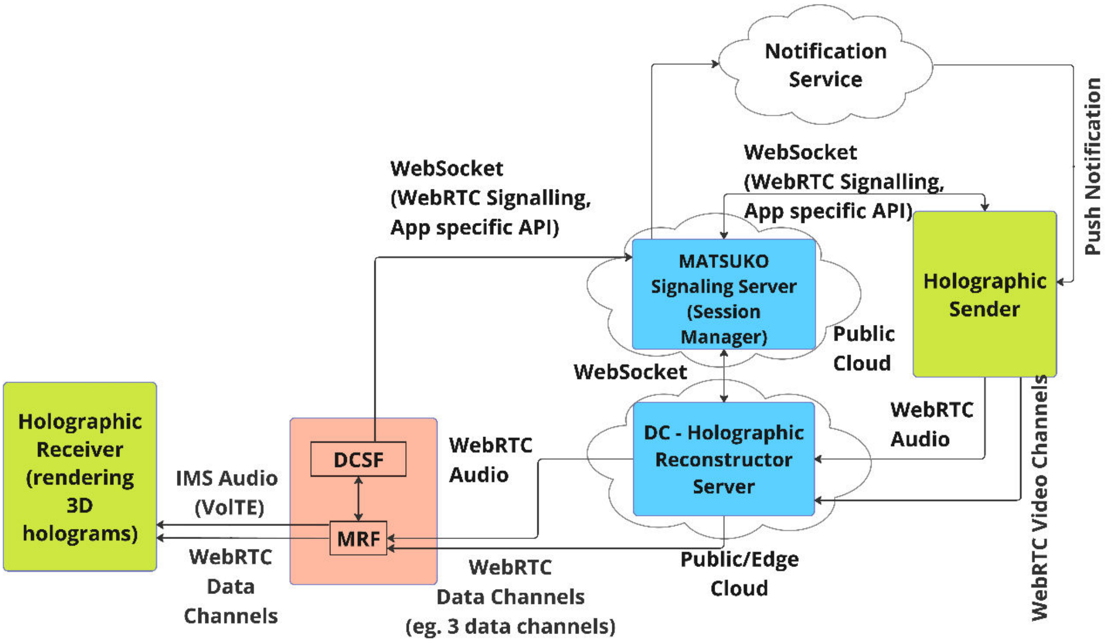


Figure 11: E2E MATSUKO Components Adaptation to IMS System – Architecture.

3.3 ADAPTATION OF COMPONENTS FOR UC3

MATSUKO holographic call application, which operates on a public cloud, utilises WebRTC[3] transfer protocols, public cloud-based hologram reconstruction, and native rendering for user devices like XR headsets.

For the system to transition and be integrated into an IMS setup, the following steps were necessary:

- Adapt and establish a signalling system.
- Adapt the WebRTC methods for transferring video/audio/data channels to suit IMS data channels.
- Reimplement the hologram rendering process in WebGL[4].

3.3.1 Adapt and establish a signalling system

The signalling server (Session Manager) is responsible for establishing data channel connectivity between MATSUKO reconstructor server and the IMS system. The Session Manager API was extended to meet the integration requirements.

The sequence diagram in Figure 12 shows the steps for a holographic call using IMS data channels.

[3] https://webrtc.org/

[4] https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API)

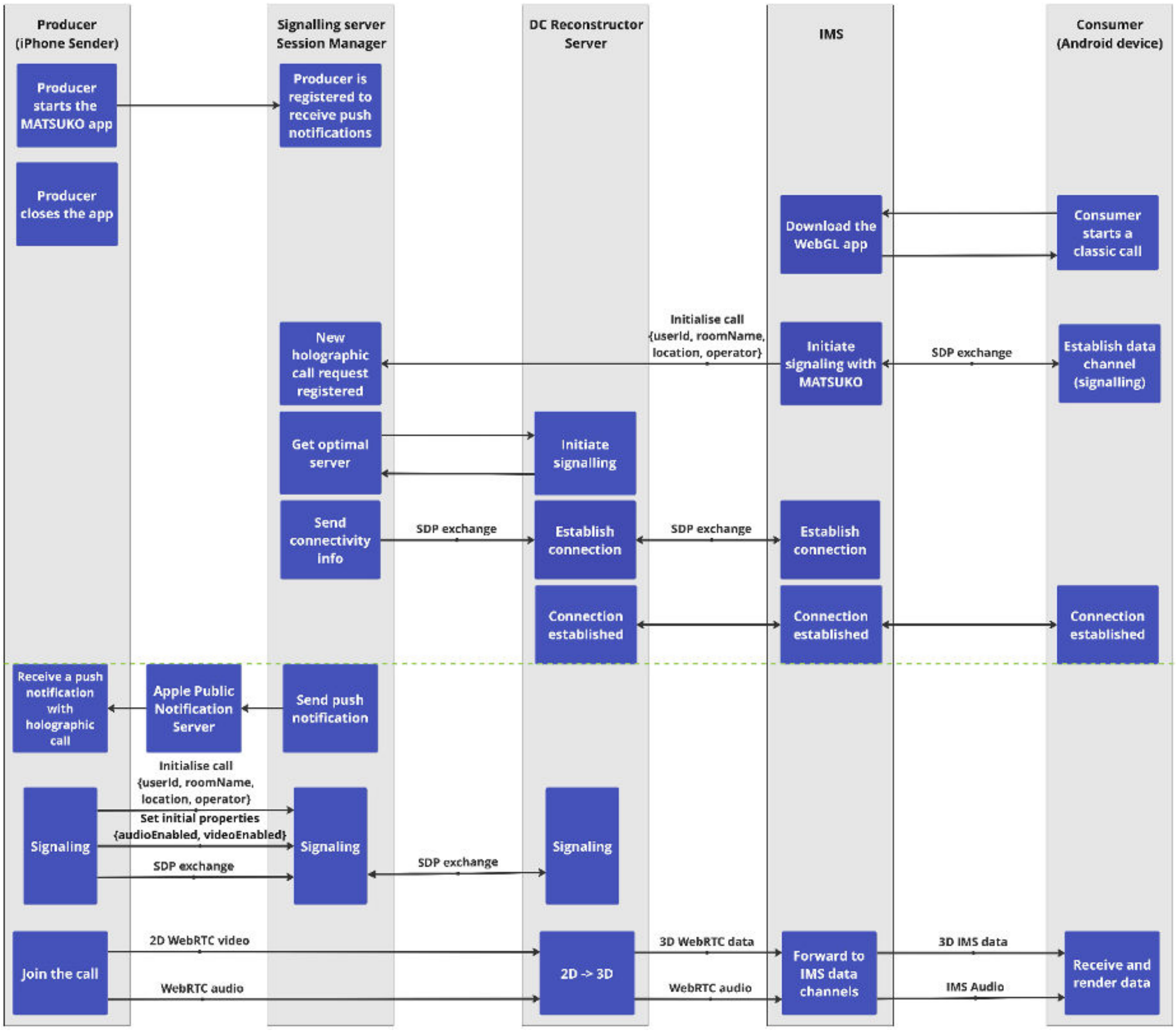


Figure 12: Sequence Diagram of Holographic Communication Service (AR platform).

3.3.2 Adapt the WebRTC methods – adaptation of media components

MATSUKO media user plane components were deployed on Microsoft Azure and Amazon AWS to meet the IMS system requirements. This ensured a seamless integration between the systems. The required application components and the network configuration were adjusted to run on Azure platform and on Amazon AWS. The containerized deployment approach ensures an adaptable way to deliver the service and makes it simple to do updates.

Between the Media Resource Function (MRF) and MATSUKO reconstructor server, WebRTC data channels were established, to transfer 3D data over these channels instead of using video channels. The server modifications were implemented to validate the connectivity.

3.3.3 Reimplement the hologram rendering process in WebGL

The holographic receiver is an application capable of establishing IMS data channels and rendering holograms in WebGL[5]. For IMS signalling, IMS Data Channel API integration was delivered for the

[5] https://developer.mozilla.org/en-US/docs/Web/API/WebGL_API

application. For rendering implementation, WebGL technology is used to display the 3D hologram on the smartphone, as depicted on Figure 13.

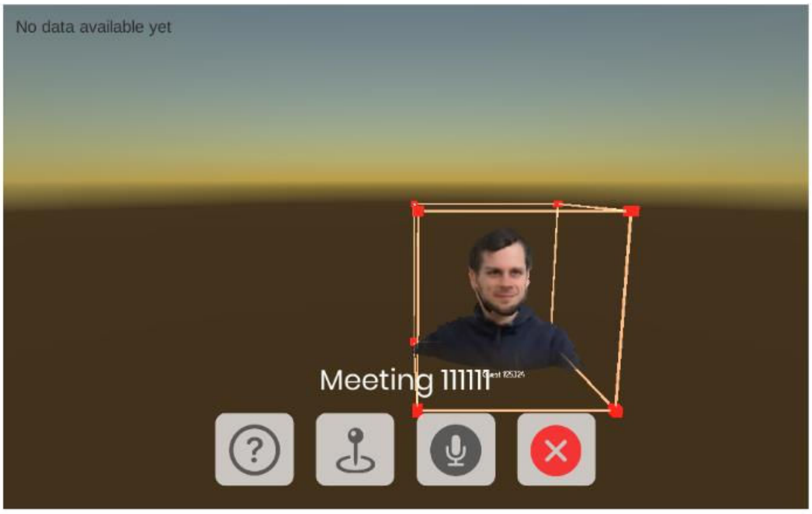


Figure 13: First tests of real-time WebGL in web browser rendering.

Following the redesign of the holographic call to incorporate IMS data channels and WebGL rendering, the application's functionality was confirmed via testing of the XR calling using a Multimedia Telephony (MMTEL) dialler in the browser. Initial tests were performed using low-resolution hologram data and basic hologram rendering algorithms and during the testing the connection to MATSUKO Media Server (hologram reconstructor), including WebGL hologram rendering, and audio were validated, as depicted on Figure 14. The client app successfully accepted signalling from the smartphone dialler.

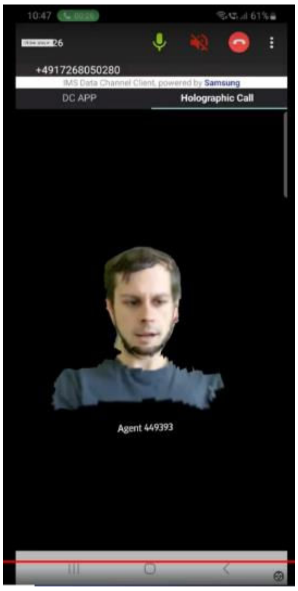


Figure 14: Screenshot from a holographic call as IMS application with WebGL rendering on a smartphone display.

As an additional validation of UX/UI, testing of implementation of the initial waiting screen during app download (waiting/progress bar) was completed, as shown on Figure 15 and Figure 16.

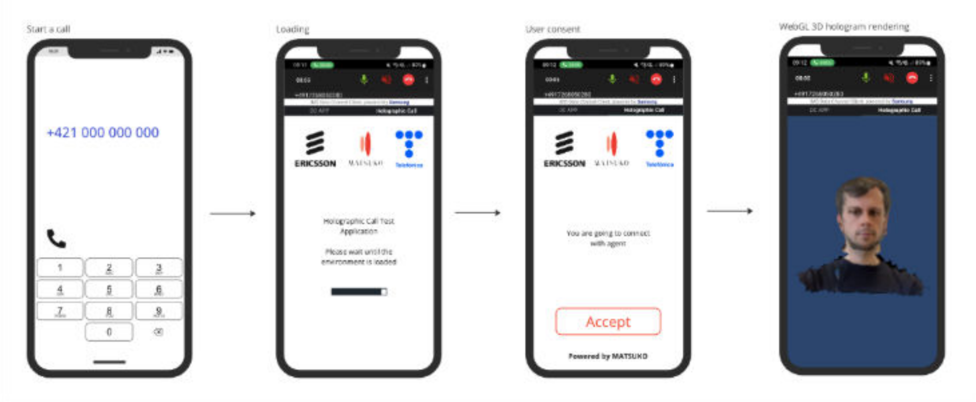


Figure 15: Initial UI design for the IMS holographic call.

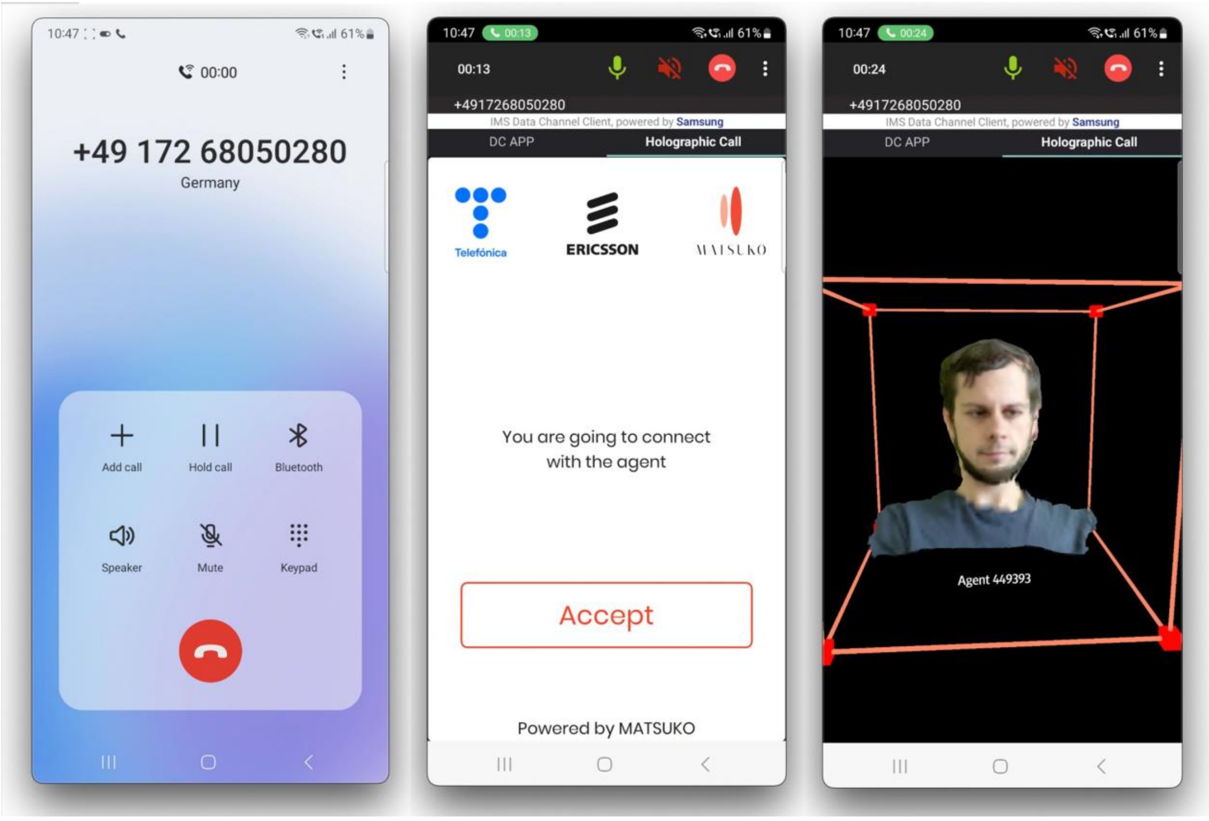


Figure 16: IMS Data Channel integration: the user calls a number, a 3D hologram appears using his/her smartphone.

The implementation and adaptation of holographic calls for 6G architecture via IMS data channels and using WebGL rendering on a smartphone was successfully validated.

3.3.4 Evaluation of the modifications

To measure the KPIs, a monitoring system was deployed along with the MATSUKO application containers to gather metrics in real-time on the receiver side during the test calls. The monitoring system automatically gathers KPIs between the Holographic Reconstructor and Holographic Receiver, such as bandwidth, latency, jitter and packet loss, which can be visualized in dashboards. Figure 19 shows a deployed dashboard with measurement of bandwidth and packet transmissions during the IMS holographic call.

Testing of MATSUKO IMS holographic calls were performed in two different setups - running MATSUKO IMS holographic call over Voice over WiFi (VoWiFi) and Voice over LTE (VoLTE).

- While running MATSUKO IMS holographic call over VoWIFI (Figure 17), average throughput was ~15,5Mbit/s (= ~1600pkts/s @ packet size 1212 Bytes, std = ~5.3 Mbit/s).
- While running MATSUKO IMS holographic call over VoLTE (Figure 18), average throughput was ~12,6Mbit/s (= ~1300pkts/s @ packet size 1212 Bytes, std = ~1.6 Mbits/s).

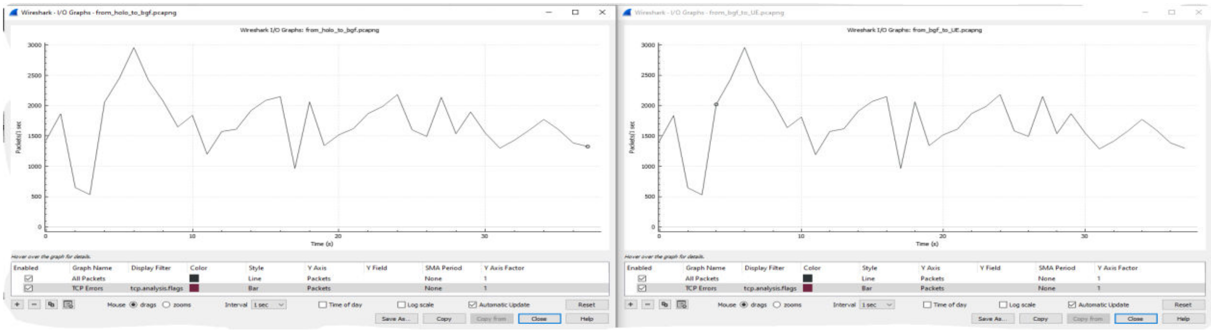


Figure 17: Graph of packet dump during MATSUKO IMS call (VoWIFI setup).

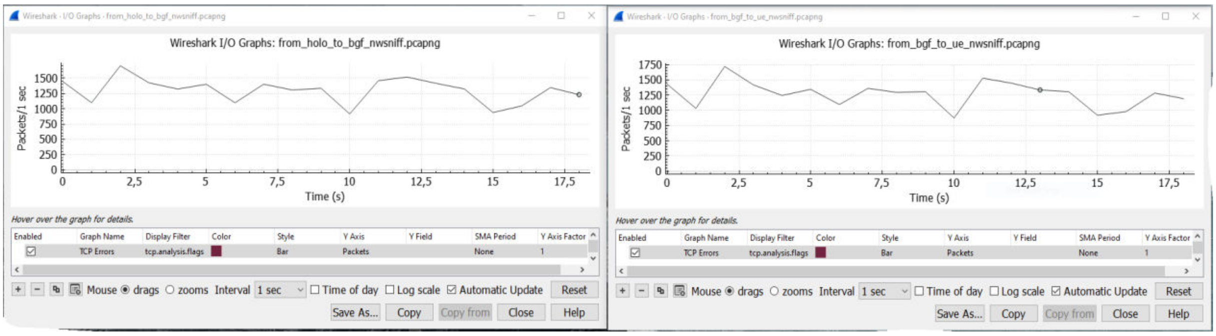


Figure 18: Graph of packet dump during MATSUKO IMS call (VoLTE setup).

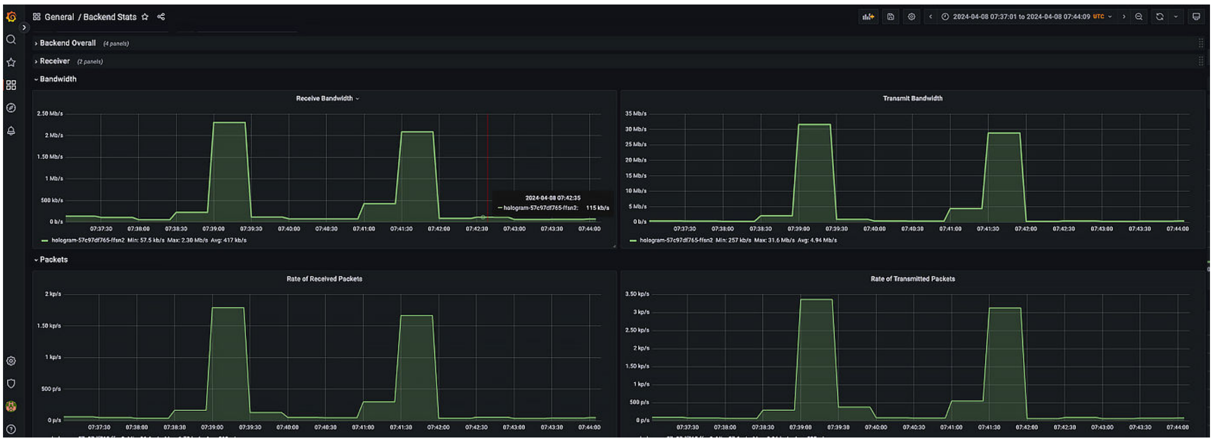


Figure 19: MATSUKO backend monitoring dashboard.

3.4 INFRASTRUCTURE SETUP FOR UC3

The infrastructure required in the South Node for the control plane use case (UC3) is illustrated in Figure 20 below. The elements of the infrastructure that have been deployed or enhanced for this project are: (i) the IMS core functionalities on an Openstack cluster running in 5TONIC (ii) the novel IMS Data Channel (IMSDC) functions in an Azure environment at Madrid area; (iii) the Matsuko application servers in an AWS environment.

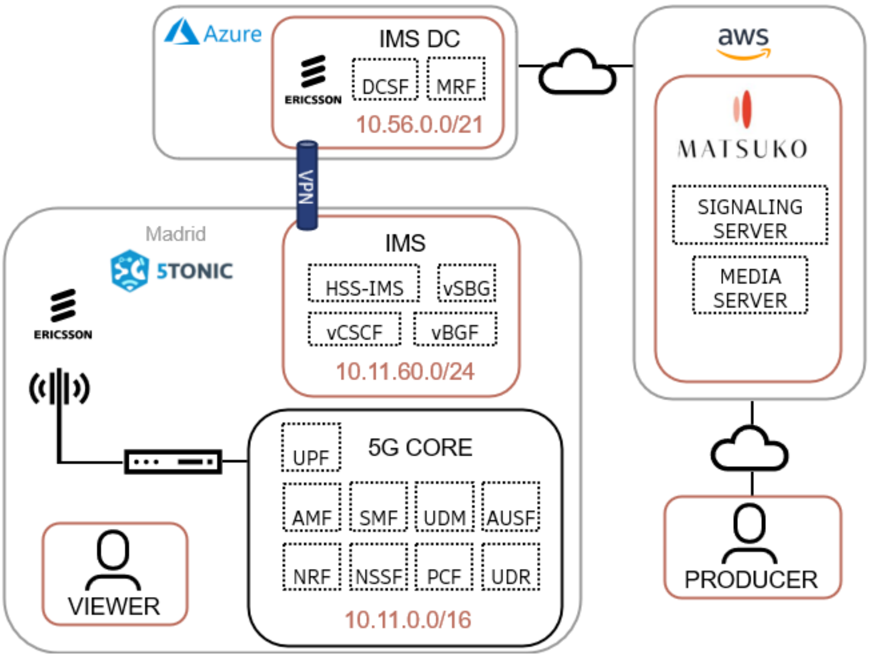


Figure 20: Infrastructure setup for UC3.

The IMS core functions are implemented in the virtualized components Call Session Control Function (CSCF), Signalling Border Gateway (SBG) and Border Gateway Function (BGF). The Home Subscriber Server for IMS (HSS-IMS) has also been deployed for this project to manage the provision of the IMS subscribers in the network. It is part of the latest releases of the containerized Unified Data Management (UDM) in the 5G Core offering by Ericsson, so the 5G Core was upgraded in 5TONIC to support that function. The IP address pool configured for the IMS subscribers is 10.3.212.0/24 so the UEs connected to the 5G network on the viewer side will get IP addresses assigned dynamically from that range. The Ericsson's IMS core platform is a mature technology and it is not the focus in terms of innovation of this project, but it had to be deployed from scratch at 5TONIC to hold the use case. More details about its operation can be found at Ericsson's portfolio webpage [7].

To be able to communicate with the specific IMSDC functions, an IPSec tunnel was configured between 5TONIC and the Azure environment where the IMSDC VMs were deployed. The VMs are using IP addresses within the range 10.56.0.0/21. As it was described in WP2 deliverables [8], the *IMSDC Server (IMSDCS)* is the enabler targeted under WP2 scope. It includes the virtualized Data Channel Signalling Function (DCSF) and the MRF.

The IMSDCS needs to have connectivity with Matsuko application servers. The signalling and media servers are deployed in an AWS environment and their session management endpoint is reachable on the URL wss://matsuko-6gxr.matsuko.com via public connectivity. The Holographic Interactive Service (Holo-IS) Data Channel Media Function (DCMF) node sits between the caller's mobile phone and the MATSUKO signalling and reconstruction servers.

Figure 21 shows an overview of the connectivity. The diagram shows all established connections among the components, explaining which type of protocols and channels are being used (IMS Audio, WebRTC Audio, WebRTC Data Channel, WebSocket for signalling).

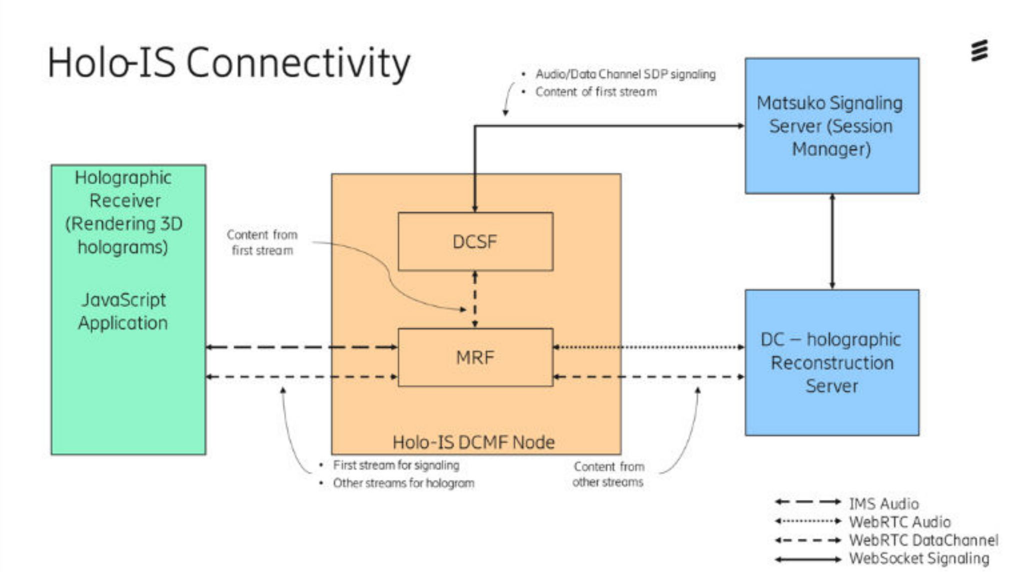


Figure 21: Signalling between the Holographic Interactive Service (Holo-IS) Data Channel Media Function (DCMF) node and the MATSUKO signalling server.

