# D6.2: 3D Digital Twin XR 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. This deliverable D6.2 describes the use cases of the collaborative 3D Digital twin VR application with sliced 5G network and remote-control robot over Wi-Fi TSN, focusing on their implementation and validation. This Deliverable consolidates the outcomes discussed across multiple Work Packages (WPs) and validates them through practical use cases. The enablers are provided by each WP: the 5G network architecture and KPI/KVI framework originate from WP1, the sliced 5G network implementation and validation from WP2, the Wi-Fi TSN evaluation from WP3, and the orchestration and disruptive RAN technologies from WP4. KPIs and KVIs are evaluated through dedicated test cases and demonetarisation interviews. |
| **Keywords** | 5G/6G, 3D Digital Twin (3D DT), Wi-Fi TSN, Deterministic Communication, 5G network slicing, API-driven orchestration |

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# EXECUTIVE SUMMARY

This document constitutes the deliverable D6.2 of Work Package 6 (WP6) – "3D Digital Twin XR Use case integration and validation and KPVI assessment". It focuses on the deployment and validation of 3D Digital Twin (DT) use case, combining VR technology with advanced networking enablers, including Wireless Time-Sensitive Networking (TSN), 5G network slicing, and edge computing. The integration and validation of the use case have been carried out at the 6G-XR North Node test facilities, namely 5G Test Network (5GTN) Oulu, Finland [1], [2].

D6.2 reports on the implementation and validation of the 3D DT use case, where remote users collaborate in a shared VR environment for design review of a digital printable 3D object and remote operation of a 3D printer. The 3D DT application was developed as a representative demonstrator of 3D DT–enabled collaboration, building on the initial architectural design described in deliverables D1.1 [3] and D1.2 [4]. The 3D DT application is running on top of sliced 5G mobile network testbed as reported in deliverables D2.2 [5] and D2.3 [6]. Furthermore, the 3D DT application was used in conjunction with the trial controller and disruptive RAN technologies, as documented in deliverablesD4.2 [7] and D4.3 [8].

Part of the work addresses the role of TSN in enabling deterministic communication for 3D DT powered robot arm control. Both wired and wireless TSN architectures are investigated: the wired deployment demonstrates clock synchronization and deterministic scheduling within 5GTN, while the wireless deployment extends TSN functionality to Wi-Fi 6 with a robot arm system. The 3D DT application integrates real-time robot control via Robot Operating System version 2 (ROS2) [9] with live video streaming, where Wi-Fi TSN ensures prioritization of mission-critical traffic.

This deliverable contributes to the overall objectives of the 6G-XR experimentation. First, heterogeneous communication of 3D DT applications was adapted to the proposed 6G architecture, integrating multimodal communication such as immersive VR collaboration and real-time robot arm control. Second, the 6G-XR infrastructure was configured to support the deployment of 3D DT services, combining the Wi-Fi TSN system with the application platform. Third, the services were tested, validated, and demonstrated over the 6G-XR experimentation facilities by applying key technological enablers for 3D DT operation, including API orchestration, 5G network slicing, Wi-Fi TSN, and the 6G-XR trial controller. Validation results confirm that the proposed approach can deliver adaptive 5G slice configurations, the deterministic performance over wireless through Wi-Fi TSN, and ensure the required Quality of Service (QoS), and reliability required for next-generation DT and XR services. As a result, the deliverable successfully addresses the 6G-XR high-level Objective 7 (Obj.7): "Develop and deploy 3D Digital Twin with XR remote control capability".

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# ABBREVIATIONS

| | |
|---|---|
| **2D** | 2-dimensional |
| **3D** | 3-dimensional |
| **3GPP** | 3rd Generation Partnership Project |
| **5G** | Fifth Generation |
| **5GTN** | 5G Test Network |
| **5QI** | 5G QoS Identifier |
| **AI** | Artificial Intelligent |
| **AP** | Access Point |
| **API** | Application Programming Interface |
| **AR** | Augmented Reality |
| **AVP** | Apple Vision Pro |
| **DDS** | Data Distribution Service |
| **DT** | Digital Twin |
| **EU** | European Union |
| **fps** | Frames Per Second |
| **GUI** | Graphical User Interface |
| **IP** | Internet Protocol |
| **KPI** | Key Performance Indicator |
| **KVI** | Key Value Indicator |
| **ML** | Machine Learning |
| **MQ3** | Meta Quest 3 |
| **NTP** | Network Time Protocol |
| **OS** | Operating System |
| **PC** | Personal Computer |
| **PTP** | Precision Time Protocol |
| **QoE** | Quality of Experience |
| **QoS** | Quality of Service |
| **RAN** | Radio Access Network |
| **ROS2** | Robot Operation System Version 2 |
| **SA** | Stand Alone |
| **SNS** | Smart Networks and Services |
| **SLA** | Service Level Agreement |
| **STA** | Station |
| **TCP** | Transmission Control Protocol |
| **TSN** | Time-Sensitive Networking |
| **UC** | Use Case |
| **UDP** | User Datagram Protocol |
| **UE** | User Equipment |
| **UOULU** | University of Oulu |
| **UPF** | User Plane Function |
| **VM** | Virtual Machine |
| **VR** | Virtual Reality |
| **WebRTC** | Web Real-Time Communication |
| **WP** | Work Package |
| **WTSN** | Wi-Fi TSN |
| **XR** | eXtended Reality |

# 1 INTRODUCTION

The main purpose of D6.2 is to summarize the outcomes of the Tasks 6.4, 6.5, 6.6 of the WP6 during M1-M34 of the 6G-XR project. The overall objective of these tasks is to respectively design, implement, and validate 3D DT Use Case that demonstrates the integration of Use Case 4 (UC4) 3D DT application with advanced 5G networking and the Time-Sensitive Networking (TSN) capabilities. The WP6 bridges application-level development with network-level innovation, thereby providing evidence of how emerging technologies can meet both the Key Performance Indicators (KPIs) and Key Value Indicators (KVIs) defined by the project.

The tasks of WP6 related to UC4 are:

- T6.4: “Remote Control with TSN and 3D Twin component Adaptation develops and deploys a 3D DT application within the 5G Test Network (5GTN) test facility. The deployment leverages API-controlled network slices to allocate dedicated resources for 3D DT traffic, thereby enabling immersive remote interaction with laboratory equipment. This task validates the feasibility and potential of XR-enabled DT environments in the real 5G system.

- T6.5: “TSN/3D Twin Use case integration” explores TSN capabilities over Wi-Fi, evaluating the extent to which wireless TSN can provide deterministic and resilient communication for XR and industrial applications.

- T6.6: “Validation and KPVI assessment of 3D Digital Twin XR” focuses on the validation of KPIs and KVIs by integrating the 3D DT application within a testbed that includes both 5G network slicing and Wi-Fi TSN functionalities. This ensures that the evaluation captures performance, user experience, and broader value dimensions across different networking features.

## 1.1 OBJECTIVES OF THE DELIVERABLE

The objective of D6.2 is to explain the design, implementation, and validation of UC4 that combine 3D DT application with sliced and orchestrated 5G network. This deliverable is aligned with the defined WP6 objectives:

(1) Adapt heterogenous communication with 3D DT applications to the proposed 6G architecture.

(2) 6G-XR infrastructure configuration for deployment of 3D DT services.
(3) Test, validate and demonstrate 3D DT services over 6G-XR experimentation facilities, by applying technological enablers from WP2-WP4 (e.g., 6G comms control plane, smart orchestration of cloud continuum resources, network-assisted XR processing, etc.).

The 6G-XR high-level Obj. 7 “Develop and deploy 3D Digital Twin with XR remote control capability” is defined to be validated by the KPIs:

| KPI | Definition |
| --- | --- |
| 7.1 | Implementation, deployment and successful piloting of a multi-user cyber-physical system prototype. |
| 7.2 | Verification of physical machine and VR human interworking. |
| 7.3 | Predictive safety, efficiency utilizing AI/ML in cyber world feedback into physical world operation. |

| | |
|---|---|
| 7.4 | Assessment of at least 4 cross-layer KPIs / QoS metrics in objective tests, in line with the expected levels detailed in Objective 2. |
| 7.5 | Assessment of at least 3 QoE metrics via questionnaires and interviews, with at least 40 end users in a user study with statistically significant benefits of 6G-XR enablers in comparison with the state-of-the-art. |

## 1.2 STRUCTURE OF THE DELIVERABLE

The structure of this document is as follows:

- Chapter 1 introduces the objectives and the overall structure of the document.
- Chapter 2 introduces the collaborative 3D DT use case.
- Chapter 3 focuses on the 3D DT system and its deployment in the 5G testbed.
- Chapter 4 presents the integration and deployment of Wi-Fi TSN.
- Chapter 5 outlines the KPIs and KVIs of the 3D DT Use Case.
- Chapter 6 describes the validation methodology.
- Chapter 7 provides the assessment of KPIs and KVIs through selected test cases.
- Chapter 8 presents the analysis of the results.
- Finally, Chapter 9 concludes the deliverable with a summary of the main findings.

## 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. It provides feedback to industry by demonstrating how 3D DT application and XR technologies can be combined with TSN and 6G advanced networking features, illustrated through real-time remote-controlled robot and industrial DT use cases.

# 2 3D DIGITAL TWIN USE CASE

The collaborative 3D DT consists in the three-dimensional virtual representation of a physical object, system, or environment that mirrors its real-world counterpart, providing a shared space for human–machine interactions and real-time collaboration. Within the 6G-XR framework, the UC4 enables a 3D DT application and demonstrates how future networks can enable immersive remote communication, remote work, and remote control in a 3D environment. By moving beyond voice and video, the 3D DT provides participants with a shared, spatially accurate environment where they can interact with objects, processes, and colleagues as if they were physically co-located. This approach underlines the role of 6G as an enabler for next-generation collaboration and operations, bridging physical and virtual worlds through enhanced capacity, ultra-low latency, and remote-control accessibility.

## 2.1 USE CASE DEFINITION

The Fab Lab at the University of Oulu (UOulu) is used as an environment for 3D DT human-machine interaction. A Fab Lab, short for "fabrication laboratory", is a small-scale workshop offering digital fabrication tools and resources, enabling individuals to create, learn, and innovate. Digital fabrication has surpassed the limits of location on a global scale, as the designs created in one location can be reproduced in other locations across the world. However, the process of producing physical objects from digital assets using fabrication tools requires collaborative interaction between the designer and Fab Lab instructor to set up the tools according to the specific requirements of the site. To address the challenges of reviewing 3D designs, setting up machines, and controlling them collaboratively in different locations between the remote user and the instructor, a digital space using XR environment synchronized with machines and human avatars is a critical need.

Beyond remote-controlled production, an important benefit of 3D DT is that the digital environment allows human collaboration and review with real outlook and scale before initiating physical production. In this scenario show in Figure 1, firstly there are limitation of conventional 2D display to review the 3D design. By using an immersive VR environment and upload the 3D design there and a remote user and a Fab Lab instructor engage in co-creative XR environment. The VR environment can be used to scale the object and allows both participants to confirm and discuss the exact size and shape of the object before fabrication using 3D printer. This approach eliminates the inefficiency of repeatedly fabricating and reviewing physical prototypes, as the digital replica shortens the iteration cycle and ensures alignment before printing.

*Figure 1: 3D Digital Twin concept showing the 2D display limitation, VR immersion, and physical outcome.*

## 2.2 USE CASE ARCHITECTURE

The architecture of the UC4 is structured to demonstrate the integration of VR enabled 3D Game engine with advanced wireless connectivity to enable a connected 3D DT application. While detailed architectural aspects are reported in 6G-XR D1.1 [3], D2.1 [5], D2.2 [6] and D4.2 [7], this work incorporates the latest system requirements and updates done after the submission of the aforementioned deliverables.

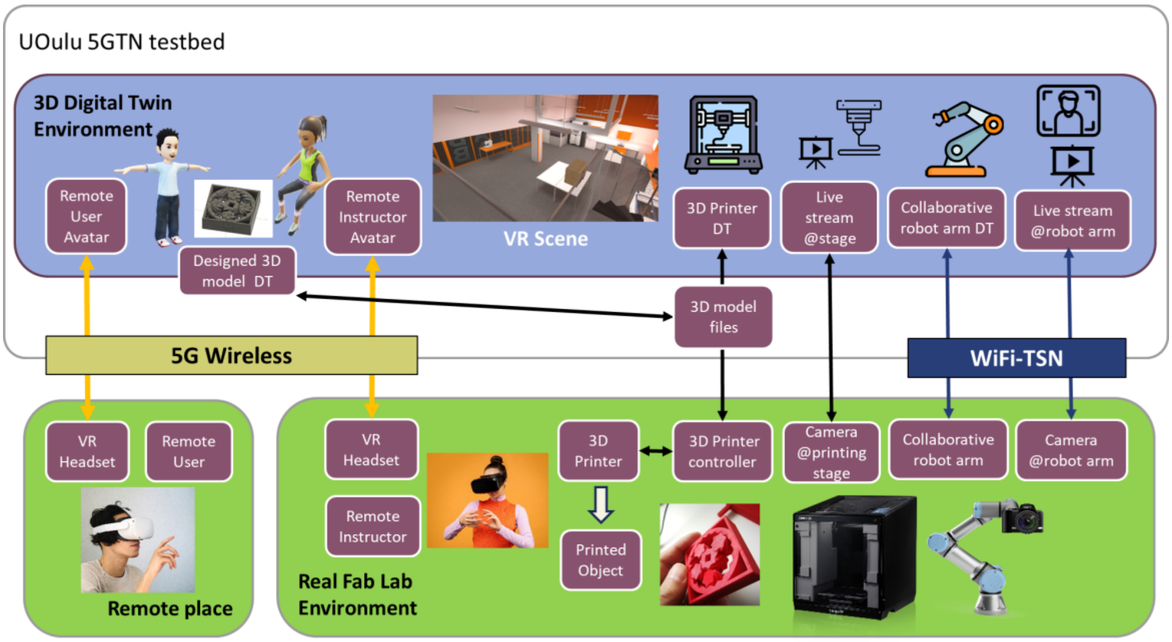



*Figure 2: 3D DT Components in the Use Case.*

The components used in UC4 are illustrated in Figure 2. Components and human agents of each of the three main spaces are presented below.

1. **Real Fab Lab Environment:**
    - VR headset used to connect to the DT,
    - Remote Instructor of the Fab Lab that inspects the object to be printed,
    - 3D Printer,
    - 3D Printer Controller,
    - Cameras in 3D Printer used to stream the printing process to the DT environment,
    - Collaborative robot arm,
    - Camera in the robot arm to stream the video with motions for surveillance of environment and reviewing the printed product.
2. **3D DT Environment of the 5GTN testbed:**
    - Remote User and Remote Instructor avatars,
    - 3D model of the designed object,
    - 3D model files,
    - VR scene of the Fab Lab,
    - Interactive 3D printer digital model,
    - Live stream video window of the physical 3D printer,
    - Interactive 3D model of the robot arm, and

- Live stream video window of the robot arm.

3. **Remote Place:**
    - Remote User,
    - VR headset used to connect to the DT environment.

The physical and digital environments are interconnected through advanced 5G based on 3GPP Release 16 and Wi-Fi 6 based TSN wireless communication networks. Specifically, the remote operation of 3D printer at the Fab Lab, as well as the immersive VR interaction between the remote user and the on-site instructor, are supported via a 5G connection. In parallel, the robotic arm, which requires real-time control and high-quality live streaming, is connected using Wi-Fi TSN to ensure deterministic latency and reliable transmission.

## 2.3 TIME-SENSITIVE NETWORKING

The demand for communication systems with predictable performance has increased with the growth of applications such as industrial automation, autonomous driving, and immersive services. These applications not only require low latency but high reliability, and deterministic transmission of data. While Ethernet is cost-effective and widely deployed, it does not itself support deterministic communication and is therefore limited when strict latency and jitter guarantees are required [10], [11]. To overcome this limitation, the IEEE 802.1 working group has standardized a set of enhancements under the title TSN. TSN extends Ethernet to support time-critical and best-effort traffic on the same physical infrastructure. Important examples include IEEE 802.1AS for time synchronization, IEEE 802.1Qbv for scheduled traffic, and IEEE 802.1CB for frame replication and elimination [12].

Practical adoption of TSN is already visible in several areas. In industrial automation, TSN enables the convergence of operational technology and information technology, removing the need for parallel dedicated networks and simplifying factory communication systems [13]. TSN has also gained relevance in mobile networks, especially in 5G fronthaul and edge computing, where deterministic transport is required for coordination between distributed elements [14]. As discussed by Sharma et al. [15], deterministic communication is a key requirement for future 6G systems. Building on this perspective, in the specific context of 3D DT and VR applications, TSN is critical to ensure deterministic QoS for real-time collaboration and control. These applications depend on continuous multimodal data exchange including video, motion tracking, and robotic commands, where latency or jitter directly affects usability and safety. By providing bounded delay and reliability through mechanisms such as time-aware scheduling, TSN enables remote equipment operation, immersive XR collaboration, and synchronized interaction between physical and virtual environments.

### 2.3.1 Core TSN Standards for Deterministic Communication

- **IEEE 802.1AS - Time Synchronization**

TSN establishes a network-wide time reference that enables coordinated operation across all network devices. The 802.1AS protocol provides sub-microsecond time synchronization accuracy, creating a common time base that allows precise scheduling of network resources. This synchronized time reference is essential for coordinating time-sensitive data flows across multiple network segments and ensuring that VR applications maintain their strict timing requirements across distributed computing architectures.

- **IEEE 802.1Qbv - Time-Aware Scheduling**

This standard implements deterministic traffic scheduling through time-based gate control. Network traffic is classified into different priority queues, each controlled by time-synchronized gates that open and close according to a pre-computed schedule. Time-critical traffic receives protected transmission windows where no other traffic can interfere, guaranteeing bounded latency and eliminating congestion-induced delays. When considering VR applications, the pose tracking data can be guaranteed transmission opportunities while high-bandwidth video streams are scheduled to avoid interference with time-critical flows.

## 2.4 USE CASE 4 SYSTEM OVERVIEW

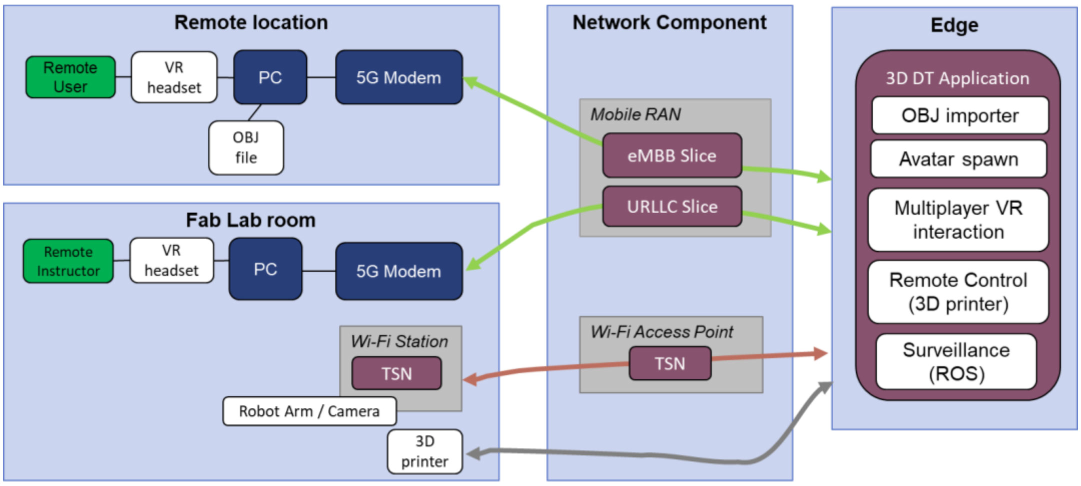



*Figure 3: 6G-XR Use Case 4 system overview.*

Figure 3 shows the use case system diagram with edge services, where the edge delivers processing and networking capabilities as a service to the end users. The Use Case 4 operates in following way:

1. The remote user, who requires a review and printing of a 3D object, uploads the object model (.obj file, .stl file) from a PC to the Object (OBJ) importer in the edge service. Then, the remote user agrees on a 3D DT online meeting with the remote instructor.
2. At the scheduled meeting time, the remote user accesses the 3D DT using a VR headset, launches the 3D DT Application, and enters the collaborative VR environment of the 3D DT environment. The remote instructor joins the same VR environment in the same way. Both participants are spawned as avatars and are able to interact with each other, discussing the design with voice and hand tracking in an immersive setting until they reach an agreement about the printability of the object in question.
3. Once the 3D object design is confirmed with the remote instructor, the remote user operates the 3D printer to start production. The printer fabricates the object model into a physical object, and a live production view is streamed into the VR scene through the camera installed inside the 3D printer.
4. During and after the production, the remote user and instructor observe the real Fab Lab environment from within the 3D DT VR scene. Under the instructor's guidance, the user monitors the production process via a live video feed. A camera mounted on the robotic arm connected with TSN deterministic communication provides real-timely controllable and adjustable viewpoints.
5. The process ends when the object is completely printed, and the remote user and instructor finalize their collaborative VR experience.

# 3 3D DIGITAL TWIN SYSTEM WITH 5G NETWORK

3D DT system requires an immersive environment for real-time interaction between users and facilities. A VR-based 3D platform built on a game engine provides dynamic rendering, synchronization, and remote operation features. This section describes how the 3D DT application is delivered and configured on the 5GTN testbed at UOulu. For functional validation, an OAI-based 5G Stand-Alone (SA) system (OAIBOX) with slicing capability is used. For KPI evaluation, the same application runs on a 3GPP-compliant 5G system with mobile-edge integration. This setup enables functional verification in the OAI environment and quantitative KPI validation in the 3GPP-compliant system, confirming interoperability and performance of the 3D DT deployment.

## 3.1 3D DT APPLICATION

The 3D DT application builds on the conceptual design reported in 6G-XR deliverable D2.1 [5] and D2.2 [6] to incorporate the latest system requirements and architectural refinements. The C-3DDT platform is powered by an open-source 3D game engine architecture centred around Babylon.js, a WebGL-based and WebXR-compliant framework for building immersive 3D applications within modern web browsers. Combined with React.js for the control interface, OpenVidu for multimedia streaming, and OctoPrint for 3D printer remote control, the platform leverages a fully open-source software stack. This design ensures accessibility across devices, avoids vendor lock-in, and supports transparency and adaptability—key requirements for educational and research use cases. This approach enables community-driven development and customization without commercial licensing restrictions, unlike proprietary game engines that may impose platform limitations. The use of open technologies aligns with the values of openness, reproducibility, and long-term sustainability.

As illustrated Figure 4, the architecture comprises of three main layers: client-side interaction (VR headsets and web interface), backend game engine coordination, and device integration interfaces. On the client side, VR headsets run WebXR-compatible browsers to render the 3D environment using Babylon.js. Users interact with the 3D DT environment through head and hand tracking, gesture recognition, and spatial voice communication. A complementary 2D interface, developed in React.js, provides session management features such as control panels, file uploads, and interaction logs.

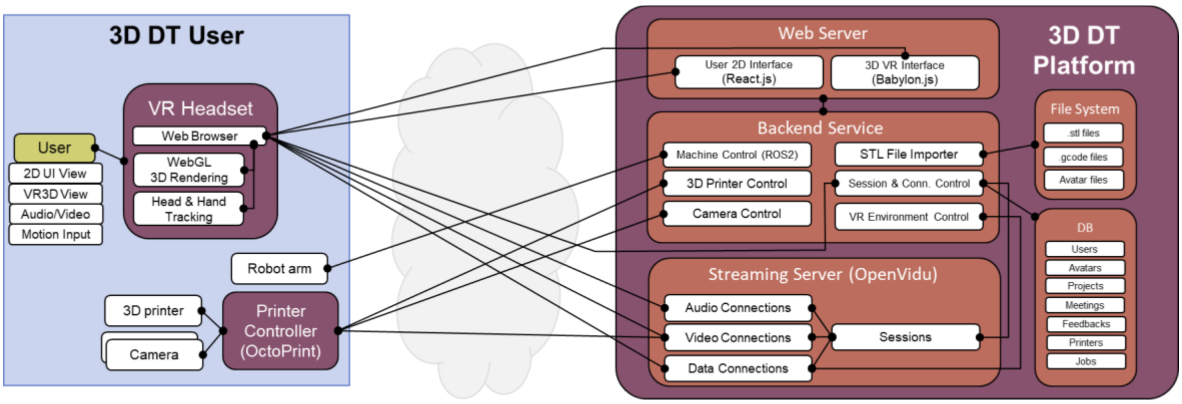



*Figure 4: Functional diagram of the 3D DT platform.*

As shown in Figure 5, the C-3DDT platform consists of three main stages. On the left, both the remote user and the remote instructor register in the system. The remote user uploads a 3D model and enters the shared 3D DT environment, which replicates a Fab Lab VR room where personalized avatars are synchronized through head- and hand-tracking. The center illustrates the immersive design review phase, in which multiple users collaboratively inspect and manipulate the 3D object in real time using voice and gesture-based interactions supported by Babylon.js and OpenVidu. On the right, the finalized 3D model is linked to the physical 3D printer, and live video streams from the fabrication process—captured from top and side cameras—are rendered within the 3D DT environment, enabling real-time remote supervision of printing.

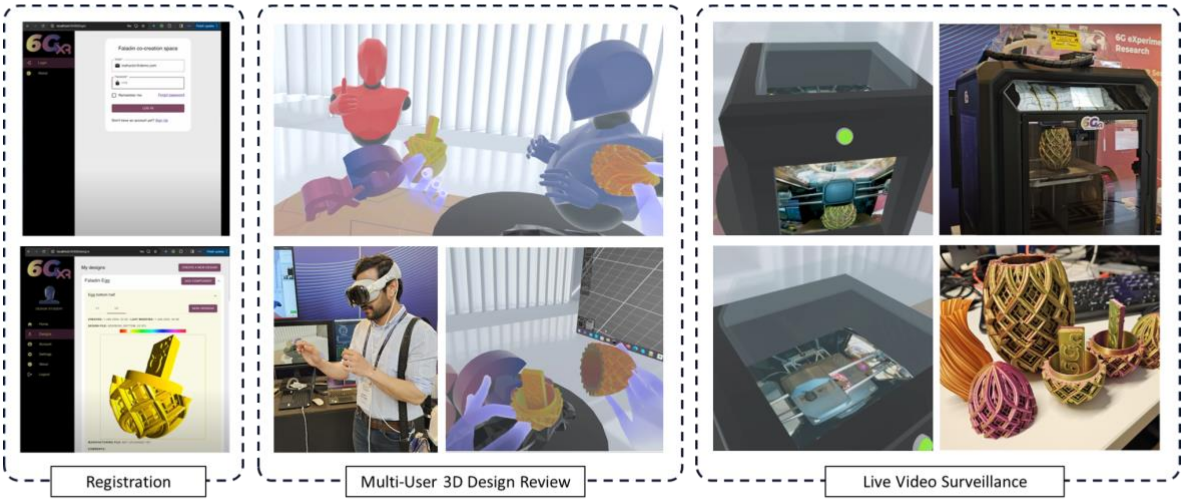



*Figure 5: 3D DT application overview.*

## 3.2 3D DT HARDWARE AND 5G CONNECTIVITY

The 3D DT platform is validated using two types of VR headsets—the Apple Vision Pro (AVP) and the Meta Quest 3 (MQ3), demonstrating cross-vendor operability through Babylon.js' multi-platform WebXR support. This interoperability enables users to access the same shared XR environment across different hardware ecosystems, including Apple's visionOS and Meta's Android-based XR platform. Each user device was assigned to a different 5G SA network slice, either Enhanced Mobile Broadband (eMBB) or Ultra-Reliable Low-Latency Communication (URLLC), to evaluate the 3D DT application over the 5G network system under different slice configurations. The slicing setup was prepared specifically for KPI evaluation, enabling the comparison of network performance and service quality between high-bandwidth and low-latency profiles. Each user handled mixed VR traffic through a single 5G modem, and the assigned slice determined the QoS parameters, including bandwidth, latency, and reliability.