4 VALIDATION AND KPVI ASSESSMENT OF HOLOGRAPHIC USE CASES

4.1 VALIDATION PLAN AND PROCESS

The preparation of the validation plan and timeline for WP6 was structured around creating a common template (Annex A) that could be applied consistently across all partners and test scenarios. This template was designed to capture the essential elements of each test case in a clear and harmonized manner, ensuring that results could be easily compared, aggregated, and analysed across different platforms and use cases.

The methodology involved collaborative input from technical partners to define the scope of fields that would cover both technical KPIs (such as bandwidth, latency, jitter) and user-centric Key Value Indicators (KVIs) (e.g., reliability, fairness), usability or QoE (e.g., perceived quality) metrics. By aligning early on a unified structure, the consortium minimized ambiguities and streamlined the validation workflow, allowing test leaders at each site to follow the same logical process for planning, executing, validating, and reporting. This shared approach also ensured traceability across the validation timeline, from initial connectivity tests through to full E2E and QoE evaluations.

Within the template, several key fields were identified to guarantee consistency in test case definition and execution. For example, each test case entry included a Test Case ID (e.g., SN_UC3_1.1), the test location (e.g. 5TONIC), and the responsible partners, providing accountability and clarity. Additional fields described the test scenario/user story, outlining the sequence of actions (e.g., establishing a holographic call between two participants). The metrics to use section specified tools such as Grafana dashboards for collecting KPIs, while the environmental conditions captured parameters like network segment (RAN, Edge, core) and whether background traffic was present. The execution fields further detailed the number of repetitions, elapsed time per test (e.g., 2-minute holographic sessions), and expected outcomes, such as validated connectivity or acceptable latency thresholds. This structured approach allowed every partner to design and execute tests in a reproducible way, forming the backbone of the validation process

The KVIs were addressed through a survey questionnaire (Annex B), which gathered participants' perceptions of the societal, cultural, and environmental impacts of XR technologies. The questionnaire included demographic and familiarity questions, performance and impact ratings, and specific items mapping to KVIs such as inclusiveness, fairness, equal access to services (education, healthcare, industry), environmental sustainability (reducing travel), and societal sustainability (lower costs, new training and business opportunities). It also assessed acceptance and comparative value of holographic communication against traditional videoconferencing.

4.2 TEST CASE DEFINITIONS

4.2.1 UC1 and UC2

UC1 of 6G-XR was split into two main Test Case categories, which are based on detecting and reacting to congestion situations in the serving 5G cell. In both categories of Test Cases, the first step consists of monitoring and detecting congestion situations, probably adding interfering traffic, and immediately notifying the Holo Orchestrator about them. However, the Test Cases differ in the specific mitigation action adopted to react / overcome the congestion situation. On the one hand, SN_UC1_1 test cases are based on indicating the active Holo Clients (SN_UC1_1.1) or Remote Renderers (SN_UC1_1.2 via WebRTC, SN_UC1_1.3 via DASH) to adapt (lower) their transmitted data rate to fit the available network resources/capacity. On the other hand, SN_UC1_2 series are based on requesting QoD to the 5G network to prioritize the involved holographic communication streams, coming from Holo Clients (UC1_2.1) or from the Remote Renderers (UC1_2.2).

Table 3: UC1 Test Cases.

Test Case Id	Test Case Title	Description and Goal	How Data is collected	Responsible Partners	Validation Period
SN_UC1_1.1	Congestion Detection and Client-driven Rate Adaptation	Detection of 5G congestion situations and request the adaptation of the clients' data rate to keep a decent QoS	Prometheus (and Grafana) on the holographic comm platform components and on the 5G network	I2CAT and Ericsson	M28-M34
SN_UC1_1.2	Congestion Detection and Rate Adaptation from Remote Renderer using WebRTC	Detection of 5G congestion situations and request the adaptation of the data rate at the Remote Renderer	Prometheus (and Grafana) on the lightweight XR Client, and ELK on the 5G network	Vicomtech	M28-M34
SN_UC1_1.3	Congestion Detection and Rate Adaptation from Remote Renderer using DASH	Detection of 5G congestion situations and lightweight XR Client adaptation of the data rate	Prometheus (and Grafana) on the lightweight XR Client, and ELK on the 5G network	Vicomtech	M28-M34
SN_UC1_2.1	Congestion Detection and QoD triggering for holographic comm streams from clients	Detection of 5G congestion situations and request QoD prioritization to the XR streams from active holographic comm components	Prometheus (and Grafana) on the holographic comm platform components and on the 5G network	I2CAT and Ericsson	M28-M34
SN_UC1_2.2	Congestion Detection and QoD triggering for holographic comm streams from Remote Renderers	Detection of 5G congestion situations and request QoD prioritization to the Remote Renderer streams		Vicomtech	M28-M34

To ensure the correct operation of UC2, four distinct test cases have been defined: SN_UC2_2.1, SN_UC2_2.2, SN_UC2_2.3, and SN_UC2_2.4.

Test cases SN_UC2_2.1 and SN_UC2_2.2 primarily aim to validate the connectivity between XR enablers (developed in WP3) deployed at the i2CAT facilities, as well as the interconnection between the i2CAT and 5TONIC testbeds respectively. These scenarios serve as preliminary setup validations, facilitating the execution of the subsequent functional tests represented by SN_UC2_2.3 and SN_UC2_2.4.

SN_UC2_2.3 and SN_UC2_2.4 focus on assessing the functionality of the Simple Edge Discovery API (WP2 compute enabler) integrated with the previously validated XR enablers (from WP3). These test cases enable the selection of the Edge node closest to the UE and allow for the collection of KPIs such as latency and Round-Trip Time (RTT) to evaluate whether this selection improves connectivity. Specifically, SN_UC2_2.3 involves selecting the Barcelona Edge, where the SFU application is deployed, while SN_UC2_2.4 targets the Madrid Edge, hosting the Remote Renderer application.

4.2.2 UC3

Test cases SN_UC3_1.1 and SN_UC3_1.2 are defined to validate the connectivity and performance of one-way IMS Data Channel–based AR communication using MATSUKO technology, where a hologram is transmitted in real time to a smartphone viewer.

Test case SN_UC3_1.1 focuses on verifying connectivity by ensuring that all system components, Ericsson 5G RAN, standalone/non-standalone 5G core, IMS Data Channel, and MEC resources at 5TONIC, are properly deployed, ports configured, and able to establish a seamless session for holographic transmission.

Test case SN_UC3_1.2 extends the scope to performance validation, assessing end-to-end session behaviour under active holographic communication. It measures key KPIs such as bandwidth, latency, and jitter collected through Grafana, confirming that the system meets the expected connectivity and quality thresholds during live hologram rendering.

Together, these test cases provide the baseline verification that underpins subsequent user experience and QoE evaluations in UC3.

Table 4: UC3 Test Cases.

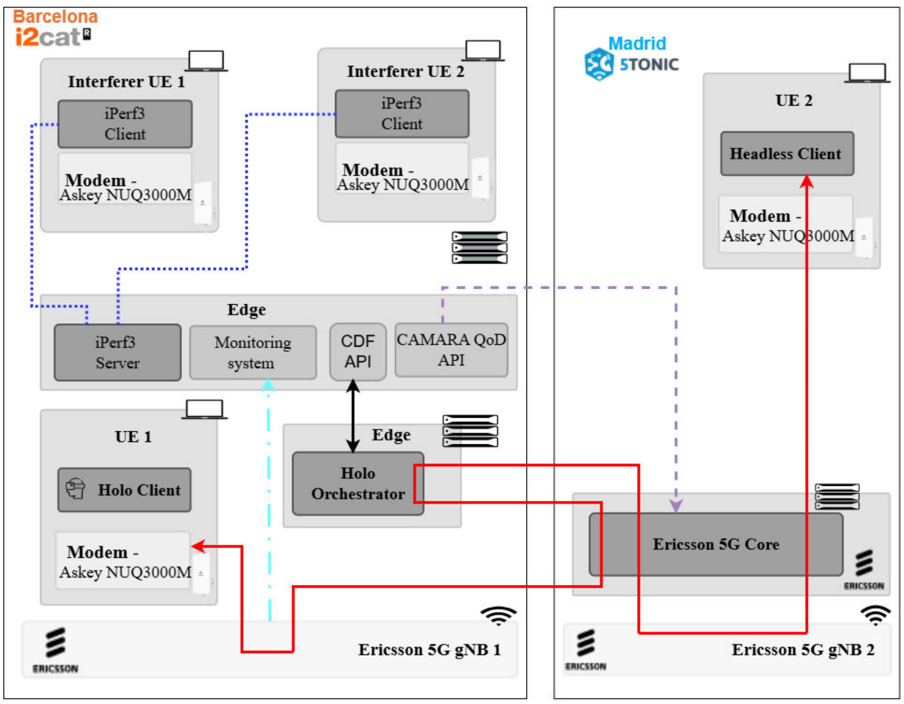
Test Case Id	Test Case Title	Description and Goal	How Data are collected	Responsible Partners	Validation Period
SN_UC3_1.1	IMS Data Channel using MATSUKO – connectivity test	Testing and validation of one-way IMS Data Channel AR Communication using MATSUKO technology, all components are connected.	Prometheus (and Grafana) on the holographic comm platform components and on the 5G network and/or logs.	MATSUKO and Ericsson	M28-M34
SN_UC3_1.2	IMS Data Channel using MATSUKO – E2E test	Testing and validation of one-way IMS Data Channel AR Communication using MATSUKO technology, one hologram is being seen in real time by a viewer on the smartphone.	Prometheus (and Grafana) on the holographic comm platform components and on the 5G network and/or logs.	MATSUKO and Ericsson	M28-M34

4.3 TEST CASE SETUP AND EXECUTION

4.3.1 UC1 and UC2

This subsection details the description, objectives, setups, conditions and expected results from each of the Test Cases as part of UC1 and UC2.

4.3.1.1 UC1 - Congestion Detection and Client-driven Rate Adaptation

	UC1- Congestion Detection and Client-driven Rate Adaptation			
Test Case Id	SN_UC1_1.1			
Test Case Name	Congestion Detection and Client-driven Rate Adaptation			
Test Case Objective	Detection of 5G congestion situations and request the adaptation of the clients' data rate to keep a decent QoS.			
Test Case Category	Validation and KPI Measurements			
Test Environment	South Node / i2CAT and 5TONIC			
Test Deployment Setup	 *Figure 22: SN_UC1_1.1 Test deployment setup.*			
Network Setup	**RAN:** Ericsson 5G gNodeB	**5G Core:** Ericsson 5G Core	**Edge:** SFU	**Band:** n77 **Bandwidth:** 40 MHz
Test Configuration	**Components under test:** Holo Client, SFU, Holo Orchestrator, CDF	**Test software:** Iperf3, Prometheus, Grafana	**Test devices:** Laptops as Holo Clients, Laptops as Interferers transmitting in the same serving 5G cell	**Testing payload data:** Audio and Point Cloud streams for holographic comm session (details in D3.2) and Iperf3 (UDP) data streams
Initial Conditions/Prerequisites				

1. The 5G access and core network infrastructure are fully operational and configured for end-to-end service connectivity. The used bandwidth on i2CAT side is 40 MHz on mid-band (n77), which allows to easily reach the congestion that the test case needs. The bandwidth on 5TONIC side is higher than on i2CAT side, so it will not limit the performance. 2. The Holo Orchestrator and Selective Forwarding Unit (SFU) components are deployed and integrated at the network Edge, enabling low-latency session management and media distribution. 3. The Congestion Detection Function (CDF) is instantiated within the infrastructure and interfaced with the 5G network for real-time monitoring of radio access performance. 4. The hardware platforms designated for Holo Client execution are provisioned and connected through 5G Customer Premises Equipment (CPE) to ensure high-throughput uplink and downlink performance. 5. The systems intended to generate controlled interfering traffic are configured and connected via 5G CPE, facilitating repeatable congestion scenarios for experimental validation. 6. All users have the same low priority profile.
Test scenario
Test steps as follows: 1. Two Holo Client create a new holographic communication session over the 5G network. 2. It is assessed whether the session is stable and of high-quality. 3. Interfering traffic sources are activated. 4. Congestion occurs, affecting to the quality and smoothness of the media session. 5. The CDF detects congestion and recommends data rate adaptations to the Holo Clients via the Holo Orchestrator. 6. The Holo Clients adapt the transmitted data rate, and the quality and smoothness of the session is re-established.
Test variables
The Holo Clients send initially a volumetric video stream around 15 Mbps, and reduced data rate around 5 Mbps upon congestion alarm notification. Congestion is added to the network using the *iperf3* tool, via UDP traffic.
Expected behaviour/Target Values
1. The holographic communication session is stable (around 15 fps, around 150 ms delays, without audiovisual artifacts) over 5G when no congestion. 2. The CDF can identify congestion situations in the 5G cell 3. QoS metrics degrade (fps, delays) and audiovisual artifacts when forcing congestion. 4. QoS metrics (fps, delays) are re-established to satisfactory ranges when applying rate adaptation (although with a slightly lower quality of the holograms

4.3.1.2 UC1 - Remote Renderer with WebRTC Network-Assisted Rate Control Test Case

	UC1- Remote Renderer with WebRTC Network-Assisted Rate Control Test Case
Test Case Id	SN_UC1_1.2
Test Case Name	Remote Renderer with WebRTC Network-Assisted Rate Control Test Case
Test Case Objective	Evaluation of WebRTC network-assisted Rate Control implemented at the Remote Renderer to adjust the video streaming to the monitored network conditions. The system is considered adequate if the Remote Renderer receives information from four full-fledged XR clients and streams the result to a lightweight XR Client, while the Rate Control instructs the Remote Renderer to adjust the video representation.
Test Case Category	Validation and KPI Measurements
Test Environment	South Node / Indoor laboratory

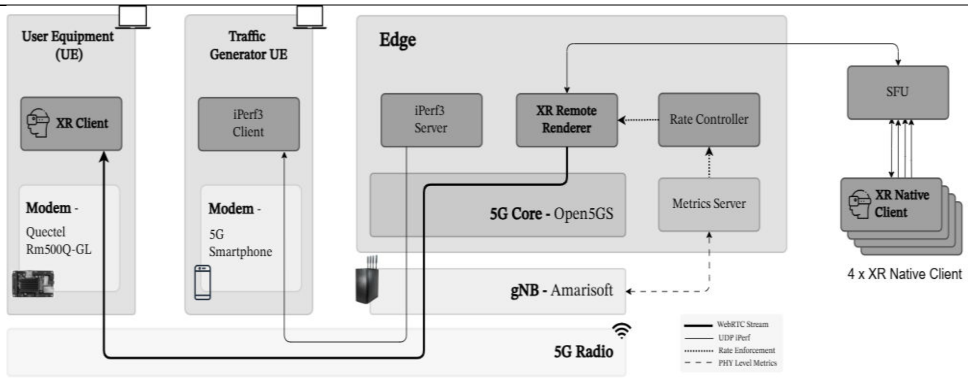
<table>
<tr><td>Test Deployment Setup</td><td colspan="4">

Figure 23: SN_UC1_1.2 Test deployment setup.</td></tr>
<tr><td>Network Setup</td><td>RAN: Amarisoft gNodeB</td><td>5G Core: Open5GS</td><td>Edge: Remote Renderer configured for WebRTC</td><td>Band: n78
Bandwidth: 100 MHz</td></tr>
<tr><td>Test Configuration</td><td>Components under test: Remote Renderer, Rate Control, lightweight Web Client</td><td>Test software: Iperf3, Prometheus, Grafana, Elastic Stack</td><td>Test devices: Laptop with Quectel modem for Web Client, Laptop with 5G smartphone for traffic generator</td><td>Testing payload data: WebRTC (SRTP/UDP) and Iperf3 (UDP) data streams</td></tr>
<tr><td colspan="5">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="5">1. The Remote Renderer is onboarded at the Edge server but not deployed.
2. The 5G Core and gNodeB are deployed and provide connection between the Edge and the UE.
3. The UE is connected to the 5G network.
4. The lightweight XR Client, based on a WebRTC web player, is deployed and accessible by the UE.</td></tr>
<tr><td colspan="5">Test scenario</td></tr>
<tr><td colspan="5">Test steps as follows:
1. Four remote users with native full-fledged XR clients are connected through the SFU.
2. The Remote Renderer is deployed at the Edge server to serve the lightweight XR Client.
3. The Remote Renderer renders the four remote interactive users in the VR scene.
4. The lightweight XR Client connects to the Remote Renderer and start an interactive WebRTC session.
5. The Remote Renderer sends the rendered VR scene through WebRTC to the lightweight XR Client, which visualizes it and interacts with it.
6. The lightweight XR Client collects its media streaming metrics during the WebRTC session.
7. Congestion is generated and the WebRTC stream visualization is affected.
8. The RAN/gNodeB informs the Rate Controller concerning the congestion.
9. The Rate Controller reduces the Remote Renderer video representation (resolution and bitrate) of the WebRTC stream.
10. The WebRTC stream visualization at the lightweight XR Client is restored at a lower video quality.
11. The lightweight XR Client is stopped, the metric collection is terminated, and the Remote Renderer frees the resources.</td></tr>
<tr><td colspan="5">Test variables</td></tr>
<tr><td colspan="5">The Remote Renderer uses WebRTC to stream video in 4K quality at 30 fps. Congestion is added to the network using the iperf3 tool. The congestion is detected, then the Remote Renderer is instructed to change the video streaming quality to 720p and 30 fps.</td></tr>
<tr><td colspan="5">Expected behaviour/Target Values</td></tr>
<tr><td colspan="5">1. The Remote Renderer renders five users in the VR scene, including 4 remote users with native full-fledged XR Clients connected through SFU and a lightweight XR Client based on a WebRTC web player.
- Remote Rendering users > 4 interactive users
2. The latency and the RTT between the Remote Renderer and the lightweight XR Client allow a smooth XR experience.
- Network RTT < 50 ms</td></tr>
</table>

- Downlink network latency < 25 ms
- WebRTC RTT < 50 ms

4.3.1.3 UC1 - Remote Renderer with DASH Client-based Rate Control Test Case

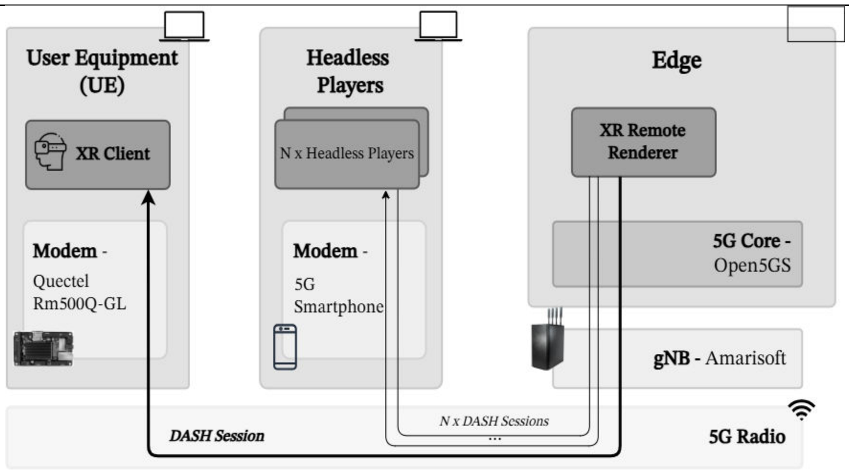
<table>
<tr><th></th><th colspan="4">UC1 - Remote Renderer with DASH Client-based Rate Control Test Case</th></tr>
<tr><td>Test Case Id</td><td colspan="4">SN_UC1_1.3</td></tr>
<tr><td>Test Case Name</td><td colspan="4">Remote Renderer with DASH Client-based Rate Control Test Case</td></tr>
<tr><td>Test Case Objective</td><td colspan="4">Evaluation of DASH rate control implemented at passive XR Client to select the appropriate representation among the available ones generated by the Remote Renderer. The system is considered adequate if the Remote Renderer can generate three representations in parallel, while the passive XR Client can switch among them based on monitored network.</td></tr>
<tr><td>Test Case Category</td><td colspan="4">Validation and KPI Measurements</td></tr>
<tr><td>Test Environment</td><td colspan="4">South Node / Indoor laboratory</td></tr>
<tr><td>Test Deployment Setup</td><td colspan="4">

Figure 24: SN_UC1_1.3 Test deployment setup.</td></tr>
<tr><td>Network Setup</td><td>RAN: Amarisoft gNodeB</td><td>5G Core: Open5GS</td><td>Edge: Remote Renderer configured for DASH</td><td>Band: n78
Bandwidth: 100 MHz</td></tr>
<tr><td>Test Configuration</td><td>Components under test: Remote Renderer, passive Web Client</td><td>Test software: Prometheus, Grafana, Elastic Stack</td><td>Test devices: Laptop with Quectel modem for Web Client, Laptop with 5G smartphone for Headless Players</td><td>Testing payload data: DASH (HTTP/TCP) data streams</td></tr>
<tr><td colspan="5">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="5">1. The Remote Renderer is onboarded at the Edge but not deployed.
2. The 5G Core and gNodeB are deployed and provide connection between the Edge and the UE.
3. The UE is connected to the 5G network.
4. The passive XR Client, based on a DASH web player, is deployed and accessible by the UE.</td></tr>
<tr><td colspan="5">Test scenario</td></tr>
</table>

Test steps as follows: 1. The Remote Renderer is deployed at the Edge server to serve the passive XR Client through its internal HTTP server that serves the generated DASH representations. 2. The passive XR Client connects to the Remote Renderer and start a DASH streaming session and visualize the remotely rendered content with the highest available video representation (highest resolution and bitrate). 3. The passive XR Client collects its media streaming metrics during the DASH session. 4. Congestion is generated by starting a number N of DASH headless players. 5. The passive XR Client detects the network congestion and selects a lower quality video representation (lower resolution and bitrate). 6. The passive XR Client is stopped, the metric collection is terminated, and the Remote Renderer frees the resources.
Test variables
The Remote Renderer provides three DASH representations at 30 fps: 1080p encoded at 15 Mbps (high), 720p encoded at 5 Mbps (medium), and 360p encoded at 1 Mbps (low). Network congestion is generated by deploying N headless players that download the DASH content. The passive XR Client player periodically measures the available throughput and selects the appropriate DASH representation.
Expected behaviour/Target Values
1. The Remote Renderer with its internal HTTP Server serves at least 100 passive users. - Remote Rendering users ≥ 100 passive users 2. The Remote Renderer generates three DASH video quality representations for passive users. - Media quality levels from Remote Rendering modules for passive consumers ≥ 3

4.3.1.4 UC1- Congestion Detection and QoD triggering for holographic communication streams, from clients

	UC1- Congestion Detection and QoD triggering for holographic communication streams, from clients
Test Case Id	SN_UC1_2.1
Test Case Name	Congestion Detection and QoD triggering for holographic communication streams, from clients
Test Case Objective	Detection of 5G congestion situations and request QoD prioritization to the XR streams from active holographic communication components
Test Case Category	Validation and KPI Measurements
Test Environment	South Node / i2CAT and 5TONIC

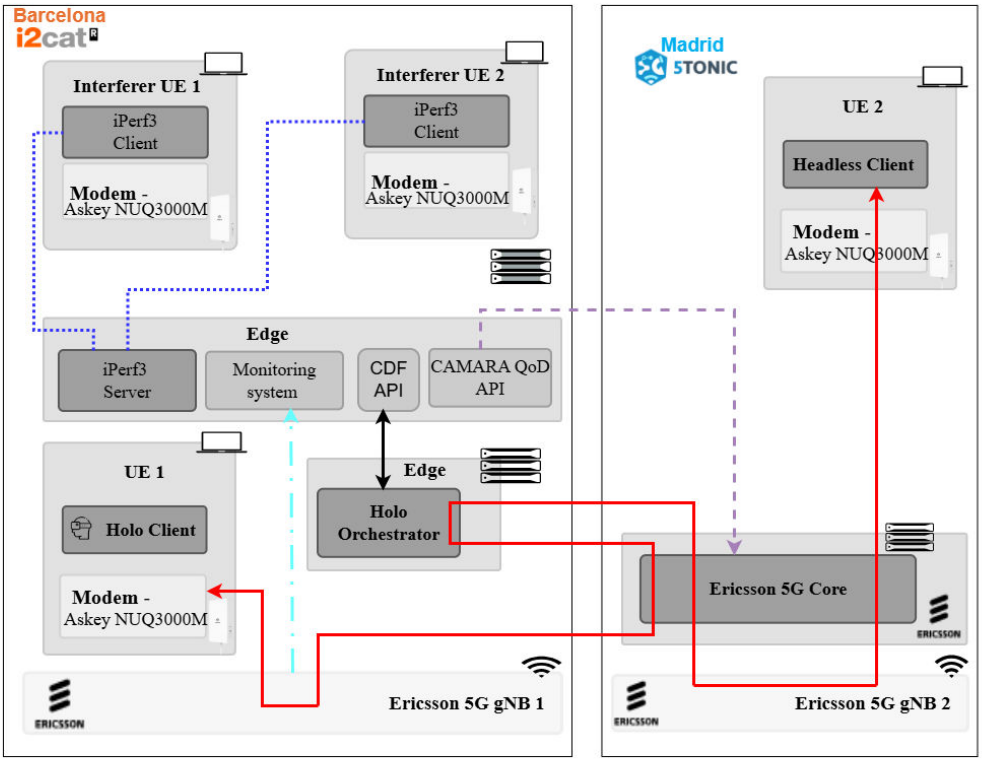
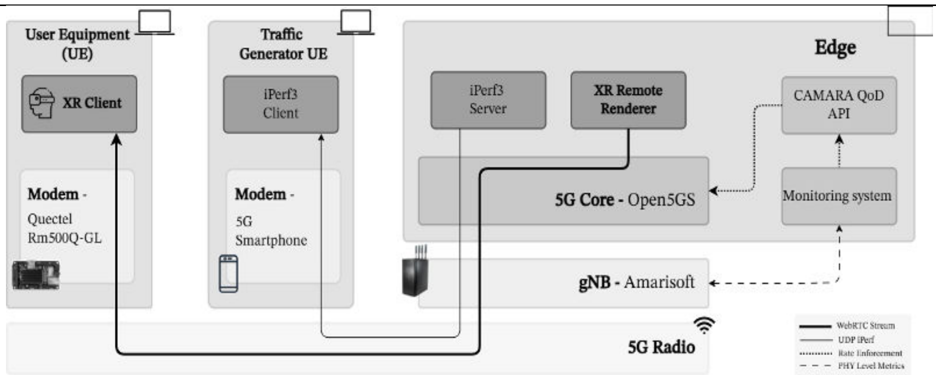
<table>
<tr><td>Test Deployment Setup</td><td colspan="4">

Figure 25: SN_UC1_2.1 Test deployment setup.</td></tr>
<tr><td>Network Setup</td><td>RAN: Ericsson 5G gNodeB</td><td>5G Core: Ericsson 5G Core</td><td>Edge: SFU</td><td>Band: n77
Bandwidth: 40 MHz</td></tr>
<tr><td>Test Configuration</td><td>Components under test: Holo Client, SFU, Holo Orchestrator, CDF, CAMARA QoD API</td><td>Test software: Iperf3, Prometheus, Grafana</td><td>Test devices: Laptops as Holo Clients, Laptops as Interferers transmitting in the same serving 5G cell</td><td>Testing payload data: Audio and Point Cloud streams for holographic comm session (details in D3.2) and Iperf3 (UDP) data streams</td></tr>
<tr><td colspan="5">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="5">1. The 5G access and core network infrastructure are fully operational and configured for end-to-end service connectivity. The used bandwidth on i2CAT side is 40 MHz on mid-band (n77), which allows to easily reach the congestion that the test case needs. The bandwidth on 5TONIC side is higher than on i2CAT side, so it will not limit the performance.
2. The Holo Orchestrator and Selective Forwarding Unit (SFU) components are deployed and integrated at the network edge, enabling low-latency session management and media distribution.
3. The Congestion Detection Function (CDF) is instantiated within the infrastructure and interfaced with the 5G network for real-time monitoring of radio access performance.
4. The hardware platforms designated for Holo Client execution are provisioned and connected through 5G Customer Premises Equipment (CPE) to ensure high-throughput uplink and downlink performance.
5. The systems intended to generate controlled interfering traffic are configured and connected via 5G CPE, facilitating repeatable congestion scenarios for experimental validation.
6. All users have the same low priority profile.</td></tr>
<tr><td colspan="5">Test scenario</td></tr>
</table>

Test steps as follows: 1. Two Holo Client create a new holographic communication session over the 5G network. 2. It is assessed whether the session is stable and of high quality. 3. Interfering traffic sources are activated. 4. Congestion occurs, affecting to the quality and smoothness of the media session. 5. The CDF detects congestion and informs the Holo Orchestrator, which decided to trigger QoD for the affected streams. 6. QoD is applied, and the quality and smoothness of the session is re-established.
Test variables
The Holo Clients send initially a volumetric video stream around 15 Mbps. Congestion is added to the network using the *iperf3* tool, via UDP traffic.
Expected behaviour/Target Values
1. The holographic communication session is stable (around 15 fps, around 150 ms end-to-end delays, without audiovisual artifacts) over 5G when no congestion. 2. The CDF can identify congestion situations in the 5G cell. 3. QoS metrics degrade (fps, delays) and audiovisual artifacts when forcing congestion. 4. QoS metrics (fps, delays) are re-established to satisfactory ranges when applying QoD.

4.3.1.5 UC1 - Quality on Demand for Remote Renderer and WebRTC streaming Test Case

	UC1 - Quality on Demand for Remote Renderer and WebRTC streaming Test Case			
Test Case Id	SN_UC1_2.2			
Test Case Name	Quality on Demand for Remote Renderer and WebRTC streaming Test Case			
Test Case Objective	Evaluation of CAMARA QoD API to prioritize WebRTC traffic generated by the Remote Renderer under network congestion scenarios. The system is considered adequate if the CAMARA QoD API guarantees the correct transmission of the WebRTC stream between the Remote Renderer and the lightweight XR Client.			
Test Case Category	Validation and KPI Measurements			
Test Environment	South Node / Indoor laboratory			
Test Deployment Setup	 *Figure 26: SN_UC1_2.2 Test deployment setup.*			
Network Setup	**RAN:** Amarisoft gNodeB	**5G Core:** Open5GS	**Edge:** Remote Renderer configured for WebRTC	**Band:** n78 **Bandwidth:** 100 MHz
Test Configuration	**Components under test:** Remote Renderer, CAMARA QoD, lightweight Web Client	**Test software:** Iperf3, Prometheus, Grafana, Elastic Stack	**Test devices:** Laptop with Quectel modem for Web Client, Laptop with 5G smartphone for traffic generator	**Testing payload data:** WebRTC (SRTP/UDP) and Iperf3 (UDP) data streams

Initial Conditions/Prerequisites
1. The Remote Renderer is onboarded at the Edge but not deployed. 2. The 5G Core and gNodeB are deployed and provide connection between the Edge and the UE. 3. The CAMARA QoD API is deployed and connected to the 5G Core. 4. The UE is connected to the 5G network. 5. The lightweight XR Client, based on a WebRTC web player, is deployed and accessible by the UE.
Test scenario
Test steps as follows: 1. The Remote Renderer is deployed at the Edge server to render the VR scene and serve the lightweight XR Client. 2. The lightweight XR Client connects to the Remote Renderer and start an interactive WebRTC session. 3. The Remote Renderer sends the rendered VR scene through WebRTC to the lightweight XR Client, which visualizes it and interacts with it. 4. The lightweight XR Client collects its media streaming metrics during the WebRTC session. 5. Congestion is generated and the WebRTC stream visualization is affected. 6. The RAN/gNodeB informs the congestion and the CAMARA QoD is activated to prioritize the WebRTC stream. 7. The WebRTC stream visualization at the lightweight XR Client is restored. 8. The lightweight XR Client is stopped, the metric collection is terminated, and the Remote Renderer frees the resources.
Test variables
In the initial state, CAMARA QoD is not employed. It is triggered upon detection of congestion to ensure WebRTC transmission between the Remote Renderer and the lightweight XR Client. Two CAMARA QoD profiles are configured to separate the traffic into different network slices: - QoS_M (UL = 4 Mbps; DL = 40 Mbps) is employed for prioritising the downlink traffic generated from the Remote Renderer to the lightweight XR Client. - QoS_S (UL = 4 Mbps; DL = 4 Mbps) is employed for the background traffic generated with iperf3 to have network congestion.
Expected behaviour/Target Values
1. The latency and the RTT between the Remote Renderer and the lightweight XR Client allow a smooth XR experience. - Network RTT < 50 ms - Downlink network latency < 25 ms - WebRTC RTT < 50 ms

4.3.1.6 UC2 – Performance validation in i2CAT testbed Test Case

	UC2 – Performance validation in i2CAT testbed Test Case
Test Case ID	SN_UC2_2.1
Test Case Name	Performance validation in i2CAT (Barcelona) testbed
Test Case Objective	Testing and validation of end-to-end communication among all use case participants including Holo Orchestrator, SFU and XR Metrics Servers. The Edge orchestrator (IEAP) is omitted as no best Edge selection is needed.
Test Case Category	Connectivity and Performance validation test
Test Environment	I2CAT (Barcelona) testbed

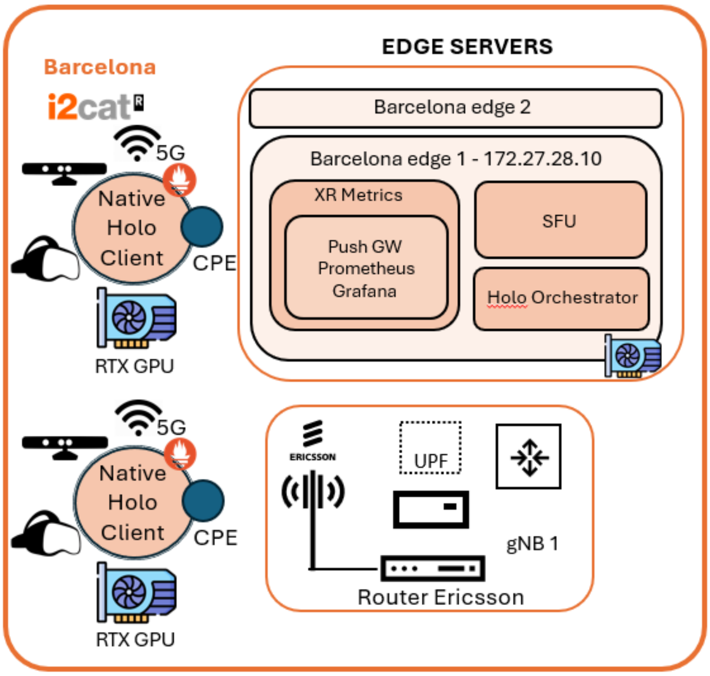
<table>
<tr><td>Test Deployment Setup</td><td colspan="7">

Figure 27: SN_UC2_2.1 Test deployment setup.</td></tr>
<tr><td>Network Setup</td><td>RAN:</td><td>Ericsson</td><td>5G Core:</td><td>Ericsson 5G Core</td><td>MEC:</td><td>-</td><td>Band: n77 + n258
Bandwidth: 440 MHz</td></tr>
<tr><td>Test Configuration</td><td>End Device Density:</td><td>2 UEs</td><td>Mobility Level:</td><td>No mobility</td><td>Has Background Traffic:</td><td colspan="2">No</td></tr>
<tr><td colspan="8">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="8">The following applications (WP3 enablers) deployed at i2CAT facilities: Holo Clients, Holo Orchestrator, SFU and XR Metrics Servers. The total amount of bandwidth available in i2CAT for this test is 40 MHz on mid-band (n77) plus 400 MHz on high-band (n258), operating in carrier aggregation mode. This grants enough capacity for the service traffic, as documented in the South Node performance evaluation reports in D4.3 [3].</td></tr>
<tr><td colspan="8">Test scenario</td></tr>
<tr><td colspan="8">1. Establish a holographic communication session with one native client.
1.1. Connect the native client to the holographic orchestrator.
1.2. Connect the native client to the SFU.
2. Attach a second native client to the holographic session.</td></tr>
<tr><td colspan="8">Test variables</td></tr>
<tr><td colspan="8">The following variables should be satisfied:
1. The end-to-end application up and running.
2. Holographic communication session established properly.</td></tr>
<tr><td colspan="8">Expected behaviour/Target Values</td></tr>
<tr><td colspan="8">Connectivity established properly.</td></tr>
</table>

4.3.1.7 UC2 – i2CAT and 5TONIC testbeds connectivity validation Test Case

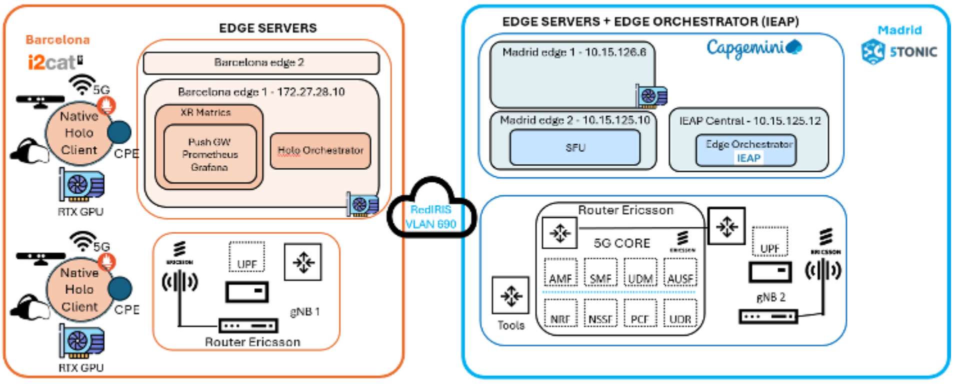
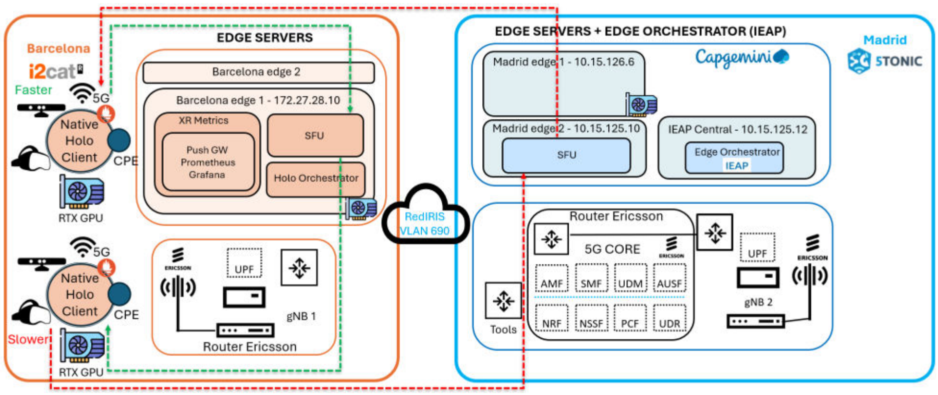
<table>
<tr><th></th><th colspan="6">UC2 – i2CAT and 5TONIC testbeds connectivity validation Test Case</th></tr>
<tr><td>Test Case ID</td><td colspan="6">SN_UC2_2.2</td></tr>
<tr><td>Test Case Name</td><td colspan="6">i2CAT and 5TONIC testbeds connectivity validation</td></tr>
<tr><td>Test Case Objective</td><td colspan="6">Test end to end communication between testbeds (5TONIC and i2CAT). To facilitate the experiment, the same scenario as SN_UC2_2.2 is deployed with the SFU at 5TONIC instead of at i2CAT, and without the Remote Renderer.</td></tr>
<tr><td>Test Case Category</td><td colspan="6">Connectivity test</td></tr>
<tr><td>Test Environment</td><td colspan="6">I2CAT (Barcelona) & 5TONIC (Madrid) testbeds</td></tr>
<tr><td>Test Deployment Setup</td><td colspan="6">

Figure 28: SN_UC2_2.2 Test deployment setup.</td></tr>
<tr><td>Network Setup</td><td>RAN:</td><td>Ericsson</td><td>5G Core:</td><td>Ericsson 5G Core</td><td>MEC:</td><td>IEAP</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td>Band: n78 + n258
Bandwidth: 440 MHz</td></tr>
<tr><td>Test Configuration</td><td>End Device Density:</td><td>2 UEs</td><td>Mobility Level:</td><td>No mobility</td><td>Has Background Traffic:</td><td>No</td></tr>
<tr><td colspan="7">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="7">The following applications deployed at i2CAT facilities: Holo Orchestrator, XR Metrics Servers. The total amount of bandwidth available in i2CAT for this test is 40 MHz on mid-band (n77) plus 400 MHz on high-band (n258), operating in carrier aggregation mode. This grants enough capacity for the service traffic, as documented in the South Node performance evaluation reports in D4.3 [3].</td></tr>
<tr><td colspan="7">Test scenario</td></tr>
<tr><td colspan="7">1. Deploy SFU in Madrid through the Trial Controller.
2. Establish a holographic communication session with 2 native clients.
2.1. Connect the native clients to the holographic orchestrator in Barcelona.
2.2. Connect the native clients to the SFU in Madrid.</td></tr>
<tr><td colspan="7">Test variables</td></tr>
<tr><td colspan="7">The following variables should be satisfied:
1. End-to-end application up and running.
2. Holographic communication session established properly.</td></tr>
<tr><td colspan="7">Expected behaviour/Target Values</td></tr>
<tr><td colspan="7">Connectivity established properly.</td></tr>
</table>

4.3.1.8 UC2 – Best Edge selection for SFU Test Case

	UC2 – Best Edge selection for SFU Test Case					
Test Case ID	SN_UC2_2.3					
Test Case Name	Best Edge selection for SFU					
Test Case Objective	With all components deployed as specified in SN_UC2_2.3, and including the IEAP orchestrator, the objective is to validate the Simple Edge Discovery functionality, enabling the User Equipment (UE) to identify and connect to the nearest Edge node hosting the SFU.					
Test Case Category	Performance: Latency & RTT					
Test Environment	I2CAT (Barcelona) & 5TONIC (Madrid) testbeds					
Test Deployment Setup	 *Figure 29: SN_UC2_2.3 Test deployment setup.*					
Network Setup	**RAN:**	Ericsson	**5G Core:**	Ericsson 5G Core	**MEC:**	IEAP	**Band:** n78 + n258 **Bandwidth:** 440 MHz
Test Configuration	**End Device Density:**	2 UEs	**Mobility Level:**	No mobility	**Has Background Traffic:**	No
Initial Conditions/Prerequisites						
The following applications deployed in Barcelona: XR Metrics Servers, SFU, Holo Orchestrator. The total amount of bandwidth available in i2CAT for this test is 40 MHz on mid-band (n77) plus 400 MHz on high-band (n258), operating in carrier aggregation mode. This grants enough capacity for the service traffic, as documented in the South Node performance evaluation reports in D4.3 [3].						
Test scenario						
1. Deploy SFU in Madrid through Trial Controller. 2. Establish a holographic communication session with 1 native client. 2.1. Connect the native client to the holographic orchestrator in Barcelona. 2.2. Connect the native client to the SFU in Madrid. 3. Add a second native client to the holographic session. 3.1. The Holographic Orchestrator triggers the Simple Edge Discovery API. 3.2. Holographic Orchestrator selects the SFU deployed in the closest Edge (Barcelona).						
Test variables						
The following variables should be satisfied: 1. End-to-end application up and running. 2. First native client connected to SFU deployed in Barcelona. 3. Holographic communication session established properly with first native client. 4. Holographic orchestrator triggers Simple Edge Discovery API properly for the second native client. 5. Second native client connected to SFU deployed in Barcelona.						

Expected behaviour/Target Values
It is expected that RTT results will be lower when the SFU is located at the closest Edge to the UE.

4.3.1.9 UC2 – Best Edge selection for Remote Renderer Test Case

	UC2 – Best Edge selection for Remote Renderer Test Case
Test Case ID	SN_UC2_2.4
Test Case Name	Best Edge selection for Remote Renderer
Test Case Objective	With all components deployed as specified in SN_UC2_2.4, and including the Remote Renderer, the objective is to validate the Simple Edge Discovery functionality, enabling the User Equipment (UE) to identify and connect to the nearest Edge node hosting the Remote Renderer.
Test Case Category	Performance: Latency & RTT
Test Environment	I2CAT (Barcelona) & 5TONIC (Madrid) testbeds

Test Deployment Setup

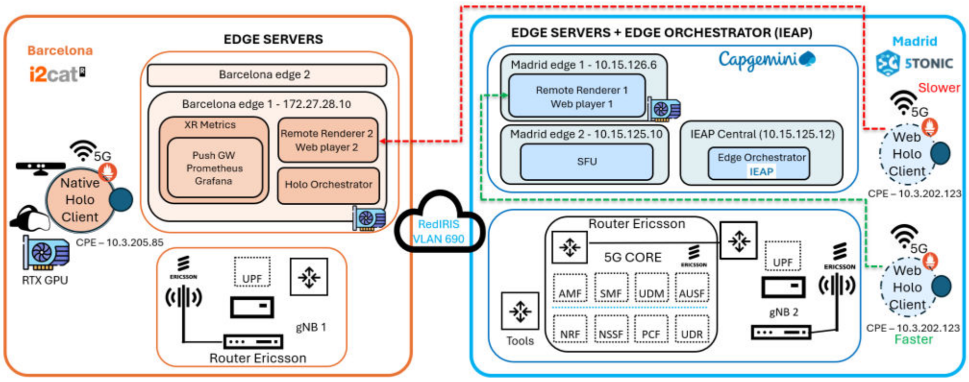


Figure 30: SN_UC2_2.4 Test deployment setup.

Network Setup	**RAN:**	Ericsson	**5G Core:**	Ericsson 5G Core	**MEC:**	IEAP	**Band:** n78 + n258 **Bandwidth:** 440 MHz
Test Configuration	**End Device Density:**	2 UEs	**Mobility Level:**	No mobility	**Has Background Traffic:**	No	

Initial Conditions/Prerequisites
The following applications deployed in Barcelona: XR Metrics Servers, Holo Orchestrator, Remote Renderer. The following applications deployed in Madrid: SFU, Remote Renderer. The total amount of bandwidth available in i2CAT for this test is 40 MHz on mid-band (n77) plus 400 MHz on high-band (n258), operating in carrier aggregation mode. This grants enough capacity for the service traffic, as documented in the South Node performance evaluation reports in D4.3 [3].

Test scenario

1. Establish a holographic communication session with one native client.
    1.1. Connect the native client from Barcelona to the holographic orchestrator.
    1.2. The holographic orchestrator creates a new holographic session with the native client connected.
2. Add a web client to the holographic session.
    2.1. Connect a second web client from Madrid to the holographic orchestrator.
    2.2. The Holographic Orchestrator selects the remote renderer located in Barcelona.
    2.3. This second client joins to the session using the remote renderer located in Barcelona.
3. Add a second web client to the holographic session.

3.1. Connect a third web client from Madrid to the holographic orchestrator. 3.2. The Holographic Orchestrator selects the remote renderer located in Madrid. 3.3. This second client joins to the session using the remote renderer located in Madrid.
Test variables
The following variables should be satisfied: 1. End-to-end application up and running. 2. Holographic orchestrator creates a new session requested by the native client. 3. Holographic orchestrator adds the first web client to the session using a remote renderer deployed in Barcelona. 4. Holographic orchestrator adds the second web client to the session using a remote renderer deployed in Madrid.
Expected behaviour/Target Values
It is expected that RTT results will be lower when the Remote Renderer is located at the closest Edge to the UE.

4.3.2 UC3

The validation plan for WP6 UC3 (holographic communication using IMS Data Channel) follows a structured testing and timeline approach that ensures both technical KPIs and user-centric KVIs are addressed.

The test plan is centred on two main experiment categories:

- Connectivity and performance validation (SN_UC3_1.1, SN_UC3_1.2),
- Quality of Experience (QoE) questionnaires.

Tests are executed at the 5TONIC facility, leveraging Ericsson's 5G RAN and core infrastructure, the IMS Data Channel, and Edge computing resources.

4.3.2.1 UC3 – IMS Data Channel using MATSUKO - connectivity

	UC3 - IMS Data Channel using MATSUKO – connectivity test
Test Case ID	SN_UC3_1.1
Test Case Name	IMS Data Channel using MATSUKO – connectivity test
Test Case Objective	Testing and validation of one-way IMS Data Channel AR Communication using MATSUKO technology, all components are connected.
Test Case Category	Connectivity test
Test Environment	5TONIC

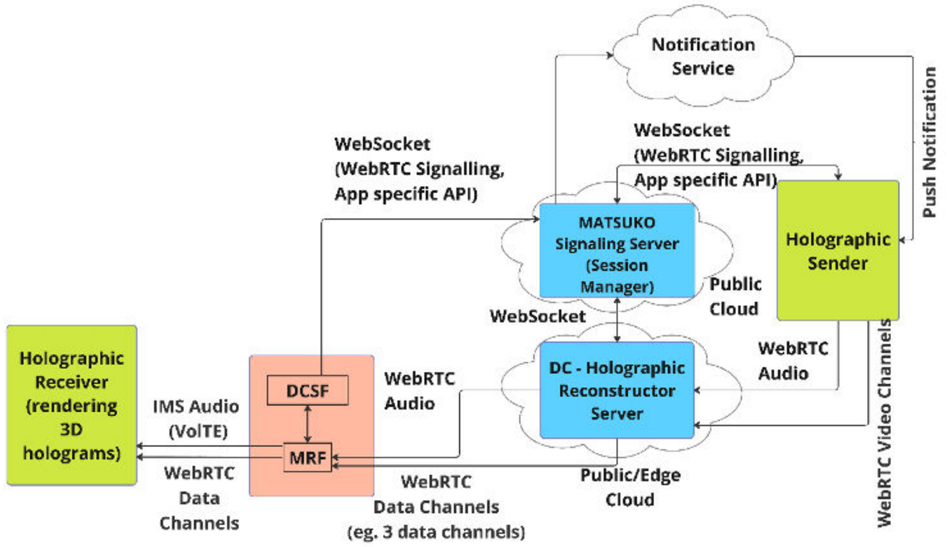
<table>
<tr><td>Test Deployment Setup</td><td colspan="6">

Figure 31: SN_UC3_1.1 Test deployment setup.</td></tr>
<tr><td>Network Setup</td><td>RAN:</td><td>Ericsson</td><td>5G Core:</td><td>Ericsson 5G Core</td><td>MEC:</td><td>Public/Edge Cloud</td></tr>
<tr><td>Test Configuration</td><td>End Device Density:</td><td>2 UEs</td><td>Mobility Level:</td><td>No mobility</td><td>Has Background Traffic:</td><td>No</td></tr>
<tr><td colspan="7">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="7">All components are deployed and firewall specific ports are configured.</td></tr>
<tr><td colspan="7">Test scenario</td></tr>
<tr><td colspan="7">1. Start the holographic session with first native client (iPhone).
1.1. Connect the first native client to the Session Manager.
2. Start the second native client.
2.1. Dial a phone number in the Dialler.
2.2. Accept/Initiate the call and connect to the Session Manager.
3. Receive a push notification on the second native client.</td></tr>
<tr><td colspan="7">Test variables</td></tr>
<tr><td colspan="7">N/A</td></tr>
<tr><td colspan="7">Expected behaviour/Target Values</td></tr>
<tr><td colspan="7">Connectivity established properly. To validate the test the following should be satisfied:
1. Both first native client and second native client are connected to the Session Manager.</td></tr>
</table>

4.3.2.2 UC3 – IMS Data Channel using MATSUKO – E2E

	UC3 – IMS Data Channel using MATSUKO – E2E
Test Case ID	SN_UC3_1.2
Test Case Name	IMS Data Channel using MATSUKO – E2E test
Test Case Objective	Testing and validation of one-way IMS Data Channel AR Communication using MATSUKO technology, one hologram is being seen in real time by a viewer on the smartphone.
Test Case Category	E2E performance test
Test Environment	5TONIC