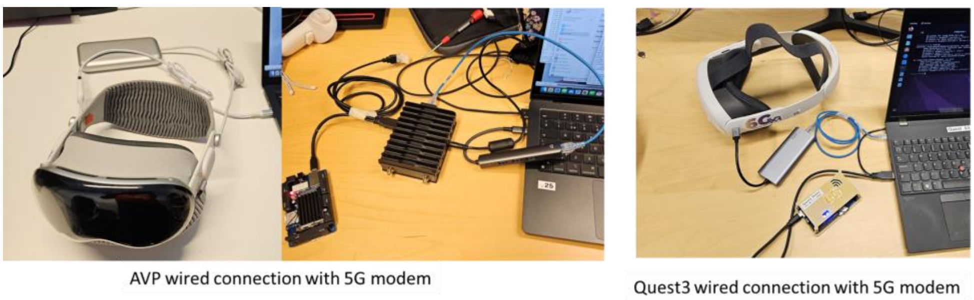



*Figure 6: 5G modem connected AVP and MQ3.*

Since most VR headsets are not natively 5G-enabled, the connection is established through a laptop PC equipped with a 5G modem. The VR headset is connected to the laptop via a wired link, and laptop

PC bridges the traffic to the wireless 5G network. It is possible to employ both AVP and MQ3. Also, the network QoS measurement probe is installed to the Ubuntu based laptop providing real-time performance monitoring and KPI data collection.

*Table 1: Sliced 5G Radio System Configurations*

| Parameter | O-RAN based System | 3GPP compliant System |
|---|---|---|
| Radio Hardware | USRP X410 | Nokia AirScale Indoor |
| Radio Band | n77 (3850.0 MHz) | n77 (3950.0 MHz) |
| Bandwidth | 100 MHz | 100 MHz |
| TDD Pattern | DDDFU | 1UL/4DL |
| Antenna Config. | 2×2 MIMO | 4×4 MIMO |
| Slice Enabler | N-RT-RIC | 5G Core |
| eMBB Slice | Proportional Fair Scheduler | 5QI: 9 |
| URLLC Slice | Designated PRBs | 5QI: 85 |
| 5G Modem | Quectel RM520Q-GL | Quectel RM520Q-GL |

In this use case development, two 5G sliced SA network system of UOulu 5GTN were used. Table 1 presents the comparison of 5G radio system configurations between the Open RAN (O-RAN)-based and 3GPP-compliant 5G networks. The configuration of eMBB and URLLC slices was defined for each system. In the O-RAN based setup, the Near-Real-Time RIC (N-RT-RIC) controlled two predefined slices: eMBB and URLLC. By adapting the radio scheduler through the N-RT-RIC, eMBB traffic was managed using the Proportional Fair Scheduler, while URLLC traffic was assigned designated Physical Resource Blocks (PRBs) to guarantee a specific performance level. In the 3GPP-compliant configuration, Cumucore provided slice isolation through distinct QoS flows defined by the 5G QoS Identifier (5QI): 5QI 9 for eMBB-type traffic and 5QI 85 for URLLC-type traffic, following 23.501 [17]. This setup implemented a fully 3GPP-compliant slicing approach, where service differentiation was achieved through standardized 5G Core QoS mechanisms.

## 3.3 O-RAN BASED SLICED 5G NETWORK

The UC4 is firstly deployed on UOulu 5GTN with O-RAN based sliced 5G SA system. The detailed results were published in K. Komatsu et al. [18], and they present the evaluation of an 3D DT application utilizing sliced 5G network, focusing on latency and throughput measurements and their relation to usability as a KVI-oriented assessment.

OAIBOX [1] was used to setup a O-RAN-based 5G network. Qosium measurement system is used to perform QoS measurements in the 5G system as illustrated in Figure 7. The setup consists of AVP and Meta Quest 3 headsets connected to the network via PCs and 5G modems, an 3D DT Application consisted of Babylon.js and OpenVidu located at the edge node, and the OAIBOX Central Unit (CU) and Distributed Unit (DU) implemented as a split solution using Universal Software Radio Peripheral (USRP) as Radio Unit (RU). Cameras using Raspberry-Pis were connected to the 3D DT Application via CU. This system allowed the evaluation of slice performance and related KPIs and KVIs while using a VR headset immersive application.

[1] OAIBOX – a plug-and-play open-source 5G/6G network testing platform based on the OpenAirInterface project. [Online]. Available: https://oaibox.sourceforge.net/

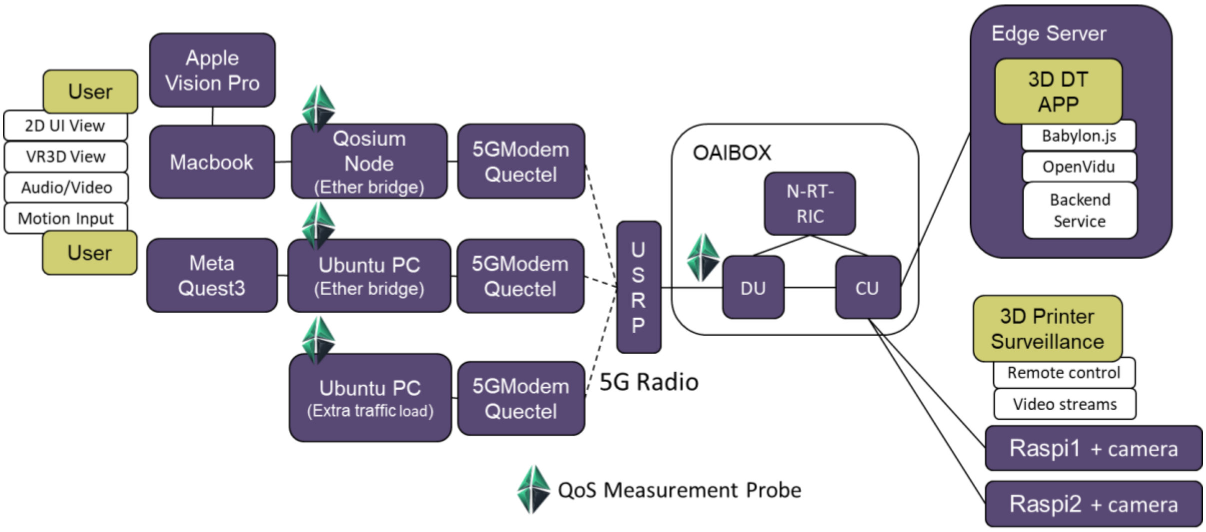



*Figure 7: System Diagram of O-RAN based EuCNC/6Gsummit 2024 demo.*

O-RAN based 3D DT demo system developed by 6G-XR for the EUCNC/6G Summit 2024 in Antwerp of Belgium, is a product of combined contribution of three 6G-XR Open Call 1 projects (Faladin, BanQ, and 6G-Slice) and UOULU efforts, as reported in the 6G-XR project [20]. A live demonstration was conducted at shown in Figure 8, two VR headsets operated over OAIBOX based sliced 5G O-RAN system, each headset in their own slices, within the same XR on-line scene, while QoS measurements for the system were done using Qosium measurement system.

*Figure 8: A Demo with Open Call projects at the event of EUCNC/6Gsummit 2024.*

## 3.4 3GPP COMPLIANT SLICED 5G NETWORK

The same 3D DT use case is deployed on another sliced 5G network at UOulu 5GTN, over 3GPP compliant system utilizing Cumucore [21]. Figure 9 illustrates the implementation of the 3D DT application over a 3GPP-based Cumucore 5G network with trial controller orchestrating with AI/ML based network optimization. On the left side of figure, the remote instructor and remote user use the non-5G-native VR headsets that connect via a 5G modem installed on a PC. The PC not only provides 5G connectivity but also functions as a Qosium network measurement point, enabling QoS and KPI measurements with data uploaded to the Measurement Storage service located at the edge service. Through the 5G radio access network, the users access the 3D DT application at the edge service.

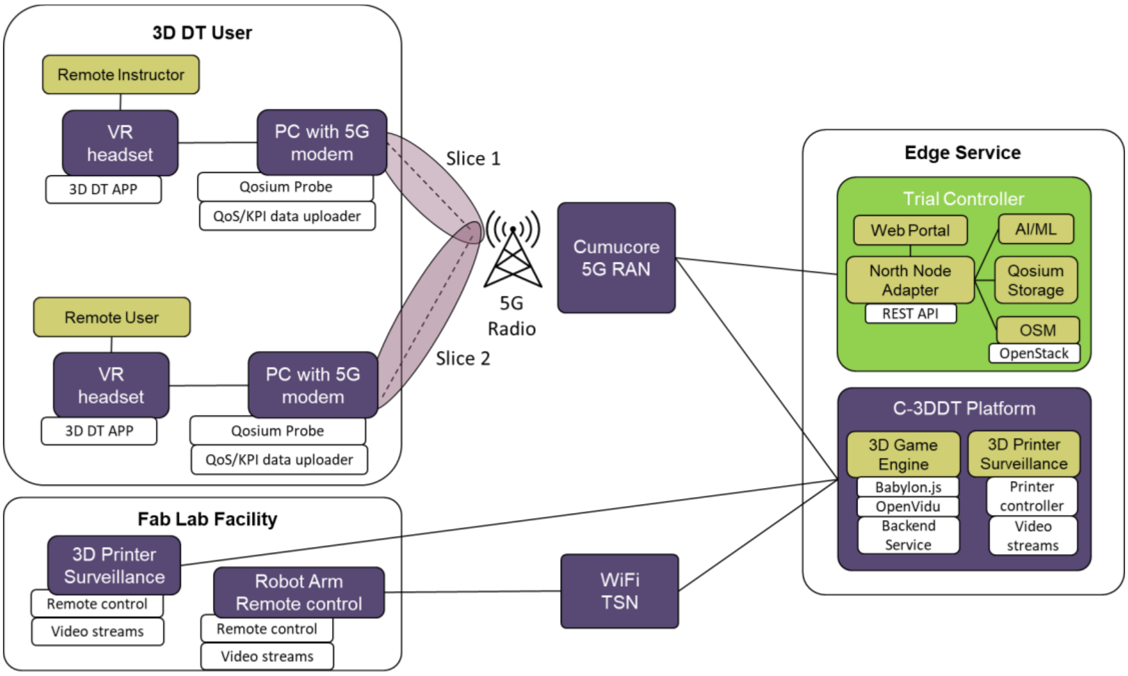



*Figure 9: System Diagram of 3GPP based 5G slices with Orchestrated Edge Services.*

The edge service on the right side of the figure hosts the orchestration service of the Trial Controller, developed under the WP4 deliverables [5], [6]. The orchestration component consists of the North Node Adapter (NNA) and the North Node Web Portal. The Web Portal provides a user interface that simplifies 5G testbed setup and operation. Figure 10 shows the North Node Web Portal serving as the front-end interface for configuring testbed experiments and presenting measurement results through a GUI dashboard.

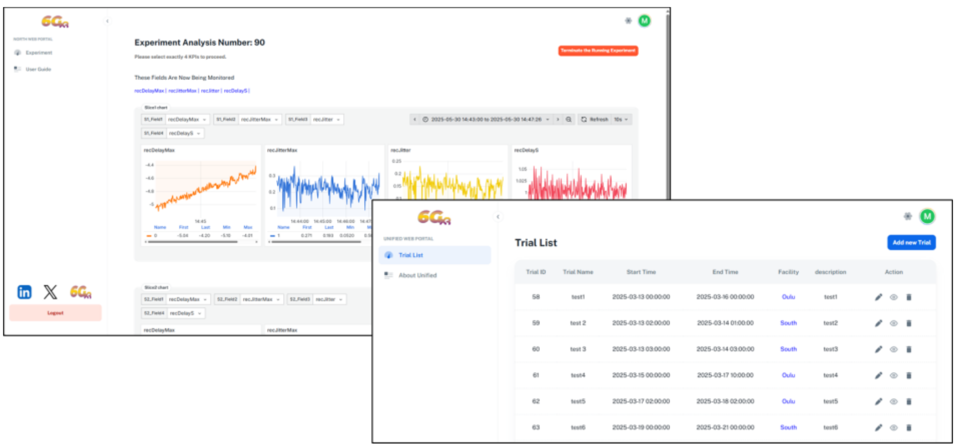



*Figure 10: North Node Web Portal Dashboard.*

The NNA enables intuitive orchestration of 5G RAN QoS/KPI measurements and dynamic resource allocation for 5G slice UPFs. The service control interface is provided through a REST API connected to the Web Portal. Once a test case is initiated by the Web Portal, the NNA orchestrates three key components: Qosium Storage, AI/ML, and the Cumucore 5G RAN.

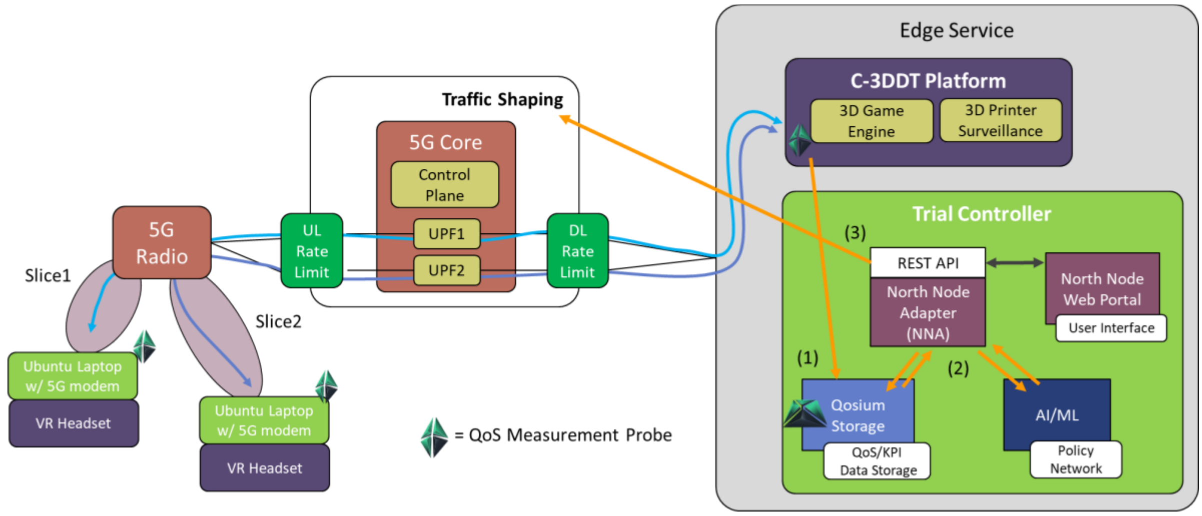



*Figure 11: AI-driven dynamic resource allocation with Trial Controller.*

Figure 11 shows the system diagram of the NNA orchestration for QoS/KPI measurement and AI-driven dynamic resource allocation in 5G slices. When 5G slicing is applied, the User Plane Function (UPF) is responsible for handling user data traffic, including packet forwarding, routing, and policy enforcement between the radio network and external data networks. In this use case, two UPFs are assigned for the eMBB and URLLC slices. For AI/ML-based adaptation, the dynamic resource allocation enabler is implemented through a traffic shaping mechanism positioned before the UPFs. The NNA regulates slice-level bandwidth through a dedicated traffic shaping layer placed in front of the UPFs, rather than directly controlling the 5G Core or UPF entities. This shaping mechanism dynamically adjusts uplink and downlink traffic for each slice according to AI/ML-driven decisions.

The AI/ML coordination process is as follows:

1. QoS and KPI measurements, together with the edge-based measurement storage system, are implemented using Kaitotek Qosium Storage. When the Web Portal sends NNA the message to initiate a testbed experiment, the NNA starts the Qosium Probes on both ends of the measurement path, the PC's with 5G modems and the Edge service. QoS parameters are then measured for this path and measurement results are uploaded to Qosium Storage at the edge. The stored data can then be accessed through the Web Portal Dashboard via REST API requests.
2. In dynamic resource allocation with AI/ML, the NNA takes the central coordination role. At regular intervals (every 1 seconds), it fetches the latest measurement data from the Qosium Storage and sends it to the AI/ML function. The data is then analysed by the pre-trained Policy Network, which returns the optimal resource allocation rates for each 5G slice. The AI/ML component applies a reinforcement learning based policy optimization approach derived from the REINFORCE algorithm, tailored for dynamic 5G slice resource allocation. The Policy Network receives real-time Key Performance Indicators (KPIs) from the NNA every second, including downlink/uplink throughput, latency, jitter, packet loss, and other congestion-related indicators. These normalized inputs form the network state used to determine the next optimal resource allocation between slices.
3. The neural network outputs parameters of a Dirichlet distribution, which represent continuous allocation ratios (e.g., URLLC = 0.8, eMBB = 0.2). The objective is to maximize a cumulative

reward function that reflects the system's quality of service improving throughput and latency while maintaining fairness and respecting Service Level Agreement (SLA) limits. The reward increases when target KPIs are achieved and decreases under SLA violations or excessive imbalance between slices. Through this formulation, the AI learns to adaptively balance and optimize slice resources in real time, ensuring stable and fair utilization under dynamic traffic conditions.

After receiving the AI/ML analysis, the NNA applies the new resource allocation parameters to the slices by sending the new configuration to Cumucore 5G RAN through its slice configuration API. Qosium probes then measure the performance of the newly configured system, and the results are again fed back to the NNA through Qosium Storage. This feedback loop ensures continuous monitoring and supports AI-driven dynamic optimization of the 5G slices.

Figure 12 shows the policy network learning curve snapshots during pre-training with real measurements from the 3D DT application over the 5G network. Each episode includes KPI traces covering a wide variable of throughput, latency, jitter, packet-loss rate, and signal strength. The pre-training results are presented as reward and loss curves, together with the average resource allocation to Slice 1 and Slice 2. The reward function is defined as a weighted combination of slice-specific performance metrics. It increases when throughput and latency targets are met. In this way, the learning agent seeks to maximize the expected cumulative reward, effectively aligning the optimization goal with balanced and efficient resource distribution across slices. This ensures that the AI continuously adapts allocations to real-time network dynamics while preserving fairness and performance stability. The snapshots illustrate the behaviour of the model at 100 episodes (top) and at 500 episodes (bottom). The steadily increasing reward demonstrates that the policy network converged to an effective allocation strategy and generalized across different KPI scenarios before online fine-tuning with live data from the NNA.

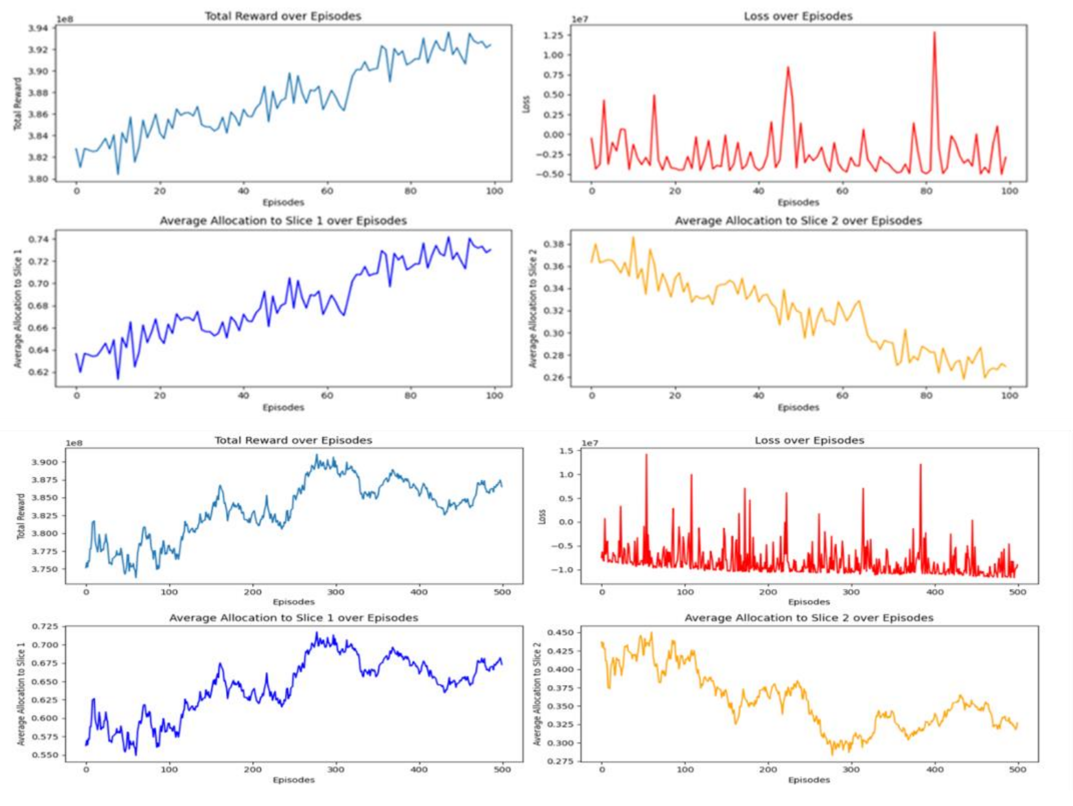



*Figure 12: Policy network pre-training and allocation trend (top:100 episodes, bottom:500 episodes).*

# 4 3D DIGITAL TWIN WITH WIFI-TSN

This chapter addresses the role of TSN in enabling the 3D DT use case within the 6G-XR experimentation environment at 5GTN. It covers the configuration and deployment of technical components provided by 6G-XR WP2 [5][6] for the 3D DT application and WP3 [22] for infrastructure with Wi-Fi TSN. This chapter focuses on a multimodal communication scenario that combines machine control signals for the robot arm with video streaming and discusses TSN optimization to control latency and jitter. This optimization ensures precise synchronization, reliable remote control, and immersive collaboration, enhancing Quality of Experience (QoE) and demonstrating the readiness of TSN for next-generation DT services.

## 4.1 WIRELESS WI-FI TSN

Recent research has investigated the extension of TSN into heterogeneous networks that combine wired and wireless domains. Sudhakaran et al. [23] presented methods for end-to-end clock synchronization in industrial systems, highlighting the feasibility of integrating wired–wireless TSN to establish unified time bases across heterogeneous TSN-capable networks. These studies illustrate that Wi-Fi TSN is actively being explored as a means of extending deterministic communication beyond wired infrastructure.

Building on this background, VR applications are transforming how we interact with digital content and collaborate in virtual environments. However, these immersive experiences impose unprecedented demands on wireless connectivity that traditional Wi-Fi cannot reliably meet. Conventional contention-based medium access creates fundamental barriers for VR applications [23]:

- **Variable Latency**: Random backoff mechanisms and collision-based recovery introduce unpredictable delays that can exceed strict timing requirements of VR applications.
- **No Performance Guarantees**: Best-effort delivery cannot provide the bounded latency and reliability needed for immersive experiences.
- **Interference Sensitivity**: real-time nature of VR makes it particularly vulnerable to interference and congestion in unlicensed spectrum.

### 4.1.1 Time synchronization

To implement 802.1AS in Wi-Fi networks, it is necessary to have a NIC with HW timestamping capabilities, to enable established clock synchronization protocols to operate with sufficient time granularity. In the test bed, we used the Intel AX210 NIC, which allows to timestamp the sent packets and thus enables to have PTP over Wi-Fi [24].

### 4.1.2 Traffic Scheduling Implementation

802.1Qbv scheduling in Wi-Fi networks can be implemented at multiple levels to provide deterministic channel access for time sensitive applications:

a) **Operating System (OS) Level Implementation**: 802.1Qbv scheduling can be implemented as a software function within the OS network stack. In this approach, time-aware gates control when different XR traffic classes (pose data, video streams, control commands) can enter the 802.11 MAC queues. The OS-level scheduler prevents conflicting channel access requests (Wi-Fi channel) by ensuring that only authorized traffic types can access the wireless medium during their designated time windows. This means, that the OS performs the time-aware gating for the wireless medium. This software-based approach provides flexibility and can be deployed on existing hardware platforms. In this test bed, we followed this approach as we do not control the access point.

b) **Access Point Level Implementation**: For more precise control, 802.1Qbv scheduling can be implemented directly within Wi-Fi Access Points that support TSN bridge functionality. The access point can maintain fine-grained control over the schedule of wireless participants, coordinating both downlink transmissions to end devices and uplink scheduling for pose data transmission. This hardware-level implementation provides tighter timing control and can leverage Wi-Fi 6 (802.11ax) OFDMA scheduling capabilities.

The integration of TSN time synchronization and scheduling with Wi-Fi networks enables VR applications to achieve deterministic, low-latency wireless connectivity while maintaining the mobility and flexibility that wireless networks provide. This foundation supports the strict timing requirements of immersive experiences across distributed edge computing architectures.

## 4.2 WI-FI TSN WITH ROBOT ARM SYSTEM

The robot arm (UR10, Universal Robots) part of the UC4 demonstrates the integration of physical equipment into a 3D DT environment. The arm is mirrored in the DT, enabling remote observation and interaction in real time. It was selected as a representative industrial task with strict requirements on latency, jitter, and reliability, making it an ideal test case for evaluating TSN. The use case highlights challenges such as ensuring deterministic communication for safety-critical control signals and maintaining synchronization between physical and virtual representations in dynamic production environments.

### 4.2.1 Use Case Requirements

The robot arm system with Wi-Fi-TSN focuses on the remote operation of a robot arm, where a remote user controls the arm while monitoring the environment through live video streaming. A robot arm equipped with cameras provides real-time surveillance of the real Fab Lab, allowing users to observe the 3D printing process and evaluate the printed object after production. Within the 3D DT VR scene, remote users can dynamically adjust the camera viewpoint and receive immersive live streams as if operating the physical robot directly. This capability enhances situational awareness and supports effective interaction with the real Fab Lab. To guarantee deterministic latency and reliable transmission, the control of the robot arm and video streaming are connected via Wi-Fi TSN. The objective of this part of the UC4 is to assess whether deterministic communication can be achieved over Wi-Fi, where latency is typically unpredictable, and to validate real-time robot arm control even under the bandwidth demands of simultaneous video streaming.

## 4.3 ARCHITECTURE

The architecture of the Wi-Fi TSN with robot arm use case is structured to demonstrate the integration of real-time motion robot arm controlled by immersive 3D DT application under deterministic communication of Wi-Fi TSN.

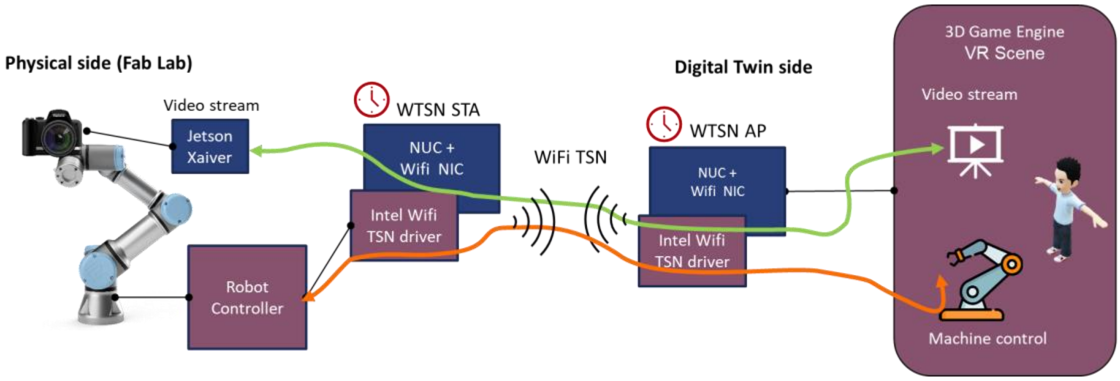



*Figure 13: Wi-Fi TSN Robot Arm Architecture.*

As shown in Figure 13, the setup implements remote robot arm control in the Fab Lab over Wi-Fi TSN, with the objective of achieving deterministic communication. The robot arm is operated through a controller handling machine control signals and is equipped with a camera streaming live video to the VR scene. Connectivity is provided by Wi-Fi TSN access point (WTSN-AP) and station (WTSN-STA), both using TSN-capable NICs and customized Wi-Fi drivers implementing IEEE 802.1AS and IEEE 802.1Qbv. Mission-critical control traffic for the robot arm is prioritized to ensure reliable real-time actuation, while video streaming and background data are scheduled to avoid interference with control flows.

### 4.3.1 3D DT Application for Wi-Fi TSN robot arm

As an immersive user interface, the Remote-Control 3D DT application has been implemented on the Babylon.js platform, following the same approach as the Faladin 3D DT application. Babylon.js is used as 3D Game Engine, which is a web-based, multi-device platform that supports WebXR, enabling compatibility across VR headsets from different vendors as well as devices such as smartphones, tablets, and PCs running WebXR-enabled browsers.

Within the Remote-Control 3D DT application in Figure 14, a dedicated VR room is provided with an avatar representation of the robot arm. Users can manipulate the avatar of the robot arm in the virtual scene, and the corresponding position data is synchronized with the physical robot arm in real time. This allows intuitive remote control, where moving the avatar directly translates into robotic motion.