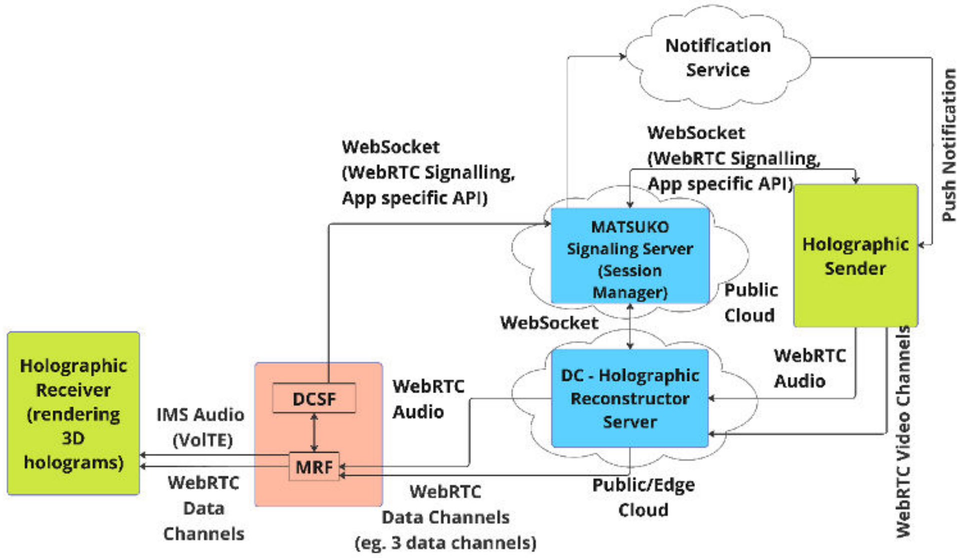
<table>
<tr><td>Test Deployment Setup</td><td colspan="6">

Figure 32: SN_UC3_1.2 Test deployment setup.</td></tr>
<tr><td>Network Setup</td><td>RAN:</td><td>Ericsson</td><td>5G Core:</td><td>Ericsson 5G Core</td><td>MEC:</td><td>Public/Edge Cloud</td></tr>
<tr><td>Test Configuration</td><td>End Device Density:</td><td>2 UEs</td><td>Mobility Level:</td><td>No mobility</td><td>Has Background Traffic:</td><td>No</td></tr>
<tr><td colspan="7">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="7">Test Case SN_UC3_1.1 passed and connectivity of all components on specific ports is ready and working.</td></tr>
<tr><td colspan="7">Test scenario</td></tr>
<tr><td colspan="7">1. Start the holographic session with first native client (iPhone).
2. Start the second native client.
3. Receive a push notification on the second native client
4. Second native client receives the streaming and renders the hologram on the smartphone display.</td></tr>
<tr><td colspan="7">Test variables</td></tr>
<tr><td colspan="7">N/A</td></tr>
<tr><td colspan="7">Expected behaviour/Target Values</td></tr>
<tr><td colspan="7">Connectivity established properly. To validate the test the following should be satisfied:
1. Both first native client and second native client are connected to the Session Manager.
2. Hologram of the first participant is rendered on the second client, on the smartphone display.</td></tr>
</table>

4.4 TEST RESULTS

4.4.1 KPIs UC1 and UC2

4.4.1.1 UC1 - Congestion Detection and Client-driven Rate Adaptation

	UC1 - Congestion Detection and Client-driven Rate Adaptation		
Test Case ID	SN_UC1_1.1		
Test Case Name	Congestion Detection and Client-driven Rate Adaptation		
Test Execution Date	21-28/10/2025		
Test Executed By	I2CAT & Ericsson		
Number of repetitions	> 5 successful repetitions (dataset) but showing evidence for one repetition in this table.		
Verification Points (VP)			
Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*A native Holo Client 1 (connected from i2CAT testbed in Barcelona) establishes a new holographic communication session, by connecting to the Holo Orchestrator via a 5G CPE.*		
ID #2	*A Holo Client 2 (connected from 5TONIC testbed in Madrid), native or headless, joins the same session via a 5G CPE.*		
ID #3	*The 2-user session is established and kept stable.*		
ID #4	*Interfering traffic sources are introduced in the serving 5G cell of Holo Client 1.*		
ID #5	*Quality of Service (QoS) metrics, like delays, frames per second (fps) and visual stability, start to get impacted.*		
ID #6	*The Congestion Detection Function (CDF) detects congestion in the 5G cell and sends a congestion alarm notification to the Holo Orchestrator.*		
ID #7	*Upon receiving the congestion alarm notification, the Holo Orchestrator triggers rate adaptation of the streams from Holo Client 1.*		
ID #8	*The QoS metrics (delays, fps) are re-established to satisfactory levels, and the hologram gets back to a fluid presentation.*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1	The Holo Client 1 connects to the 5G network and transmits uplink traffic corresponding to its audio and volumetric video stream for the hologram presentation. Figure 33 illustrates the uplink PRB utilization by the Holo Client 1 during the test session.	Pass
ID #2	1	The Holo Client 2, connected from the Madrid testbed—either native or headless —joins the same holographic session through a 5G CPE, thus establishing a live holographic call, with bi-directional low-latency communication.	Pass
ID #3	1	The two-user holographic session is successfully established and maintained in a stable manner, ensuring continuous bidirectional data exchange between both Holo Clients through the 5G network. Figure 34 shows the hologram received at Holo Client 2, illustrating the reconstructed 3D representation for the person captured by Holo Client 1 in real time.	Pass
ID #4	1	Two interfering traffic sources are activated within the serving 5G cell of Holo Client 1, generating competing uplink data flows that affect the available radio resources.	Pass
ID #5	1	As network load increases, QoS metrics—such as delay and fps — for the	Pass

		holographic video stream begin to degrade due to resource contention. Figure 35 illustrates the impact of these effects, showing noticeable increase in latency and decrease of received fps, with magnified fluctuations for both metrics, at the receiver side.	
ID #6	1	The Congestion Detection Function (CDF) identifies congestion in the serving 5G cell based on real-time PRB utilization metrics, and it triggers a congestion alarm notification to the Holo Orchestrator. Figure 36 illustrates the corresponding API calls exchanged between the CDF and the Holo Orchestrator during this event. Figure 37 shows the dashboard with the flag “Congestion Detected” when interference is added.	Pass
ID #7	1	Upon receiving the congestion notification, the Holo Orchestrator triggers the rate adaptation for the client by applying new compression settings.	Pass
ID #8	1	After the rate adaptation, key QoS metrics—such as latency and frame rates stabilize, restoring smooth hologram playback and re-establishing satisfactory performance for real-time conversational services. Figure 38 illustrates this improvement for the registered metrics, showing the enhanced performance after prioritization.	Pass
Results / Diagrams			

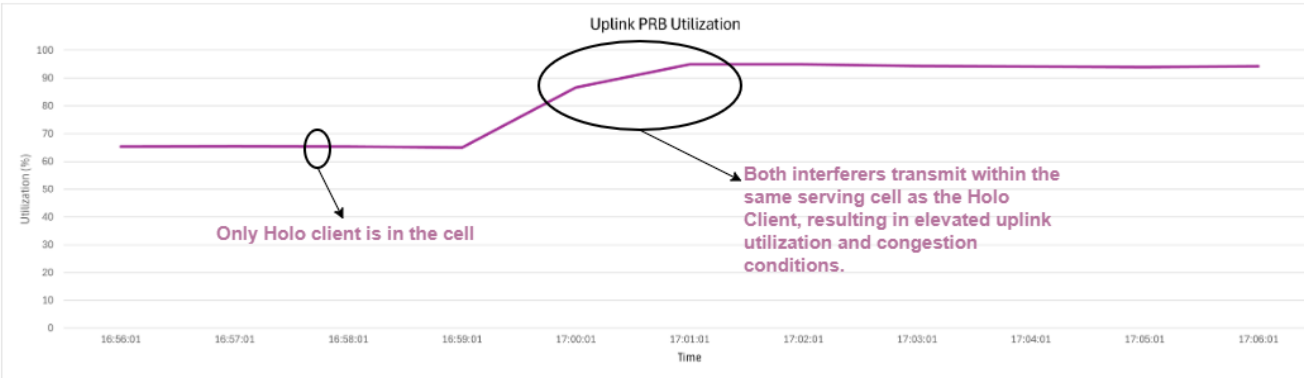


Figure 33: Uplink PRB utilization of Holo Client 1 during the holographic session, showing low utilization when the Holo user is alone in the cell and a sharp increase once the interferers start transmitting.

Figure 34: Hologram received at Holo Client 2, representing the real-time 3D person representation captured and reconstructed by Holo Client 1 and sent to Holo Client 2 via the 5G network.

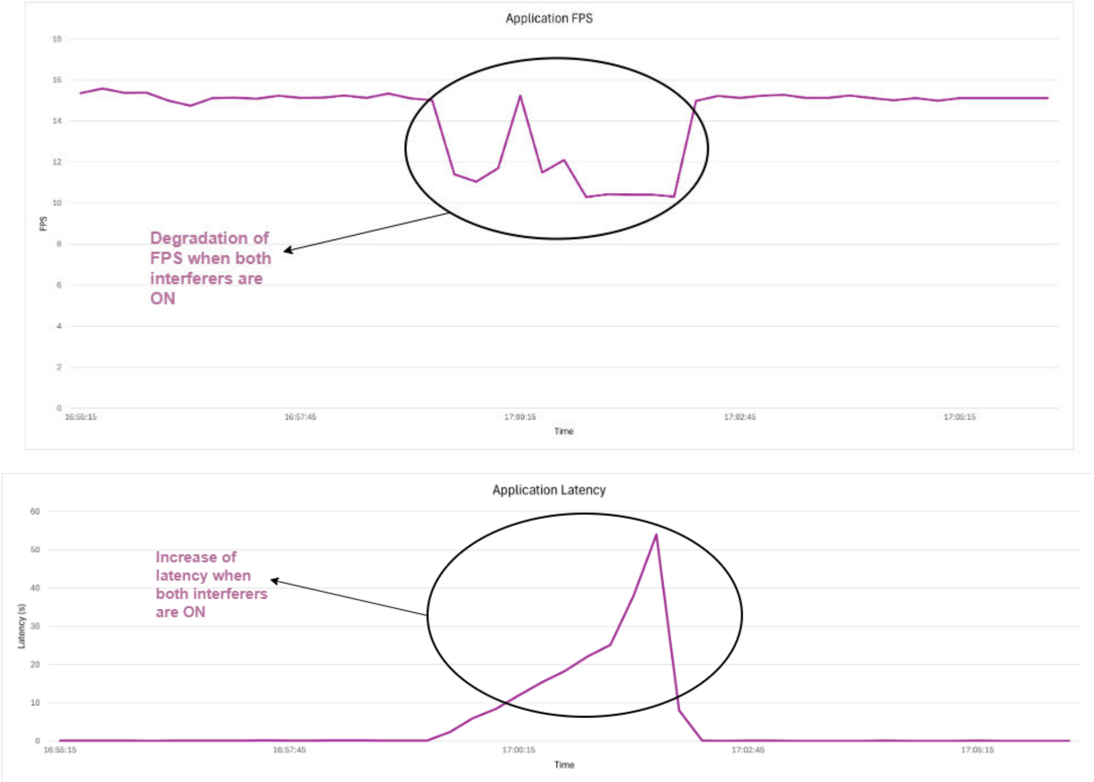


Figure 35: Degradation of QoS metrics (FPS and Latency) due to uplink congestion.

Figure 36: API call sequence between the Congestion Detection Function (CDF) and the Holo Orchestrator following congestion detection.

Figure 37: Congestion alarm flag displayed in the dashboard, indicating that network congestion is detected when interfering traffic sources are introduced.

Figure 38: Recovery of QoS and hologram playback smoothness after rate adaptation for Holo Client 1.

4.4.1.2 UC1 - Remote Renderer with WebRTC Network-Assisted Rate Control Test Case

	UC1 - Remote Renderer with WebRTC Network-Assisted Rate Control Test Case
Test Case ID	SN_UC1_1.2
Test Case Name	Remote Renderer with WebRTC Network-Assisted Rate Control Test Case
Test Execution Date	15-19/09/2025
Test Executed By	VICOM
Number of repetitions	Two repetitions are performed without congestion (Test run 1-2). Two repetitions are performed with congestion (Test run 3-4).
Verification Points (VP)	
Checkpoint ID	**Description of Validation Criteria for checkpoint**
ID #1	*Measurement of network latency and RTT between Edge and UE.*
ID #2	*Deployment of Remote Renderer with WebRTC configuration.*
ID #3	*Remote Renderer renders four remote users in the VR scene and generates the WebRTC stream for a fifth user connected with a lightweight XR Client.*
ID #4	*Lightweight XR Client visualizes the WebRTC stream and collects media session metrics.*
ID #5	*If network is congested, WebRTC stream experiences higher packet loss.*
ID #6	*If network is congested, RAN/gNodeB reports it.*
ID #7	*If network is congested, the video representation of WebRTC stream is reduced to compensate it.*
ID #8	*Remote Renderer and lightweight XR Client are stopped, datasets (WebRTC logs and Prometheus metrics) are exported, and average RTT of WebRTC session is calculated.*
Test Validation	All checkpoints have passed in all the repetitions.

Conditions			
Test results	**Test run**	**Description**	**Result**
ID #1	1-2	Figure 39	Pass
ID #2	1-2	Figure 40	Pass
ID #3	1-2	Figure 41 and Figure 42	Pass
ID #4	1-2	Figure 41 and Figure 42	Pass
ID #5	1-2	Figure 42	Pass
ID #6	1-2	Figure 43	Pass
ID #7	1-2	Figure 42	Pass
ID #8	1-2	Figure 44. Collected data and logs at https://github.com/SNS-JU/6gxr-_uc1_remote_renderer_dataset/	Pass

Results / Diagrams

Figure 39: Network latency and RTT for test run 1 (left) and 2 (right).

Figure 39 shows the measurements obtained for the network latency and RTT, measured through qperf and ping tools at the beginning of test runs 1 and 2. These results prove that the network is working correctly, guaranteeing minimal delay for the video streaming between the Remote Renderer and the lightweight XR Client.

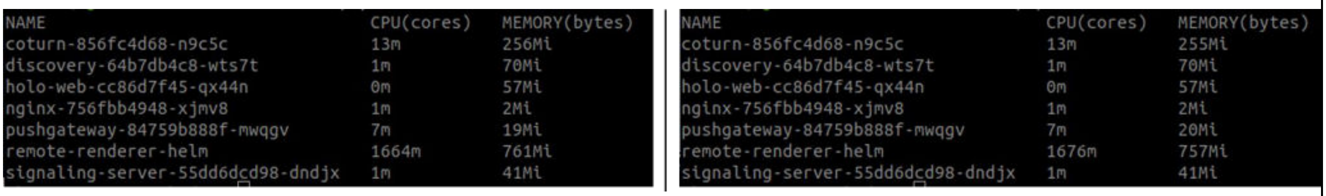


Figure 40: Usage of CPU and RAM when the Remote Renderer is started during test run 1 (left) and 2 (right).

Figure 40 shows the CPU and RAM consumed by the Remote Renderer to execute the rendering process and generate the WebRTC stream during the test runs 1 and 2.

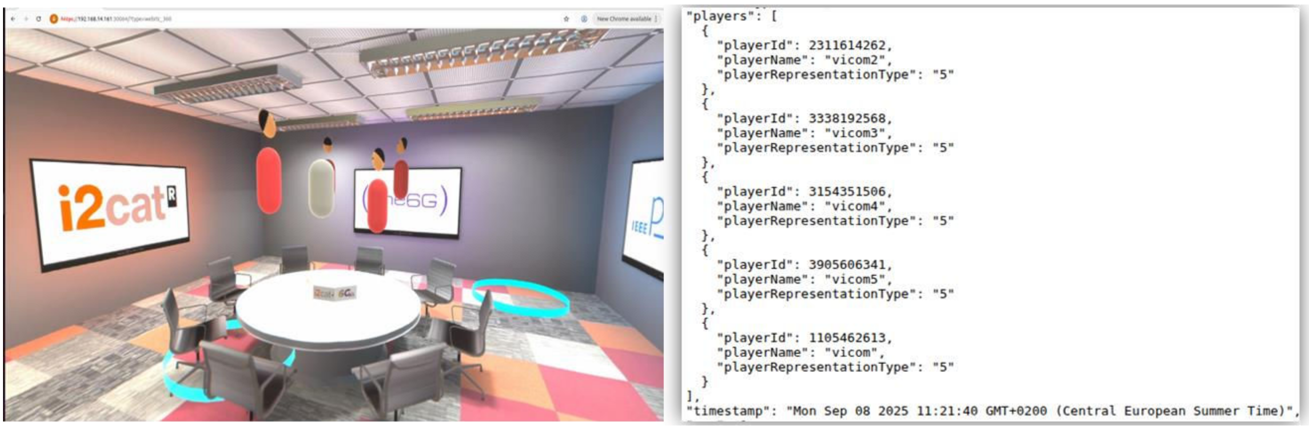


Figure 41: Visualization of WebRTC stream from lightweight XR Client and list of active user sessions.

Figure 41 presents the WebRTC stream visualized by the lightweight XR Client, where the VR scene includes the other four remote users. The figure also presents the list of five active user sessions at the Holo Orchestrator. Similar results are obtained for both test runs 1 and 2.

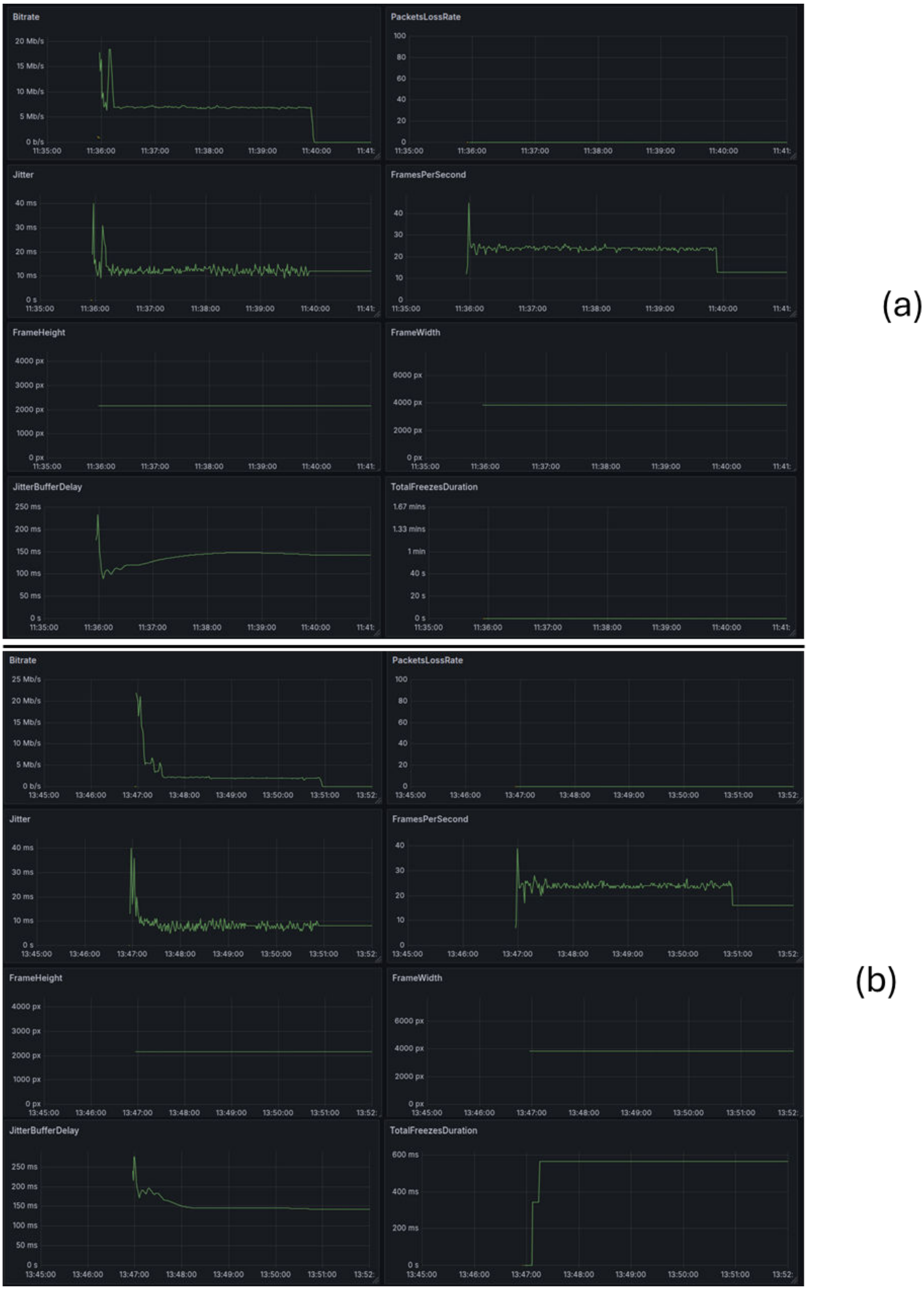


Figure 42: WebRTC session metrics collected during test run 1 (a) and 2 (b).

Figure 42 presents the video streaming metrics collected at the lightweight XR Client during test runs 1 and 2. These metrics confirm that network worked properly during all the media session, as no congestion was presented in the network. The Remote Renderer did not reduce the video representation of the WebRTC stream, as packet loss and video freezes were adequate for streaming the video at 4K.

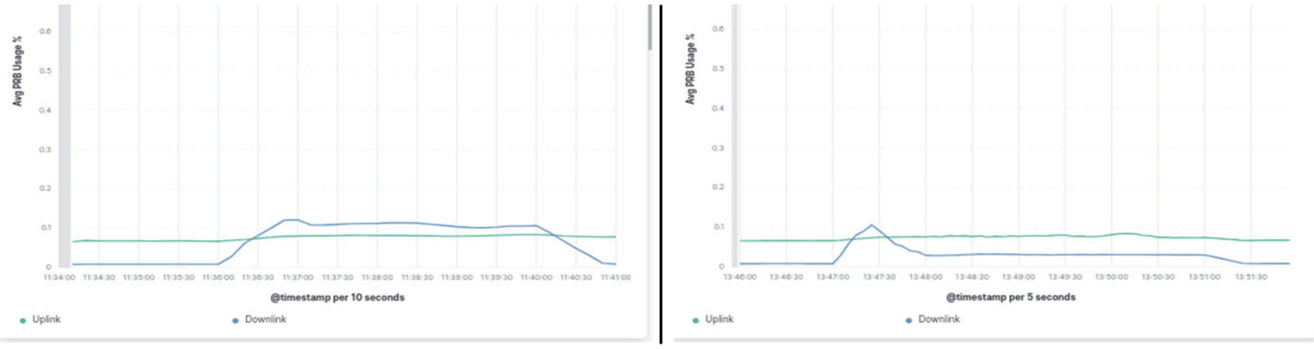


Figure 43: Average Physical Resource Blocks (PRBs) usage during test run 1 (left) and 2 (right).

The PRBs usage at the gNodeB, presented in Figure 43, shows that during test runs 1 and 2 the network was not saturated and still capable to allocate more network traffic.

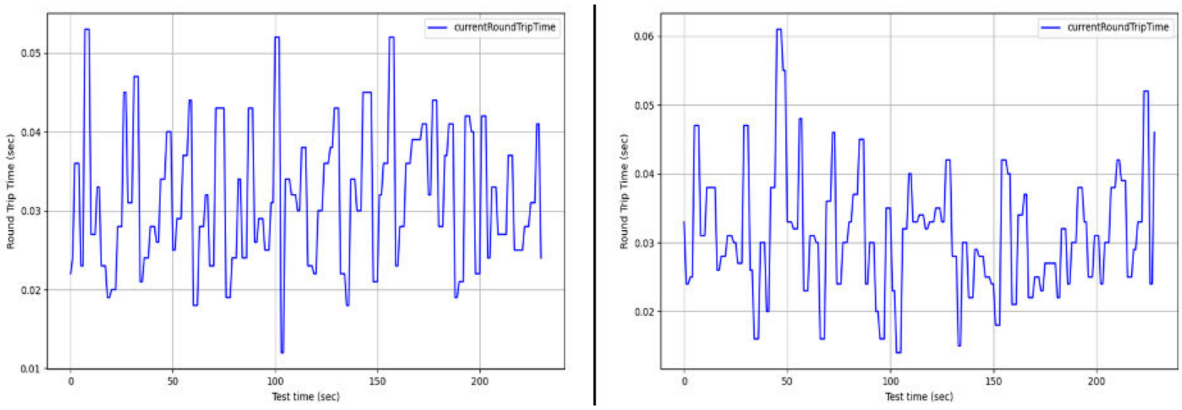


Figure 44: Current RoundTripTime of WebRTC during test run 1 (left) and 2 (right).

The RTT measurements performed by WebRTC protocol are shown in Figure 44. The average RTT during test run 1 was 31.8 ms with, while during test run 2 was 31.1 ms.

Test results	Test run	Description	Result
ID #1	3-4	Figure 45	Pass
ID #2	3-4	Figure 46	Pass
ID #3	3-4	Figure 48 and Figure 49	Pass
ID #4	3-4	Figure 47 and Figure 49	Pass
ID #5	3-4	Figure 47	Pass
ID #6	3-4	Figure 48	Pass
ID #7	3-4	Figure 48 and Figure 49	Pass
ID #8	3-4	Figure 50. Collected data and logs at https://github.com/SNS-JU/6gxr-_uc1_remote_renderer_dataset/	Pass
Results / Diagrams			

```
tcp_lat:
    latency         =  11.4 ms

--- 192.168.14.161 ping statistics ---
10 packets transmitted, 10 received, 0% packet loss, time 9016ms
rtt min/avg/max/mdev = 12.789/20.212/28.543/4.912 ms
```

```
tcp_lat:
    latency         =    11 ms

--- 192.168.14.161 ping statistics ---
10 packets transmitted, 10 received, 0% packet loss, time 9015ms
rtt min/avg/max/mdev = 16.111/25.974/34.822/6.143 ms
```

Figure 45: Network latency and RTT for test run 3 (left) and 4 (right).

Figure 45 shows the measurements obtained for the network latency and RTT, measured through *qperf* and *ping* tools at the beginning of test runs 3 and 4. These results prove that the network is working correctly, guaranteeing minimal delay for the video streaming between the Remote Renderer and the lightweight XR Client.

```
NAME                                CPU(cores)   MEMORY(bytes)
coturn-856fc4d68-n9c5c              10m          262Mi
discovery-64b7db4c8-wts7t           1m           70Mi
holo-web-cc86d7f45-qx44n            1m           56Mi
nginx-756fbb4948-xjmv8              0m           2Mi
pushgateway-84759b888f-mwqgv        6m           18Mi
remote-renderer-helm                1742m        667Mi
signaling-server-55dd6dcd98-dndjx   1m           42Mi
```

```
NAME                                CPU(cores)   MEMORY(bytes)
coturn-856fc4d68-n9c5c              38m          266Mi
discovery-64b7db4c8-wts7t           1m           70Mi
holo-web-cc86d7f45-qx44n            0m           56Mi
nginx-756fbb4948-xjmv8              1m           2Mi
pushgateway-84759b888f-mwqgv        7m           20Mi
remote-renderer-helm                1713m        703Mi
signaling-server-55dd6dcd98-dndjx   0m           42Mi
```

Figure 46: Usage of CPU and RAM when the Remote Renderer is started during test run 3 (left) and 4 (right).

Figure 46 shows the CPU and RAM consumed by the Remote Renderer to execute the rendering process and generate the WebRTC stream during the test runs 3 and 4.

Figure 47: Visualization of WebRTC stream at 4K (left) and 720p (right) from lightweight XR Client.

Figure 47 presents the WebRTC stream visualized by the lightweight XR Client, where the VR scene includes the other four remote users. The left image shows the 4K video at the beginning of the transmission, while the right one the 720p video after the Remote Renderer switch the video representation. Similar results are obtained for both test runs 3 and 4.

(a)

(b)

Figure 48: WebRTC session metrics collected during test run 3 (a) and 4 (b).

Figure 48 presents the video streaming metrics collected at the lightweight XR Client during test runs 3 and 4. The figure shows that the video was affected by packet loss and presented freezes during its playback. As a result, the Remote Renderer changed the video representation of the WebRTC stream from 4K to 720p to reduce the amount of network resources needed for the transmission.

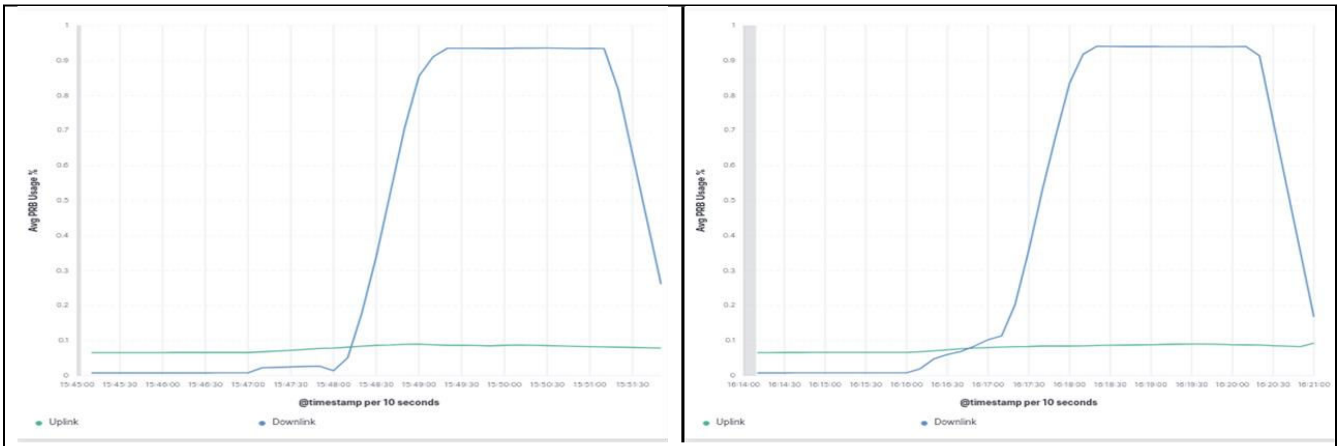


Figure 49: Average Physical Resource Blocks (PRBs) usage during test run 3 (left) and 4 (right).

The PRBs usage at the gNodeB, presented in Figure 49, shows that during test runs 3 and 4 the network was congested, affecting the video transmission at 4K and forcing the Remote Renderer to switch to 720p.

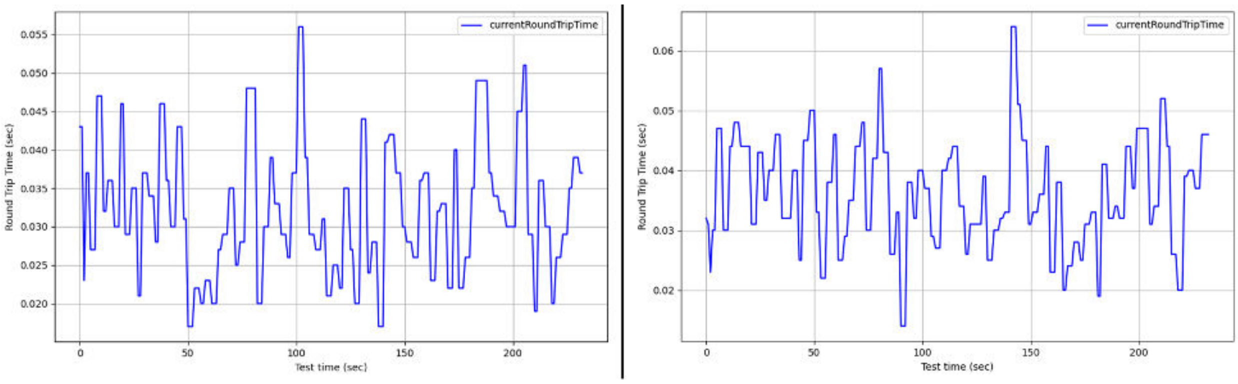


Figure 50: RoundTripTime of WebRTC during test run 3 (left) and 4 (right).

The RTT measurements performed by WebRTC protocol are shown in Figure 50. The average RTT during test run 3 was 32.1 ms with, while during test run 4 was 36.1 ms. These values are higher than the obtained in test runs 1 (31.8 ms) and 2 (31.1 ms), but still adequate for real-time video streaming between the Remote Renderer and the lightweight XR Client.

4.4.1.3 UC1 - Remote Renderer with DASH Client-based Rate Control Test Case

	UC1 - Remote Renderer with DASH Client-based Rate Control Test Case
Test Case ID	SN_UC1_1.3
Test Case Name	Remote Renderer with DASH Client-based Rate Control Test Case
Test Execution Date	15-19/09/2025
Test Executed By	VICOM
Number of repetitions	Four repetitions with different congestion scenarios: Test run 1 with 0 headless players, Test run 2 with 10 headless players, Test run 3 with 50 headless players, Test run 4 with 100 headless players.
Verification Points (VP)	

Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*Deployment of Remote Renderer with DASH configuration.*		
ID #2	*Remote Renderer generates the DASH stream with three different video representations (resolutions and bitrates).*		
ID #3	*Passive XR Client visualizes the DASH stream with the highest video representation and collects media session metrics.*		
ID #4	*N headless DASH players are started to generate network congestion.*		
ID #5	*If passive XR Client detects congestion, it selects a lower video representation.*		
ID #6	*Remote Renderer is stopped, and datasets (Prometheus metrics) are exported.*		
Test Validation Conditions	All checkpoints have passed in all the repetitions		
Test results	**Test run**	**Description**	**Result**
ID #1	1-4	Figure 51	Pass
ID #2	1-4	Figure 52 and Figure 51	Pass
ID #3	1-4	Figure 52 and Figure 51	Pass
ID #4	1-4	Figure 51	Pass
ID #5	1-4	Figure 51	Pass
ID #6	1-4	Collected data and logs at https://github.com/SNS-JU/6gxr-_uc1_remote_renderer_dataset/	Pass

Final Diagrams

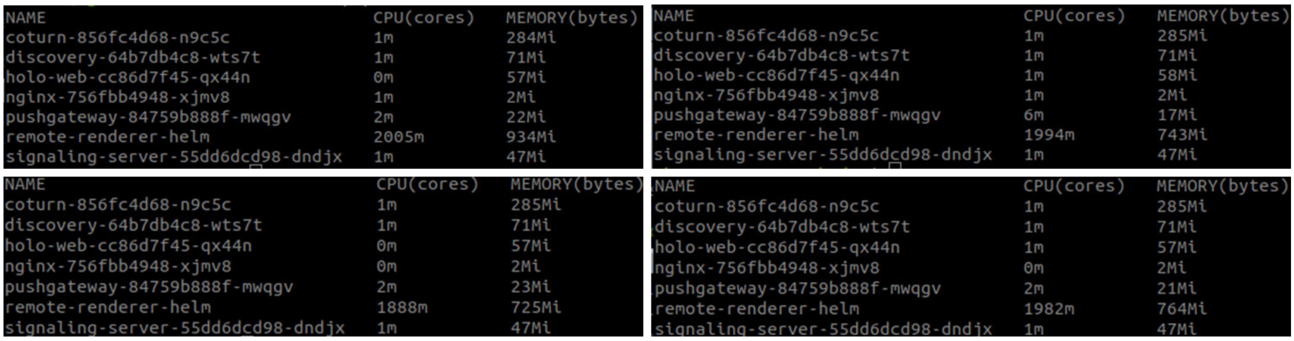


Figure 51: Usage of CPU and RAM when the Remote Renderer is started during test runs 1-4.

Figure 51 shows the CPU and RAM consumed by the Remote Renderer to execute the rendering process and generate the DASH stream with three video and one audio representations during the test runs 1-4.

Figure 52: DASH MPD with three video and one audio representations employed during test runs 1-4.

Figure 52 presents the DASH Media Presentation Description (MPD) generated by the Remote Renderer when encoding three video and one audio representations. The figure also shows the DASH stream visualized by the passive XR Client. Similar results are obtained for the four test runs.

4.4.1.4 UC1 - Congestion Detection and QoD triggering for holographic comm streams, from clients

	UC1 - Congestion Detection and QoD triggering for holographic comm streams, from clients		
Test Case ID	SN_UC1_2.1		
Test Case Name	Congestion Detection and QoD triggering for holographic comm streams, from clients		
Test Execution Date	21-28/10/2025		
Test Executed By	I2CAT & Ericsson		
Number of repetitions	> 5 successful repetitions (dataset), but showing evidences for one repetition in this table.		
Verification Points (VP)			
Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*A native Holo Client 1 (connected from i2CAT testbed in Barcelona) establishes a new holographic communication session, by connecting to the Holo Orchestrator via a 5G CPE.*		
ID #2	*A Holo Client 2 (connected from 5TONIC testbed in Madrid), native or headless, joins the same session via a 5G CPE.*		
ID #3	*The 2-user session is established and kept stable.*		
ID #4	*Interfering traffic sources are introduced in the serving 5G cell of Holo Client 1.*		
ID #5	*Quality of Service (QoS) metrics, like delays, frames per second (fps) and visual stability, start to get impacted.*		
ID #6	*The Congestion Detection Function (CDF) detects congestion in the 5G cell and sends a congestion alarm notification to the Holo Orchestrator.*		
ID #7	*Upon receiving the congestion alarm notification, the Holo Orchestrator triggers QoD to raise the priority of the streams from Holo Client 1.*		
ID #8	*The QoS metrics (delays, fps) are re-established to satisfactory levels and the hologram gets back to a fluid presentation.*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1	The Holo Client connects to the 5G network and transmits uplink traffic corresponding to its audio and volumetric video stream for the hologram presentation. Figure 53 illustrates the uplink throughput experienced by the Holo Client 1 during the test session.	Pass
ID #2	1	The Holo Client 2, connected from the Madrid testbed—either native or headless —joins the same holographic session through a 5G CPE, thus establishing a live holographic call, with bi-directional low-latency communication.	Pass
ID #3	1	The two-user holographic session is successfully established and maintained in a stable manner, ensuring continuous bidirectional data exchange between both Holo Clients through the 5G network. Figure 54 shows the hologram received at Holo Client 2, illustrating the reconstructed 3D representation for the person captured by Holo Client 1 in real time.	Pass
ID #4	1	Two interfering traffic sources are activated within the serving 5G cell of Holo	Pass

		Client 1, generating competing uplink data flows that affect the available radio resources. Figure 55 and Figure 56 show the activity of both interferers, confirming that each is actively transmitting traffic during the holographic session.	
ID #5	1	As network load increases, QoS metrics—such as delay and fps — for the holographic video stream begin to degrade due to resource contention. Figure 57 illustrates the impact of these effects, showing noticeable increase in latency and decrease of received fps, with magnified fluctuations for both metrics, at the receiver side.	Pass
ID #6	1	The Congestion Detection Function (CDF) identifies congestion in the serving 5G cell based on real-time PRB utilization metrics, and it triggers a congestion alarm notification to the Holo Orchestrator. Figure 58 illustrates the corresponding API calls exchanged between the CDF and the Holo Orchestrator during this event. Figure 59 shows the dashboard with the flag "Congestion Detected" when interference is added.	Pass
ID #7	1	Upon receiving the congestion notification, the Holo Orchestrator triggers the QoD mechanism, which dynamically adjusts network policies to elevate the priority of the streams from Holo Client 1. This ensures preferential resource allocation and improved service continuity under congested conditions.	Pass
ID #8	1	Following the activation of QoD, the QoS metrics—including latency, and fps—recover to stable and satisfactory levels, and the playback continuity and smoothness of the hologram, as well as the real-time conversational services, are restored to satisfactory levels. Figure 60 illustrates this improvement for the registered metrics, showing the enhanced performance after prioritization.	Pass

Results / Diagrams

Figure 53: Uplink throughput of Holo Client 1 during the holographic session, showing sustained transmission rates over the 5G network.

Figure 54: Hologram received at Holo Client 2, representing the real-time 3D person representation captured and reconstructed by Holo Client 1 and sent to Holo Client 2 via the 5G network.

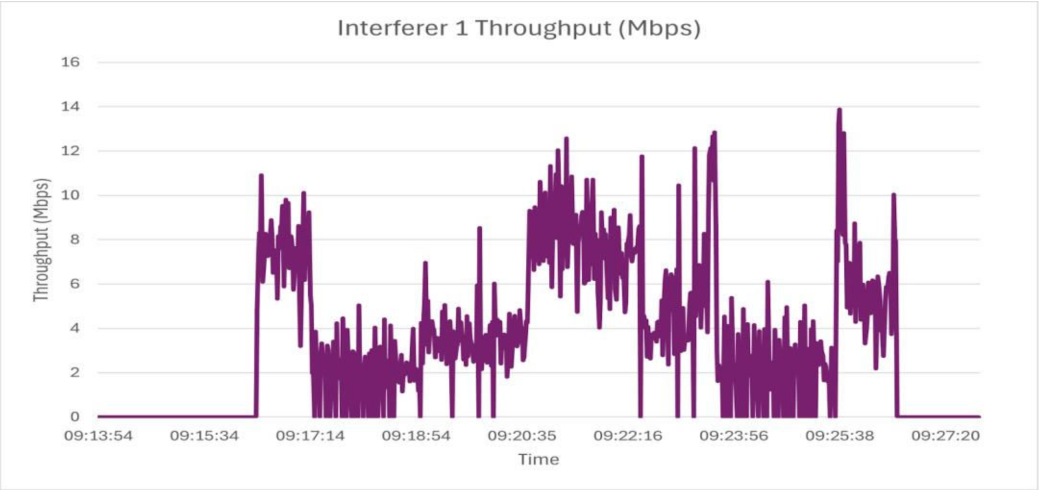


Figure 55: Traffic activity of Interferer 1 within the serving 5G cell of Holo Client 1, indicating active uplink transmission and thus contributing to increased network load.

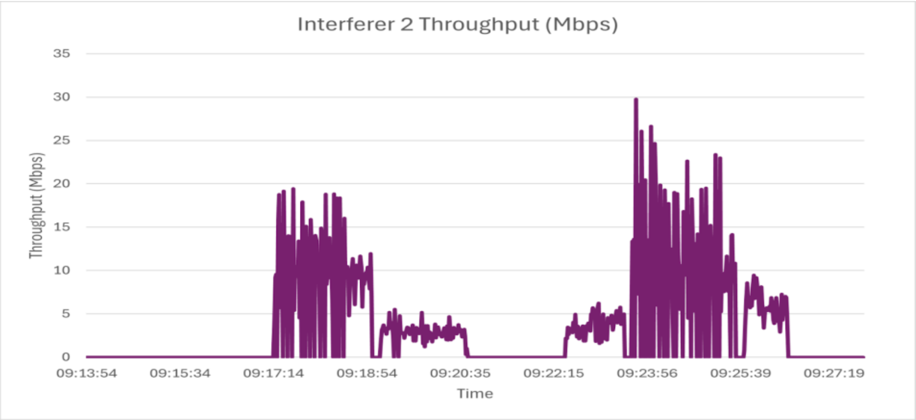


Figure 56: Traffic activity of Interferer 2 within the same 5G cell, contributing to increased network load.

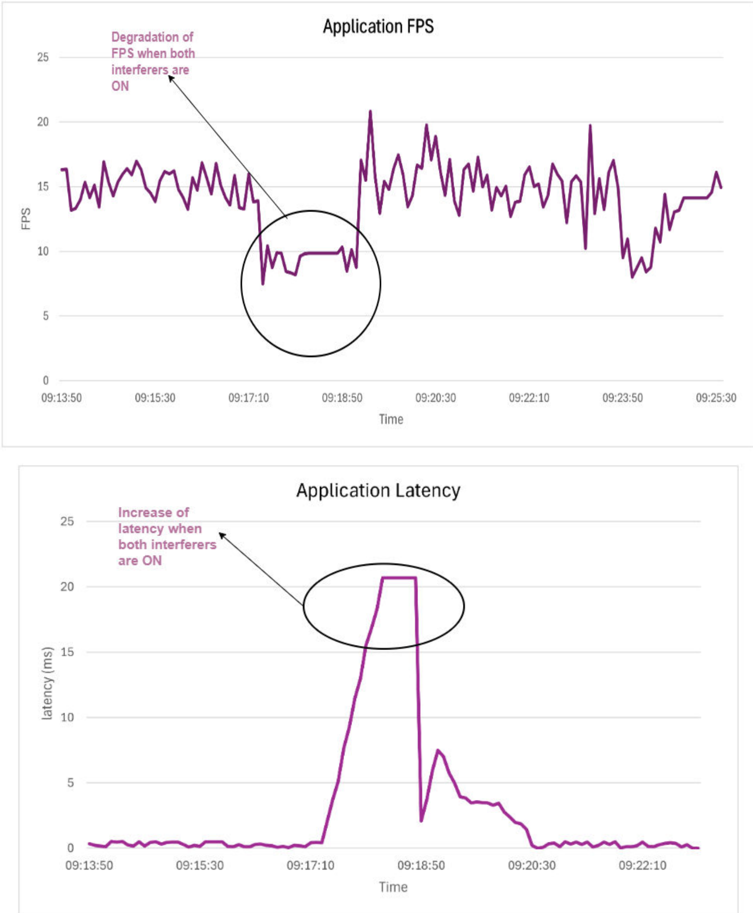


Figure 57: Degradation of QoS metrics (FPS and Latency) due to uplink congestion.

Figure 58: API call sequence between the Congestion Detection Function (CDF) and the Holo Orchestrator following congestion.

Figure 59: Congestion alarm flag displayed in the dashboard, indicating that network congestion is detected when interfering traffic sources are introduced.

Figure 60: Recovery of QoS and hologram playback smoothness after activation of the QoD mechanism for Holo Client 1.

4.4.1.5 UC1 - Quality on Demand for Remote Renderer and WebRTC streaming Test Case

	UC1 - Quality on Demand for Remote Renderer and WebRTC streaming Test Case
Test Case ID	SN_UC1_2.2
Test Case Name	Quality on Demand for Remote Renderer and WebRTC streaming Test Case
Test Execution Date	15-19/09/2025
Test Executed By	VICOM
Number of repetitions	Two repetitions are performed without congestion (Test run 1-2). Two repetitions are performed with congestion (Test run 3-4).
Verification Points (VP)	
Checkpoint ID	**Description of Validation Criteria for checkpoint**
ID #1	*Measurement of network latency and RTT between Edge and UE.*
ID #2	*Deployment of Remote Renderer with WebRTC configuration.*
ID #3	*Lightweight XR Client connects to the Remote Renderer, visualizes the WebRTC stream and collects media session metrics.*
ID #4	*If network is congested, WebRTC stream experiences higher packet loss.*
ID #5	*If network is congested, RAN/gNodeB reports it.*
ID #6	*If network is congested, CAMARA QoD API is triggered, and the WebRTC stream experiences lower packet loss.*

ID #7	*Remote Renderer and lightweight XR Client are stopped, datasets (WebRTC logs and Prometheus metrics) are exported, and average RTT of WebRTC session is calculated.*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1-2	Figure 61	Pass
ID #2	1-2	Figure 62	Pass
ID #3	1-2	Figure 63	Pass
ID #4	1-2	Figure 63	Pass
ID #5	1-2	Figure 64	Pass
ID #6	1-2	Figure 63	Pass
ID #7	1-2	Figure 65. Collected data and logs at https://github.com/SNS-JU/6gxr-_uc1_remote_renderer_dataset/	Pass

Results / Diagrams

Figure 61: Network latency and RTT for test run 1 (left) and 2 (right).

Figure 61 shows the measurements obtained for the network latency and RTT, measured through *qperf* and *ping* tools at the beginning of test runs 1 and 2. These results prove that the network is working correctly, guaranteeing minimal delay for the video streaming between the Remote Renderer and the lightweight XR Client.

Figure 62: Usage of CPU and RAM when the Remote Renderer is started during test run 1 (left) and 2 (right).

Figure 62 shows the CPU and RAM consumed by the Remote Renderer to execute the rendering process and generate the WebRTC stream during the test runs 1 and 2.

(a)

(b)

Figure 63: WebRTC session metrics collected during test run 1 (a) and 2 (b).

Figure 63 presents the video streaming metrics collected at the lightweight XR Client during test runs 1 and 2. These metrics confirm that network worked properly during all the media session, as no congestion was presented in the network. The Remote Renderer generated a 4K video representation during all the media sessions and the CAMARA QoD API was not triggered, as packet loss and video freezes were adequate for the streaming.

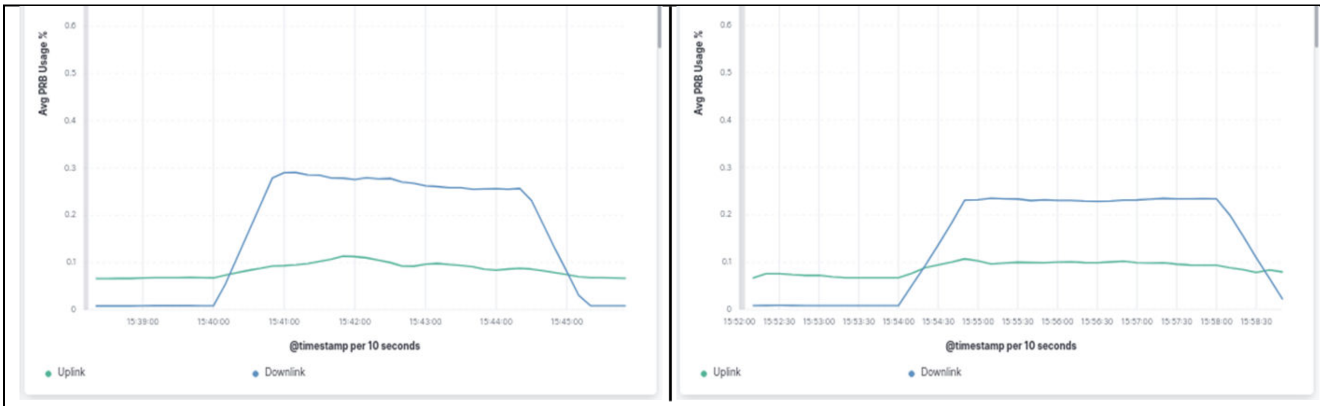


Figure 64: Network bitrate and average Physical Resource Blocks (PRBs) usage during test run 1 (left) and 2 (right).

The PRBs usage at the gNodeB, presented in Figure 64 shows that during test runs 1 and 2 the network was not saturated and still capable to allocate more network traffic.

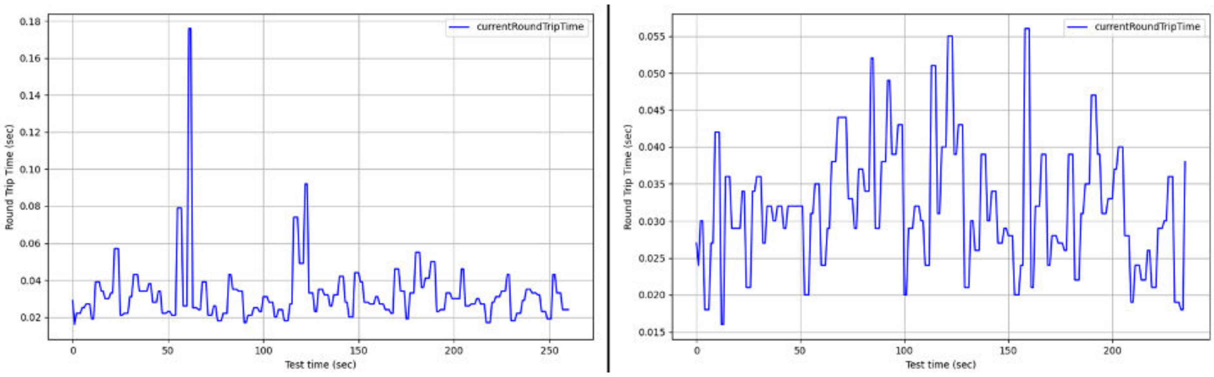


Figure 65: RoundTripTime of WebRTC during test run 1 (left) and 2 (right).

The RTT measurements performed by WebRTC protocol are shown in Figure 65. The average RTT during test run 1 was 32.6 ms with, while during test run 2 was 25.9 ms.

Test results	Test run	Description	Result
ID #1	3-4	Figure 66	Pass
ID #2	3-4	Figure 67	Pass
ID #3	3-4	Figure 68	Pass
ID #4	3-4	Figure 68	Pass
ID #5	3-4	Figure 69	Pass
ID #6	3-4	Figure 68 and Figure 69	Pass
ID #7	3-4	Figure 67	Pass
ID #8	3-4	Figure 70. Collected data and logs at https://github.com/SNS-JU/6gxr-_uc1_remote_renderer_dataset/	Pass
Results / Diagrams			


```
tcp_lat:
    latency        =  11 ms

--- 192.168.14.161 ping statistics ---
10 packets transmitted, 10 received, 0% packet loss, time 9015ms
rtt min/avg/max/mdev = 16.565/25.288/34.278/5.934 ms
```

```
tcp_lat:
    latency        =  10.7 ms

--- 192.168.14.161 ping statistics ---
10 packets transmitted, 10 received, 0% packet loss, time 9014
rtt min/avg/max/mdev = 14.846/24.678/33.257/6.055 ms
```

Figure 66: Network latency and RTT for test run 3 (left) and 4 (right).