The Babylon.js application is integrated with ROS2 [9] through rosbridge suite [26]. ROS2 replaces the centralized master of ROS version 1 with a decentralized communication model based on the Data Distribution Service (DDS). Unlike MQTT, DDS enables direct peer-to-peer data exchange without a central broker. Thanks to this architecture, ROS2 is better suited for distributed, modular, and flexible defined robotic systems. The robot arm position updates are converted into ROS2 topics and transmitted to the robot side. On the robot side, the ROS2 driver of robot arm receives these topics and translates them into control commands for the robot arm synchronized motions, ensuring accurate execution of the user’s actions in the physical world.

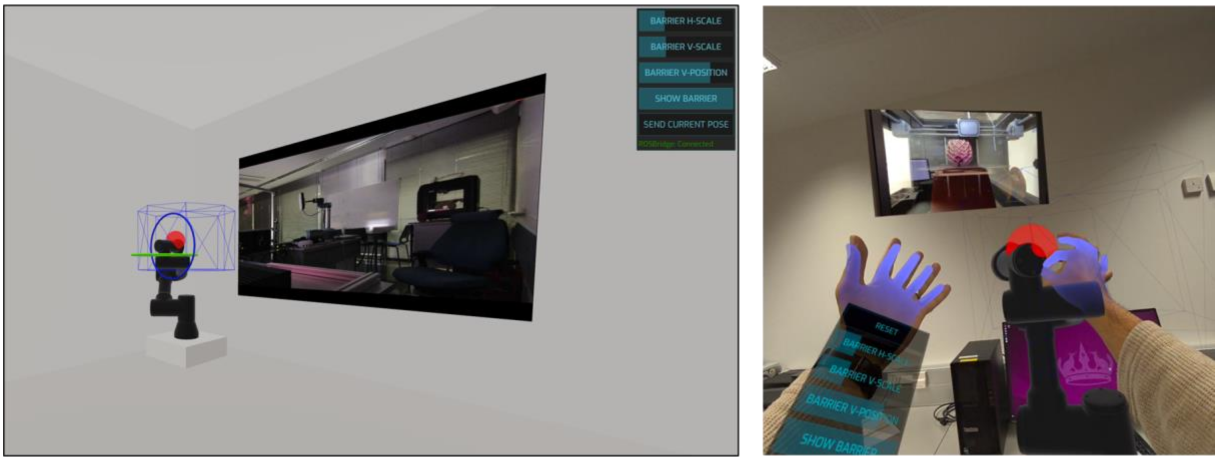



*Figure 14: Robot Arm Remote Control XR Application view (left: PC, right: VR Headset).*

### 4.3.2 Functional system design

The Wi-Fi TSN system implements the Remote-Control 3D DT application, which consists of three functional components interconnected through Wi-Fi TSN, as shown in Figure 15:

- Server Node: The Remote-Control 3D DT application provides the user interface for immersive remote operation of the robot arm. The application handles heterogeneous communication including live video streaming, robot control ROS2 signals, and a safety heartbeat signal via Wi-Fi TSN.
- Robot Control Node: The UR Robot ROS2 driver executes actuation commands from the 3D DT application to the robot arm. For safety, a heartbeat signal is transmitted at a constant 200 ms interval, enabling detection of alarms or abnormal conditions from the environment or the robot.
- Camera Node: The video encoder processes the video stream from the USB camera and transmits it to the server.

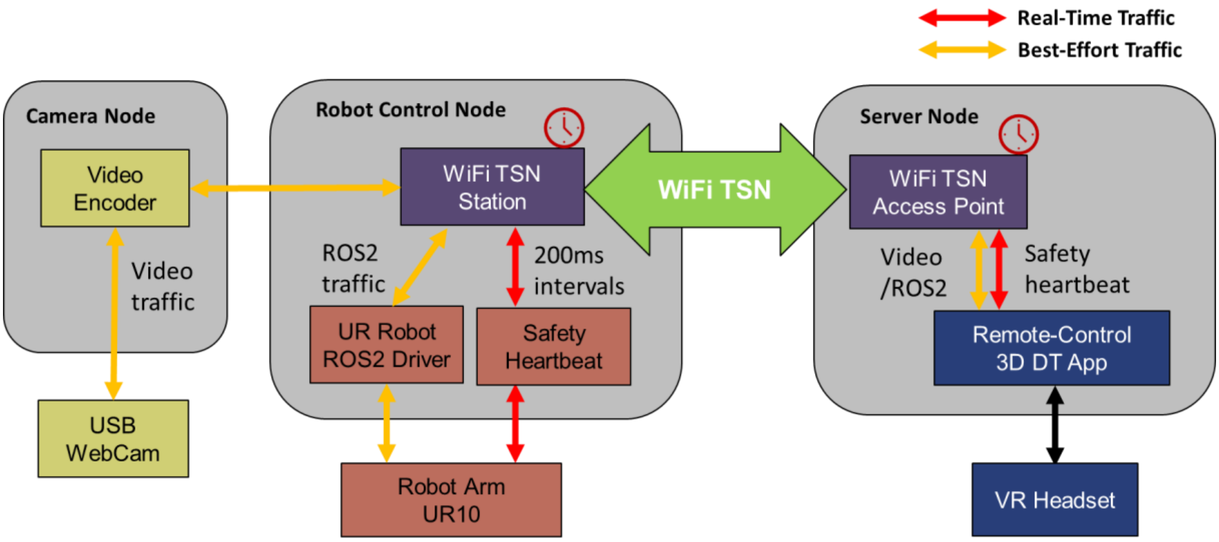



*Figure 15: Functional system diagram of Robotic Arm Remote Control VR Application.*

The connectivity of Wi-Fi TSN consists in WTSN-AP and WTSN-STA, which were configured with IEEE 802.1AS clock synchronization and IEEE 802.1Qbv time-aware scheduling. The traffic scheduling was set to prioritize Real-Time (RT) traffic over Best-Effort (BE) one. In this use case, RT traffic consists of a safety heartbeat message sent at 200 ms intervals between the robot controller and the remote XR application, ensuring deterministic delivery of critical safety information. The remaining ROS2 and video streaming traffic was classified as BE. This demonstrates that Wi-Fi TSN can ensure deterministic communication for robotic safety control, while simultaneously supporting video streaming and ROS2 communications.

As a challenge, deterministic communication was initially considered for machine control traffic based on ROS2. However, the underlying topic and messages used in ROS2, the communication protocol DDS aggregates not only robot control signals but also various other topic signals. While this makes ROS2 convenient to use, it also means that all network-level signal control is handled internally by DDS, effectively making it a black box. This prevented the extraction of a constant interval signal required for time-aware deterministic scheduling. Therefore, instead of directly using ROS2 traffic, a 200 ms safety heartbeat signal from the robot arm was designated as the high-priority RT flow for time-aware scheduling, and this was used in the validation.

## 4.4 IMPLEMENTATIONS

For the preparation of end-to-end system validation of KPVIs, the required hardware was integrated into the system, and the basic functionality of Wi-Fi TSN was verified according to the standards.

### 4.4.1 Hardware System

To enable the XR application for remote operation of a robot arm holding a surveillance camera, a Wi-Fi TSN–based system was implemented. The system shown in

Figure 16 is built with the following devices:

- WTSN-AP and WTSN-STA: Both using the Intel Wi-Fi 6E AX210 module integrated as NIC in an Asus PL64 Mini-PC with Intel Core i3-1215U processor, running Ubuntu 22.04 OS.
- Robot arm: Universal Robot UR10, supporting external control via Ethernet with real-time data exchange (RTDE) and socket-based interfaces, enabling integration with ROS2. The UR10 Robot arm is connecting to WTSN-STA via Ethernet IP connection by the controller.
- Surveillance Camera: Jetson Xavier NX, running Jetpack 5 with low power GPU capability, with an USB camera. It is connected to the WTS-STA and sends the video streaming from the camera to the server.

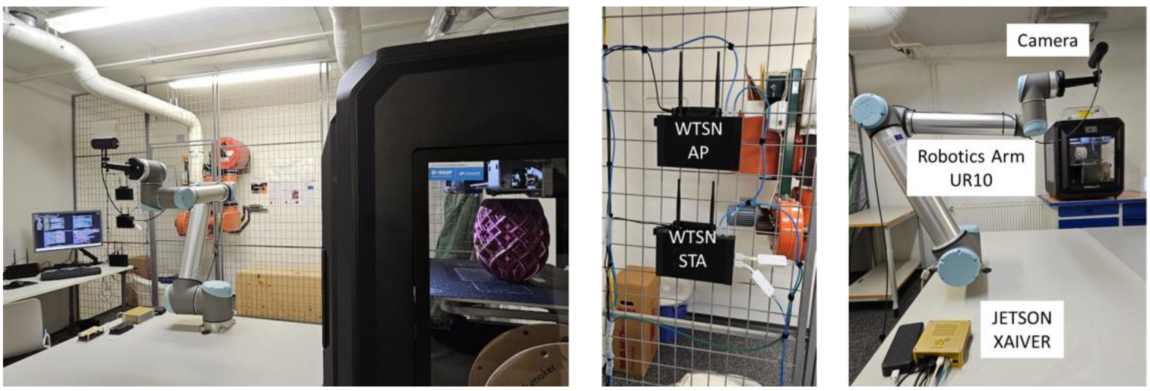



*Figure 16: Robot arm with Camera for 3D printer Surveillance.*

### 4.4.2 Wi-Fi TSN 802.1AS Implementation

Time synchronization, as specified in IEEE 802.1AS, is implemented using the *LinuxPTP* [2] toolset. The two main components are:

- **ptp4l**: It provides the implementation of the Precision Time Protocol (PTP, IEEE 1588) and its TSN profile (802.1AS), enabling sub-microsecond synchronization between network devices equipped with PTP Hardware Clock (PHC).
- **phc2sys**: It synchronizes the system clock (e.g., CLOCK_REALTIME) with the PHC, ensuring that both kernel and user applications operate on a time base aligned with the network reference.

The Wi-Fi physical module used in this implementation is the Intel AX210 [29], compliant with the IEEE 802.11ax (Wi-Fi 6), which defines enhancements to MAC and PHY layers to improve performance, efficiency, and latency in dense wireless environments. In the UC4, the AX210 is operated in the 5 GHz band with OFDMA support and 80 MHz channel bandwidth. As shown in Figure 17, the WTSN-AP is acting as the master clock source, and providing synchronization to its follower WTSN-STA.

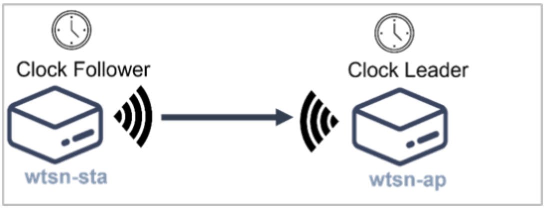



*Figure 17: TSN 801.AS Clock Synchronization between Wi-Fi Access Point and Station.*

The implementation of Wi-Fi 6 with Intel TSN driver in WTSN-AP enables the Wi-Fi module to operate as a NIC with hardware timestamping capability, synchronized by *ptp4l*. In this setup, *ptp4l* disciplines the PHC according to the PTP protocol. Subsequently, *phc2sys* aligns the OS clock with the local PHC of the Wi-Fi NIC. In this case, *phc2sys* was used to ensure that both the hardware and software domains of the same system operated on a unified time base. As shown in Figure 18, immediately after executing the *phc2sys* command, the large initial offset was corrected, and drift compensation reduced the offset to below 1000 ns. This confirms that the system clock was synchronized with the PHC, establishing a common time base between the OS and the network domain.

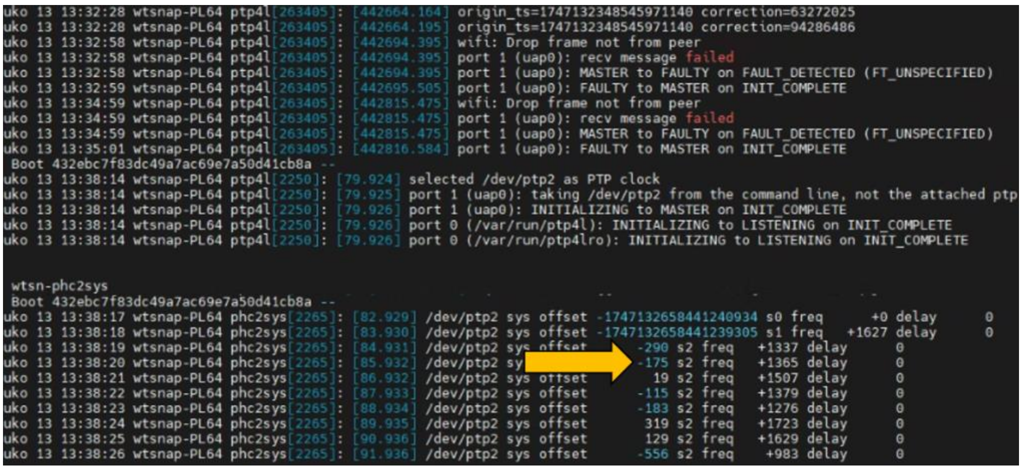



*Figure 18: Clock synchronization between WTSN-AP and Wi-Fi network module.*

[2] LinuxPTP – The Linux PTP Project (Precision Time Protocol implementation for Linux). [Online]. Available: https://linuxptp.sourceforge.net/

As shown in Figure 19, the WTSN-STA was connected to the WTSN-AP over the wireless link of Wi-Fi, and both ptp4l and phc2sys were executed on the WTSN-STA. The clock synchronization source was set to the PHC of the WSTN-AP, transmitted via the Wi-Fi link. After the start of phc2sys, a gradual reduction in offset was observed, and the values eventually stabilized under ±2000 ns, confirming successful clock alignment between the WTSN-AP and the WTSN-STA.

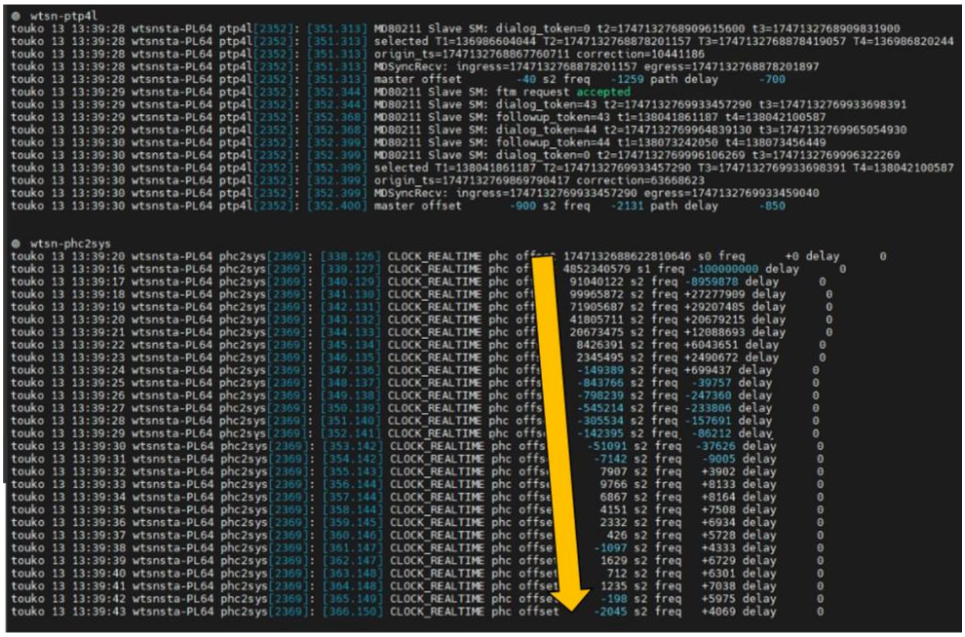
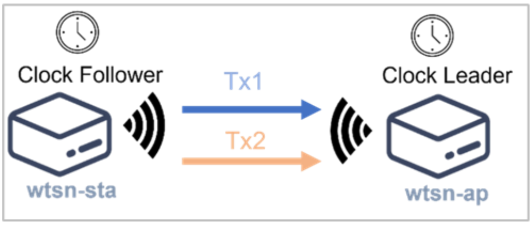


*Figure 19: Clock synchronization between Station and Access Point.*

### 4.4.3 Details on Wi-Fi TSN 802.1Qbv Implementation

An implementation of IEEE 802.1Qbv traffic scheduling was carried out to evaluate the use of a synchronized clock for deterministic communication. The scheduling was realized using the Linux Traffic Control (TC) framework, with separate queues for RT and BE traffic. In this setup, the Time-Aware Shaper (TAS) aligned transmission and reception windows according to the common time base, ensuring that real-time packets were delivered in protected time slots without interference, while BE traffic was deferred to the remaining windows. *Iperf2* network performance measurement tool was used in the experiment [25]. The functional evaluation was conducted using active measurements with constant traffic generated by *iperf2* between the WTSN-AP and WTSN-STA. As shown in Figure 20, the measurement was configured as follows: RT traffic consisted of 64-byte packets transmitted at 1000 packets per second, while BE traffic consisted of 100-byte packets at 100 Mbps using 10 parallel streams.




| Traffic Tag | Packet Size | Rate | Proto |
|---|---|---|---|
| TSN Traffic 1 | 64 bytes | 10 ms | UDP |
| BE Traffic | 100 bytes | 100 Mbps | UDP |

*Figure 20: IEEE 802.1Qbv traffic shaper setup in WTSN-AP and WTSN-STA.*

As shown in Figure 21, the test results obtained with *iperf2* under the configured BE and RT traffic conditions demonstrate the impact of Wi-Fi TSN scheduling. Without TSN, the measurements showed jitter in the range of 0.6–0.8 ms and latency at the 5 ms level. With TSN enabled, the results improved significantly, with jitter reduced to 0.02–0.2 ms and latency to approximately 1.3–1.5 ms, clearly reflecting the effect of the TC-based scheduling period.

```
      [ ID] Interval            Transfer     Bandwidth        Jitter   Lost/Total  Latency avg/min/max/stdev PPS NetP
[  1] 0.0000-1.0000 sec  63.4 KBytes   520 Kbits/sec   0.704 ms 0/1015 (0%) 5.365/4.095/18.248/1.272 ms 1015 pps 12
[  1] 1.0000-2.0000 sec  62.4 KBytes   511 Kbits/sec   0.703 ms 0/999 (0%) 5.783/3.582/23.559/2.640 ms 1000 pps 11
[  1] 2.0000-3.0000 sec  62.6 KBytes   513 Kbits/sec   0.740 ms 0/1001 (0%) 5.251/3.950/7.233/0.555 ms 1000 pps 12
[  1] 3.0000-4.0000 sec  62.5 KBytes   512 Kbits/sec   0.769 ms 0/1000 (0%) 5.272/3.931/7.319/0.546 ms 1000 pps 12
[  1] 4.0000-5.0000 sec  62.5 KBytes   512 Kbits/sec   0.714 ms 0/1000 (0%) 5.300/4.133/7.172/0.555 ms 1000 pps 12
[  1] 5.0000-6.0000 sec  62.5 KBytes   512 Kbits/sec   0.752 ms 0/1000 (0%) 5.289/4.204/7.868/0.532 ms 1000 pps 12
[  1] 6.0000-7.0000 sec  62.5 KBytes   512 Kbits/sec   0.721 ms 0/1000 (0%) 5.334/3.881/7.341/0.555 ms 1000 pps 12
[  1] 7.0000-8.0000 sec  62.4 KBytes   511 Kbits/sec   0.786 ms 0/999 (0%) 5.591/3.805/26.851/2.398 ms 1000 pps 11
[  1] 8.0000-9.0000 sec  62.5 KBytes   512 Kbits/sec   0.673 ms 0/1000 (0%) 5.257/3.908/7.720/0.553 ms 1000 pps 12
[  1] 9.0000-9.9842 sec  61.8 KBytes   515 Kbits/sec   0.764 ms 0/989 (0%) 5.288/1.410/8.240/0.632 ms 1004 pps 12
[  1] 0.0000-9.9842 sec   625 KBytes   513 Kbits/sec   0.764 ms 0/10003 (0%) 5.373/1.410/26.851/1.297 ms 1002 pps 12
```

```
      Jitter   Lost/Total  Latency avg/min/max/stdev PPS NetPwr
[  2] 0.0000-1.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.035 ms 0/1000 (0%) 1.432/1.141/5.207/0.414 ms -146 pps 1026
[  2] 1.0000-2.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.206 ms 0/1000 (0%) 1.441/1.172/5.425/0.422 ms 1000 pps 1020
[  2] 2.0000-3.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.076 ms 0/1000 (0%) 1.418/1.173/5.716/0.376 ms 1000 pps 1036
[  2] 3.0000-4.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.052 ms 0/1000 (0%) 1.441/1.186/5.760/0.419 ms 1000 pps 1020
[  2] 4.0000-5.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.029 ms 0/1000 (0%) 1.432/1.167/5.099/0.393 ms 1000 pps 1026
[  2] 5.0000-6.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.013 ms 0/1000 (0%) 1.418/1.172/6.431/0.398 ms 1000 pps 1036
[  2] 6.0000-7.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.230 ms 0/1000 (0%) 1.413/1.172/5.432/0.345 ms 1000 pps 1040
[  2] 7.0000-8.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.038 ms 0/1000 (0%) 1.419/1.179/4.360/0.338 ms 1000 pps 1036
[  2] 8.0000-9.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.171 ms 0/1000 (0%) 1.397/1.176/4.159/0.303 ms 1000 pps 1052
[  2] 9.0000-10.0000 sec  1.40 MBytes  11.8 Mbits/sec   0.051 ms 0/1000 (0%) 1.407/1.136/6.451/0.393 ms 1000 pps 1045
[  2] 0.0000-10.0030 sec  14.0 MBytes  11.8 Mbits/sec   0.047 ms 0/10004 (0%) 1.422/1.136/6.451/0.382 ms 1000 pps 1034
[ ID] Interval       Transfer     Bandwidth        Jitter   Lost/Total Datagrams
```

*Figure 21: IEEE 802.1 Qbv traffic scheduling measurement results, without TSN (top) and with TSN (bottom).*

# 5 3D DIGITAL TWIN USE CASE REQUIREMENTS AND METRICS

The 6G-XR UC4, i.e., 3D DT use case, entails a considerable set of well-defined KPIs to ensure seamless interaction between the virtual and physical components. These KPIs establish performance targets across multiple dimensions such as connectivity, latency, reliability, mobility, density, energy efficiency, synchronization, and 5G slices availability. The overall objective of the target KPI values is to guarantee immersive and real-time experience for the end users, while ensuring robust integration with supporting systems like VR devices, robot arms, and wireless networks.

In addition to technical KPIs, the 6G-XR UC4 case also defines a set of KVIs to reflect the societal, economic, and environmental impact of the system. The focus of the KVIs is to capture the broader value created through the adoption of DT technologies in real-world scenarios. These KVIs demonstrate how collaborative 3D DT environments can enhance productivity, sustainability, inclusiveness, and ethical practices by highlighting the expected benefits for individuals, organizations, and society at large.

The 6G-XR UC4 is further specified through a comprehensive set of user requirements, which are categorized into functional and non-functional dimensions of the system. These requirements ensure that the system not only meets the performance targets, but also delivers functional usability, reliability, and scalability. Non-functional requirements cover the system setup, environment replication, connectivity, service quality, and accessibility to the system complementing the KPIs by providing operational boundaries and quality expectations. Functional requirements define the capabilities the system must provide to its users to support the intended user case. These include the digital environment setup, capabilities such as mirroring objects between environments and enabling video and camera integration, and the support of network slicing.

## 5.1 KPIS

Table 2 presents all KPIs relevant to 6G-XR UC4, identified in 6G-XR deliverable D1.1 [3]. It covers critical concepts such as high-capacity data links to support VR traffic, 3D rendering and video streaming, and low end-to-end latency to enable responsive interactions between the virtual environment and the game engine. It further includes high reliable transmission of data packets, mobility and density support for users, energy efficiency, time synchronization via Wi-Fi TSN, and network slicing for flexible allocation of wireless resources.

*Table 2: List of KPIs and Target Values*

| No. | Category | Reference | Target Value |
|---|---|---|---|
| 1 | VR glasses Link Data Rate: Link Capability | 3D printer monitoring video | 2 Mbps |
| | | VR glasses (3D data + audio + control) | 1 Mbps |
| | | 3D printer virtual User Interface (UI) (remote desktop browser) | 1 Mbps |
| | | Wi-Fi towards the VR glasses (wireless uplink and downlink) | 400 Mbps |
| | | Wi-Fi traffic towards 5GTN (wired) | 10 Gbps |
| | | 5G downlink | 400 Mbps |
| | | 5G uplink | 50 Mbps |

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| 2 | Latency: End-to-end for both 5G and Wi-Fi | Downlink (from VR glasses to game engine) | 10 ms |
| | | Uplink (from game engine to VR glasses) | 14 ms |
| | | Game engine processing time | 16.6 ms (60 fps) |
| 3 | Reliability: Percentage of packets delivered within the target latency KPI | | 99.99% |
| 4 | Mobility | Users located indoors | Low |
| 5 | Density | Users located in indoor rooms | $10/m^2$ |
| 6 | Energy efficiency | | Nominal |
| 7 | Wi-Fi TSN between VR and robot arm (PC on the lab and robot connected to a PC with a Wi-Fi TSN Network Interface Card) | Time Synchronization Accuracy | ~10 µs |
| | | Bounded Latency for 200 ms cyclic signal from robot | 1-10 ms |
| | | Video payload | 1 Mbps (30 fps) with lower resolution |
| 8 | Slicing (optional) | Wireless connectivity | Two separate slices exist, and user and instructor can connect to different slices. |

## 5.2 KVIS

In Table 3, KVIs established under D1.1 [3] are outlined, addressing multiple dimensions such as:

- Societal productivity and efficiency by enabling remote collaboration and bridging geographical divisions
- Sustainability by minimizing carbon footprints and disparities
- Digital inclusion ensuring usability across diverse user group leading to fair access
- Economic sustainability and innovation by enabling customization, process efficiency, and improved product development
- Data privacy and security by maintaining trust and compliance with regulations
- Knowledge sharing
- Simplified daily life and optimized activities
- Optimized resources through efficient allocation
- Ethical assurance by supporting adherence to social, governmental, and corporate guidelines.

*Table 3: List of KVIs and Enablers*

| Category | KVI Description | KV Enablers |
|---|---|---|
| Societal productivity and efficiency | Remote collaboration enhances societal and team productivity/efficiency. Real collaboration around a common asset, machine, manufacturing place, or environment is enabled thanks to a | - Digital presence.<br>- Rural and industrial equality.<br>- Telepresence. |

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

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| | | - Productivity.<br>- Accessibility. |
| Data Privacy and security | Measures the effectiveness of the privacy and security of 3D DT environments. Key points to check are user data, privacy, and confidentiality as well as other potential security leaks. Virtual interaction needs to comply with general and industry standards. | - VR telepresence avatars, edge cloud, E2E communications.<br>- SDK to implement masks in the communication and video streaming.<br>- Edge and cloud combination to reduce potential points of attack.<br>- Encrypted information. |
| Knowledge sharing | Measures the increase of participation and involvement of the local community with knowledge sharing and transfer among global communities. When transferred to the collaborative 3D DT environment knowledge sharing is boosted thanks to the cross-cultural collaboration, idea exchange, and individual knowhow shared. | - Utilization rate of application and usability, accessibility.<br>- Cultural exchange.<br>- Amount of content stored in the environment.<br>- Type of content consumed.<br>- Number of ideas generated.<br>- Category of the people using and consuming the collaborative information and environments. |
| Simplified life | Reduced travel and immersive experience that improve the quality of life by saving time and increasing quality of communication. | - Utilization rate of application and usability, accessibility. |
| Optimized daily activities | Improvement of the communications and effectiveness of the information shared while people's time is saved as no travel is needed. | - Utilization rates of the application.<br>Time saved while using the application in comparison with travel.<br>-Reduction of misunderstandings due to the immersion of the solution.<br>- Common asset as centre of discussion. |
| Optimized resources | Resources (material, energy, equipment, supply chain, personal, etc.) optimization due to the decentralized location of the people and assets. Then, the optimal allocation of the resources can be selected according to the restrictions in place or organizational decisions. | - Decentralization of the knowhow allowing to access global talent.<br>- Optimization of the energetical resources consumption.<br>- Global vision of the complete |

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| | | environment resource consumption. |
| Ethical assurance | Ensure the adherence to ethical practices in place in both manufacturing and sociological practices. Having a 3D DT environment helps in the guidance and implementation of corporative, social, or governmental ethical guidelines. | - Proof of ethical compliance and channel to introduce potential ethical limitations.<br>- Register potential deviations of the ethical politics and ensure corrective actions.<br>- Modules and SDKs to enable ethical assurance standardized. |

## 5.3 FUNCTIONAL AND NON-FUNCTIONAL REQUIREMENTS

Table 4 presents user and 3D DT virtual environment requirements, encompassing non-functional aspects of the 3D DT system. These requirements were additionally introduced in D1.1 [3].