Figure 66 shows the measurements obtained for the network latency and RTT, measured through *qperf* and *ping* tools at the beginning of test runs 3 and 4. These results prove that the network is working correctly, guaranteeing minimal delay for the video streaming between the Remote Renderer and the lightweight XR Client.

```
NAME                                 CPU(cores)   MEMORY(bytes)
coturn-856fc4d68-n9c5c               1m           287Mi
discovery-64b7db4c8-wts7t            1m           70Mi
holo-web-cc86d7f45-qx44n             0m           57Mi
nginx-756fbb4948-xjmv8               1m           2Mi
pushgateway-84759b888f-mwqgv         3m           22Mi
remote-renderer-helm                 1692m        535Mi
signaling-server-55dd6dcd98-dndjx    1m           43Mi
```

```
NAME                                 CPU(cores)   MEMORY(byt
coturn-856fc4d68-n9c5c               13m          449Mi
discovery-64b7db4c8-wts7t            1m           70Mi
holo-web-cc86d7f45-qx44n             1m           58Mi
nginx-756fbb4948-xjmv8               0m           2Mi
pushgateway-84759b888f-mwqgv         3m           23Mi
remote-renderer-helm                 1663m        1107Mi
signaling-server-55dd6dcd98-dndjx    1m           45Mi
```

Figure 67: Usage of CPU and RAM when the Remote Renderer is started during test run 3 (left) and 4 (right).

Figure 67 shows the CPU and RAM consumed by the Remote Renderer to execute the rendering process and generate the WebRTC stream during the test runs 3 and 4.

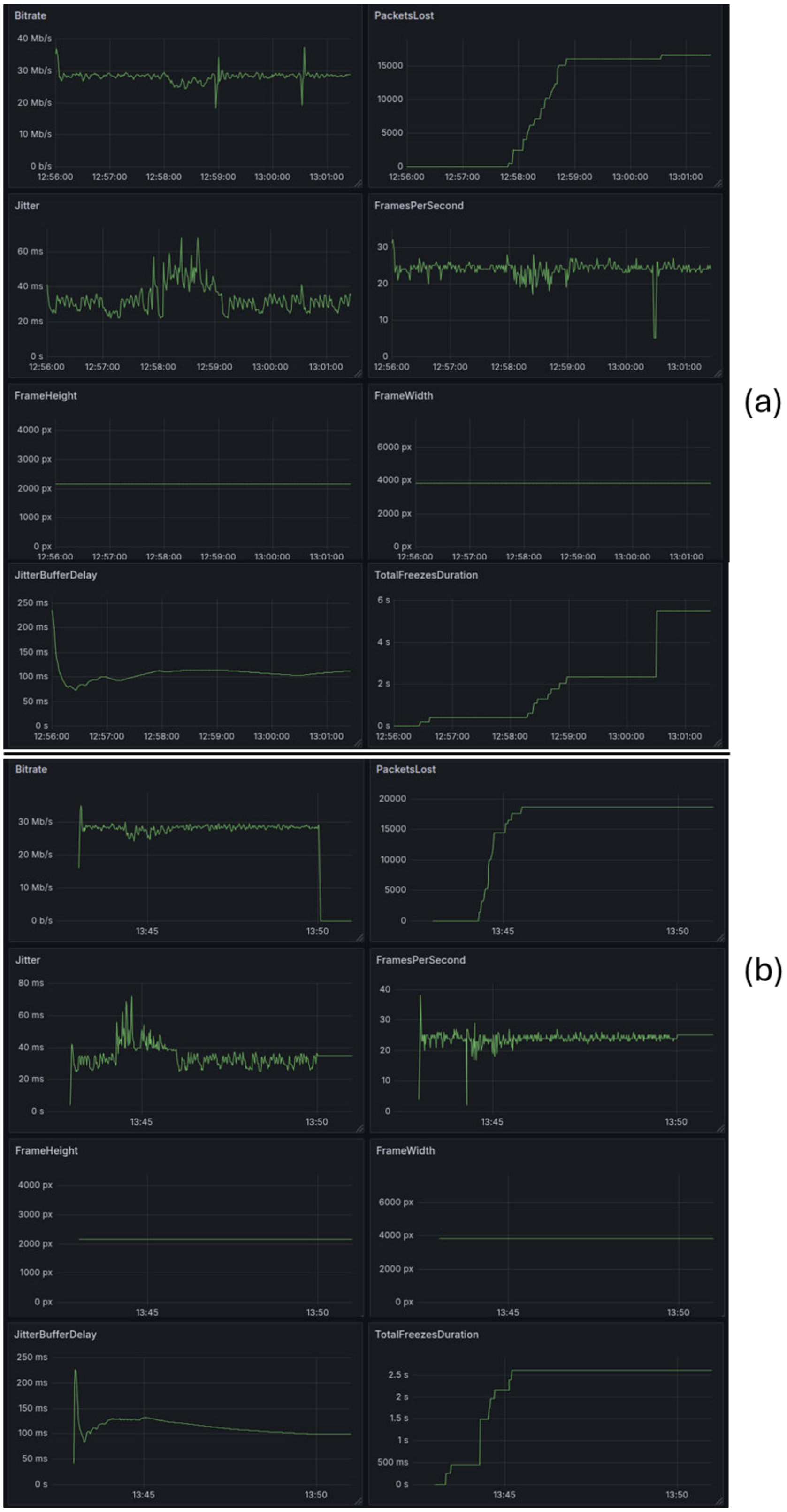


Figure 68: WebRTC session metrics collected during test run 3 (a) and 4 (b).

Figure 68 presents the video streaming metrics collected at the lightweight XR Client during test runs 3 and 4. The figure shows that the video was affected by packet loss and presented freezes during its playback. As a result, the CAMARA

QoD API was triggered to separate the WebRTC traffic from the background traffic generated through *iperf* tool. After triggering CAMARA QoD API, the video transmission reduced the amount of lost packets and experienced less freezes.

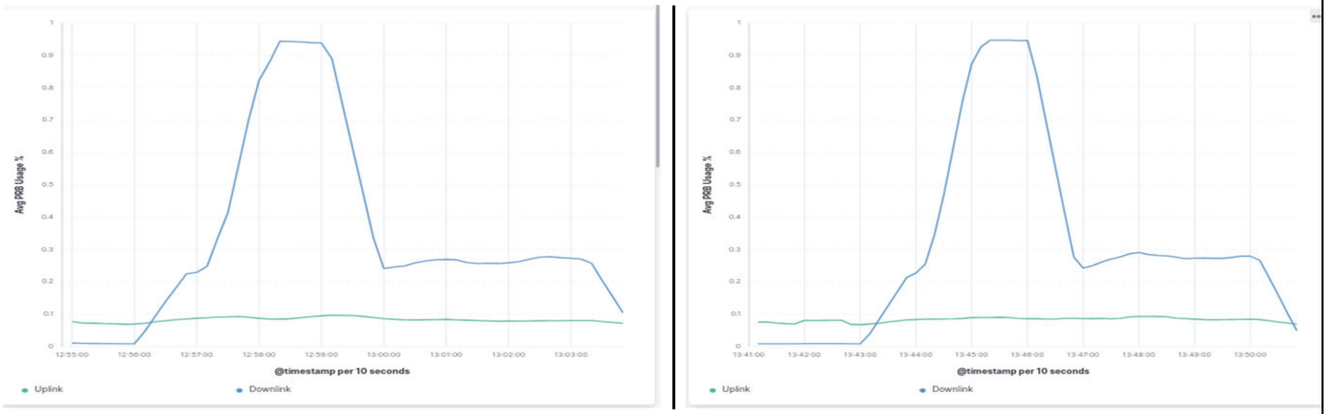


Figure 69: Average Physical Resource Blocks (PRBs) usage during test run 3 (left) and 4 (right).

The PRBs usage at the gNodeB, presented in Figure 69 shows that during test runs 3 and 4 the network had congestion (PRBs usage around 0.9), but this was alleviated by triggering CAMARA QoD API.

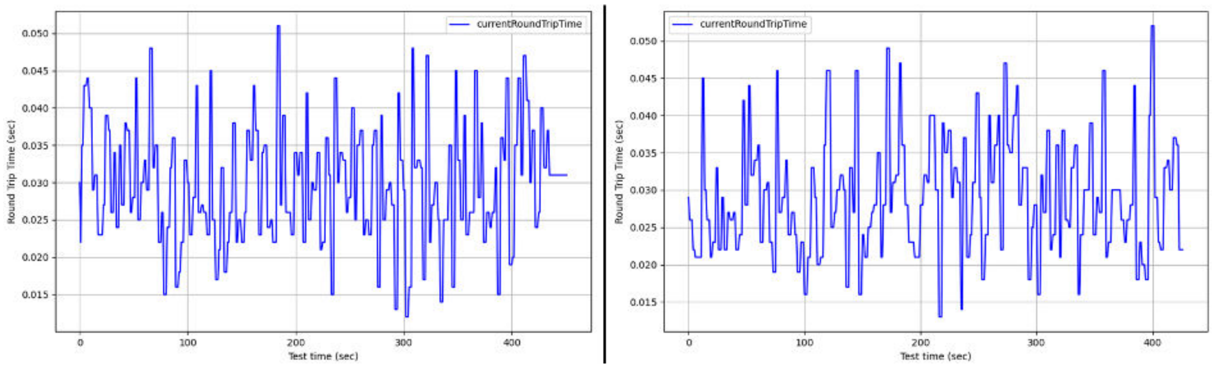


Figure 70: RoundTripTime of webrtc during test run 3 (left) and 4 (right).

The RTT measurements performed by WebRTC protocol are shown in Figure 70. The average RTT during test run 3 was 29.7 ms with, while during test run 4 was 29.0 ms. These values are aligned with the ones obtained in test runs 1 (32.6 ms) and 2 (25.9 ms) and adequate for real-time video streaming between the Remote Renderer and the lightweight XR Client.

SN_UC1 was demonstrated live at the 6G-XR Impact Day hosted at 5TONIC. The video is accessible here: 6G-XR - YouTube

4.4.1.6 UC2 – Performance validation in Barcelona testbed Test Case

	UC2 – Performance validation in Barcelona testbed Test Case
Test Case ID	SN_UC2_2.1
Test Case Name	Performance validation in Barcelona testbed

Test Execution Date	22/10/2025		
Test Executed By	I2CAT		
Number of repetitions	One repetition		
Verification Points (VP)			
Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*Connect first native client to holographic orchestrator.*		
ID #2	*Connect first native client to SFU.*		
ID #3	*Connect second native client to holographic orchestrator.*		
ID #4	*Connect second native client to SFU.*		
ID #5	*Validate both users see each other in the session.*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1	Figure 71	Pass
ID #2	1	Figure 71	Pass
ID #3	1	Figure 71	Pass
ID #4	1	Figure 71	Pass
ID #5	1	Figure 72	Pass
Results / Diagrams			

```
{
  "sessions": [
    {
      "_id": "690a2021288079e8500a8edb",
      "sessionId": "1646159208",
      "sessionName": "6gxr_test",
      "scenarioId": "Pilot0",
      "architecture": "1",
      "sessionType": "1",
      "players": [
        {
          "playerId": "1261807198",
          "playerName": "10.3.205.85",
          "playerRepresentationType": "HOLOCAPTURER_DEPTH"
        },
        {
          "playerId": "1697244656",
          "playerName": "10.3.202.123",
          "playerRepresentationType": "HOLOCAPTURER_DEPTH"
        }
      ],
      "timestamp": "Tue Nov 04 2025 15:47:45 GMT+0000 (Coordinated Universal Time)",
      "fov": false,
      "__v": 0
    }
  ]
}
```


Figure 71: Holo Orchestrator number of players in a certain session.

Figure 72: Session with two clients connected.

4.4.1.7 UC2 – i2CAT and 5TONIC testbeds connectivity validation Test Case

	UC2 – i2CAT and 5TONIC testbeds connectivity validation Test Case		
Test Case ID	SN_UC2_2.2		
Test Case Name	i2CAT and 5TONIC testbeds connectivity validation		
Test Execution Date	23/10/2025		
Test Executed By	I2CAT & Capgemini		
Number of repetitions	One repetition		
Verification Points (VP)			
Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*Deploy SFU in Madrid through Trial Controller.*		
ID #2	*Connect two native clients to holographic orchestrator.*		
ID #3	*Connect two native clients to SFU in Madrid.*		
ID #4	*Validate both users see each other in the session.*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1	Figure 73 and Figure 74	Pass
ID #2	1	Figure 71 (Validated in TestCase SN_UC2_2.1)	Pass
ID #3	1	Figure 75	Pass
ID #4	1	Figure 72 (Validated in TestCase SN_UC2_2.1)	Pass
Results / Diagrams			

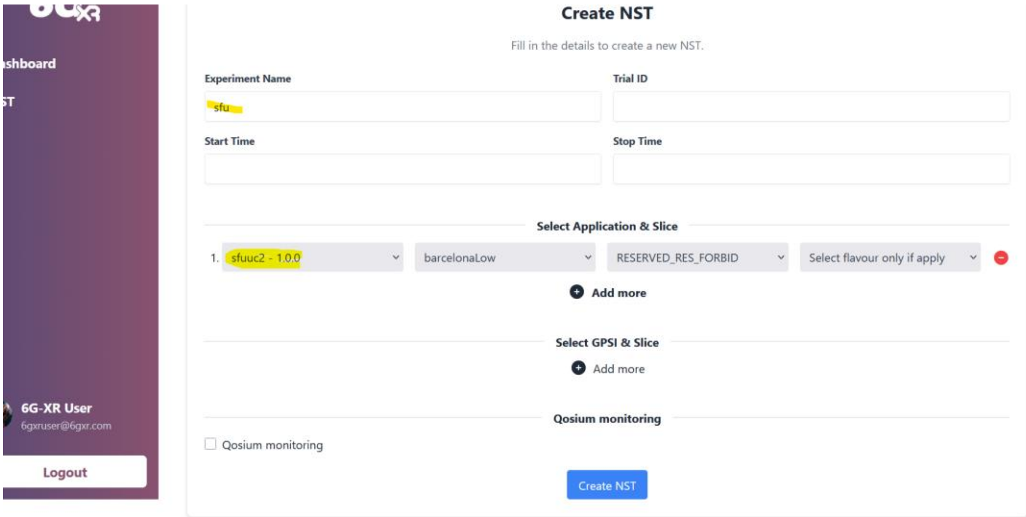
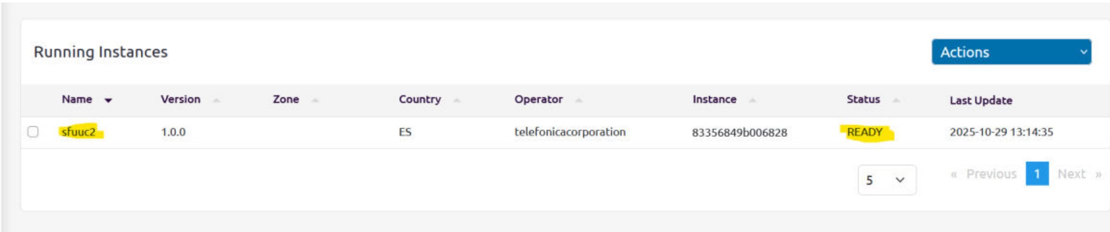


Figure 73: Experiment creation through Trial Controller for SFU deployment in Madrid.



Running Instances — Actions

Name	Version	Zone	Country	Operator	Instance	Status	Last Update
sfuuc2	1.0.0		ES	telefonicacorporation	83356849b006828	READY	2025-10-29 13:14:35

5 « Previous 1 Next »

Figure 74: SFU instance created in Madrid.


```
{
  "media": [
    {
      "managerId": 3772588376,
      "managerServiceType": "media",
      "managerIP": "10.15.125.10",
      "managerPort": "30002",
      "timestamp": 1762268442165,
      "active": true,
      "activeUsers": [
        "1261807198"
      ],
      "zoneId": "Omega12345"
    },
    {
      "managerId": 1052476495,
      "managerServiceType": "media",
      "managerIP": "172.27.28.10",
      "managerPort": "30002",
      "timestamp": 1762268442608,
      "active": true,
      "activeUsers": [
        "1697244656"
      ],
      "zoneId": "Omega12345"
    }
  ],
  "events": [
    {
      "managerId": 1825039775,
      "managerServiceType": "events",
      "managerIP": "172.27.28.10",
      "managerPort": "30001",
      "timestamp": 1762268414250,
      "active": true,
      "activeUsers": [
        "1261807198",
        "1697244656"
      ]
    }
  ]
}
```


Figure 75: Holo Orchestrator active users per SFU.

4.4.1.8 UC2 – Best Edge selection for SFU Test Case

	UC2 – Best Edge selection for SFU Test Case		
Test Case ID	SN_UC2_2.3		
Test Case Name	Best Edge selection for SFU		
Test Execution Date	24/10/2025		
Test Executed By	I2CAT & Capgemini		
Number of repetitions	One repetition		
Verification Points (VP)			
Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*Connect first native client to holographic orchestrator.*		
ID #2	*Holographic Orchestrator triggers Simple Edge Discovery API with an IP address of a device located in Madrid.*		
ID #3	*Connect first native client to SFU in Madrid.*		
ID #4	*Connect second native client to holographic orchestrator.*		
ID #5	*Holographic Orchestrator triggers Simple Edge Discovery API with its own IP address.*		
ID #6	*Connect second native client to SFU in Barcelona.*		
ID #7	*Obtain RTT metrics from the first client to the SFU in Madrid.*		
ID #8	*Obtain RTT metrics from the second client to the SFU in Barcelona.*		
ID #9	*Validate both users see each other in the session.*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1	Figure 71 (Validated in TestCase SN_UC2_2.1)	Pass
ID #2	1	Figure 76	Pass
ID #3	1	Figure 75 (Validated in TestCase SN_UC2_2.2)	Pass
ID #4	1	Figure 71 (Validated in TestCase SN_UC2_2.1)	Pass
ID #5	1	Figure 76	Pass
ID #6	1	Figure 75 (Validated in TestCase SN_UC2_2.2)	Pass
ID #7	1	Figure 77	Pass
ID #8	1	Figure 77	Pass
ID #9	1	Figure 72 (Validated in TestCase SN_UC2_2.1)	Pass
Results / Diagrams			

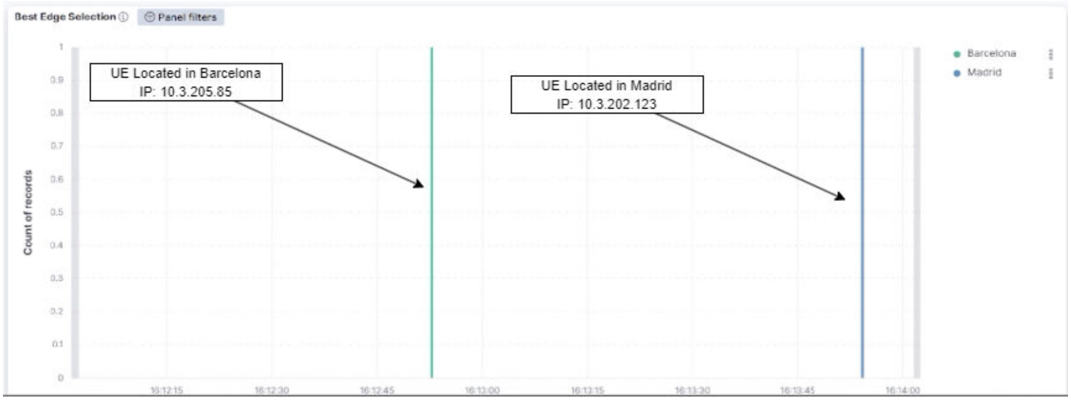


Figure 76: Simple Edge Discovery calls from a UE located in Barcelona and for one located in Madrid.

To validate the benefit of using the Simple Edge Discovery, the Holo Orchestrator calls the Simple Edge Discovery API using on one hand an IP address from Barcelona (real location) and on the other hand another IP address from Madrid (simulated location). In this way, one UE will be connected to the SFU located at Barcelona (which would be the optimal Edge achieving minimum delay) and the other to the SFU located in Madrid (higher delay). Thus, the metrics comparison is done effectively. The same happens in the TestCase SN_UC2_2.4, but for the remote renderers selection instead of SFUs.

Figure 77: Latency for UE interacting with SFU in Barcelona (yellow) and for UE interacting with SFU in Madrid (purple).

4.4.1.9 UC2 – Best Edge selection for Remote Renderer Test Case

	UC2 – Best Edge selection for Remote Renderer Test Case
Test Case ID	SN_UC2_2.4
Test Case Name	Best Edge selection for Remote Renderer
Test Execution Date	24/10/2025
Test Executed By	I2CAT & Capgemini
Number of repetitions	> 5 successful repetitions, but showing evidences for one repetition in this table
Verification Points (VP)	

Checkpoint ID	**Description of Validation Criteria for checkpoint**
ID #1	*Connect first native client (located in Barcelona) to holographic orchestrator.*
ID #2	*Connect first native client to SFU in Madrid.*
ID #3	*Connect first web client (located in Madrid) to holographic orchestrator.*
ID #4	*Connect first web client to SFU in Madrid.*
ID #5	*Holographic Orchestrator triggers Simple Edge Discovery API with an IP address of a device located in Barcelona.*
ID #6	*Connect first web client to remote renderer located in Barcelona.*
ID #7	*Connect second web client (located in Madrid) to holographic orchestrator.*
ID #8	*Connect second web client to SFU in Madrid.*
ID #9	*Holographic Orchestrator triggers Simple Edge Discovery API with its own IP address.*
ID #10	*Connect second web client to remote renderer located in Madrid.*
ID #11	*Obtain RTT metrics from first web client to the remote renderer in Barcelona.*
ID #12	*Obtain RTT metrics from second web client to the remote renderer in Madrid.*
ID #13	*Validate both web clients see each other and the native client*
Test Validation Conditions	All checkpoints have passed in all the repetitions.

Test results	**Test run**	**Description**	**Result**
ID #1	1	Figure 71 (Validated in TestCase SN_UC2_2.1)	Pass
ID #2	1	Figure 75 (Validated in TestCase SN_UC2_2.2)	Pass
ID #3	1	Figure 71 (Validated in TestCase SN_UC2_2.1)	Pass
ID #4	1	Figure 75 (Validated in TestCase SN_UC2_2.2)	Pass
ID #5	1	Figure 76 (Validated in TestCase SN_UC2_2.3)	Pass
ID #6	1	Figure 76 (Validated in TestCase SN_UC2_2.3)	Pass
ID #7	1	Figure 71 (Validated in TestCase SN_UC2_2.1)	Pass
ID #8	1	Figure 75 (Validated in TestCase SN_UC2_2.2)	Pass
ID #9	1	Figure 76 (Validated in TestCase SN_UC2_2.3)	Pass
ID #10	1	Figure 76 (Validated in TestCase SN_UC2_2.3)	Pass
ID #11	1	Figure 78	Pass
ID #12	1	Figure 78	Pass
ID #13	1	Figure 79	Pass

Results / Diagrams

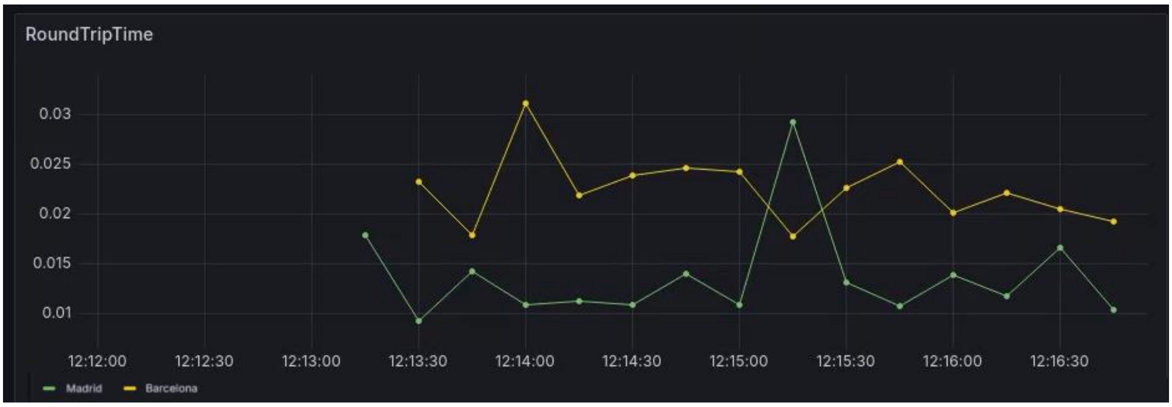


Figure 78: RTT metrics comparison between Madrid and Barcelona.

Figure 79: Web client located in Madrid (lower) and web client located in Barcelona (upper).

SN_UC2 was demonstrated live at the 6G-XR Impact Day hosted at 5TONIC. The video is accessible here: [6G-XR - YouTube]

4.4.2 KVIs and QoE for UC1 and UC2

In this section we report on the obtained results from user studies evaluating the UC1 variant based on adapting the client's data rate to overcome detected (forced) 5G network congestions. This study was undertaken as part of a public demo that was showcased live at EuCNC'25 in June 2025, using an identical setup to that from Test Case UC1_1.1, with the exception of using a local 5G access network based on Amarisoft.

The setup consisted of two users connected via a Holo Client (laptop connected to an RGB-D camera and to a Quest 3 headset, running in XR passthrough mode) to the same local 5G network, with an established holographic communication session between the two. At the beginning, the audiovisual interaction between the two users was fluid. At some point (after approx. 1-2 minutes), congestion was forced in the 5G network, so audiovisual artifacts and increasing delays occurred, severely impacting the Quality of Service (QoS) and perceived Quality of Experience (QoE) in the session. As a mitigation action, the CDF in collaboration with the Holo Orchestrator instructed the remote Holo

Client(s) to adjust/lower the data rate to fit the available bandwidth capacity. At this stage, the audiovisual quality, playback continuity, and delays were restored back to satisfactory levels to keep a natural and high-quality holographic conversation. Each session took around 5 minutes.

Overall, 23 participants (34.8% female) took part in the study. 60.9% were aged between 20-40 years old, 30.4% between 40-60, and 8.7% over 60 years old. Their levels of familiarity with XR and 6G technologies is indicated in Figure 80.