*Table 4: Non-functional Requirements for the 3D DT System*

| No. | Requirements |
|---|---|
| UC4.R1 | Create a 3D object to be reviewed in defined format. |
| UC4.R2 | The Remote User needs to be able to deliver the 3D object in question on-line to a pre-defined location. |
| UC4.R3 | The Remote User is to agree review time with Instructor with pre-defined methods. |
| UC4.R4 | The Remote User needs VR equipment compatible with DT environment. |
| UC4.R5 | Live 3D environment is delivered to the Remote User 3D glasses. |
| UC4.R6 | Bi-directional live audio is delivered between the Remote User and DT environment. |
| UC4.R7 | The Remote User needs to be able to interact with DT environment. This includes movement and object interaction. |
| UC4.R8 | The Remote User can monitor the progress of the printing process through the virtual UI and live video stream from the physical Fab Lab space. |
| UC4.R9 | The Remote Instructor is to agree review time with Remote User with pre-defined methods. |
| UC4.R10 | The Remote Instructor is to be able to retrieve the delivered 3D object in question from the pre-defined on-line location. |
| UC4.R11 | The Remote Instructor needs VR equipment compatible with DT environment. |
| UC4.R12 | Live 3D environment is delivered to Remote Instructor 3D glasses. |
| UC4.R13 | Bi-directional real-time audio is delivered between the Remote Instructor and DT environment. |
| UC4.R14 | The Remote Instructor needs to be able to interact with DT environment. This includes movement and object interaction. |
| UC4.R15 | After approved review process the Remote Instructor starts the printing process. |
| UC4.R16 | The Remote Instructor needs to be able to re-format the 3D object for printing and upload the re-formatted model to the real world FabLab 3D-printer through the virtual UI. |
| UC4.R17 | The Remote Instructor needs to be able to set the printing parameters through the virtual UI and starts the actual printing process. |
| UC4.R18 | The Remote Instructor needs to be able to monitor the progress of the printing process through the virtual UI and live video stream from the physical Fab Lab space. |

 

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| UC4.R19 | After the printing has been completed, the Remote Instructor notifies the Remote User about that using a pre-defined method. |
| UC4.R20 | Lastly, the Remote Instructor needs to send the printed object to the Remote User by post mail. |
| UC4.R21 | The environment needs to be an exact replica of the physical Fab Lab space of the University of Oulu. |
| UC4.R22 | The environment needs to enable remote online access for two simultaneous users (Remote User and Remote Instructor). |
| UC4.R23 | The environment needs to provide a UI/portal for its users for identity verification and avatar selection. |
| UC4.R24 | The environment needs to provide three pre-defined avatars so that the users can select one to use when entering the environment. |
| UC4.R25 | The DT needs to support access (virtual UI) to the real-world 3D printer. |
| UC4.R26 | The DT needs to be able to receive the live video stream from the 3D printer printing stage. |
| UC4.R27 | The DT needs to enable bi-directional real-time audio communication between the Remote User and the Remote Instructor. |
| UC4.R28 | The DT needs to be able to access the file system where the 3D models are located. |
| UC4.R29 | The DT needs to be able to recreate the 3D object as real scale into the virtual environment. |
| UC4.R30 | The DT environment needs to enable Remote User and Remote Instructor interaction with the 3D object. |
| UC4.R31 | The DT needs to connect with the robot arm camera at the real Fab Lab via TSN services. |
| UC4.R32 | The robot arm camera motion/position is synchronized with virtual environment. |
| UC4.R33 | Optional: 5G Network is to support 2 simultaneous URLLC slices. |

Moreover, Table 5 contains the functional requirements the 3D DT system is required to fulfill.

*Table 5: Functional requirements for the 3D DT System*

| No. | Requirements |
|---|---|
| UC4.FR1 | **DT Environment set up:** Remote Instructor needs to be able to launch the VR game engine loading the DT environment of Fab Lab room replica. |
| UC4.FR2 | **Mirror Windows PC:** Remote User and Remote Instructor shall be able to see the mirror Windows PC mirror 3D object in VR scene. |
| UC4.FR3 | **Review 3D model in VR:** Remote User is to create 3D model data file (.obj). |
| UC4.FR4 | **Configure 3D printer:** Remote User and Remote Instructor shall be able to see the mirror Windows PC mirror 3D object in VR scene. |
| UC4.FR5 | **Reviewing printed model with robot arm camera:** Remote User and Remote Instructor shall be able to see the physical replica of arm camera robot and the video stream 3D objects in VR scene. |
| UC4.FR6 | **Network slicing for 3D DT service:** The service provides the network slicing function into the 5G mobile networks related Core network and base stations. Two slices are prepared in the 5G network communications. One for the Remote User (remote area) and second the Remote Instructor (the Fab Lab room) in the same local network. |

# 6 VALIDATION METHODOLOGY

To meet the high-level objectives (Obj. 7) in 6G-XR and validate the UC4, a series of test plans certify the readiness and benefits of the infrastructure. This evaluation encompasses a wide range of scenarios, closely aligned with functional and non-functional requirements, as well as KPIs and KVIs, to identify the performance characteristics assured by the system.

## 6.1 VALIDATION PROCESS

To carry out extensive validation and qualitative results, a systematic V-model approach is taken to perform the validation as presented in Figure 22.

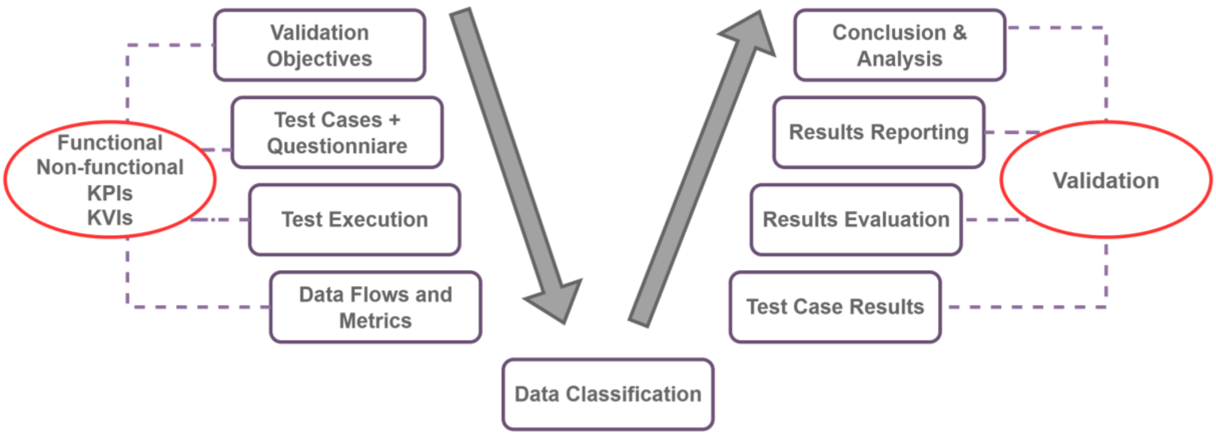



*Figure 22: V-Model Validation Process.*

The process begins by gathering the functional requirements, non-functional requirements, KPIs, and KVIs. These form the basis of validation and define what the system should achieve both technically and experimentally. Specific test cases are designed to map with the KPI metrics as well as functional and non-functional requirements. Moreover, a questionnaire is designed to cover the KVI expectations of the system. These tests are carried out under controlled scenarios facilitating the collection of performance data, user experience metrics, and system logs during the execution.

The collected data is classified and organized to prepare for analysis. The data obtained from the tools list in Table 6 including average values, flow statistics, and console outputs are mapped to checkpoint IDs corresponding to the required verification points. These checkpoint IDs are then organized to align with each generated test case, ensuring that the results remain traceable to the respective test objectives and requirements.

Test case results are then prepared evaluating the output of each test case. These gathered values are compared against KPIs, KVIs, functional, and non-functional requirements. Findings are then summarized for the stakeholders. Finally, the insights captured by this analysis provides the useful information on readiness, strengths, and limitations of the system.

This systematic approach has relevant importance, as it aligns the evaluation with the requirements, KPIs, KVIs, and their association with the metrics, data flows and logs of the respective measurements. The testing setup, indicators, tools, and templates are further detailed in the following subsections.

## 6.2 TESTING FRAMEWORK AND SETUP

The testing framework employs a structured template, presented in Annex A – Test Case Template, which is applied throughout the 6G-XR project for each planned test case. This ensures consistency and order in the testing process, as well as systematic recording of the obtained results with the appropriate data presentation.

### 6.2.1 Measurement Indicators

The fundamental quantitative measurement indicators for validating the 3D DT system represent the first point in the V-Model process. These include link capacity, end-to-end latency capturing both delay and jitter, and the reliability of data traffic across wireless 5G and wired connectivity. In addition, the system is evaluated in terms of user mobility and density, as well as processing and energy efficiency of the system. The creation of network slices for 5G wireless connectivity is also verified to ensure their proper existence and functionality. The TSN component within the 3D DT system is assessed through time synchronization accuracy, latency considering both delay and jitter, and video payload handling.

The basic definitions for these KPIs are presented in Section 5.1. The Table 6 presents an overview of the metrics and the relevant tools for evaluation of these metrics. For each performance parameter, the system metrics are calculated using the Qosium tool [19], which includes the Qosium Probe responsible for capturing packets and performs measurement calculations, and the Qosium Scope which controls the measurement runs and displays the analysed results on the dashboard. The Qosium tool is facilitated by related network traffic monitoring tools including Ping and iPerf3 [28]. Moreover, htop (interactive processor viewer) package [27] and NETIO PowerBOX 4KF [29] are also utilized to check the processing and energy efficiency of the system.

*Table 6: Measurement Indicators*

| Performance Parameter | Calculated System Metric | Tools |
|---|---|---|
| Link Capability | Upload UDP rates in bps Max/Min/Avg.<br>Download UDP rates in bps Max/Min/Avg.<br>Upload TCP rates in bps Max/Min/Avg.<br>Download TCP rates in bps Max/Min/Avg. | Qosium, iPerf3 |
| Latency | Delay metric in ms is measured between UE and game engine (edge processing server).<br>Jitter metric in ms is measured between UE and game engine. | Qosium |
| Link Reliability | End-to-end packet reliability between UE and game engine. | Qosium, iPerf3, Ping (ICMP) |
| Mobility & Density | Delay metric is measured in ms between UE and game engine for low mobility user conditions.<br>Jitter metric is measured in ms between UE and game engine for low mobility user conditions. | Qosium, iPerf3 |

| | | |
|---|---|---|
| | Delay metric is measured in ms between UE and game engine, with increased user density simulated by generating traffic to game engine using iPerf3.<br>Jitter metric is measured in ms between UE and game engine, with increased user density simulated by generating traffic to game engine using iPerf3. | |
| Efficiency | Energy and processing efficiency of the 3D DT system is evaluated both in idle and active states. | htop (interactive processor viewer), NETIO PowerBOX 4KF |
| Slice/Service Availability | Multiple slices exist for remote user and instructor to access the 3D DT System. | Multiple VR Headsets connected to different slices to access the virtual environment |

### 6.2.2 Test Environment

To evaluate the 3D DT system, a dedicated testing setup has been designed to ensure that all the required metrics can be accurately collected representing the Test Execution phase of the V-model process. The setup is carefully structured to enable the extraction of real-time values, and to capture the necessary data metrics using multiple set of tools and measurement methods. This approach ensures that the collected data reflects the actual behaviour of the system when users are interacting under realistic operating conditions. To ensure the validation of functional, non-functional, and quantitative KPI metrics described under Sections 5.1 and 5.3, two dedicated testing setups have been constructed, as outlined below and illustrated with figures.

#### 6.2.2.1 Testing Setup 1

- 5G RAN Network
    - Two 5G Quectel RM500Q-GL modems are used to connect the VR headsets to the 5G network.
    - The operating frequency band is n77, provided by a Nokia Pico base station.
    - These modems are configured to use separate network slices, with remote instructor using eMBB slice and remote user utilizing URLLC slice respectively.
- 5G Core Network
    - The core functions for the 5G network are provided by Cumucore, which is compliant with the 3GPP Release 16 and includes all the required functionalities for end-to-end 5G network operations with its Service Based Architecture (SBA).
    - Cumucore slicing manager also enables the configuration of different traffic rules for each slice.
    - The core is deployed on bare-metal server within the 5GTN, with a mirrored VM running alongside the Cumucore to capture the traffic.
- VR Headsets
    - Two Meta Quest 3 headsets are used to access the DT of the Fab Lab environment; one intended for the remote instructor and other for the remote user.

  - Each VR headset is connected to a laptop, which has a 5G modem connected, allowing the 5G network to be extended from the modems to the VR headsets, as these devices cannot connect directly to 5G network using a SIM card.

- Gaming engine (Edge Processing Server)
  - An edge processing server deployed on a Linux-based VM supports the game engine by hosting web, backend, and streaming services for the VR environment.
  - The VM is provisioned in the 5GTN environment, and it communicates with both the 5G core and end devices, such as VR headsets.

- 3D Printer
  - A Creality Sermoon D3 3D printer is integrated with the 3D DT system, connected with the 5GTN.
  - It receives and executes commands from the virtual environment based on the instructions provided by the connected VR headsets users.

- Video Streaming Cameras
  - Two Raspberry Pi camera modules are mounted on top and side of the 3D printer to capture video of the printing process. The captured video is streamed to the 3D DT environment for monitoring the printing process.

- Laptops
  - Three Lenovo laptops are used in the system, all running Linux-based OS two with Ubuntu 22.04 and one with 24.04.
  - Two laptops are used to connect the 5G modems and VR headsets, one modem and one VR headset each, helping to extend the 5G network from the modems to the headsets. Both have Qosium probe package running to set the measurement probes.
  - One laptop has the Qosium scope package to collect the measurements data.

- Network Switch
  - A 5GTN infrastructure switch Juniper EX4100F provides the interconnectivity to all the devices in the testing setup.
  - The uplink fibre connected with this switch has 10 Gigabits (GB) capacity towards the edge server VM residing under 5GTN server racks.

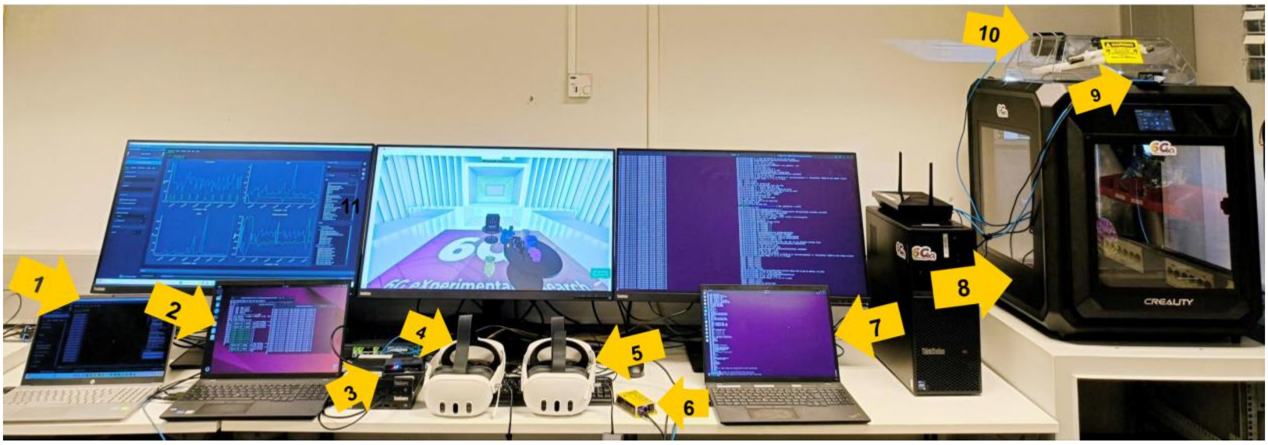



*Figure 23: 3D DT Testing Setup 1.*

Figure 23 depicts the first testing environment at UOULU lab with all the components interconnected under 5GTN infrastructure switch having uplink connectivity towards the edge server, highlighted with arrows:

1. Laptop with Qosium scope to collect KPI metrics.
2. Laptop for connectivity with remote user UE and VR Headset.
3. UE for remote user (slice 1).
4. VR Headset for remote user.
5. VR Headset for remote instructor.
6. UE for remote instructor (slice 2).
7. Laptop for connectivity with remote instructor UE and VR Headset.
8. 3D printer.
9. Raspberry Pi camera module 1.
10. Raspberry Pi camera module 2.

#### 6.2.2.2 Testing Setup 2

- Next Unit Computing (NUC) MiniPC
    - Two ASUS PL64 NUC MiniPCs are used, equipped with Intel Wi-Fi 6e AX210 Modules, which support the Wi-Fi TSN features.
    - One device act as Wi-Fi STA and the other as Wi-Fi AP.
- Robot Arm
    - UR10 is integrated and controlled via remote robot VR application.
- Video Streaming Camera
    - Dell Ultrasharp webcam is installed to support video streaming data.
- VR Headset
    - A Meta Quest 3 VR headset is used to control the robot remote arm from the virtual environment.
- Network Switch Unmanaged
    - An unmanaged network switch is present for the interconnectivity between the NUC, robot arm, camera, and VR headset.

- Laptop
  - A Lenovo laptop having Linux-based OS Ubuntu 22.04 is used with all the required Qosium packages to collect the measurements data.

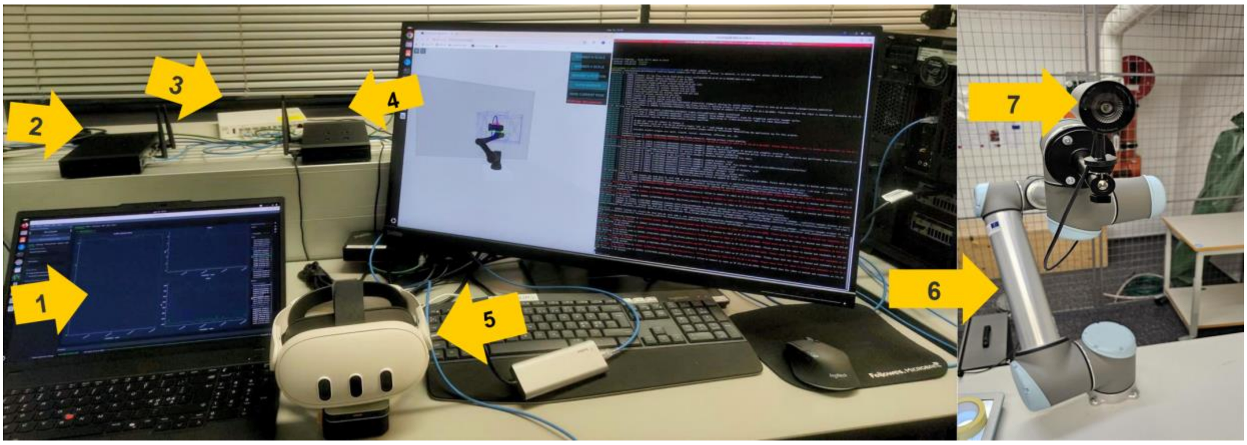



*Figure 24: Robot arm with wireless TSN: Testing Setup 2.*

Figure 24 illustrates the second testing environment to validate Wi-Fi TSN metrics, the setup is present in UOULU 5GTN lab and related components are highlighted:

1. Laptop with Qosium scope to collect KPI metrics.
2. Wi-Fi AP.
3. 5GTN network switch.
4. Wi-Fi STA.
5. VR Headset.
6. Robot arm.
7. Video stream camera.

## 6.3 TEST CASE SPECIFICATIONS

Following the definition of the testing environment characteristics and the validation process based on the V-model assessment approach, the next step involves the description of test cases executed for each scenario. The test cases are designed to address the quantitative aspects of the system and are mapped to the KPI metrics, as well as the functional and non-functional requirements described in Sections 5.1 and 5.3. These test cases specify the testing environment setup, deployment procedures, test configurations, and monitored parameters thereby facilitating the evaluation of the system and enabling the collection of required set of performance indicators.

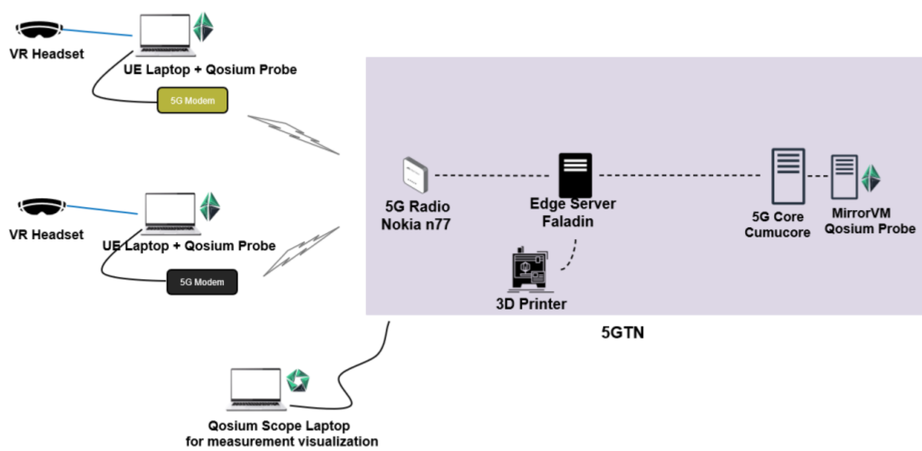
Below Table 7 summarizes the validation objectives and linkage with the corresponding test cases conducted to assess the system. Each test case is uniquely identified with a corresponding Test ID referred to as North Node (NN) for traceability across the validation framework. A total of seven test cases from NN1.1 to NN1.7 are designed and grouped to map with validation objectives of functional, non-functional and KPI metrics of the developed system.

*Table 7 Validation Objectives and corresponding Test Cases*

| Validation Objective | Test Case | Test ID |
|---|---|---|
| Functional and Non-Functional Requirements | Remote User 3D Review and Interaction Validation Test Case | NN1.1 |
| | Remote Instructor 3D Review, Printing & Delivery Validation Test Case | NN1.2 |
| | Network Slicing Validation for 3D DT Service Test Case | NN1.3 |
| KPI Metrics | Integrated Data Rate, Network Performance, Latency, and Reliability Test Case | NN1.4 |
| | Operational and Environmental KPI Validation Test Case | NN1.5 |
| | Wi-Fi TSN KPI Validation for Robot Arm Integration Test Case | NN1.6 |
| | End-to-End System Validation Utilizing Trial Controller Test Case | NN1.7 |

### 6.3.1 Remote User 3D Review and Interaction Validation Test Case

| UOULU | Remote User 3D Review and Interaction Validation Test Case |
|---|---|
| **Test Case Name** | Remote User 3D Review and Interaction Validation Test Case (Test ID: NN1.1) |
| **Test Case Objective** | To verify that Remote User is able to create, upload, review, interact with, and monitor a 3D object in DT environment, while ensuring all technical enablers function correctly. |
| **Test Case Category** | User Requirement, Virtual Environment and Function Requirement Validation for UC4 |
| **Test Environment** | 5GTN Laboratory |
| **Test Deployment Setup** | <br>*Figure 25: Test Case Network Deployment.* |
| **Initial Conditions/Prerequisites** | |
| 3D DT system is fully operational with all components available and functioning. | |
| **Test scenario** | |

| |
|---|
| Test steps are as follows:<br>1. 3D Object Creation: Create a 3D object in the required format and save it.<br>2. 3D Object Delivery: Upload the 3D object to the predefined location and access it.<br>3. Review Time Scheduling: Schedule a review session with the instructor.<br>4. VR Equipment Compatibility: Connect the VR headset for remote user and access the DT environment.<br>5. Live 3D Environment Delivery: Connect the VR headset for remote user and observe the live 3D environment through it.<br>6. Communication between the user and instructor: Connect the VR headset for remote user's access to the 3D environment and communicate with the microphone and speaker of the headset.<br>7. Interaction with DT Environment: Connect the VR headset for remote user and use the hand gestures to move and interact with the virtual objects in the 3D environment.<br>8. Monitoring the Printing Process: Connect the VR headset for remote user, pick one object and print in the 3D environment, then observe the printing process through the UI in browser and live video feed in 3D environment. |
| **Test variables** |
| System configuration components being tested (hardware/software). |
| **Expected behavior/Target Values** |
| All the components present in the system should successfully pass the validation and work as expected. |

### 6.3.2 Remote Instructor 3D Review, Printing & Delivery Validation Test Case

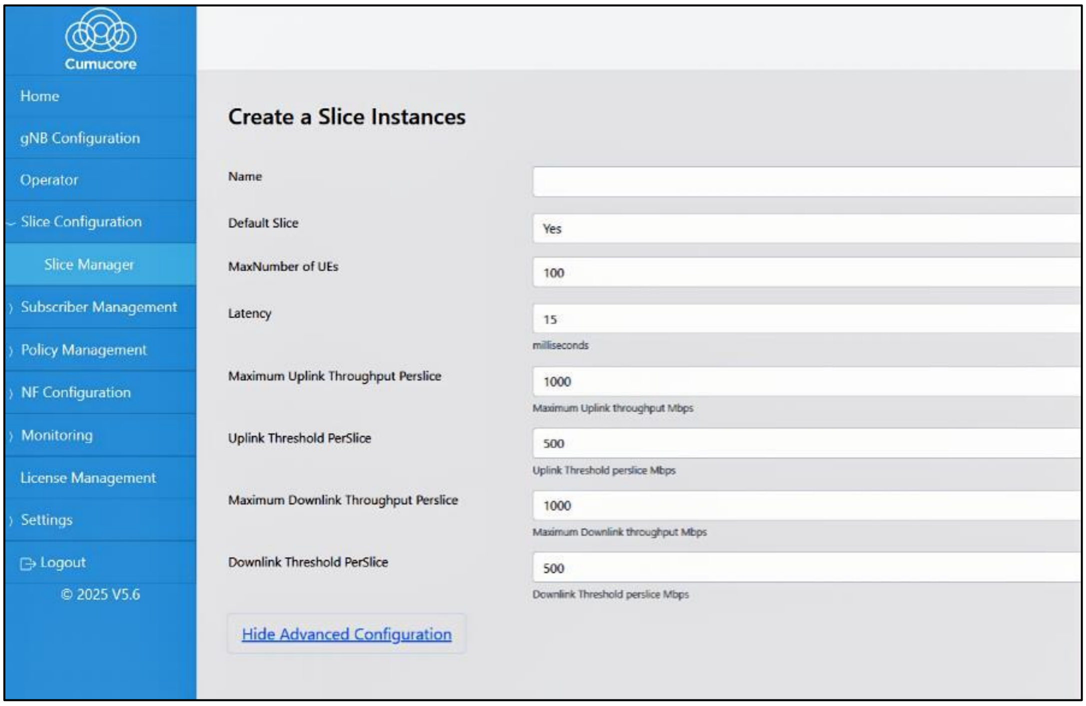
| UOULU | Remote Instructor 3D Review, Printing & Delivery Validation Test Case |
|---|---|
| **Test Case Name** | Remote Instructor 3D Review, Printing & Delivery Validation Test Case (Test ID: NN1.2) |
| **Test Case Objective** | To verify that the Remote Instructor can successfully review, retrieve, interact, print, and deliver a 3D object, while ensuring all technical enablers function correctly. |
| **Test Case Category** | User Requirement, Virtual Environment and Function Requirement Validation for UC4 |
| **Test Environment** | 5GTN Laboratory |
| **Test Deployment Setup** | Same as Figure 25. |
| **Initial Conditions/Prerequisites** | |
| 3D DT system is fully operational, with all components available and functioning. | |
| **Test scenario** | |

| |
|---|
| Test steps are as follows:<br>1. Review Time Scheduling: Remote Instructor schedules a review session with the remote user.<br>2. Retrieve 3D Object: Access the online location and download the 3D object.<br>3. VR Equipment Compatibility: Connect the VR headset for remote instructor and access the DT environment.<br>4. Live 3D Environment Delivery: Connect the VR headset for remote instructor and observe live 3D environment through the headset.<br>5. Communication between user and instructor: Connect the VR headset for remote instructor to access the 3D environment and communicate with the microphone and speaker of headset.<br>6. Interaction with DT Environment: Connect the VR headset for remote instructor and use the hand gestures to interact with the virtual objects in the 3D environment.<br>7. Start Printing Process: After the review is approved, the remote instructor can initiate the printing process.<br>8. 3D Object Re-Formatting for Printing: The remote instructor modifies the 3D object before printing and then uploads it.<br>9. Setting Printing Parameters: The remote instructor configures the printing parameters and starts the printing process.<br>10. Monitoring Printing Progress: Connect the VR headset for remote instructor, pick one object and print in the 3D environment, then observe the printing process through the UI in browser and live video feed in 3D environment.<br>11. Notify Remote User of Completion: Once the printing process is completed, remote instructor informs remote user of completion. |
| **Test variables** |
| System configuration components being tested (hardware/software) |
| **Expected behavior/Target Values** |
| All the components present in the system should successfully pass the validation and work as expected. |

### 6.3.3 Network Slicing Validation for 3D DT Service Test Case

| UOULU | Network Slicing Validation for 3D DT Service Test Case |
|---|---|
| **Test Case Name** | Network Slicing Validation for 3D DT Service Test Case (Test ID: NN1.3) |
| **Test Case Objective** | To verify and validate the working of network slicing function of the connected 5G network with the 3D DT environment. |
| **Test Case Category** | Function Requirement Validation for UC4 |
| **Test Environment** | 5GTN Laboratory |
| **Test Deployment Setup** | Same as Figure 25. |
| **Initial Conditions/Prerequisites** | |

| |
|---|
| The 3D DT system is fully operational, and the connected 5G network is up. Slices configuration is done at the gNodeB and in the 5G Core. The configuration is performed via web user interface of the Cumucore, under slice configuration manager (Figure 26), where Slice Service Type (SST) and Slide Differentiator (SD) values are defined. The Access Management Function (AMF) and Session Management Function (SMF) configurations are then updated. Finally, the User Plane Functions (UPFs) are mapped to specific slices. The UEs utilize the required slices, set up under subscriber management, and the corresponding slices related UPFs are invoked when connecting to the system.<br><br>*Figure 26: Slice Configuration Manager User Interface.* |
| **Test scenario** |
| Test steps are as follows:<br>1. 5G Network Slice Provisioning of URLLC and eMBB slices: Connect two users via VR headsets with two UEs configured as URLLC and eMBB slices in the 5G core network.<br>2. Connectivity Check for Remote User: Connect remote user to a designated slice, URLLC or eMBB, individually.<br>3. Connectivity Check for Remote Instructor: Connect remote instructor to a designated slice URLLC or eMBB, individually.<br>4. End-to-End 3D DT Communication Test: Connect remote user to one slice and remote instructor with the second slice, then interact with each other in the 3D environment.<br>5. Network Slice Failover Test between the URLLC and eMBB slices: Connect remote user to one slice and remote instructor with the second slice, then simulate a temporary failure of one slice to reroute the traffic to the other operating slice. |
| **Test variables** |
| System configuration components being tested (hardware/software) |
| **Expected behavior/Target Values** |
| All the components present in the system should successfully pass the validation and work as expected. |

### 6.3.4 Integrated Data Rate, Network Performance, Latency, and Reliability Test Case

<table>
<tr><th>UOULU</th><th colspan="7">Integrated Data Rate, Network Performance, Latency, and Reliability Test Case</th></tr>
<tr><td>Test Case Name</td><td colspan="7">Integrated Data Rate, Network Performance, Latency, and Reliability Test Case (Test ID: NN1.4)</td></tr>
<tr><td>Test Case Objective</td><td colspan="7">Measuring data rate, network performance, and latency values by verifying link capabilities between the UC4 components. The system is considered adequate if each specified KPI value is met.</td></tr>
<tr><td>Test Case Category</td><td colspan="7">KPI Measurements</td></tr>
<tr><td>Test Environment</td><td colspan="7">5GTN Laboratory</td></tr>
<tr><td>Test Deployment Setup</td><td colspan="7">Same as Figure 25.</td></tr>
<tr><td>Network Setup</td><td>RAN:</td><td>Nokia Base-station n77</td><td>5G Core:</td><td>Cumucore</td><td>Edge:</td><td>Faladin Application Server</td><td>Band: 3.9 - 4.0GHz Bandwidth: 100MHz</td></tr>
<tr><td>Test Configuration</td><td>Components Under Test:</td><td>VR Headsets, 3D Printer, Test UEs (5G-Capable), Edge Application Server</td><td>Test Software:</td><td>iPerf3, Qosium Probe, Qosium Scope</td><td>Test Devices:</td><td>Laptop for UE Connectivity, Laptop for Qosium Scope, VR Headsets, Ethernet Cables, Ethernet to USB Converters, 3D Printer, Faladin Edge Application Server</td><td>Testing Payload Data: TCP and UDP Data streams</td></tr>
<tr><td colspan="8">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="8">1. 3D DT system is operational with all its components running.<br>2. The VR headsets are connected to respective modems with Ethernet cables and converters.<br>3. Qosium probe is running on both laptops where the modems are connected to.<br>4. Qosium probe is running on the mirror VM for traffic capture intended for Cumucore.<br>5. Qosium scope is running on a laptop where the measurements results will be collected.<br>6. End to end reachability between the probes is established.<br>7. iPerf3 packages are present on both the laptop and the core to generate traffic from both ends.</td></tr>
<tr><td colspan="8">Test scenario</td></tr>
</table>

| |
|---|
| In this test after the 5G connection is established via the UEs, the VR headsets are connected to the laptop with Ethernet cables and network sharing is turned on to extend the 5G network to the VR headsets. Qosium tools are employed to collect the KPI values across multiple required metrics. Qosium probe service is running on the laptops where UEs are connected and iPerf3 packages are also installed on these laptops to generate and receive traffic. These 5G modems are registered with the Cumucore. A mirror VM is deployed alongside Cumucore to capture traffic intended for the Cumucore. This mirrored traffic is the replica of the traffic received at Cumucore to assess the measurement data. Qosium probe service and iPerf3 packages are also available on this system. An edge server running the 3D DT services is reachable from the UEs. The 3D printer is available, and it comprises of Raspberry Pi devices connected with cameras to deliver video streaming of the printing process.<br>Test steps are as follows:<br>1. The user uses the VR headset to enters the VR environment. The user presses the print button on the 3D printer and camera stream starts. Qosium probe is started at the UE laptop and steam bitrate is observed via Qosium scope.<br>2. The instructor also enters the VR environment. Qosium probe is also started at the second laptop. Both user and instructor interact with objects, perform printing process and communicate with each other. The combined data are observed via Qosium scope.<br>3. Virtual Browser UI is observed remotely, and traffic is observed.<br>4. Traffic generated from VR headsets over the wireless link is observed.<br>5. Wireless traffic from VR headsets towards 5GTN edge server over wired connection is observed.<br>6. 5G downlink data rate is observed.<br>7. 5G uplink data rate is observed.<br>8. Latency and delay values are observed from the VR headsets to the edge server (uplink).<br>9. Latency and delay values are observed from the edge server to VR headsets (downlink).<br>10. Processing time of the edge server hosting the 3D services is observed.<br>11. Reliability percentage of the packets within the target latency range values is also observed. |
| **Test variables** |
| Single and multiple users generated data |
| **Expected behavior/Target Values** |
| Expected behavior of the generated data traffic should align with the below target KPI values:<br>1. Camera stream bitrate $\geq$ 2 Mbps.<br>2. VR headsets 3D, audio and control data $\geq$ 1Mbps.<br>3. 3D Printer virtual browser UI data $\geq$ 1 Mbps.<br>4. Wireless link is able to accommodate traffic from the VR glasses up to 400Mbps.<br>5. Wired link towards 5GTN edge server has the capacity up to 10Gbps.<br>6. 5G downlink traffic up to 400Mbps.<br>7. 5G uplink traffic up to 50Mbps.<br>8. Latency and delay downlink $\leq$ 10ms.<br>9. Latency and delay uplink $\leq$ 14ms.<br>10. Processing time of 3D DT application server $\leq$ 16.6ms (60 fps).<br>11. Packet reliability within the target latency with 99.9% of reliability. |

### 6.3.5 Operational and Environmental KPI Validation Test Case

| UOULU | Operational and Environmental KPI Validation Test Case |
|---|---|
| **Test Case Name** | Operational and Environmental KPI Validation Test Case Test Case (Test ID: NN1.5) |

<table>
<tr><td>Test Case Objective</td><td colspan="8">Measure the user’s mobility, density, and energy efficiency of the 3D DT System.</td></tr>
<tr><td>Test Case Category</td><td colspan="8">KPI Measurements</td></tr>
<tr><td>Test Environment</td><td colspan="8">5GTN Laboratory</td></tr>
<tr><td>Test Deployment Setup</td><td colspan="8">Same as Figure 25.</td></tr>
<tr><td>Network Setup</td><td>RAN:</td><td>Nokia Base-station n77</td><td>5G Core:</td><td>Cumucore</td><td>Edge:</td><td>Faladin Application Server</td><td>Band: 3.9 - 4.0GHz<br>Bandwidth: 100MHz</td></tr>
<tr><td>Test Configuration</td><td>Components Under Test:</td><td>VR Headsets, 3D Printer, Test UEs (5G-Capable), Edge Application Server</td><td>Test Software:</td><td>iPerf3, Qosium Probe, Qosium Scope</td><td>Test Devices:</td><td>Laptop for UE Connectivity, Laptop for Qosium Scope, VR Headsets, Ethernet Cables, Ethernet to USB Converters, 3D Printer, Faladin Edge Application Server</td><td>Testing Payload Data: TCP and UDP Data streams</td></tr>
<tr><td colspan="9">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="9">1. 3D DT system is operational with all its components running.<br>2. The VR headsets are connected to respective modems with Ethernet cables and converters.<br>3. Qosium probe is running on both laptops equipped with the modems, as well as on the mirror VM.<br>4. Qosium scope is running on another laptop where the measurements results are collected.<br>5. End to end reachability between the probes is established.<br>6. iPerf3 packages are present on both the laptops and edge to generate traffic from both ends.</td></tr>
<tr><td colspan="9">Test scenario</td></tr>
</table>

| |
|---|
| In this test scenario after 5G connection is established to the UEs, the VR headsets are connected to the same laptop via Ethernet cables and network sharing is turned on to extend the 5G network to the VR headsets. Qosium tools are employed to collect the KPI values across multiple required metrics. Qosium probe service is running on the laptops, where UEs are connected, and iPerf3 packages are also installed to generate and receive traffic. The 5G modems are registered with the Cumucore. The mirror VM alongside Cumucore for traffic capture is also present. Qosium probe service and iPerf3 packages are available on this system. An edge server running the 3D DT services is reachable from the UEs. The 3D printer is also part of 5GTN environment, and it comprises of Raspberry Pi devices connected with cameras to deliver video streaming of the printing process.<br>Test steps are as follows:<br>1. Multiple users are connected to the VR headsets and enter the virtual environment. Users move indoors simulating the typical indoor environment. Walking around the room, rotating the body, and using multiple hand represent low indoor mobility. Qosium probes are running on the end devices and traffic is monitored via Qosium scope to observe throughput, latency, delay, and session interruptions during the mobility of the users.<br>2. The number of connected users is increased in the VR environment to increase the high device/user density up to 10 users/m$^2$, and Qosium scope is used to monitor for the degradation of services. Throughput, latency, delay, and session interruptions are observed with the increase in users.<br>3. The energy efficiency of the DT system is observed both when the system is idle and when it is processing multiple requests from multiple users simultaneously. |
| **Test variables** |
| Single and multiple users generated data |
| **Expected behavior/Target Values** |
| 1. The throughput generated during low indoor mobility of users, delay and jitter values should be low, with no session interruptions.<br>2. The number of connected users is increased, resulting in an increased density of 10 users/m$^2$, while the values of delay and jitter should remain low, with no session interruptions. The overall performance should not degrade severely.<br>3. The energy efficiency of the DT system is evaluated during both idle and active virtual environment processing states. Efficiency of the system should be nominal with non-excessive levels. |

### 6.3.6 Wi-Fi TSN KPI Validation for Robot Arm Integration Test Case

| UOULU | Wi-Fi TSN KPI Validation for Robot Arm Integration Test Case |
|---|---|
| **Test Case Name** | Wi-Fi TSN KPI Validation for Robot Arm Integration Test Case (Test ID: NN1.6) |
| **Test Case Objective** | Measure the time synchronization accuracy, bounded latency for robot arm cyclic signal and video payload from the camera. |
| **Test Case Category** | KPI Measurements |
| **Test Environment** | 5GTN Laboratory |

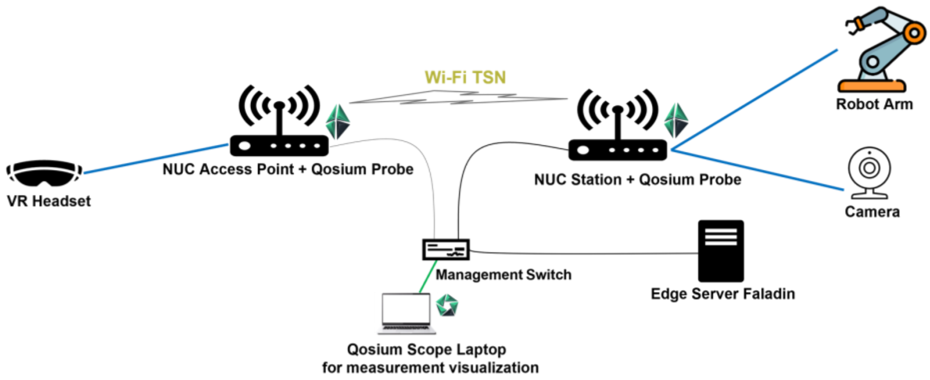
<table>
<tr><td>Test Deployment Setup</td><td colspan="7">

Figure 27: NN1.6 Test Case Network Deployment.</td></tr>
<tr><td>Network Setup</td><td>Wireless</td><td>Wi-Fi TSN Technology</td><td>Wired</td><td>Wired Ethernet connection for management</td><td>Application</td><td>Robot remote XR Application</td><td>Band: 5Ghz Bandwidth: 40 Mhz</td></tr>
<tr><td>Test Configuration</td><td>Components Under Test:</td><td>Robot Arm, VR Headset, NUC MiniPC, Wi-Fi 6E Module</td><td>Test Software:</td><td>PTP for Linux (ptp4l), Qosium Probe, Qosium Scope</td><td>Test Devices:</td><td>Laptop for Qosium Scope, VR Headset, Ethernet Cables, Ethernet to USB Converters, Robot Arm, Intel Wi-Fi 6e AX210 Module, ASUS PL64 NUC Mini PC</td><td>Testing Payload Data: TCP and UDP Data streams</td></tr>
<tr><td colspan="8">Initial Conditions/Prerequisites</td></tr>
</table>

| |
|---|
| 1. Wi-Fi TSN system is operational with all components running.<br>2. VR headset is connected to the system.<br>3. Qosium probe is running on both the NUC WI-FI AP and the NUC WI-FI STA.<br>4. Qosium scope is running on a laptop to collect the measurement results.<br>5. Robot arm and streaming camera are operational with end-to-end reachability.<br>6. Robot remote VR application is working correctly and reachable from the VR headset. |
| **Test scenario** |
| The test scenario consists of a set of NUCs equipped with Wi-Fi TSN supported modules. These NUCs are interconnected via Wi-Fi. One device is the Wi-Fi AP which also acts a Grandmaster source, while the other device is Wi-Fi STA which acts as slave. These devices are also connected via wired link to the 5GTN network, which hosts an edge server running the Robot remote XR application. The robot arm, camera, and VR headset also have wired Ethernet connections to the NUC Mini PCs. All the components are accessible through a network switch, which also facilitates device management.<br>Test steps are as follows:<br>1. The robot remote VR application is run on the edge server.<br>2. The camera stream is verified within the application.<br>3. The TSN configurations are implemented and on both the WI-FI AP and STA, and PTP time synchronization between the Wi-Fi TSN devices is verified.<br>4. The robot arm traffic is sent over the Wi-Fi TSN and is isolated from the remaining routed traffic.<br>5. VR headset is connected to the VR application and user enters the VR environment to control the movements of the robot arm.<br>6. The Qosium probe is run on both the WI-FI AP and STA devices to observe traffic metrics from the robot arm to the application. |
| **Test variables** |
| Single user generated data from the VR headset to control the robot arm over Wi-Fi TSN. |
| **Expected behavior/Target Values** |
| Wi-Fi TSN traffic between the application and robot arm is observed, which should align with the target KPI values below:<br>1. Time synchronization accuracy between the Wi-Fi TSN AP and STA clocks $\leq$ 10 µs.<br>2. Latency bounds generated by 200 ms cyclic signal from the robot arm should be in between 1-10 ms.<br>3. Video payload from the camera = 1 Mbps (30 fps). |

### 6.3.7 End-to-End System Validation Utilizing Trial Controller Test Case

| UOULU | End-to-End System Validation Utilizing Trial Controller Test Case |
|---|---|
| **Test Case Name** | End-to-End System Validation Utilizing Trial Controller Test Case (Test ID: NN1.7) |
| **Test Case Objective** | Measuring network performance metrics by creating automated slices using the trial controller for 3D DT users. |
| **Test Case Category** | Trial controller functional Validation |
| **Test Environment** | 5GTN Laboratory |

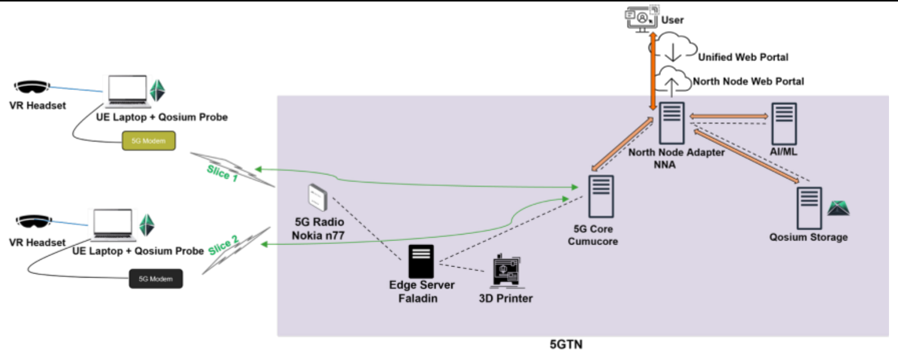
<table>
<tr><td>Test Deployment Setup</td><td colspan="7">

Figure 28: Test Case Network Deployment.</td></tr>
<tr><td>Network Setup</td><td>RAN:</td><td>Nokia Base-station n77</td><td>5G Core:</td><td>Cumucore</td><td>Edge:</td><td>Faladin Application Server</td><td>Band: 3.9 - 4.0GHz Bandwidth: 100MHz</td></tr>
<tr><td>Test Configuration</td><td>Components Under Test:</td><td>VR Headsets, 3D Printer, Test UEs (5G-Capable), Edge Application Server</td><td>Test Software:</td><td>Qosium Probe, Qosium Storage</td><td>Test Devices:</td><td>Laptop for UE Connectivity, VR Headsets, Ethernet Cables, Ethernet to USB Converters, 3D Printer, Faladin Edge Application Server</td><td>Testing Payload Data: TCP and UDP Data streams</td></tr>
<tr><td colspan="8">Initial Conditions/Prerequisites</td></tr>
<tr><td colspan="8">1. 3D DT system is operational with all its components running.<br>2. The VR headsets are connected to respective modems with Ethernet cables and converters.<br>3. Qosium probe is running on both laptops where the modems are connected.<br>4. User access to the Unified and North Node web portal is granted.<br>5. North node adapter is functioning properly and reachable from both Qosium storage and AI/ML nodes.</td></tr>
<tr><td colspan="8">Test scenario</td></tr>
</table>

| |
|---|
| The test scenario comprises of multiple 5G modems connected with laptops to gain access to 5G network. Unified web portal is accessed, and a new trial is created by selecting UOULU (North Node) facility. The North Node portal is accessed with the generated trial ID. A new experiment is created on this portal. The experiment is executed selecting two slice options, one for each remote user and instructor. The North Node Adapter gets the information and creates required slices on Cumucore. Measurement data is managed by Qosium storage, and once the experiment is completed, the measurement results are extracted from the Qosium storage are presented on the data visualization dashboard. The results are verified with the target metrics.<br>Test steps are as follows:<br>1. The user connects to the 5G slice created by Cumucore after the trial is initiated by the trial controller. Using a VR headset, the user enters the VR environment, presses the print button on the 3D printer, and the camera stream starts.<br>2. The instructor connects to the second 5G slice created by Cumucore after the trial is initiated by the trial controller. Using a VR headset, the instructor enters the VR environment, presses the print button on the 3D printer, and camera stream starts.<br>3. The experiment is stopped, and measurement metrics are observed on the web portal. |
| **Test variables** |
| Multiple users generated data |
| **Expected behavior/Target Values** |
| All the components present in the system should successfully pass the validation as expected. |

## 6.4 VALIDATION OF KVIS

While the test case specifications allow for the measurement of quantitative KPI metrics and functional and non-functional requirements, certain KVIs reflecting user experience and perceived value could not be directly obtained through system measurements. To address this, a questionnaire-based evaluation is conducted among a target public audience. The selected venue for the KVI questionnaire execution was the annual Researchers' Night[3] at UOulu, 2025 edition. The Researchers' Night is a multidisciplinary event for the whole family, offering a chance to explore the work of researchers and the role of science in our everyday lives. At the Researchers' Night, one can dive into the world of science by taking part in workshops, exhibitions, and popular science talks. The programme includes a wide range of activities and experiences for all ages. The event is free and open for all. Hence, the venue is an excellent opportunity to collect opinions of people from multiple age and gender groups as well as nationalities. The 2025 edition gathered more than 3000 attendees from the influence area of UOulu.

The questionnaire is designed to validate the qualitative aspects of the system, such as user experience, satisfaction, and perceived usability. The collected responses provide insights into the dimensions of validation that are complementary to cover the KVIs of the 3D DT System. Annex B - KVI Questionnaire contains the questionnaire utilized to collect data from the diverse audience. This questionnaire covers all the KVI categories and their relevant key value enablers.

The evaluation process applied to the collective responses gathered from the questionnaire are mapped into two dimensions. The passive responses collected for each category represent the negative impact of the system on the audience, broadly classified as Footprints. On the other hand, the positive outcomes corresponding to each category represent the attractive contributions of the system, grouped as Handprints. The Table 8 summarizes the outcomes mapped as handprints and

[3] https://www.oulu.fi/en/events/researchers-night

footprints across each KVI dimension structured for 3D DT system. Handprints highlight the contribution of the DT system to sustainability, inclusivity, enhanced productivity, and knowledge sharing, including time saving, reduced carbon footprint, and fair participation enablement. On the other hand, footprints capture the concerns that may limit the adoption of system, including increased complexity, high energy consumption, potential ethical misuse, and privacy risks.

*Table 8: KVI Handprints and Footprints*

| KVI Dimension | Handprints | Footprints |
|---|---|---|
| Cost and Efficiency | Saving time and resources.<br>Productivity boost.<br>Enabling remote work. | Increased complexity.<br>Adoption costs.<br>Unequal access. |
| Sustainability | Reduces carbon footprint.<br>Supports innovations.<br>Sustainable economy. | High energy and resource usage. |
| Digital and Security | Accessibility for diverse users.<br>Fair participation.<br>Digital inclusion. | Privacy and Security Concerns. |
| Knowledge and Learning | Improved knowledge sharing.<br>Better real-time collaboration compared with existing tools. | Difficulty in collaboration compared to existing tools. |
| Social Impact and Quality of Life | Easy and simple communication. | Risk of unethical usage. |

# 7 KPVI ASSESSMENT

This section presents the results of the test cases, using quantitative analysis and graphic visualisation to capture KPI metrics and system requirements for all components of 3D DT system covering the subsequent classification, results, evaluation and reporting stages of the V-Model process. The results are depicted using the Test case template based on Annex A – Test Case Template.

## 7.1 PRESENTATION OF TEST CASE RESULTS

### 7.1.1 Remote User 3D Review and Interaction Validation Test Case Results

| **UOULU** | **Remote User 3D Review and Interaction Validation Test Case** | | |
|---|---|---|---|
| **Test Case Name** | Remote User 3D Review and Interaction Validation Test Case (Test ID: NN1.1) | | |
| **Test Execution Date** | 20-25/04/2025 | | |
| **Test Executed By** | UOULU | | |
| **Number of repetitions** | 1 | | |
| **Test's comments** | Tests were performed physically in 5GTN laboratory with fully operational 3D DT system. | | |
| **Verification Points (VP)** | | | |
| **Checkpoint ID** | **Description of Validation Criteria for checkpoint** | | |
| ID #1 | The object can be saved in correct format. | | |
| ID #2 | The file is accessible in the correct location. | | |
| ID #3 | The session with the instructor is successfully scheduled. | | |
| ID #4 | The VR headset works without any compatibility issues. | | |
| ID #5 | The remote user can see the environment clearly through the headset. | | |
| ID #6 | The remote user is able to communicate with the instructor via headset and hear clearly. | | |
| ID #7 | The remote user can successfully interact with the virtual object. | | |
| ID #8 | The remote user is able to see the printing process through browser UI and video feed in 3D environment. | | |
| **Test Validation Conditions** | Tests were performed with VR headsets, and all checkpoints for each component's validation were checked. | | |
| **Test results** | **Test run** | **Description** | **Result** |
| ID #1 | 1 | The object is saved in correct format. | Pass |
| ID #2 | 1 | File is accessible in the predefined location. | Pass |
| ID #3 | 1 | Session was successfully established. | Pass |
| ID #4 | 1 | VR headset has no compatibility issues. | Pass |
| ID #5 | 1 | Remote user is able to see the environment clearly. | Pass |
| ID #6 | 1 | Remote user is able to communicate and hear the instructor. | Pass |
| ID #7 | 1 | Remote user can interact with the virtual object. | Pass |
| ID #8 | 1 | Remote user is able to see the printing process feed in browser UI and in 3D environment. | Pass |

### 7.1.2 Remote Instructor 3D Review, Printing & Delivery Validation Test Case Results

| UOULU | Remote Instructor 3D Review, Printing & Delivery Validation Test Case | | |
|---|---|---|---|
| **Test Case Name** | Remote Instructor 3D Review, Printing & Delivery Validation Test Case (Test ID: NN1.2) | | |
| **Test Execution Date** | 20-25/04/2025 | | |
| **Test Executed By** | UOULU | | |
| **Number of repetitions** | 1 | | |
| **Test's comments** | Tests were performed physically in 5GTN laboratory with fully operational 3D DT system. | | |
| **Verification Points (VP)** | | | |
| **Checkpoint ID** | **Description of Validation Criteria for checkpoint** | | |
| ID #1 | The session is successfully scheduled with remote user. | | |
| ID #2 | The file is accessible in the correct location. | | |
| ID #3 | The VR headset works without any compatibility issues. | | |
| ID #4 | The remote instructor can see the environment clearly through the headset. | | |
| ID #5 | The remote instructor is able to communicate with the remote user via headset and hear clearly. | | |
| ID #6 | The remote instructor can successfully interact with the virtual object. | | |
| ID #7 | The remote instructor can successfully start the printing process. | | |
| ID #8 | The remote instructor can successfully modify the object before printing. | | |
| ID #9 | The remote instructor is able to set printing parameters before starting the printing process. | | |
| ID #10 | The remote instructor is able to see the printing process or not through browser UI and video feed in 3D environment. | | |
| ID #11 | The remote instructor is able to notify the remote user about completion of printing. | | |
| **Test Validation Conditions** | Tests were performed with VR headsets, and all checkpoints for each component's validation were checked. | | |
| **Test results** | **Test run** | **Description** | **Result** |
| ID #1 | 1 | Session was successfully established. | Pass |
| ID #2 | 1 | File is accessible in the predefined location. | Pass |
| ID #3 | 1 | VR headset has no compatibility issues. | Pass |
| ID #4 | 1 | Remote instructor is able to see the environment clearly. | Pass |
| ID #5 | 1 | Remote instructor is able to communicate and hear the remote user. | Pass |
| ID #6 | 1 | Remote instructor can interact with the virtual object. | Pass |
| ID #7 | 1 | Remote instructor is able to start the printing process. | Pass |
| ID #8 | 1 | Remote instructor is able modify the object before printing. | Pass |
| ID #9 | 1 | Remote instructor is able to set printing parameters before starting the printing process. | Pass |
| ID #10 | 1 | Remote instructor is able to see the printing process feed in browser UI and not in 3D environment. | Pass |
| ID #11 | 1 | Remote instructor is able to notify the remote user of completion of printing. | Pass |