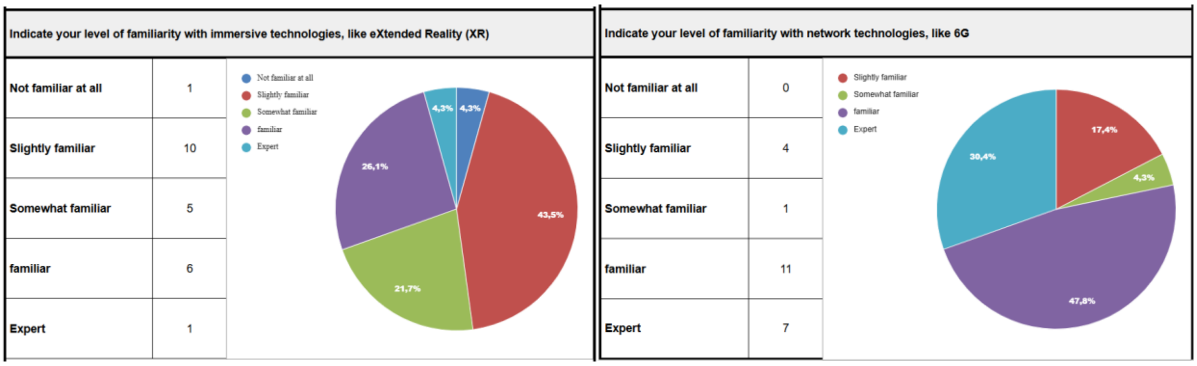
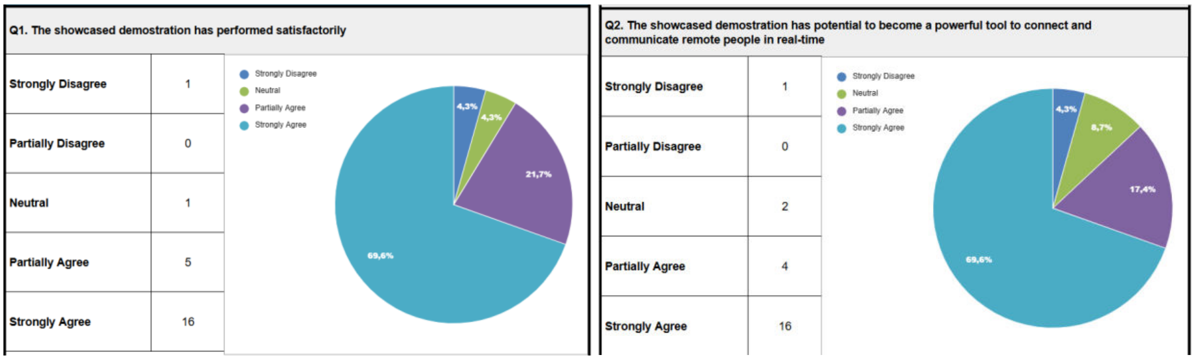


Figure 80: Familiarity of participants with XR and 6G technologies.

Participants were asked about the perceived performance and the impact of the showcased technology. As reported in Figure 81, most of them perceived a satisfactory performance (Q1), believe in the potential of the technology to connect remote people (Q2), believe that 6G technologies will contribute to increase performance and interoperability of XR services (Q3), and that the presented network-assisted rate recommendation feature provides added-value in the XR domain (Q4).



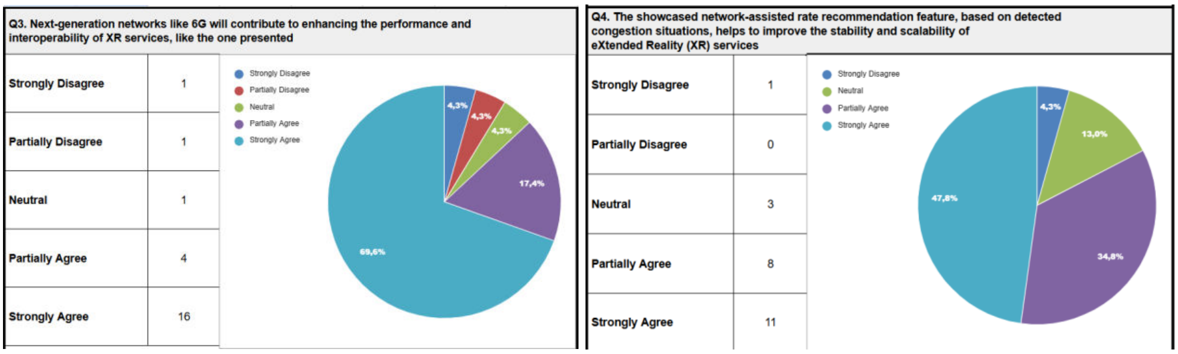


Figure 81: Perceived performance and impact.

Participants were also asked about their opinion regarding relevant Key Value Indicators (KVIs) for the presented technology (Figure 82), and their feedback was encouraging, due to their positive receptiveness and feelings about inclusiveness and fairness (Q5), environmental sustainability by reducing the need for travels (Q6) and societal impact by providing new business opportunities (Q7).

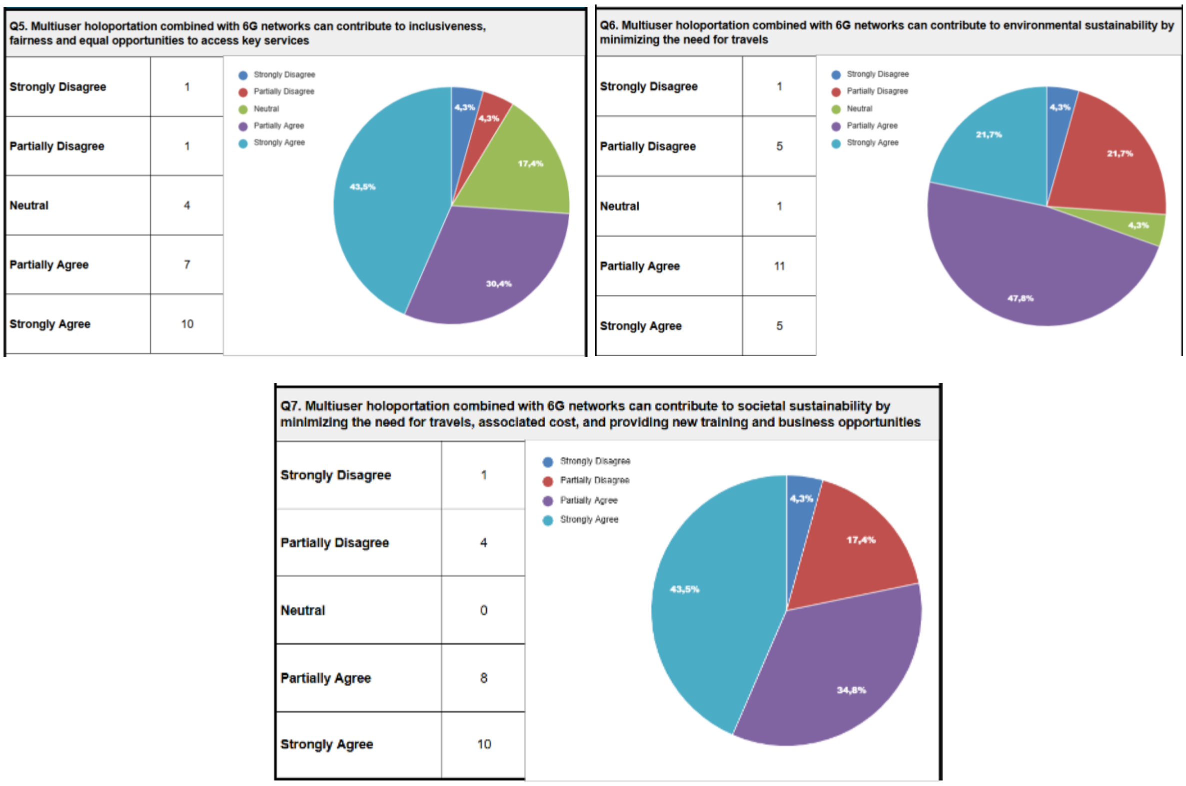


Figure 82: Participants' feedback on KVIs.

Finally, participants were asked about general feedback. In general, they liked and enjoyed the presented technology (with only 1 indicating to dislike it), and they believed that holographic communications can become more effective than traditional 2D videoconferencing tools (with only 1 indicating to disagree with that).

4.4.3 KPIs UC3

To measure KPIs, a monitoring system was deployed along with the MATSUKO application containers to gather metrics in real-time during the test calls. The monitoring system automatically gathers KPIs, such as bandwidth, latency, jitter and packet loss.

4.4.3.1 UC3 – IMS Data Channel using MATSUKO - connectivity

	UC3 – IMS Data Channel using MATSUKO - connectivity		
Test Case ID	SN_UC3_1.1		
Test Case Name	IMS Data Channel using MATSUKO - connectivity		
Test Execution Date	27/10/2025		
Test Executed By	Ericsson & MATSUKO		
Number of repetitions	Three repetitions		
Verification Points (VP)			
Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*First native client connected to the Session Manager*		
ID #2	*Second native client connected to the Session Manager*		
ID #3	*Push notification received on the second native client*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1-3	Run 1: Figure 83, Run 2: Figure 84, Run 3: Figure 85	Pass
ID #2	1-3	Run 1: Figure 83, Run 2: Figure 84, Run 3: Figure 85	Pass
ID #3	1-3	Run 1: Figure 83, Run 2: Figure 84, Run 3: Figure 85	Pass
Results / Diagrams			

```
ID#1

2025/10/27 10:24:14 New receiver websocket connection
2025/10/27 10:24:14 Registering receiver with the manager
2025/10/27 10:24:14 Receiver location: 50,40, receiver operator: 21407
2025/10/27 10:24:14 Registering a new receiver 34e4MMfQ1p0WdWfeuN5NlG5ZDIO (user 33fb5791-bf63-4a98-9da2-3791464d3b43) to room
111111

ID#2

2025/10/27 10:24:23 New sender websocket connection
2025/10/27 10:24:23 sending message to sender: {"config":{"iceServers":[{"urls":["stun:stun.l.google.com:19302"]}]}}
2025/10/27 10:24:23 received message from sender: {"properties":{"userName":"Agent
597298","audioEnabled":true,"videoEnabled":true,"isPresentationMode":true}}
2025/10/27 10:24:23 Registering sender with the manager
2025/10/27 10:24:23 Sender location: 50.0,40.0, sender operator: 12345
2025/10/27 10:24:23 check sender hologram length
2025/10/27 10:24:23 sender.holograms length is zero
2025/10/27 10:24:23 iterating over receivers in the room
2025/10/27 10:24:23 Receiver hologram match, hologram.location: 50.0,40.0
2025/10/27 10:24:23 r.hologram.id: 34dr2jz3YCMHkM1b9BHmfWbIpKT
2025/10/27 10:24:23 Hologram not registered, register sender
2025/10/27 10:24:23 Registering sender with the manager - assign sender to hologram: 34dr2jz3YCMHkM1b9BHmfWbIpKT
2025/10/27 10:24:23 check sender hologram length
2025/10/27 10:24:23 Sender hologram id: %s 34dr2jz3YCMHkM1b9BHmfWbIpKT
2025/10/27 10:24:23 Registering a new sender 34e4NU1NhLkB25B586fpj4iGc6K (user 6A781D7A-C445-4910-AAD2-F5AB7663EA72)
to room 111111
2025/10/27 10:24:23 Check if sender is already present in room
2025/10/27 10:24:23 New sender: %s 34e4NU1NhLkB25B586fpj4iGc6K

ID#3

2025/10/27 10:24:14 SEND NOTIFICATION
Sent to bebdd5a4d7ca43c69be041f16ee7173b2edde4f44c8bd20b25cbe8fe45a06056, response: &{200
5390B3C7-9EDD-FDBB-8FFA-25D1A0DCC5D3 0001-01-01 00:00:00 +0000 UTC }
```

Figure 83: SN_UC3_1.1 - 251027 - Run 1.

ID#1

```
2025/10/27 11:19:45 New receiver websocket connection
2025/10/27 11:19:45 Registering receiver with the manager
2025/10/27 11:19:45 Receiver location: 50.2,40.5, receiver operator: 21407
2025/10/27 11:19:45 Registering a new receiver 34eB6zcJWn05SYeNk0goESo7HW6 (user 214050000001157) to room 111111
```

ID#2

```
2025/10/27 11:19:52 New sender websocket connection
2025/10/27 11:19:52 sending message to sender: {"config":{"iceServers":[{"urls":["stun:stun.l.google.com:19302"]}]}}
2025/10/27 11:19:52 received message from sender: {"properties":{"userName":"Agent
655909","audioEnabled":true,"videoEnabled":true,"isPresentationMode":true}}
2025/10/27 11:19:52 Registering sender with the manager
2025/10/27 11:19:52 Sender location: 50.0,40.0, sender operator: 12345
2025/10/27 11:19:52 check sender hologram length
2025/10/27 11:19:52 sender.holograms length is zero
2025/10/27 11:19:52 iterating over receivers in the room
2025/10/27 11:19:52 Receiver hologram match, hologram.location: 50.0,40.0
2025/10/27 11:19:52 r.hologram.id: 34dr2jz3YCMHkM1b9BHmfWbIpKT
2025/10/27 11:19:52 Hologram not registered, register sender
2025/10/27 11:19:52 Registering sender with the manager - assign sender to hologram: 34dr2jz3YCMHkM1b9BHmfWbIpKT
2025/10/27 11:19:52 check sender hologram length
2025/10/27 11:19:52 Sender hologram id: %s 34dr2jz3YCMHkM1b9BHmfWbIpKT
2025/10/27 11:19:52 Registering a new sender 34eB7tBnbnzsisN4M9Mca7x64g6 (user A0D137D5-FAFF-4F18-BE72-C7D503D3E90A)
to room 111111
2025/10/27 11:19:52 Check if sender is already present in room
2025/10/27 11:19:52 New sender: %s 34eB7tBnbnzsisN4M9Mca7x64g6
```

ID#3

```
2025/10/27 11:19:45 SEND NOTIFICATION
Sent to bebdd5a4d7ca43c69be041f16ee7173b2edde4f44c8bd20b25cbe8fe45a06056, response: &{200
08CAAC27-BB34-91B1-EF3A-2960A9B88952 0001-01-01 00:00:00 +0000 UTC }
```

Figure 84: SN_UC3_1.1 - 251027 - Run 2.

ID#1

```
2025/10/27 14:00:19 New receiver websocket connection
2025/10/27 14:00:19 Registering receiver with the manager
2025/10/27 14:00:19 Receiver location: 50.2,40.5, receiver operator: 21407
2025/10/27 14:00:19 Registering a new receiver 34eUdhqPzOKS8GXft1VfK7ngZIs (user 214050000001158) to room 111111
```

ID#2

```
2025/10/27 14:00:26 New sender websocket connection
2025/10/27 14:00:26 sending message to sender: {"config":{"iceServers":[{"urls":["stun:stun.l.google.com:19302"]}]}}
2025/10/27 14:00:26 received message from sender: {"properties":{"userName":"Agent
377243","audioEnabled":true,"videoEnabled":true,"isPresentationMode":true}}
2025/10/27 14:00:26 Registering sender with the manager
2025/10/27 14:00:26 Sender location: 50.0,40.0, sender operator: 12345
2025/10/27 14:00:26 check sender hologram length
2025/10/27 14:00:26 sender.holograms length is zero
2025/10/27 14:00:26 iterating over receivers in the room
2025/10/27 14:00:26 Receiver hologram match, hologram.location: 50.0,40.0
2025/10/27 14:00:26 r.hologram.id: 34eGFZVFcT4Id70cfrQWRfQ71H7
2025/10/27 14:00:26 Hologram not registered, register sender
2025/10/27 14:00:26 Registering sender with the manager - assign sender to hologram: 34eGFZVFcT4Id70cfrQWRfQ71H7
2025/10/27 14:00:26 check sender hologram length
2025/10/27 14:00:26 Sender hologram id: %s 34eGFZVFcT4Id70cfrQWRfQ71H7
2025/10/27 14:00:26 Registering a new sender 34eUeUbZNrj7esNl2B7Luur882L (user A0D137D5-FAFF-4F18-BE72-C7D503D3E90A)
to room 111111
2025/10/27 14:00:26 Check if sender is already present in room
2025/10/27 14:00:26 New sender: %s 34eUeUbZNrj7esNl2B7Luur882L
```

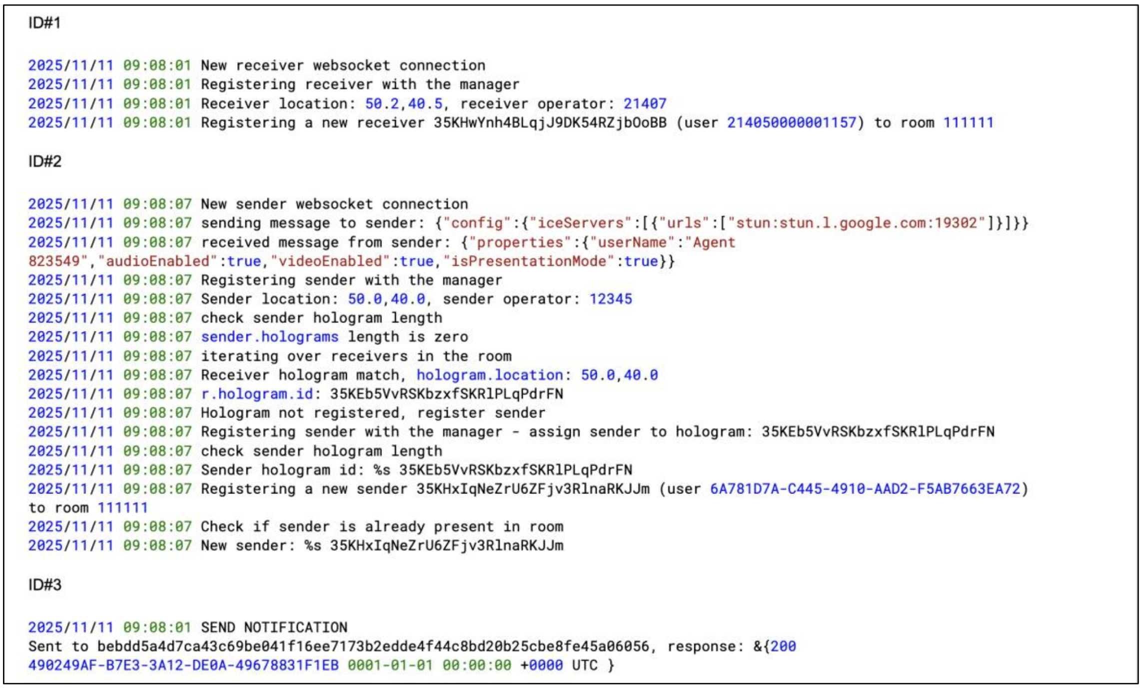
ID#3

```
2025/10/27 14:00:19 SEND NOTIFICATION
Sent to bebdd5a4d7ca43c69be041f16ee7173b2edde4f44c8bd20b25cbe8fe45a06056, response: &{200
A1794687-4392-49F9-15B3-A4862FD93606 0001-01-01 00:00:00 +0000 UTC }
```

Figure 85: SN_UC3_1.1 - 251027 - Run 3.

4.4.3.2 UC3 – IMS Data Channel using MATSUKO - connectivity

	UC3 – IMS Data Channel using MATSUKO - connectivity		
Test Case ID	SN_UC3_1.1		
Test Case Name	IMS Data Channel using MATSUKO - connectivity		
Test Execution Date	11/11/2025		
Test Executed By	Ericsson & MATSUKO		
Number of repetitions	Three repetitions		
Verification Points (VP)			
Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*First native client connected to the Session Manager*		
ID #2	*Second native client connected to the Session Manager*		
ID #3	*Push notification received on the first native client*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1-3	Run 1: Figure 86, Run 2: Figure 87, Run 3: Figure 88	Pass
ID #2	1-3	Run 1: Figure 86, Run 2: Figure 87, Run 3: Figure 88	Pass
ID #3	1-3	Run 1: Figure 86, Run 2: Figure 87, Run 3: Figure 88	Pass
Results / Diagrams			



```
ID#1

2025/11/11 09:08:01 New receiver websocket connection
2025/11/11 09:08:01 Registering receiver with the manager
2025/11/11 09:08:01 Receiver location: 50.2,40.5, receiver operator: 21407
2025/11/11 09:08:01 Registering a new receiver 35KHwYnh4BLqjJ9DK54RZjbOoBB (user 214050000001157) to room 111111

ID#2

2025/11/11 09:08:07 New sender websocket connection
2025/11/11 09:08:07 sending message to sender: {"config":{"iceServers":[{"urls":["stun:stun.l.google.com:19302"]}]}}
2025/11/11 09:08:07 received message from sender: {"properties":{"userName":"Agent
823549","audioEnabled":true,"videoEnabled":true,"isPresentationMode":true}}
2025/11/11 09:08:07 Registering sender with the manager
2025/11/11 09:08:07 Sender location: 50.0,40.0, sender operator: 12345
2025/11/11 09:08:07 check sender hologram length
2025/11/11 09:08:07 sender.holograms length is zero
2025/11/11 09:08:07 iterating over receivers in the room
2025/11/11 09:08:07 Receiver hologram match, hologram.location: 50.0,40.0
2025/11/11 09:08:07 r.hologram.id: 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:08:07 Hologram not registered, register sender
2025/11/11 09:08:07 Registering sender with the manager - assign sender to hologram: 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:08:07 check sender hologram length
2025/11/11 09:08:07 Sender hologram id: %s 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:08:07 Registering a new sender 35KHxIqNeZrU6ZFjv3RlnaRKJJm (user 6A781D7A-C445-4910-AAD2-F5AB7663EA72)
to room 111111
2025/11/11 09:08:07 Check if sender is already present in room
2025/11/11 09:08:07 New sender: %s 35KHxIqNeZrU6ZFjv3RlnaRKJJm

ID#3

2025/11/11 09:08:01 SEND NOTIFICATION
Sent to bebdd5a4d7ca43c69be041f16ee7173b2edde4f44c8bd20b25cbe8fe45a06056, response: &{200
490249AF-B7E3-3A12-DE0A-49678831F1EB 0001-01-01 00:00:00 +0000 UTC }
```

Figure 86: SN_UC3_1.1 - 251111 - Run 1.

```
ID#1

2025/11/11 09:10:56 New receiver websocket connection
2025/11/11 09:10:56 Registering receiver with the manager
2025/11/11 09:10:56 Receiver location: 50.2,40.5, receiver operator: 21407
2025/11/11 09:10:56 Registering a new receiver 35KIIYxKLX1w3Qyt2KAdYe56TZ9 (user 214050000001157) to room 111111

ID#2

2025/11/11 09:11:03 New sender websocket connection
2025/11/11 09:11:03 sending message to sender: {"config":{"iceServers":[{"urls":["stun:stun.l.google.com:19302"]}]}}
2025/11/11 09:11:03 received message from sender: {"properties":{"userName":"Agent
627028","audioEnabled":true,"videoEnabled":true,"isPresentationMode":true}}
2025/11/11 09:11:03 Registering sender with the manager
2025/11/11 09:11:03 Sender location: 50.0,40.0, sender operator: 12345
2025/11/11 09:11:03 check sender hologram length
2025/11/11 09:11:03 sender.holograms length is zero
2025/11/11 09:11:03 iterating over receivers in the room
2025/11/11 09:11:03 Receiver hologram match, hologram.location: 50.0,40.0
2025/11/11 09:11:03 r.hologram.id: 35KD0x6HOtLaXIC3ZMOTGGf1t9d
2025/11/11 09:11:03 iterating over receivers in the room
2025/11/11 09:11:03 Receiver hologram match, hologram.location: 50.0,40.0
2025/11/11 09:11:03 r.hologram.id: 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:11:03 Hologram not registered, register sender
2025/11/11 09:11:03 Registering sender with the manager - assign sender to hologram: 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:11:03 check sender hologram length
2025/11/11 09:11:03 Sender hologram id: %s 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:11:03 Registering a new sender 35KIJKbB95R1lsSYWrEjHRJHR18 (user 6A781D7A-C445-4910-AAD2-F5AB7663EA72)
to room 111111
2025/11/11 09:11:03 Check if sender is already present in room
2025/11/11 09:11:03 New sender: %s 35KIJKbB95R1lsSYWrEjHRJHR18

ID#3

2025/11/11 09:10:56 SEND NOTIFICATION
Sent to bebdd5a4d7ca43c69be041f16ee7173b2edde4f44c8bd20b25cbe8fe45a06056, response: &{200
113F340A-C96A-C8E3-C6DA-3FBBE682A391 0001-01-01 00:00:00 +0000 UTC }
```

Figure 87: SN_UC3_1.1 - 251111 - Run 2.

```
ID#1

2025/11/11 09:14:53 New receiver websocket connection
2025/11/11 09:14:53 Registering receiver with the manager
2025/11/11 09:14:53 Receiver location: 50.2,40.5, receiver operator: 21407
2025/11/11 09:14:53 Registering a new receiver 35KImFM4FGg1HsO20a27Rkp9HsM (user 214050000001157) to room 111111

ID#2

2025/11/11 09:14:58 New sender websocket connection
2025/11/11 09:14:58 sending message to sender: {"config":{"iceServers":[{"urls":["stun:stun.l.google.com:19302"]}]}}
2025/11/11 09:14:58 received message from sender: {"properties":{"userName":"Agent
891844","audioEnabled":true,"videoEnabled":true,"isPresentationMode":true}}
2025/11/11 09:14:58 Registering sender with the manager
2025/11/11 09:14:58 Sender location: 50.0,40.0, sender operator: 12345
2025/11/11 09:14:58 check sender hologram length
2025/11/11 09:14:58 sender.holograms length is zero
2025/11/11 09:14:58 iterating over receivers in the room
2025/11/11 09:14:58 Receiver hologram match, hologram.location: 50.0,40.0
2025/11/11 09:14:58 r.hologram.id: 35KD0x6HOtLaXIC3ZMOTGGf1t9d
2025/11/11 09:14:58 iterating over receivers in the room
2025/11/11 09:14:58 Receiver hologram match, hologram.location: 50.0,40.0
2025/11/11 09:14:58 r.hologram.id: 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:14:58 Hologram not registered, register sender
2025/11/11 09:14:58 Registering sender with the manager - assign sender to hologram: 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:14:58 check sender hologram length
2025/11/11 09:14:58 Sender hologram id: %s 35KEb5VvRSKbzxfSKRlPLqPdrFN
2025/11/11 09:14:58 Registering a new sender 35KImuWI5omZyQBNc9twgFTSe0Z (user 6A781D7A-C445-4910-AAD2-F5AB7663EA72)
to room 111111
2025/11/11 09:14:58 Check if sender is already present in room
2025/11/11 09:14:58 New sender: %s 35KImuWI5omZyQBNc9twgFTSe0Z

ID#3

2025/11/11 09:14:53 SEND NOTIFICATION
Sent to bebdd5a4d7ca43c69be041f16ee7173b2edde4f44c8bd20b25cbe8fe45a06056, response: &{200
C646EB00-CDC8-5D98-84E7-74A4FE318C3C 0001-01-01 00:00:00 +0000 UTC }
```

Figure 88: SN_UC3_1.1 - 251111 - Run 3.