### 7.1.3 Network Slicing Validation for 3D DT Service Test Case Results

| UOULU | Network Slicing Validation for 3D DT Service Test Case | | |
|---|---|---|---|
| **Test Case Name** | Network Slicing Validation for 3D DT Service Test Case (Test ID: NN1.3) | | |
| **Test Execution Date** | 20-25/04/2025 | | |
| **Test Executed By** | UOULU | | |
| **Number of repetitions** | 1 | | |
| **Test's comments** | Tests were performed physically in 5GTN laboratory with fully operational 3D DT system. | | |
| **Verification Points (VP)** | | | |
| **Checkpoint ID** | **Description of Validation Criteria for checkpoint** | | |
| ID #1 | The two users (remote user and instructor) are able to connect using the two configured UE slices. | | |
| ID #2 | Remote user is able to connect with the designated slice. | | |
| ID #3 | Remote instructor is able to connect with the designated slice. | | |
| ID #4 | The two users connected via the configured UE slices are able to interact with the 3D DT environment. | | |
| ID #5 | Remote user with one slice and remote instructor with second slice are able to switch over in case of temporary failure of one of the connected slices. | | |
| **Test Validation Conditions** | Tests were performed with VR headsets, and an operation 3D DT system all checkpoints for each component's validation were checked. | | |
| **Test results** | **Test run** | **Description** | **Result** |
| ID #1 | 1 | Two users were connected successfully with the configured UE slices. | Pass |
| ID #2 | 1 | Remote user is able to connect with their designated slice. | Pass |
| ID #3 | 1 | Remote instructor is able to connect with its designated slice. | Pass |
| ID #4 | 1 | Remote user and instructor, connected via different slices, are able to interact in the 3D DT environment. | Pass |
| ID #5 | 1 | The switchover from the temporary failed slice to the active one was successful between the remote user and instructor. | Pass |

### 7.1.4 Integrated Data Rate, Network Performance, Latency, and Reliability Test Case Results

| UOULU | Integrated Data Rate, Network Performance, Latency and Reliability Test Case |
|---|---|
| **Test Case Name** | Integrated Data Rate, Network Performance, Latency, and Reliability Test Case (Test ID: NN1.4) |
| **Test Execution Date** | 16-18/06/2025 |
| **Test Executed By** | UOULU |
| **Number of repetitions** | 3 |

| | | | |
|---|---|---|---|
| **Test's comments** | Tests were performed physically in 5GTN laboratory with fully operational 3D DT system. | | |
| **Verification Points (VP)** | | | |
| **Checkpoint ID** | **Description of Validation Criteria for checkpoint** | | |
| ID #1 | The camera stream bitrate exceeds 2 Mbps when users are connected in the virtual environment. | | |
| ID #2 | The user data from VR headsets, including 3D virtual environment data, audio, and control data exceeds 1 Mbps. | | |
| ID #3 | The virtual browser UI data exceeds 1 Mbps. | | |
| ID #4 | The wireless link can accommodate the traffic generated by multiple VR headsets users up to 400 Mbps. | | |
| ID #5 | The wired link towards 5GTN edge server has up to 10 Gbps of capacity. | | |
| ID #6 | 5G downlink throughput support up to 400 Mbps of traffic. | | |
| ID #7 | 5G uplink throughput supports up to 50 Mbps of traffic. | | |
| ID #8 | 5G downlink latency and delay should be below 10 ms for required throughput. | | |
| ID #9 | 5G uplink latency and delay should be below 14 ms for required throughput. | | |
| ID #10 | Processing time of 3D DT edge application should be below 16.6 ms when multiple users are utilizing the virtual environment. | | |
| ID #11 | Packet reliability should be 99.9% for both uplink and downlink channels within the target latency values. | | |
| **Test Validation Conditions** | Tests were performed with VR headsets, and all checkpoints for each component's validation were checked and measurement data values are collected. | | |
| **Test results** | **Test run** | **Description** | **Result** |
| ID #1 | 1-3 | Figure 29 and Figure 30 | Pass |
| ID #2 | 1-3 | Figure 29 and Figure 30 | Pass |
| ID #3 | 1-3 | Figure 29 and Figure 30 | Pass |
| ID #4 | 1-3 | Figure 31 and Figure 32 | Pass |
| ID #5 | 1-3 | Figure 31 and Figure 32 | Pass |
| ID #6 | 1-3 | Figure 33 and Figure 34 | Pass |
| ID #7 | 1-3 | Figure 35 and Figure 36 | Pass |
| ID #8 | 1-3 | Figure 33 and Figure 34 | Pass |
| ID #9 | 1-3 | Figure 35 and Figure 36 | Pass |
| ID #10 | 1-3 | Figure 33 and Figure 34 | Pass |
| ID #11 | 1-3 | Figure 33, Figure 34, Figure 35, and Figure 36 | Pass |
| **Results Diagrams** | | | |

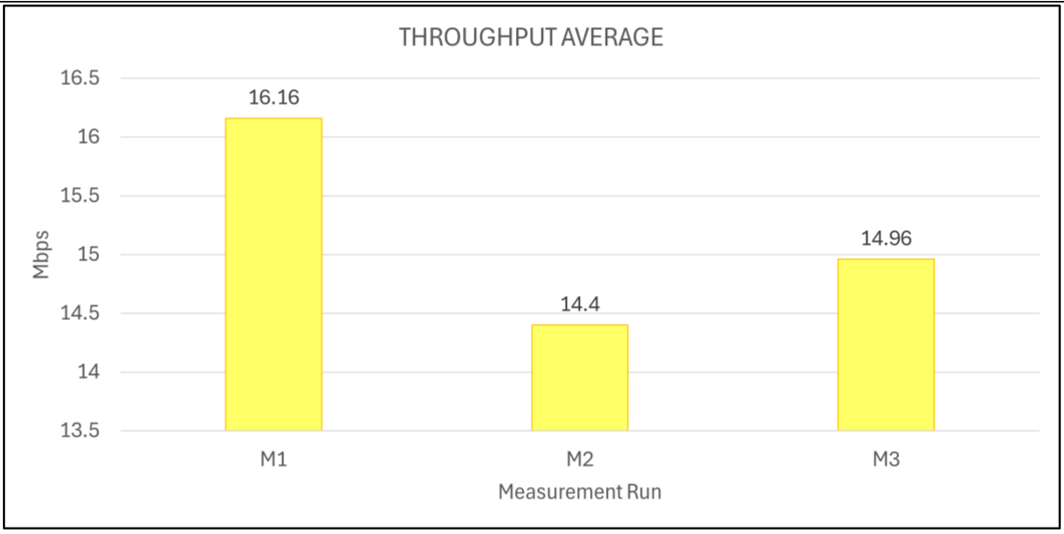



*Figure 29: Combined Throughput Traffic Averages.*

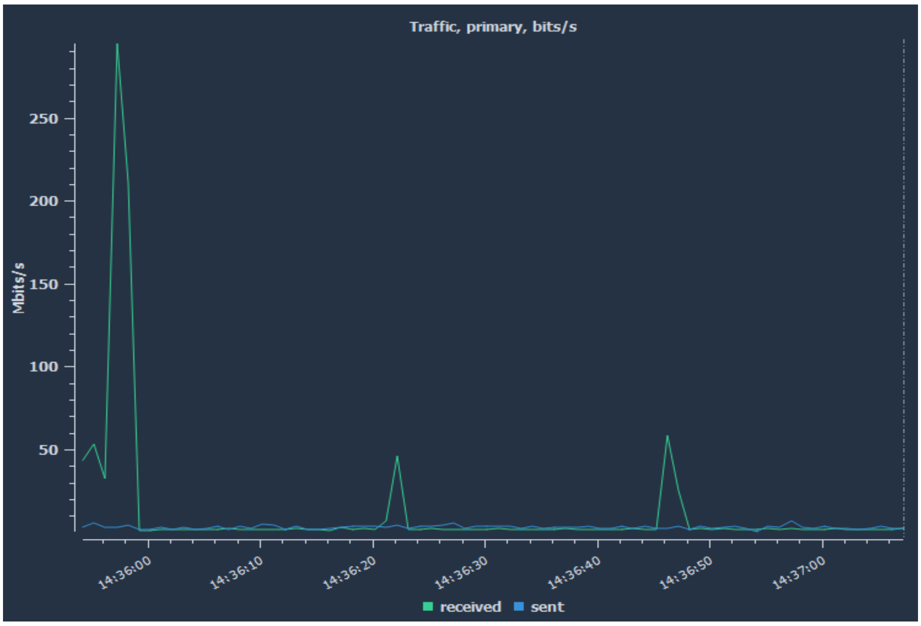



*Figure 30: Combined Throughput Traffic over time.*

The Figure 29 presents the averages of three test runs. These throughput values are taken when users connect to the virtual environment through VR headsets. The Figure 30 illustrates the traffic throughput over time. The combined data throughput includes camera stream, 3D virtual environment, audio, control, and UI data generated by the users when they connect with the virtual environment. Across these test runs, the throughput meets the below target KPI values, showing that the mentioned metrics generate traffic above the required thresholds:

- Camera Stream Data Rate is above 2 Mbps constantly.
- 3D Virtual Environment Audio and Control Data Rate is above 1 Mbps constantly.
- Virtual Browser UI Data Rate is also above 1 Mbps during the measurement run.

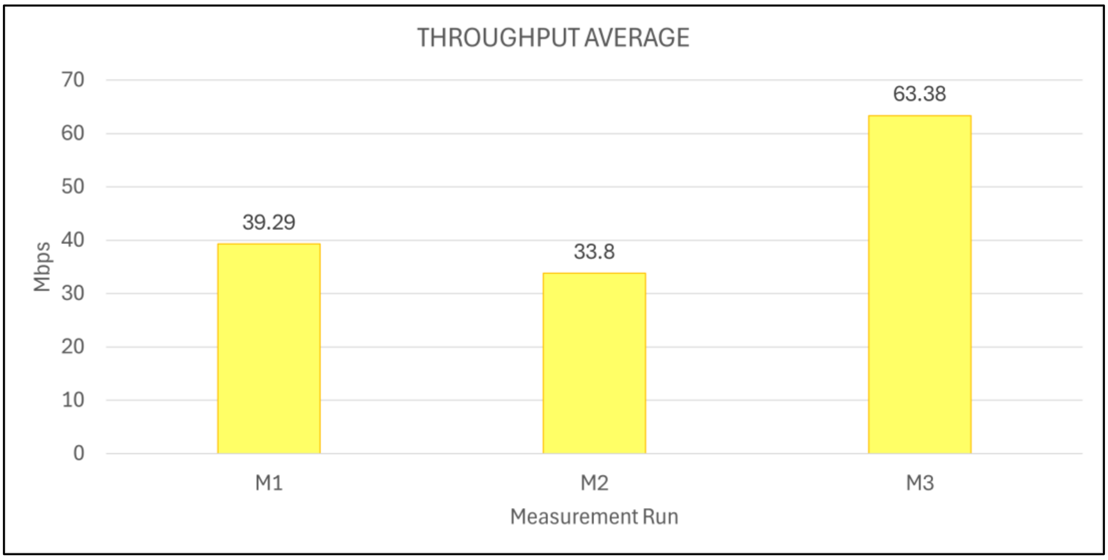



*Figure 31: Average Throughput of User Traffic during 3D DT Environment Utilization.*

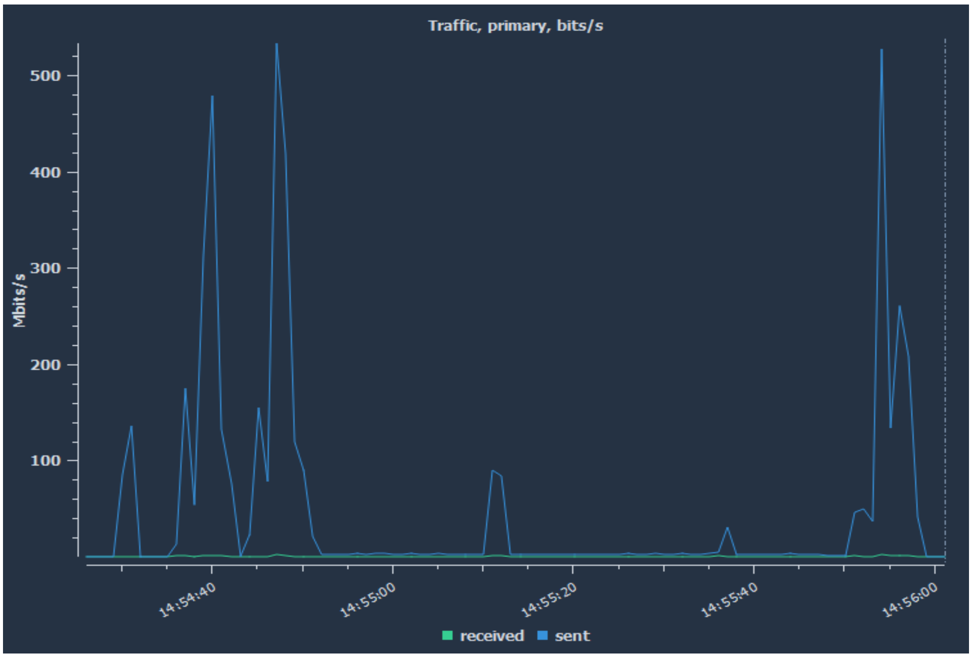



*Figure 32: Values over time of User Traffic Throughput during 3D DT Environment Utilization.*

The Figure 31 presents the average values throughput in Mbps during three test runs. The remote user and the instructor interact with objects, perform printing tasks and communicate with each other. The Figure 32 presents the generated traffic over time. One can see the generated traffic intended for the 3D DT Engine edge server hosted in 5GTN reaches maximum peak values of 500 Mbps during active use. The wireless links are sufficient to accommodate the intended traffic, on the other hand wired uplink towards the 5GTN edge server has 10GB capacity end-to-end, which confirms the suitability and satisfy target KPI values:

- Wireless link is able to accommodate up to 400 Mbps of traffic throughput generated by VR headsets during active use.
- Wired link towards 5GTN edge server has a 10 Gbps capacity (6.2.2.1) which is enough to accommodate traffic generated by VR headsets during active usage.

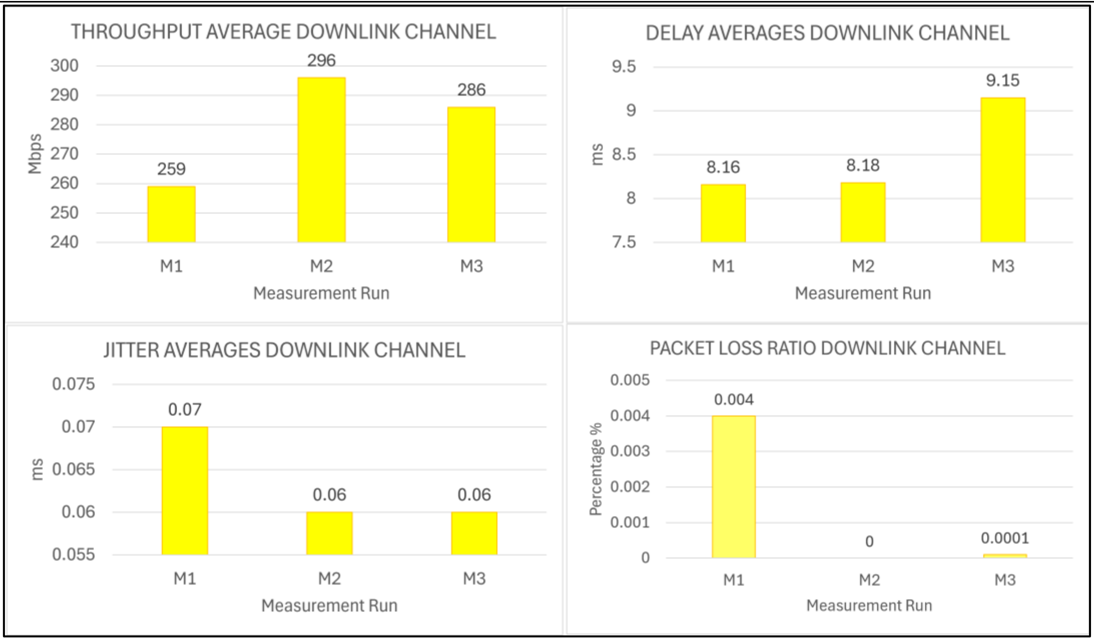



*Figure 33: Downlink Channel Average Values.*

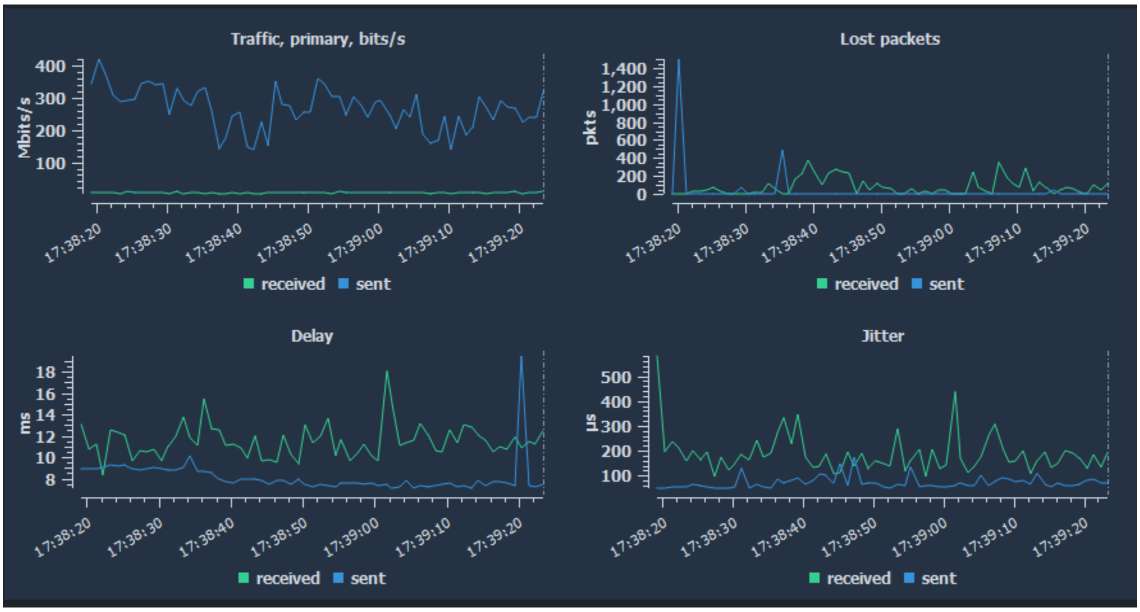



*Figure 34: Downlink Channel Traffic over time.*

The Figure 33 shows the average values of throughput in Mbps, delay and jitter in ms, and packet loss ratio percentage (%). The Figure 34 presents the variation of these parameters over time. The blue line indicates sent traffic utilizing the downlink channel. It can be observed the downlink channel is able to accommodate peak value around 400 Mbps as required, while delay and jitter remain under the required threshold. Moreover, packet loss ratio is minimal across the set of test runs. The measurement clearly demonstrates that target KPI values are met:

- Downlink Channel is able to serve 400 Mbps traffic.
- The delay and jitter values for downlink channel during the whole measurement stays below 10 ms with only one spike observed above the threshold.
- The packet reliability is over 99.9% for the generated traffic over test runs with few lost packets.

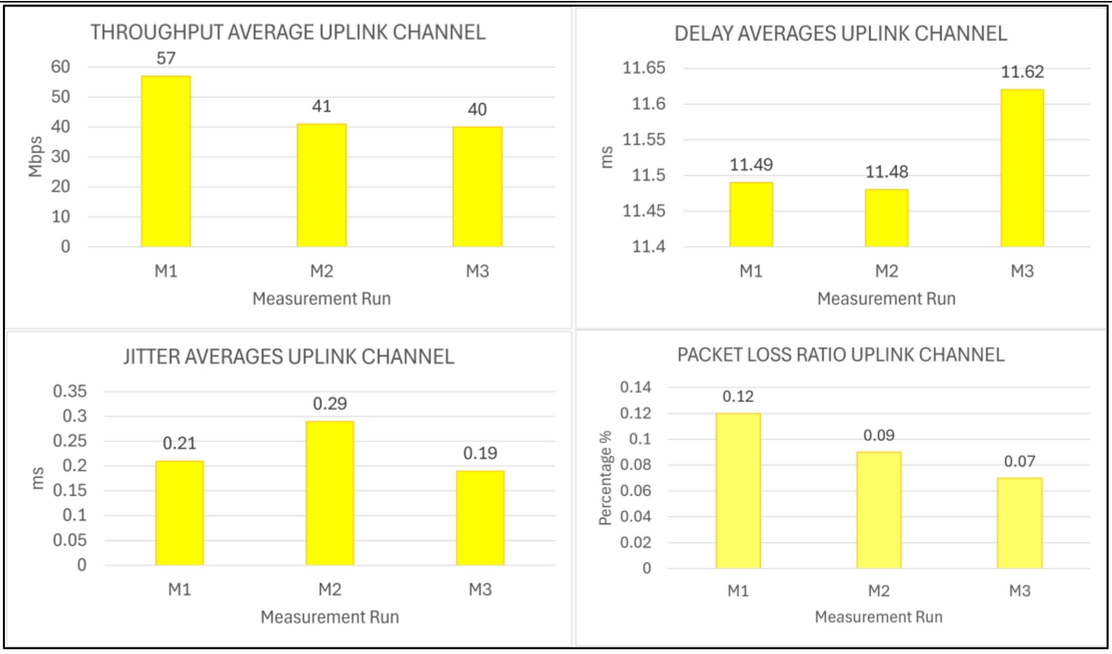



*Figure 35: Uplink Channel Average Values.*

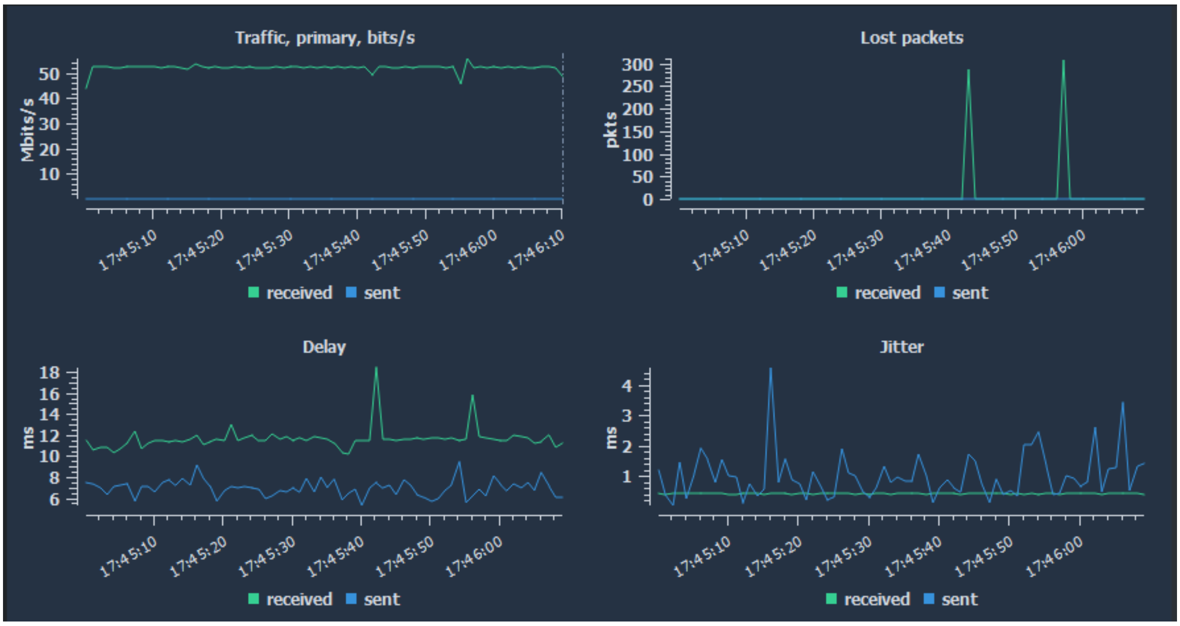



*Figure 36: Uplink Channel Traffic over time.*

The Figure 35 shows the average values of throughput in Mbps, delay and jitter in ms, and packet loss ratio percentage (%) for the uplink channel. The Figure 36 illustrates the variation of the traffic over time. It can be observed that uplink channel is also able to accommodate required peak value around 50 Mbps indicated by green line, while delay and jitter remain under the required threshold. Furthermore, the first test run showed a packet loss ratio of about 0.12%, whereas the average across all three runs is 0.093%, indicating minimal loss for the uplink channel with only occasional minor spikes. The measurement conforms with the target KPI values:

- Uplink Channel is able to serve 50 Mbps traffic.
- The delay and jitter values for uplink channel during the whole measurement stays below 14 ms threshold.

- The packet reliability is also 99% for the generated traffic with few lost packets.

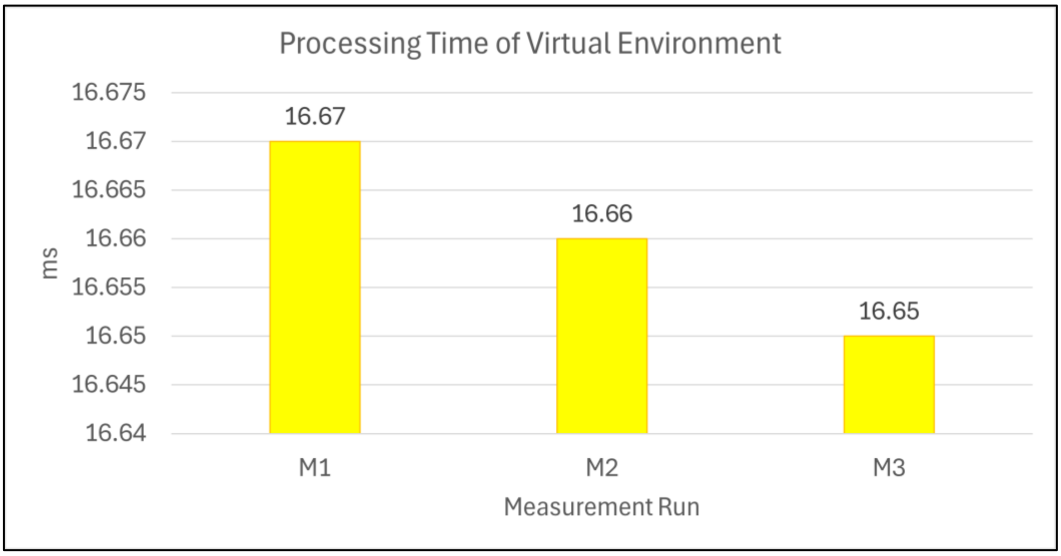



*Figure 37: Processing Time Average.*

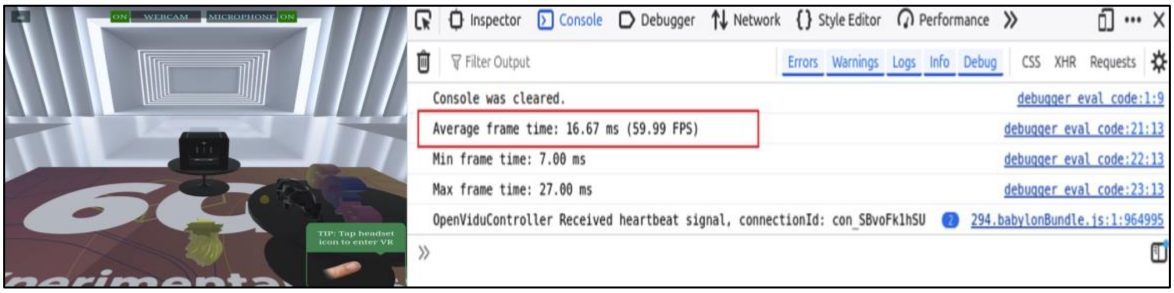



*Figure 38: Processing Time of Virtual Environment.*

The Figure 37 presents the average values of processing time of the 3D DT virtual environment over three test runs. The Figure 38 shows the value from the virtual environment application web page. It can be observed that the VR application satisfies the below target KPI value for processing time.

- Processing time of 3D DT edge application server is 16.67 ms (60 frames per second).

### 7.1.5 Operational and Environmental KPI Validation Test Case Results

| UOULU | Operational and Environmental KPI Validation Test Case |
|---|---|
| **Test Case Name** | Operational and Environmental KPI Validation Test Case (Test ID: NN1.5) |
| **Test Execution Date** | 23-26/06/2025 |
| **Test Executed By** | UOULU |
| **Number of repetitions** | 3 |

<table>
<tr><td>Test's comments</td><td colspan="3">Tests were performed physically in 5GTN laboratory with fully operational 3D DT system.</td></tr>
<tr><td colspan="4">Verification Points (VP)</td></tr>
<tr><td>Checkpoint ID</td><td colspan="3">Description of Validation Criteria for checkpoint</td></tr>
<tr><td>ID #1</td><td colspan="3">Operating under low mobility conditions, delay and jitter values of the traffic should be within 10 ms downlink and 14 ms uplink, respectively, with no session interruptions.</td></tr>
<tr><td>ID #2</td><td colspan="3">Operating under increased user density, delay and jitter values of 10 ms and 14 ms should be maintained during the most of measurements, with occasional expected spikes and no session interruptions or degraded service.</td></tr>
<tr><td>ID #3</td><td colspan="3">Energy efficiency of the system is evaluated in idle and active processing states, having nominal usage in both states.</td></tr>
<tr><td>Test Validation Conditions</td><td colspan="3">Tests were performed with VR headsets, and all checkpoints for each component's validation were checked and measurement data values are collected.</td></tr>
<tr><td>Test results</td><td>Test run</td><td>Description</td><td>Result</td></tr>
<tr><td>ID #1</td><td>1-3</td><td>Figure 39 and Figure 40</td><td>Pass</td></tr>
<tr><td>ID #2</td><td>1-3</td><td>Figure 41 and Figure 42</td><td>Pass</td></tr>
<tr><td>ID #3</td><td>1</td><td>Figure 43, Figure 44 and Figure 45</td><td>Pass</td></tr>
<tr><td colspan="4">Results Diagrams</td></tr>
</table>


*Figure 39: Average Values under Low Mobility usage.*

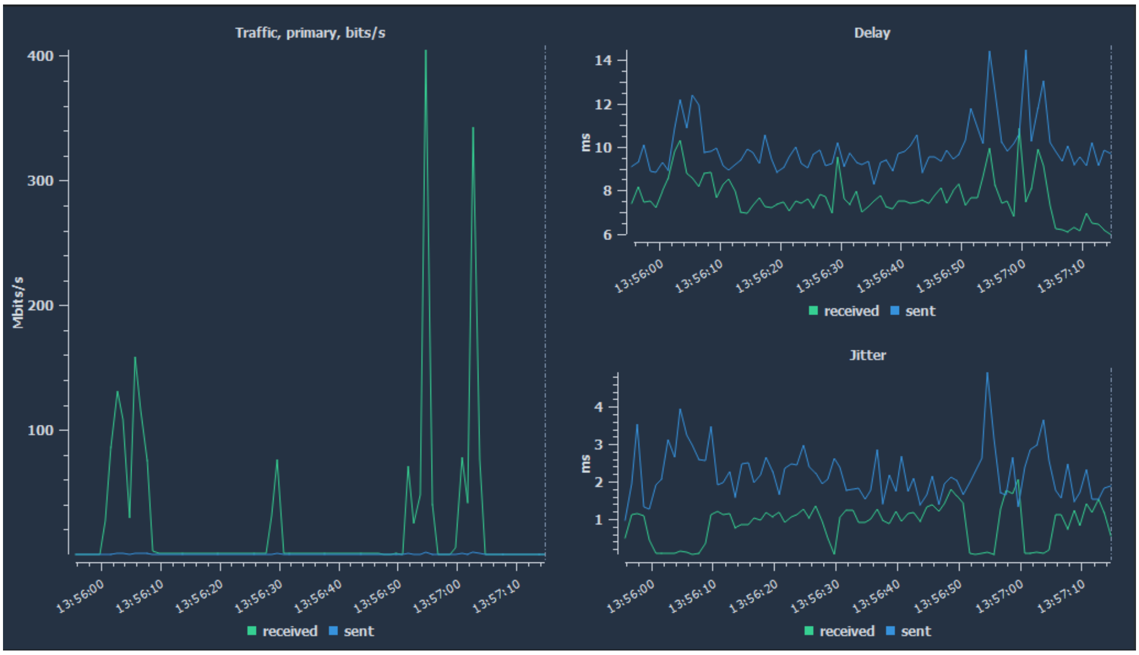



*Figure 40: Low Mobility Usage over time.*

The Figure 39 presents the average values of throughput in Mbps, and delay and jitter in ms for the generated traffic, when indoor users are under low mobile conditions. Figure 40 shows the variation of these parameters over time. It is observed that the generated downlink traffic, represented by the green line, reaches several peaks. However, the delay and jitter remain as low as in other test cases, thus fulfilling the KPI requirements as below:

- Operating under low indoor mobile conditions, the generated throughput traffic should have low delay and jitter values with no session interruptions.

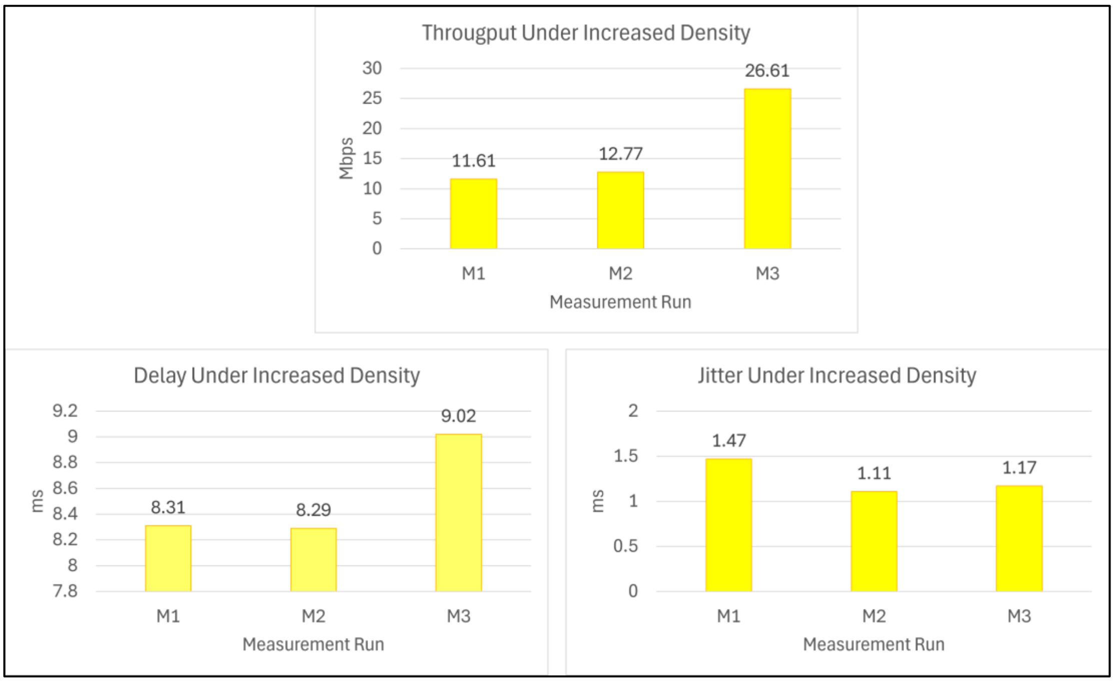



*Figure 41: Average Values of Increased User Density.*

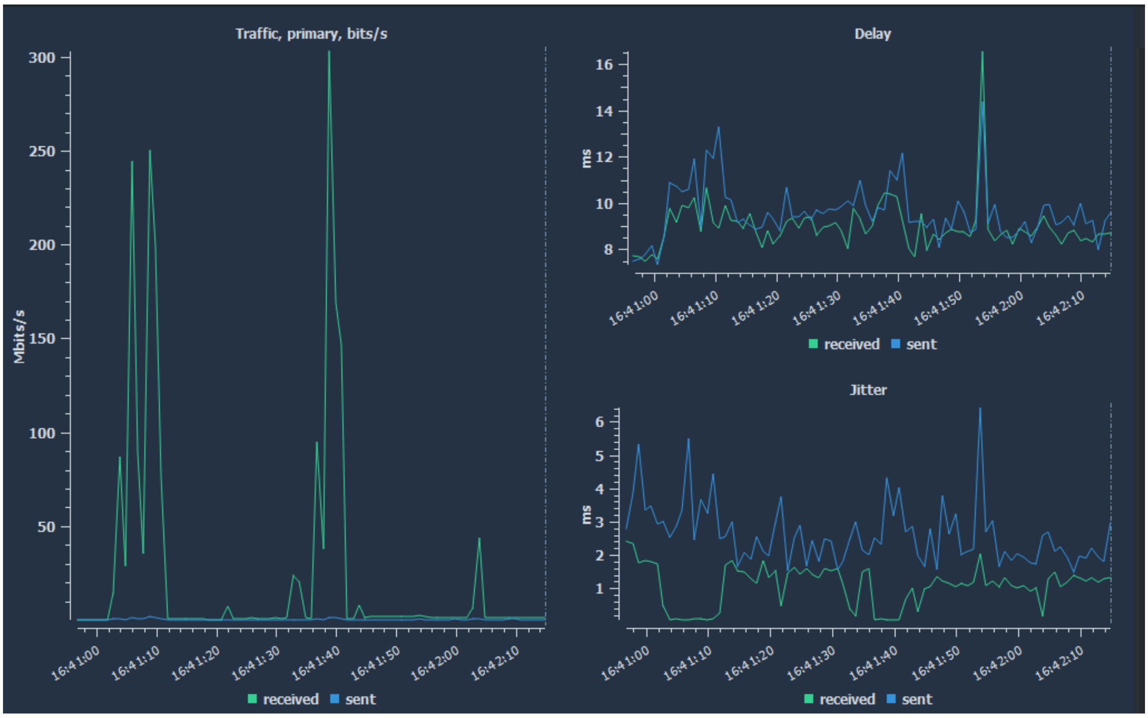



*Figure 42: Increased User Density over time.*

The Figure 41 presents the average values for throughput in Mbps, and delay and jitter in ms under increased user density. Moreover, the Figure 42 depicts the variation of these parameters over time, with green line depicting the generated downlink traffic. It is observed that, with increased user density, the delay and jitter values remain low as observed in the other test case measurements. However, one spike for delay is observed throughout the measurement but otherwise the values are low. This fulfill the KPI requirements as below:

- Operation under increased user density 10/m$^2$, the generated throughput should have low delay and jitter with no severe degradation observed in service.

The Faladin edge application server (game engine) for the 3D DT system is being hosted on a VM in the 5GTN. The 3D printer is controlled and managed via this server as well. For this test, the consumption of the edge application server is monitored in the idle and processing states when users are utilizing the 3D DT system for printing process.

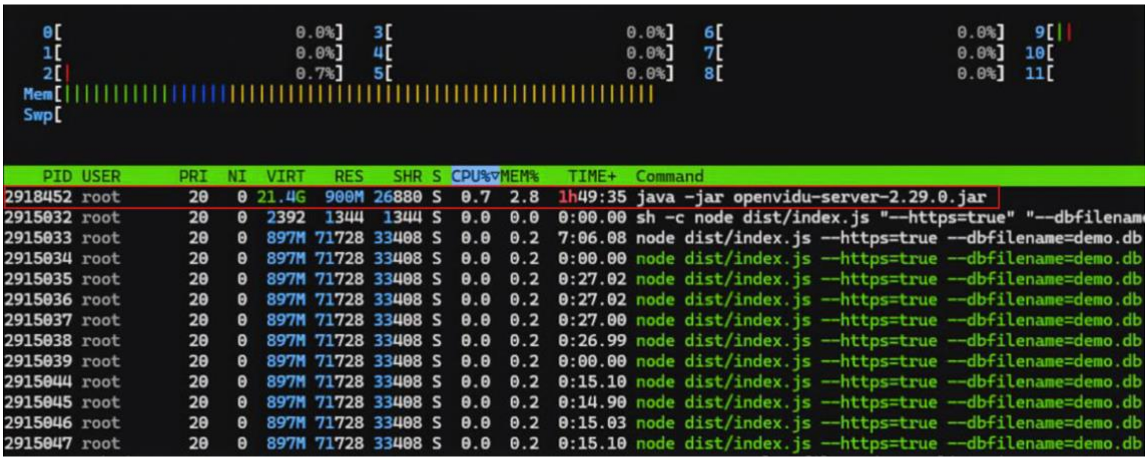



*Figure 43: 3D DT game engine system performance in idle state.*

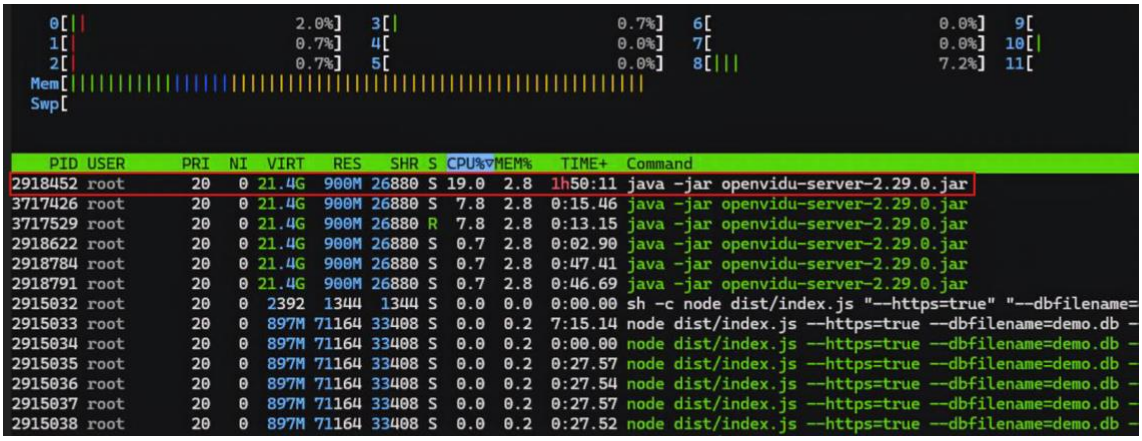



*Figure 44: 3D DT game engine system performance in active state.*

The Figure 43 represents the CPU usage, memory, and load averages of the edge application server in the idle state. The edge application server runs a Java-based archive file (.JAR) containing an *Open-Vidu* Web Real-Time Communication (WebRTC) platform, which enables real-time video streaming, audio, recording and signalling between VR participants. The CPU usage is around 0.7% in the idle state, memory usage is approximately 2.6% per thread on a 24-thread system which indicates that server is very lightly loaded.

The Figure 44 represents the CPU usage, memory, and load averages of the edge application server during active processing. The *Open-Vidu* platform is actively running and interacting with VR headset client sessions. CPU usage increases to around 19%, and memory usage rises slightly to 2.8% per thread. The parallel CPU utilization indicates efficient use of system resources. Furthermore, under active session load, the edge server delivers required performance for supporting multiple users in the VR environment users while maintaining low resource consumption hence low energy usage.

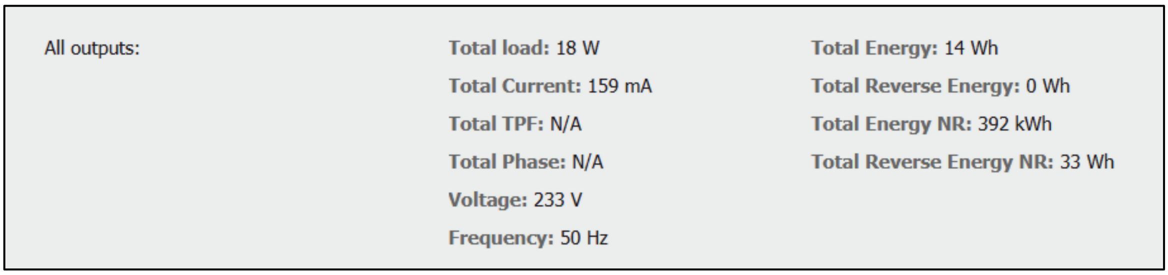



*Figure 45: Energy Consumption Output.*

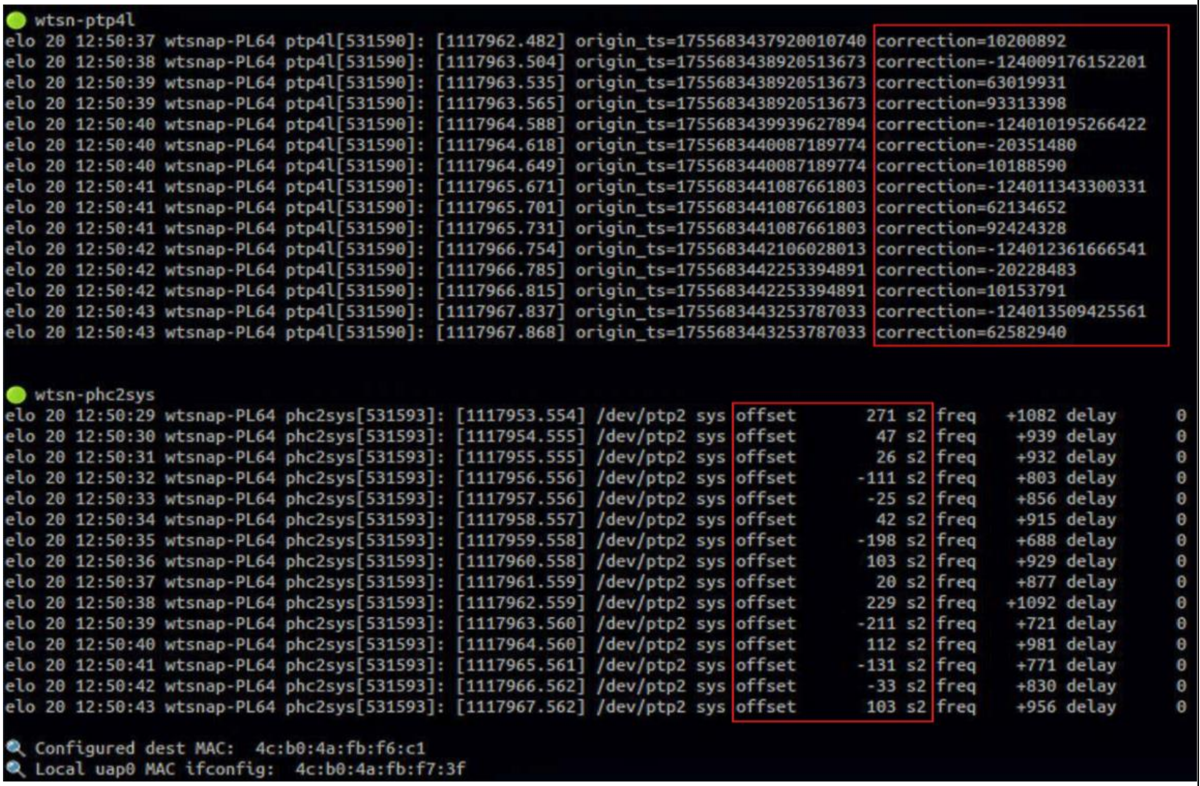
The Figure 45 shows the output taken from PowerBox4KF smart power strip to check the energy consumption of the game engine during one-hour active virtual environment processing, which further justifies the target KPI for energy efficiency of the system as per below target:

- Energy efficiency of the system in idle and active processing states has nominal usage.

### 7.1.6 Wi-Fi TSN KPI Validation for Robot Arm Integration Test Case Results

| UOULU | Wi-Fi TSN KPI Validation for Robot Arm Integration Test Case |
|---|---|
| **Test Case Name** | Wi-Fi TSN KPI Validation for Robot Arm Integration Test Case (Test ID: NN1.6) |
| **Test Execution Date** | 1-20/08/2025 |
| **Test Executed By** | UOULU |
| **Number of repetitions** | 3 |
| **Test's comments** | Tests were performed physically in 5GTN laboratory with fully operational Wi-Fi TSN system. |
| **Verification Points (VP)** | |
| **Checkpoint ID** | **Description of Validation Criteria for checkpoint** |
| ID #1 | Time synchronization accuracy between the Wi-Fi TSN AP and STA clocks during the operation is under 10 µs. |
| ID #2 | Latency bounds generated by the robotic arm for 200 ms cyclic signals lie in between 1-10 ms. |
| ID #3 | Video payload from the installed camera is around 1 MBps (30fps). |

| **Test Validation Conditions** | Tests were performed with a set of VR headsets and an operational Wi-Fi TSN system operating the robot arm via virtual environment, all checkpoints are verified, and measurement data values are collected. | | |
|---|---|---|---|
| **Test results** | **Test run** | **Description** | **Result** |
| ID #1 | 1-3 | Figure 46 and Figure 47 | Pass |
| ID #2 | 1-3 | Figure 48 and Figure 49 | Pass |
| ID #3 | 1 | Figure 50 and Figure 51 | Pass |
| **Results Diagrams** | | | |



```
wtsn-ptp4l
elo 20 12:50:37 wtsnap-PL64 ptp4l[531590]: [1117962.482] origin_ts=1755683437920010740 correction=10200892
elo 20 12:50:38 wtsnap-PL64 ptp4l[531590]: [1117963.504] origin_ts=1755683438920513673 correction=-124009176152201
elo 20 12:50:39 wtsnap-PL64 ptp4l[531590]: [1117963.535] origin_ts=1755683438920513673 correction=63019931
elo 20 12:50:39 wtsnap-PL64 ptp4l[531590]: [1117963.565] origin_ts=1755683438920513673 correction=93313398
elo 20 12:50:40 wtsnap-PL64 ptp4l[531590]: [1117964.588] origin_ts=1755683439939627894 correction=-124010195266422
elo 20 12:50:40 wtsnap-PL64 ptp4l[531590]: [1117964.618] origin_ts=1755683440087189774 correction=-20351480
elo 20 12:50:40 wtsnap-PL64 ptp4l[531590]: [1117964.649] origin_ts=1755683440087189774 correction=10188590
elo 20 12:50:41 wtsnap-PL64 ptp4l[531590]: [1117965.671] origin_ts=1755683441087661803 correction=-124011343300331
elo 20 12:50:41 wtsnap-PL64 ptp4l[531590]: [1117965.701] origin_ts=1755683441087661803 correction=62134652
elo 20 12:50:41 wtsnap-PL64 ptp4l[531590]: [1117965.731] origin_ts=1755683441087661803 correction=92424328
elo 20 12:50:42 wtsnap-PL64 ptp4l[531590]: [1117966.754] origin_ts=1755683442106028013 correction=-124012361666541
elo 20 12:50:42 wtsnap-PL64 ptp4l[531590]: [1117966.785] origin_ts=1755683442253394891 correction=-20228483
elo 20 12:50:42 wtsnap-PL64 ptp4l[531590]: [1117966.815] origin_ts=1755683442253394891 correction=10153791
elo 20 12:50:43 wtsnap-PL64 ptp4l[531590]: [1117967.837] origin_ts=1755683443253787033 correction=-124013509425561
elo 20 12:50:43 wtsnap-PL64 ptp4l[531590]: [1117967.868] origin_ts=1755683443253787033 correction=62582940

wtsn-phc2sys
elo 20 12:50:29 wtsnap-PL64 phc2sys[531593]: [1117953.554] /dev/ptp2 sys offset       271 s2 freq  +1082 delay      0
elo 20 12:50:30 wtsnap-PL64 phc2sys[531593]: [1117954.555] /dev/ptp2 sys offset        47 s2 freq   +939 delay      0
elo 20 12:50:31 wtsnap-PL64 phc2sys[531593]: [1117955.555] /dev/ptp2 sys offset        26 s2 freq   +932 delay      0
elo 20 12:50:32 wtsnap-PL64 phc2sys[531593]: [1117956.556] /dev/ptp2 sys offset      -111 s2 freq   +803 delay      0
elo 20 12:50:33 wtsnap-PL64 phc2sys[531593]: [1117957.556] /dev/ptp2 sys offset       -25 s2 freq   +856 delay      0
elo 20 12:50:34 wtsnap-PL64 phc2sys[531593]: [1117958.557] /dev/ptp2 sys offset        42 s2 freq   +915 delay      0
elo 20 12:50:35 wtsnap-PL64 phc2sys[531593]: [1117959.558] /dev/ptp2 sys offset      -198 s2 freq   +688 delay      0
elo 20 12:50:36 wtsnap-PL64 phc2sys[531593]: [1117960.558] /dev/ptp2 sys offset       103 s2 freq   +929 delay      0
elo 20 12:50:37 wtsnap-PL64 phc2sys[531593]: [1117961.559] /dev/ptp2 sys offset        20 s2 freq   +877 delay      0
elo 20 12:50:38 wtsnap-PL64 phc2sys[531593]: [1117962.559] /dev/ptp2 sys offset       229 s2 freq  +1092 delay      0
elo 20 12:50:39 wtsnap-PL64 phc2sys[531593]: [1117963.560] /dev/ptp2 sys offset      -211 s2 freq   +721 delay      0
elo 20 12:50:40 wtsnap-PL64 phc2sys[531593]: [1117964.560] /dev/ptp2 sys offset       112 s2 freq   +981 delay      0
elo 20 12:50:41 wtsnap-PL64 phc2sys[531593]: [1117965.561] /dev/ptp2 sys offset      -131 s2 freq   +771 delay      0
elo 20 12:50:42 wtsnap-PL64 phc2sys[531593]: [1117966.562] /dev/ptp2 sys offset       -33 s2 freq   +830 delay      0
elo 20 12:50:43 wtsnap-PL64 phc2sys[531593]: [1117967.562] /dev/ptp2 sys offset       103 s2 freq   +956 delay      0

Configured dest MAC:  4c:b0:4a:fb:f6:c1
Local uap0 MAC ifconfig:  4c:b0:4a:fb:f7:3f
```

*Figure 46: Time Synchronization Logs Wi-Fi AP.*

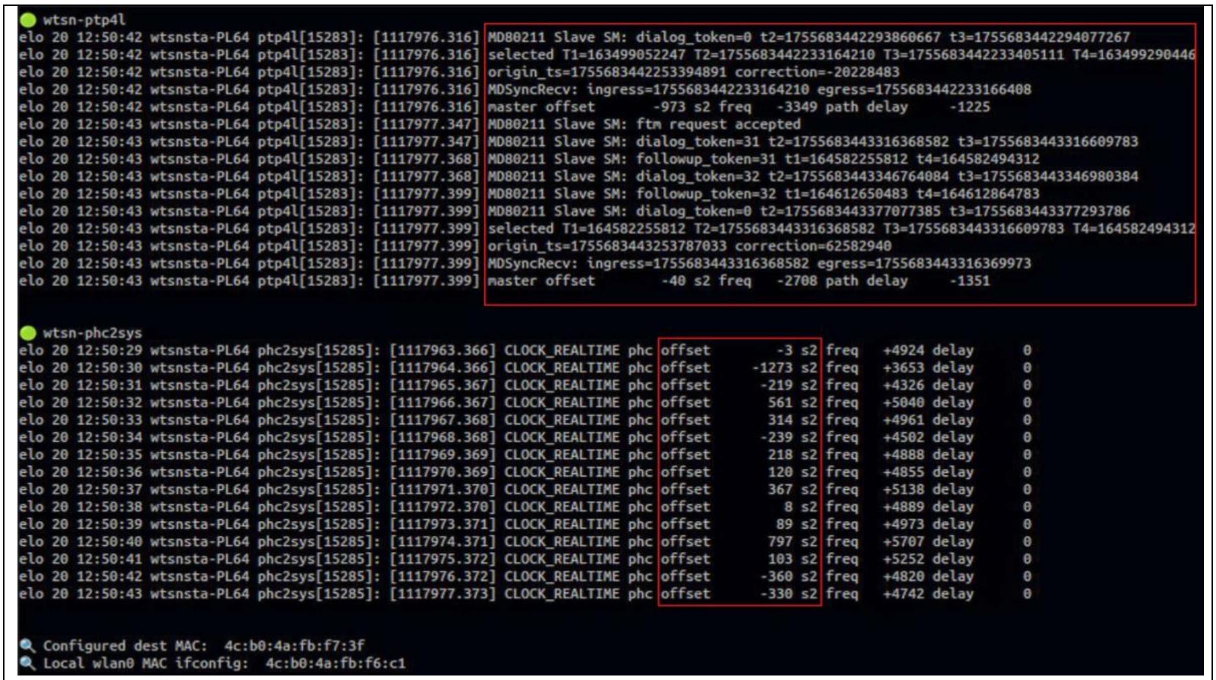



*Figure 47: Time Synchronization Logs Wi-Fi Station.*

Figure 46 shows the log output for PTP for Linux (*ptp4l*) and PTP hardware clock (*phc2sys*) from Wi-Fi NUC AP. A similar log output is shown in Figure 47 from Wi-Fi NUC STA. These logs values are taken when robot arm is connected and controlled by user via virtual environment. The AP is acting as Grandmaster source, while the STA is slave. In *ptp4l* logs the master offset values which show current offset from slave clock relative to master is in nanoseconds. Similarly, *phc2sys* logs show the difference between the system clock and physical hardware clock.