4.4.3.3 UC3 – IMS Data Channel using MATSUKO – E2E

	UC3 – IMS Data Channel using MATSUKO – E2E		
Test Case ID	SN_UC3_1.2		
Test Case Name	IMS Data Channel using MATSUKO – E2E		
Test Execution Date	11/11/2025		
Test Executed By	Ericsson & MATSUKO		
Number of repetitions	Three repetitions		
Verification Points (VP)			
Checkpoint ID	**Description of Validation Criteria for checkpoint**		
ID #1	*Push notification received on the first native client*		
ID #2	*First native client starts the capture and streaming of himself/herself*		
ID #3	*Second native client receives the streaming and the hologram is rendered on the smartphone display*		
Test Validation Conditions	All checkpoints have passed in all the repetitions.		
Test results	**Test run**	**Description**	**Result**
ID #1	1-3	Figure 89	Pass
ID #2	1-3	Figure 90	Pass
ID #3	1-3	Figure 91	Pass
Results / Diagrams			

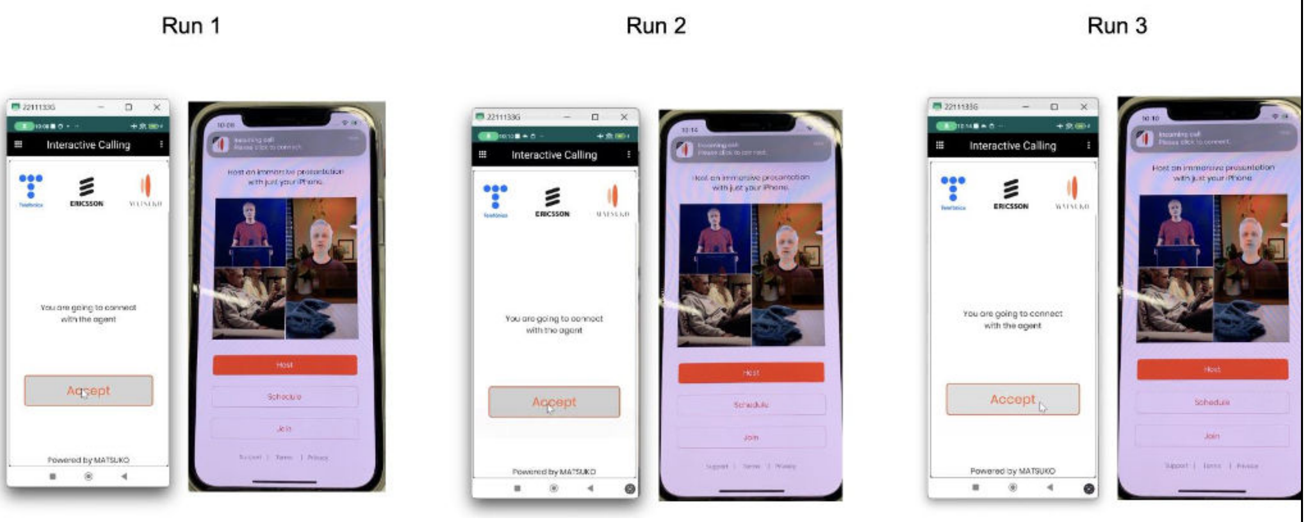


Figure 89: SN_UC3_1.2 - 251111 – ID #1.

Run 1 Run 2 Run 3

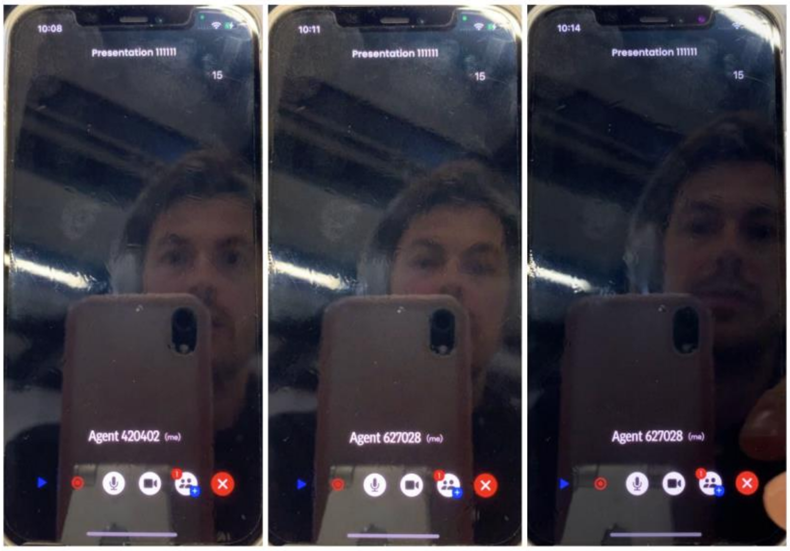


Figure 90: SN_UC3_1.2 - 251111 – ID #2.

Run 1 Run 2 Run 3

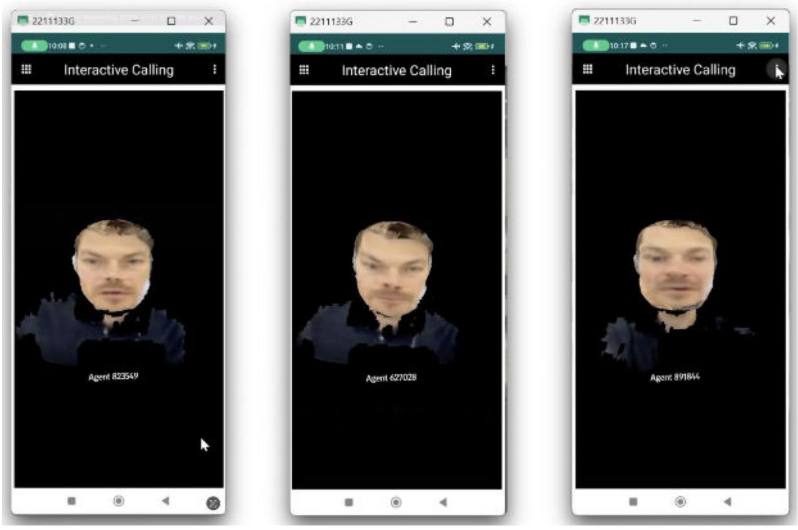


Figure 91: SN_UC3_1.2 - 251111 – ID #3.

Run 1:

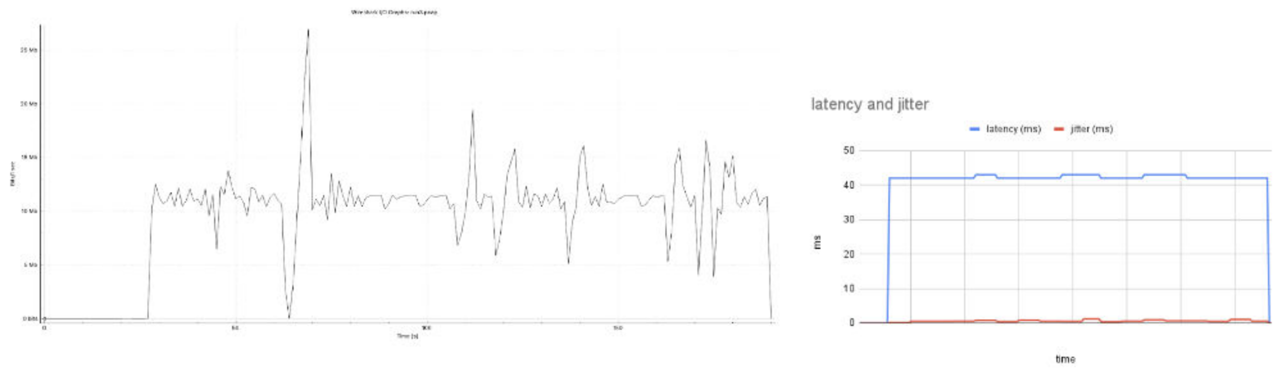


Figure 92: SN_UC3_1.2 - 251111 – Run 1 – Bandwidth, Latency and Jitter.

Run 2:

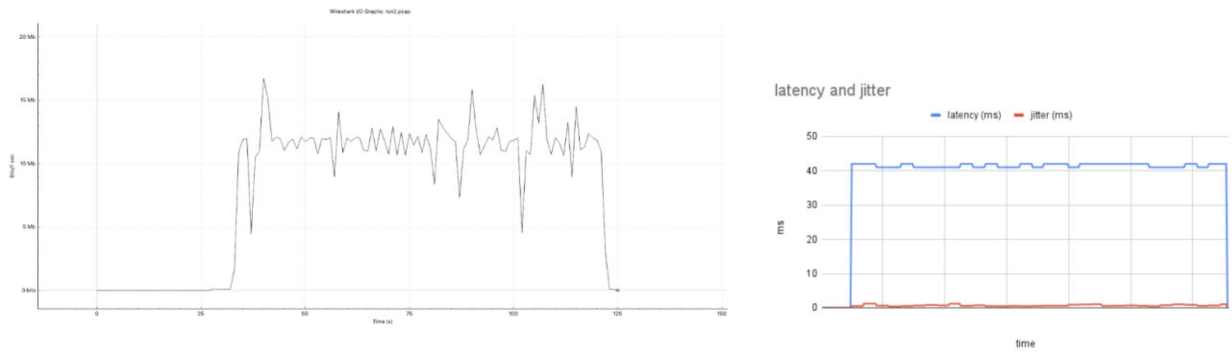


Figure 93: SN_UC3_1.2 - 251111 – Run 2 – Bandwidth, Latency and Jitter.

Run 3:

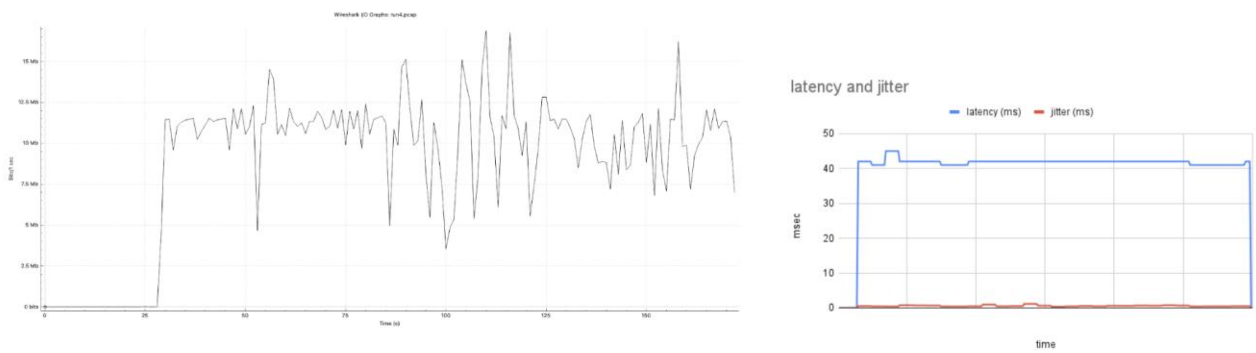


Figure 94: SN_UC3_1.2 - 251111 – Run 3 – Bandwidth, Latency and Jitter.

SN_UC3 was demonstrated live at the 6G-XR Impact Day hosted at 5TONIC. The video is accessible here: [6G-XR - YouTube]

4.4.4 KVIs and QoE for UC3

The surveys were conducted as part of a public live demonstration held during the 6G-XR Impact Day at 5TONIC premises in Madrid on 28 October 2025.

The setup involved two users, same as the configuration described in Test Case UC3_1.2. First participant used an iPhone, while the other used an Android smartphone to start the call via the dialler. Once the holographic call was established, the first user streamed his/her hologram through IMSDC, and the second user observed the hologram rendered in real time on the Android smartphone's display.

A total of 16 participants took part in the study:

- 12.5% identified as female.
- 18.8% were aged between 20 and 40 years.
- 81.3% were aged between 40 and 60 years.

Participants' levels of familiarity with XR and 6G technologies are presented in Figure 95.

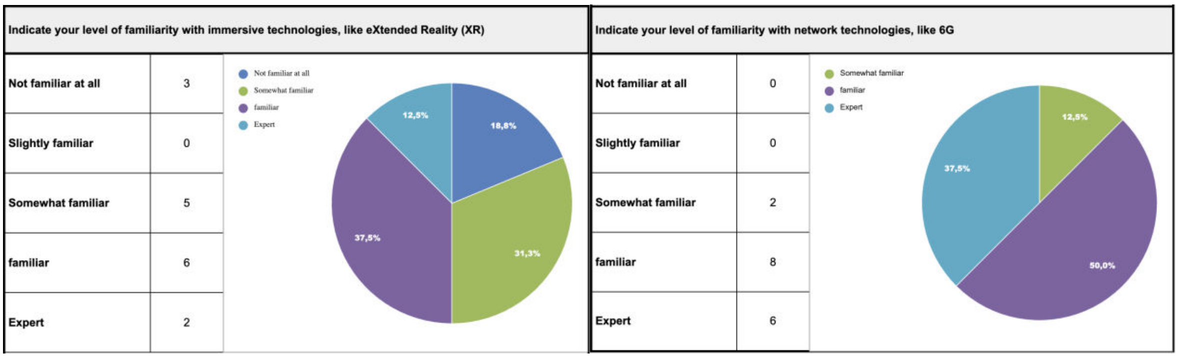


Figure 95: Familiarity of participants with XR and 6G technologies.

Participants were invited to provide their feedback on the perceived performance and overall impact of the demonstrated technology. As shown in Figure 96, the results indicate that:

- Q1: the majority (87.5%) expressed satisfaction with the performance of the presented technology.
- Q2: most participants (75.0%) recognized its potential to facilitate connections among remote users.
- Q3: most participants (87.5%) agreed that 6G technologies will enhance the performance and interoperability of XR services.
- Q4: most participants (62.5%) acknowledged that social and cultural expectations influence who is encouraged to engage with XR technologies.

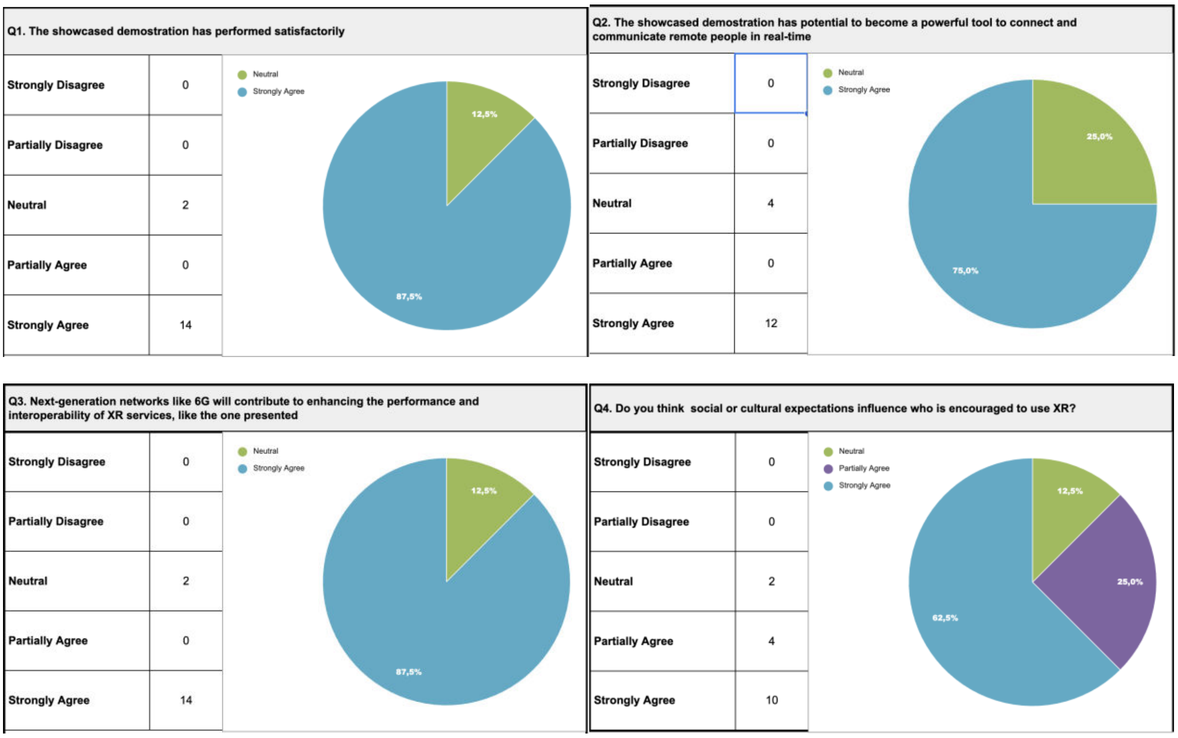
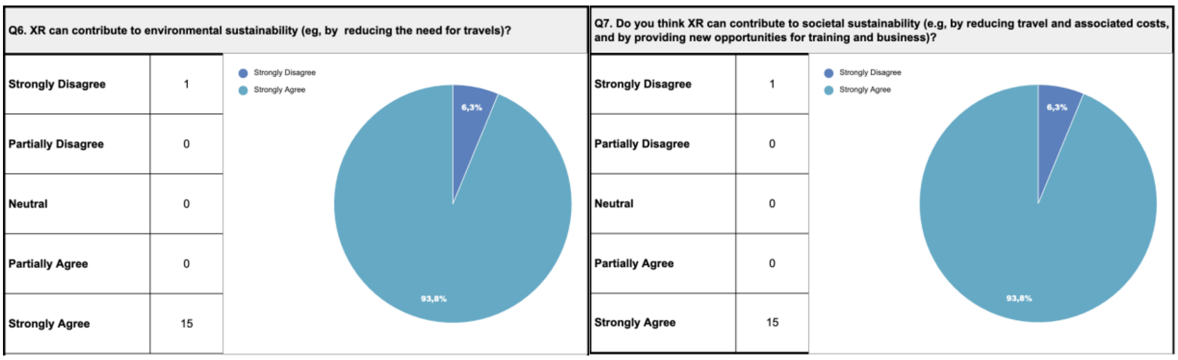


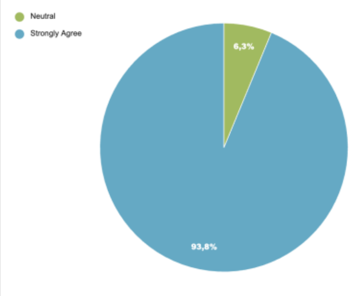
Figure 96: Participants' feedback on the performance and impact.

Participants were further asked to evaluate relevant Key Value Indicators (KVIs) for the showcased technology Figure 97. Their responses were generally positive, highlighting:

- Q5: most participants (81.3%) recognized favorable perceptions regarding inclusiveness and fairness.
- Q6: most participants (93.8%) acknowledged positive contribution on environmental sustainability through reduced travel requirements.
- Q7: most participants (93.8%) acknowledged the technology's potential for positive societal impact by enabling new business opportunities.



Q8. I enjoyed the showcased demonstration.	
Strongly Disagree	0
Partially Disagree	0
Neutral	1
Partially Agree	0
Strongly Agree	15



Q9. Holographic communication technologies, like the one showcased, can become more effective tools than traditional 2D videoconferencing solutions in certain use cases	
Strongly Disagree	1
Partially Disagree	0
Neutral	1
Partially Agree	0
Strongly Agree	14

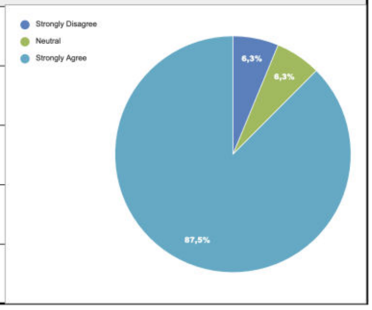
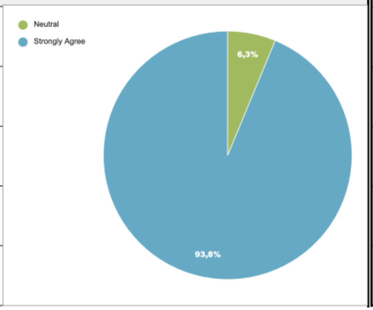


Figure 97: Participants' feedback on KVIs.

The participants were also asked to provide general feedback. They expressed appreciation for the demonstrated technology and confirmed that holographic communication could become a more effective than conventional 2D videoconferencing tools, as shown in Figure 98.

Q8. I enjoyed the showcased demonstration.	
Strongly Disagree	0
Partially Disagree	0
Neutral	1
Partially Agree	0
Strongly Agree	15



Q9. Holographic communication technologies, like the one showcased, can become more effective tools than traditional 2D videoconferencing solutions in certain use cases	
Strongly Disagree	1
Partially Disagree	0
Neutral	1
Partially Agree	0
Strongly Agree	14

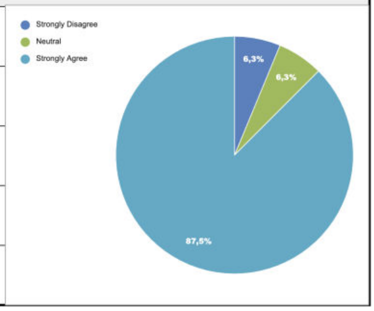


Figure 98: General feedback.

5 CONCLUSIONS

6G-XR project demonstrates in this document the two functioning end-to-end holographic communication architectures built in the South Node: (i) a VR platform powered by i2CAT application combined with data connectivity via UPF over a beyond 5G network, which holds UC1 and UC2; and (ii) an AR platform powered by MATSUKO application combined with data connectivity and signalling over the novel IMS Data Channel, which sustains UC3.

From the network and application enablers developed in the project, the VR platform has integrated the Notification of Congestion Detection, the Rate Recommendation, the QoD triggering, the Holo Clients, the Holo Orchestrator, the Remote Renderer, the Edge Orchestrator features for closest Edge discovery and selection, the Edge federation, plus the CAMARA-based and NEF APIs for interaction with the network. The AR platform has leveraged the whole IMSDC solution, has defined a new signalling communication system, has adapted the WebRTC methods and has reimplemented the hologram rendering service in WebGL.

In terms of technical demands and performance, the results show that the deployed platforms successfully supported the use cases and met the expectations. The participants of the survey reported high satisfaction with perceived user experience and had positive views on 6G and XR technologies having potential to improve the real-time remote communication among people. The participants partly agreed that these services could bring environmental benefits from reduced travel. Overall, these results indicate that the technology is on a promising trajectory toward real-world deployment and transformative XR experiences.

Next steps should focus on further validation at scale, real-world deployments, and continued integration with network exposure APIs, security hardening, and governance to address privacy and regulatory considerations. Future XR projects should include a concrete plan for transitioning from demonstration to pilot deployments, including success metrics, risk assessment, and sustainability considerations.

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ANNEX A – TEST CASE TEMPLATE

The template presented below refers to Test Cases descriptions used in the 6G-XR, within which the validation methodology is executed. It contains the test cases specification part and results presentation part.

Test Location	**User Story/Scenario**						
Test Case Name	*Delay performance measurement for 3D DT*						
Test Case Objective/KPI	*Performance*						
Test Execution Date							
Test Executed By							
Test Case Category	*Requirements/KPI/KVI/QoE*						
Test Environment	*Laboratory / field and list endpoints that logs were collected from*						
Test Deployment Setup	*Add a diagram with the components under test*						
Network Setup	**RAN:**		**5G Core:**		**EDGE**	*Application*	**Band:** *3,4-3,7GHz* **Bandwidth:** *100MHz*
Test Configuration	**Condition 1**		**Condition 2**		**Condition 3**		
Initial Conditions/Prerequisites							
Refer to anything (ex.slices available/test cases loaded/resources etc.) IF NECESSARY for the execution of the test.							
Test scenario							
Refer to the steps of execution, especially referring to the metrics collection steps							
Test variables							
Variables that do not have static values							
Expected behaviour/Target Values							
Refer here to the conditions (including KPI metrics) that are considered sufficient for the completion of the test case							
Number of repetitions							
Test's comments							
Verification Points (VP)							
Checkpoint ID	**Description of Validation Criteria for checkpoint**						
ID #1	*Performance at condition #X*						
ID #2	*Performance at condition #Y*						
ID #3	….						
Test Validation Conditions	All checkpoints have passed in all the repetitions						
Naming convention	**Define log file naming logic**						
Test results	**Test run 1**	**Test run 2**	**Test run 3**	**Diagrams**			**Result**

Checkpoint ID #1	*logfileA*	*logfileD*	*logfileG*	Refer to the relevant diagram below and explain verdict	Pass/Fail
Checkpoint ID #2	*logfileB*	*logfileE*	*logfileH*		
Checkpoint ID #3	*logfileC*	*logfileF*	*logfileI*		
Final Diagrams					
insert here the main diagrams explaining the verdict					

ANNEX B – KVI – QOE - QUESTIONNAIRE

Questionnaire

DEMOGRAPHICS AND BACKGROUND

How old are you?

☐ 0-19
☐ 20-39
☐ 40-59
☐ Over 60
☐ I prefer not to disclose
☐ I prefer to specify my age: ___________

What is your gender?

☐ Male
☐ Female
☐ Non-binary
☐ I prefer not to disclose
☐ I prefer to self-describe: ___________

How would you describe your current familiarity with immersive technologies, such as eXtended reality (XR/VR, AR, holograms)?

☐ I've never used XR
☐ I've tried XR a few times
☐ I occasionally use XR
☐ I use XR frequently
☐ I work with XR professionally or academically

How familiar are you with network technologies, such as 6G?

☐ Not familiar at all
☐ Slightly familiar
☐ Somewhat familiar
☐ Familiar
☐ Expert

In your opinion, are there social or cultural expectations that influence who is encouraged to use XR or advanced technologies?

☐ Yes, significantly
☐ Somewhat
☐ Not really

☐ Not at all
☐ Unsure

PERFORMANCE AND IMPACT

Q.1 The showcased demonstration performed well.

☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree

Q2. The showcased demonstration has the potential to become a powerful tool for connecting and communicating with people remotely in real time.

☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree

Q3. Next-generation networks like 6G will contribute to increasing the performance and interoperability of XR services, like the one presented.

☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree

Q4. The showcased network-assisted rate recommendation feature, based on detected congestion situations, helps to improve the stability and scalability of eXtended Reality (XR) services.

☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree

KEY VALUE INDICATORS (KVIs)

Q5. Multiuser holoportation combined with 6G networks can contribute to inclusiveness, fairness, and equal access to key services, such as education, healthcare, and industry expertise.

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☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree

Q6. Multiuser holoportation combined with 6G networks can contribute to environmental sustainability by minimizing the need for travels.

☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree

Q7. Multiuser holoportation combined with 6G networks can contribute to societal sustainability by reducing travel and associated costs, and by providing new opportunities for training and business.

☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree

GENERAL FEEDBACK

Q8. I enjoyed the showcased demonstration

☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree

Q9. Holographic communication technologies can become more effective tools than traditional 2D videoconferencing solutions in certain use cases.

☐ Strongly Disagree
☐ Partially Disagree
☐ Neutral
☐ Partially Agree
☐ Strongly Agree