It is observed that the Wi-Fi AP side correction values are in tens to hundreds of nanoseconds and Wi-Fi STA offset is reported in hundreds of nanoseconds as well, meaning that STA is staying within few hundred nanoseconds of the AP. The offsets are consistently in hundreds of nanoseconds, well below the target KPI threshold value, thereby fulfilling the requirement:

- Time synchronization accuracy between the Wi-Fi TSN AP and STA is below 10 µs.

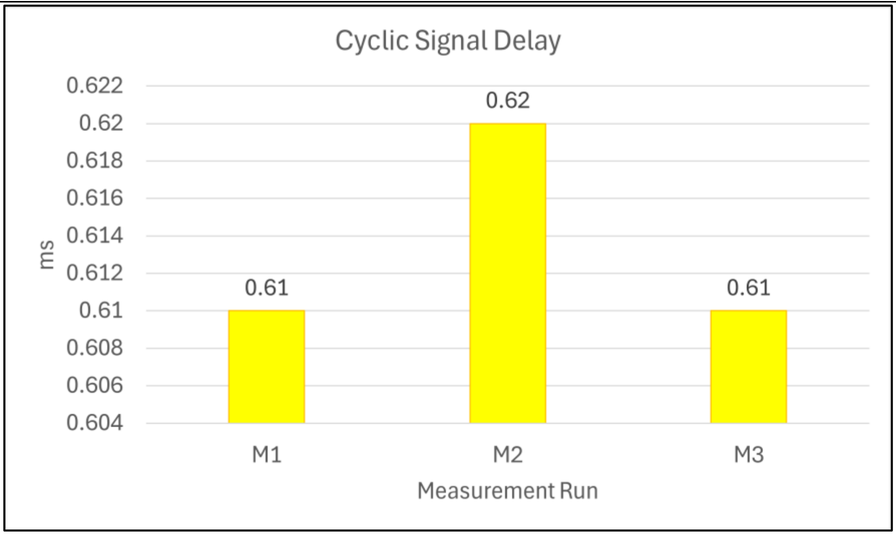



*Figure 48: Average Values for Cyclic Signal Delay.*


*Figure 49: Values for Cyclic Signal over time.*

The Figure 48 presents the average values for delay parameters in ms for continuous cyclic signal generated by the robot arm. Moreover, the Figure 49 shows the graph of these metrics. It can be observed that the continuous cyclic signal delay and jitter values remain in microseconds, which is well below the required KPI threshold hence the requirement is fulfilled:

- Latency bounds generated by 200 ms robotic arm cyclic signal should be in between 1-10 ms.

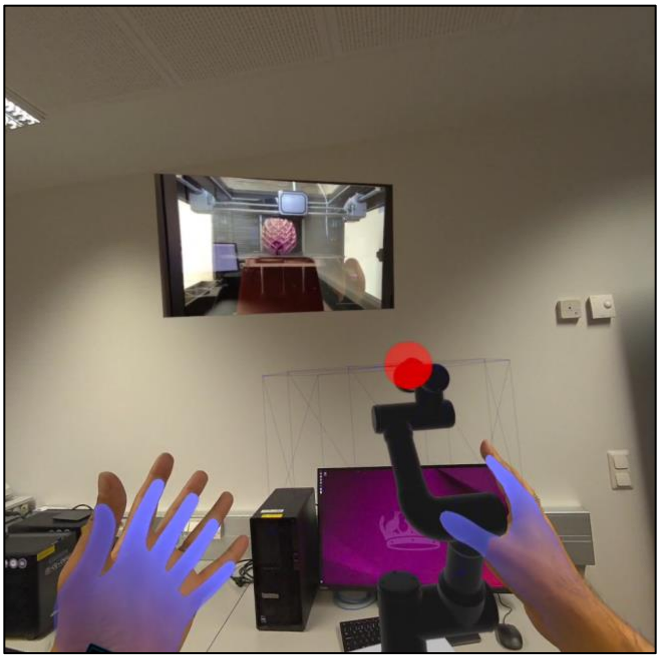


*Figure 50: Video image from installed camera.*


*Figure 51: Data traffic of installed camera video payload over time.*

Figure 50 shows the image taken from the VR environment for the installed video camera. Moreover, Figure 51 shows the data traffic due to the generated video payload. It can be seen traffic around 1 MBps (megabyte per second) is generated by the camera, while and delay and jitter values are below 10 ms. This confirms the below required KPIs:

- Video payload of the installed camera is around 1 MBps (30fps).

### 7.1.7 End-to-End System Validation Utilizing Trial Controller Test Case Results

| **UOULU** | **End-to-End System Validation Utilizing Trial Controller Test Case** | | |
|---|---|---|---|
| **Test Case Name** | End-to-End System Validation Utilizing Trial Controller Test Case (Test ID: NN1.7) | | |
| **Test Execution Date** | 10-13/10/2025 | | |
| **Test Executed By** | UOULU | | |
| **Number of repetitions** | 1 | | |
| **Test's comments** | Tests were performed physically in 5GTN laboratory with fully operational 3D DT system. | | |
| **Verification Points (VP)** | | | |
| **Checkpoint ID** | **Description of Validation Criteria for checkpoint** | | |
| ID #1 | Unified web portal is accessible. | | |
| ID #2 | North Node web portal is accessible. | | |
| ID #3 | Trial is created at UOULU (North Node) site. | | |
| ID #4 | Experiment under trial is run for two network slices to support 3D DT users. | | |
| ID #5 | Experiment results are extracted and visualized at the web portal dashboard. | | |
| **Test Validation Conditions** | Tests are performed with two VR headsets connected with separate slices configured by the trial controller. All checkpoints for each component's validation were checked. | | |
| **Test results** | **Test run** | **Description** | **Result** |
| ID #1 | 1 | Unified Web portal is accessible. | Pass |
| ID #2 | 1 | North Node web portal is accessible. | Pass |
| ID #3 | 1 | Figure 52 | Pass |
| ID #4 | 1 | Figure 53 | Pass |
| ID #5 | 1 | Figure 54 and Figure 55 | Pass |
| **Results Diagrams** | | | |

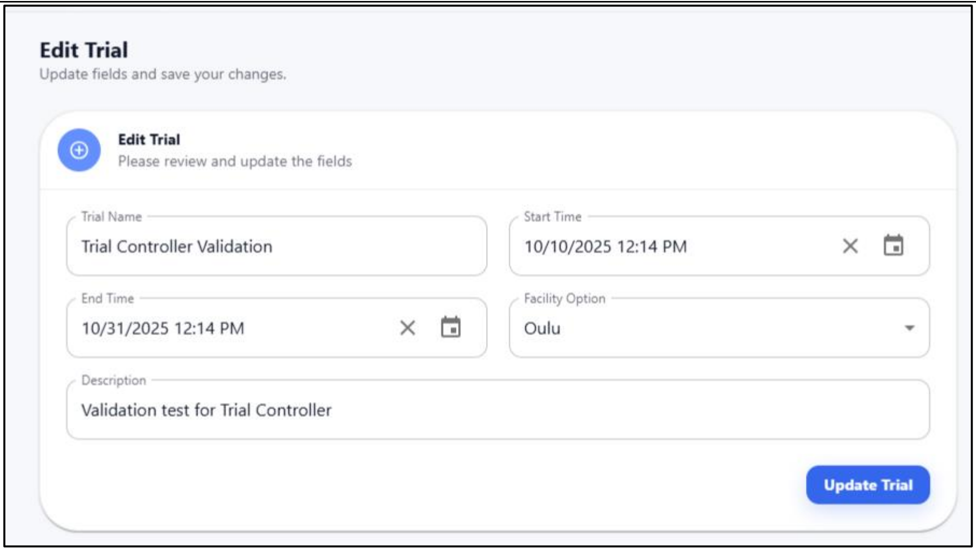



*Figure 52: Trial Creation.*

The Figure 52 shows the trial creation at unified web portal, where start and end times are selected, description for the trial validation is added, and Oulu facility is selected.

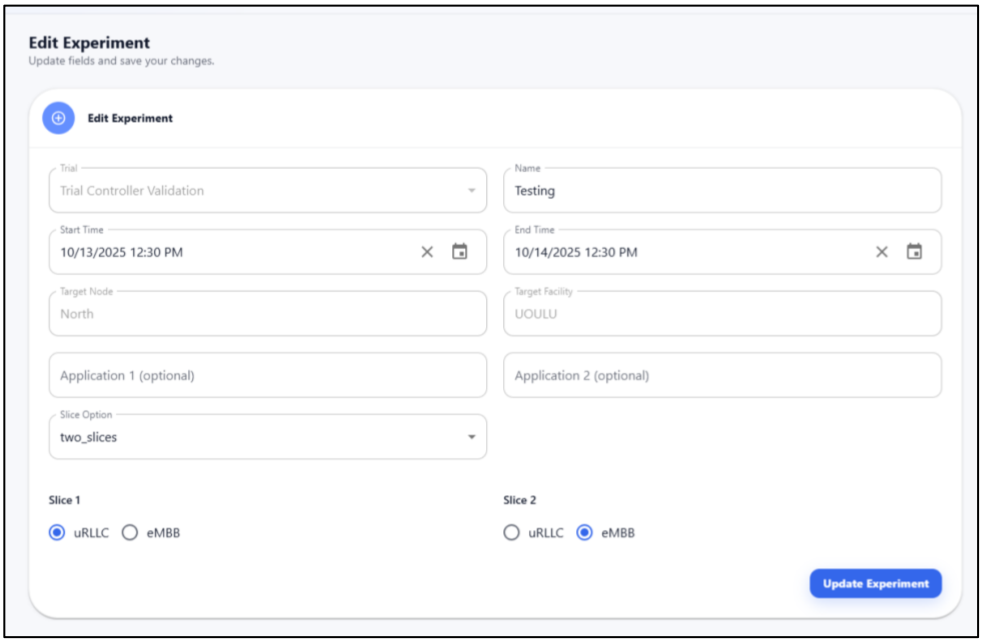



*Figure 53: Experiment Creation for two slices for VR users.*

The Figure 53 shows the experiment creation at North Node web portal under the created trial, where the two slice options is selected for each VR headset user.

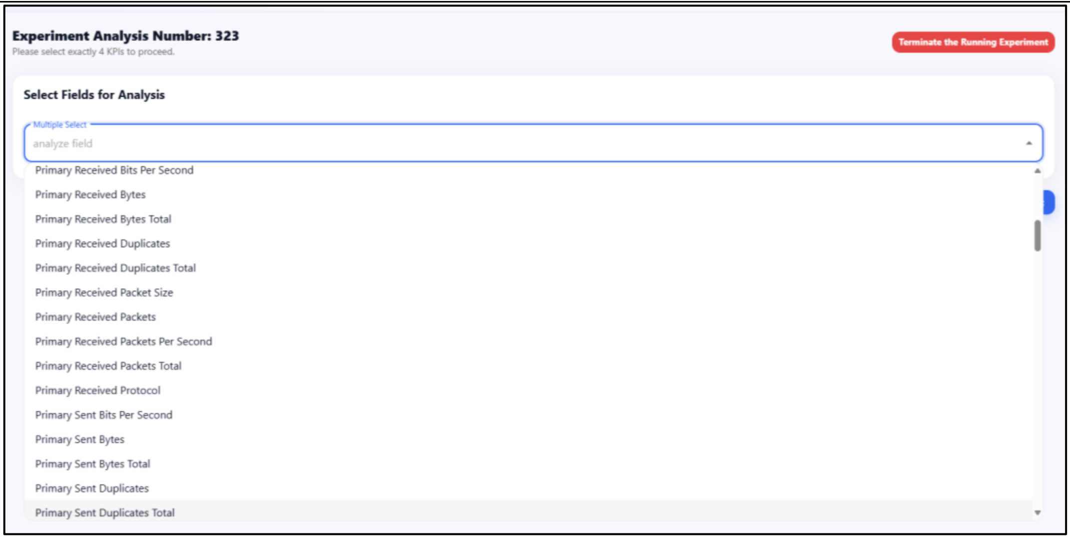



*Figure 54: Experiment Analysis field selection for measurement visualization.*

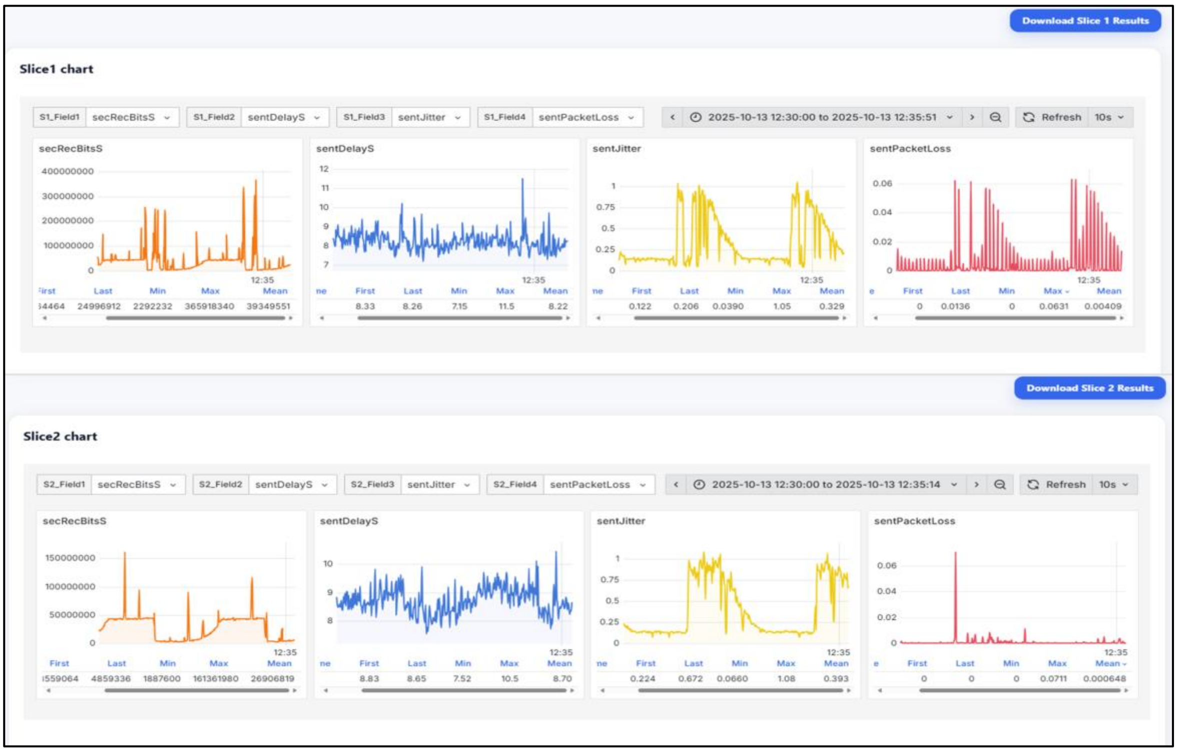



*Figure 55: Measurements visualization on the web portal.*

The Figure 54 and the Figure 55 show the extracted measurement visualizations on the web portal dashboard, after the slices were created for the VR headsets. The measurement results, such as throughput, delay, jitter, and packet loss percentage for downlink channel, are extracted upon selection. The results are separately shown for each configured slice, with minimal delay and jitter values observed.

## 7.2 PRESENTATION OF KVI RESULTS

A demonstration of the 3D DT system was conducted during the Researcher's Night at UOulu. Responses were collected using the questionnaire provided in Annex B, after the demonstration was explained to the audience and they had a possibility to test out the system.

*Figure 56: Demonstration at UOulu during the Researcher's Night.*

Figure 56 shows that many people with diverse backgrounds participated in the demonstration, their responses were collected, and the data was gathered and analysed accordingly. Overall, 94 voluntary responses, either in digital or paper form, were gathered from the participants during the four hours dedicated for the event. The respondents comprised 62 Males, 29 Females, and 3 participants who identified in Other gender group. The questionnaire did not include any aspects leading to GDPR issues, as the responses were collected anonymously and they cannot be traced to any individual people.

Pertaining to the demographics and the background of the audience, the results are summarized, and trends are analysed based on gender and age groups of the participants. The most active participation was observed among the age groups of between 20 and 40 years. Moreover, the audience's familiarity with the immersive technologies such as VR, XR and AR, as well as wireless network technologies like 5G and 6G, is considered.

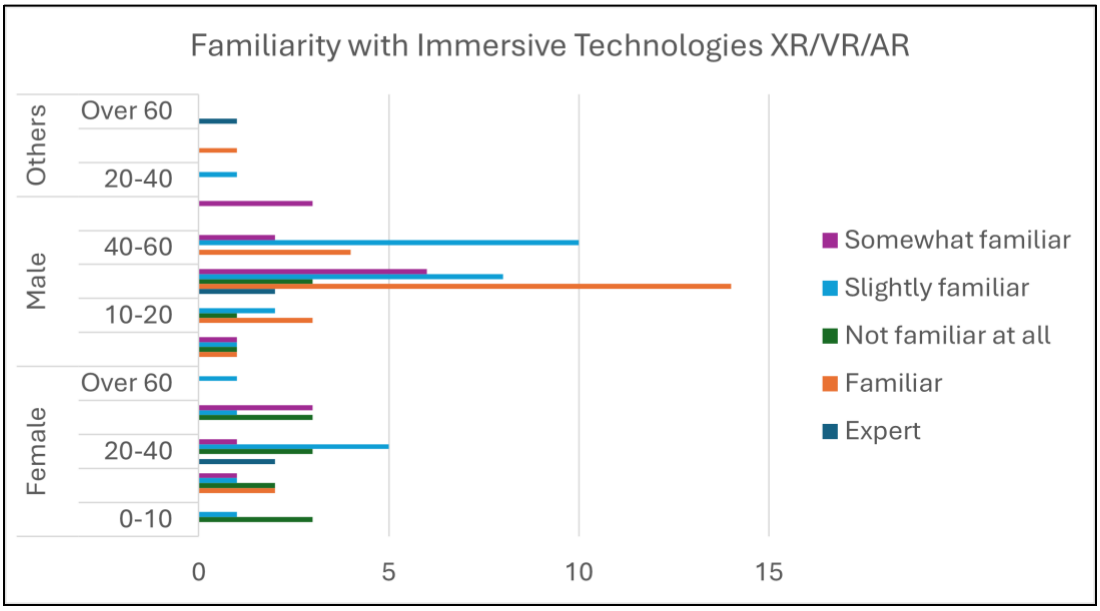



*Figure 57: Trends in audience's familiarity with immersive technologies.*

Figure 57 shows the trends in audience's familiarity across different genders and age groups with immersive technologies. It is observed males across all age groups generally claim somewhat familiar, while females generally claim slightly familiar on the technologies. Participants identifying with other gender groups are observed to claim at least familiarity with the technologies.

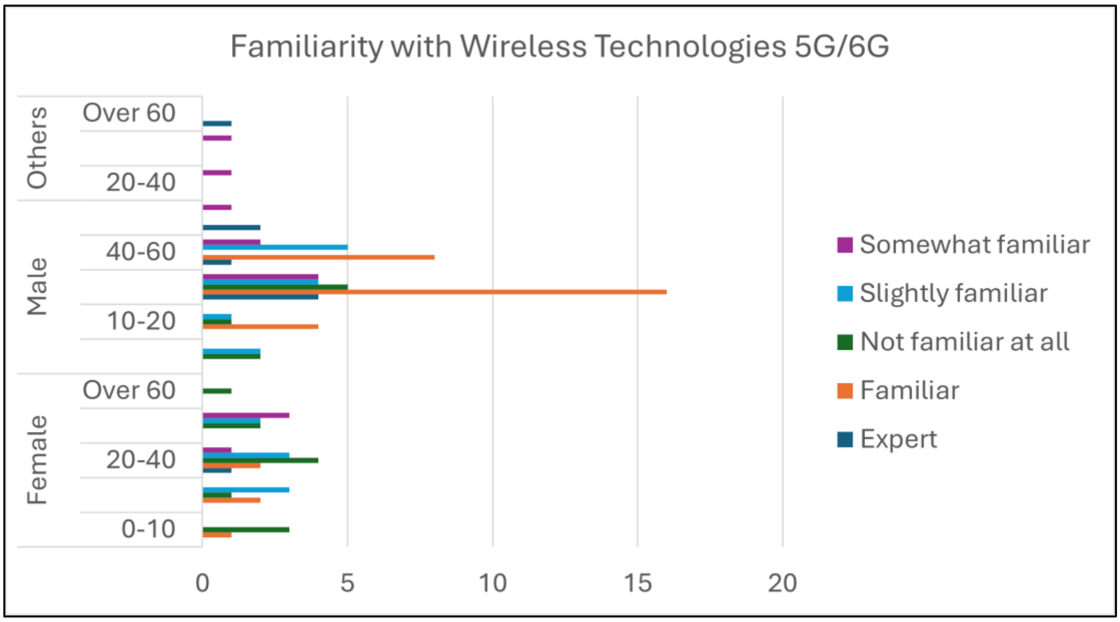



*Figure 58: Trends for the familiarity with wireless technologies.*

Figure 58 presents the trends for the familiarity of the audience with wireless technologies, with males in general claiming familiarity across all age groups and females' claims trending towards to slightly familiar. Participants identifying with the other gender group claim at least somewhat familiar in this case.

### 7.2.1 Observed Patterns in KVI Categories

The following patterns were extracted and observed across each KVI category in the questionnaire, where each category consisted of multiple questions. The following figures only depict the responses over the entire group of participants, for simplicity of observation, while the analysis also covers all the gender groups. The responses based on age group division are omitted from the analysis below.

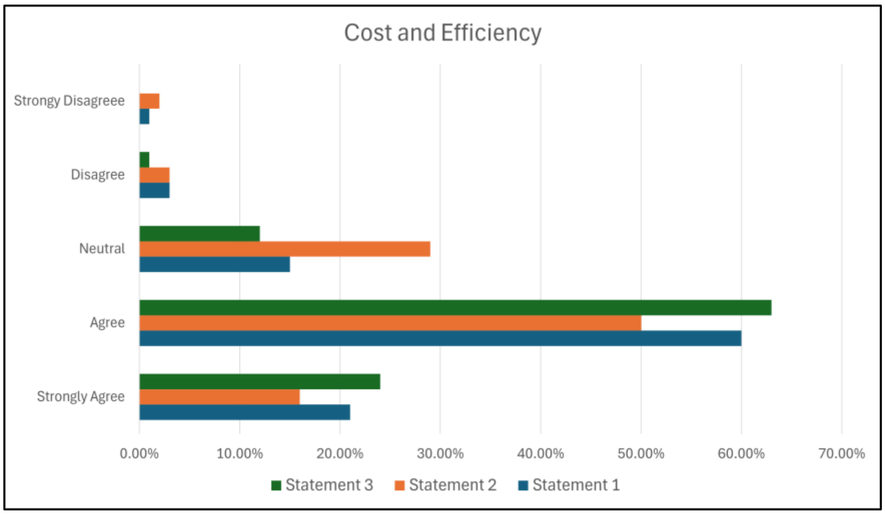



*Figure 59: Cost and Efficiency Category Trends.*

Figure 59 shows the trend of responses under the cost and efficiency category; approximately 81% of all responders across all age groups “Agree” or “Strongly Agree” that the 3D DT system improves collaboration and productivity (Statement 1). By gender , 86% of males, 69% of females, and 67% of other gender groups responded “Agree” or “Strongly Agree”. For help with completing daily tasks (Statement 2), approximately 66% of responders “Agree” or “Strongly Agree”. By gender, 67% of males, 66% of females, and 33% of other gender groups responded “Agree” or “Strongly Agree”. Finally, people “Agree” or “Strongly Agree” that system helps in reducing resource usage (Statement 3) with approximately 87% of all responders across all age groups. By gender, 89% males, 79% females and 100% of other gender groups responded in this way.

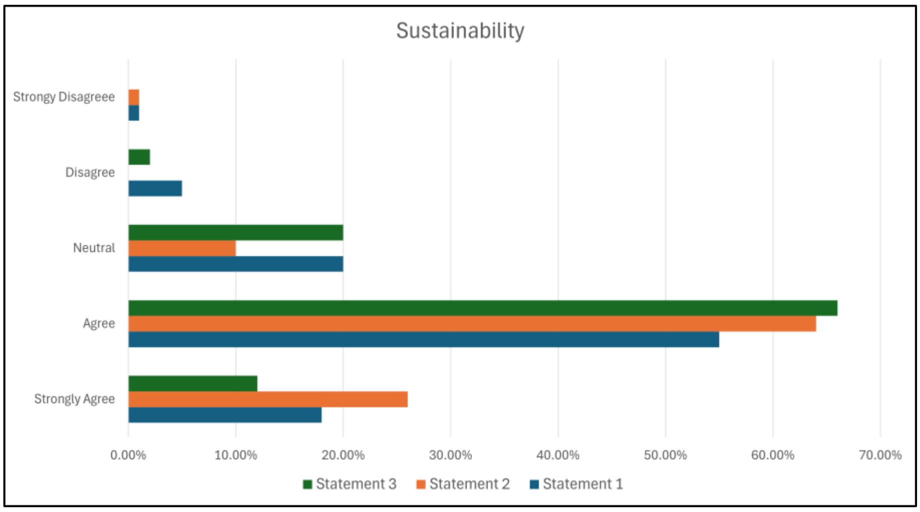



*Figure 60: Sustainability Category Trends.*

Figure 60 presents the response trends of sustainability category. It is observed approximately 73% of all responders across all age groups “Agree” or “Strongly Agree” that system reduces carbon footprint (Statement 1). By gender, 73% of males, 76% of females, and 33% of other gender groups responded similarly. Furthermore, 89% of people of all gender groups “Agree” or “Strongly Agree” with system helping in future innovations (Statement 2). By gender, 89% of males, 86% of females, and 67% of other gender groups responded similarly. For the system supporting more economic models (Statement 3), 78% of responders “Agree” or “Strongly Agree” with the question across all age groups. By gender, 78% of males, 72% of females, and 100% of other gender groups responded similarly.

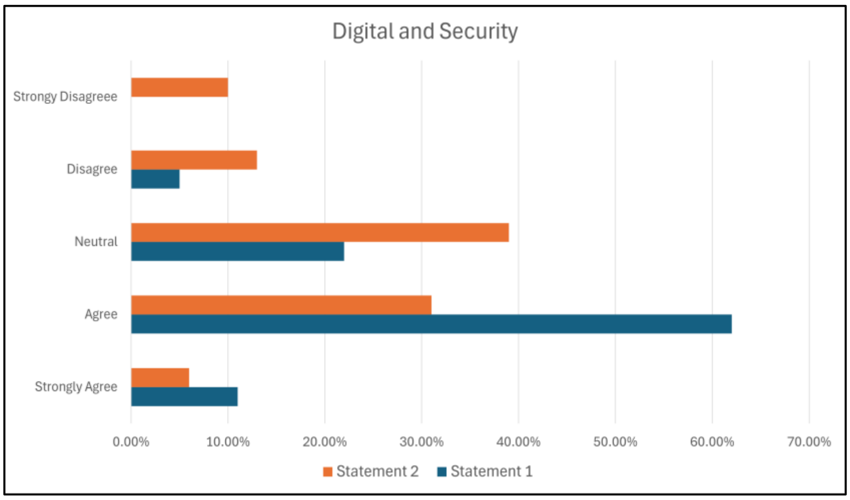



*Figure 61: Digital and Security Category Trends.*

Figure 61 illustrates the trends for the digital and security category responses. It is observed that approximately 72% of all responders “Agree” or “Strongly Agree” that system is accessible for people having different backgrounds (Statement 1). By gender, 73% of males, 69% of females, and 67% of other gender groups responded “Agree” or “Strongly Agree”. Moreover, concerning privacy and security (Statement 2), most of the people across all age groups responded either “Neutral” (39%) or “Agree” (31%), totalling around 70%. By gender, 46% of males are “Neutral” and 29% “Agree”, 34% of females “Agree” and 28% stated “Neutral”, while for other gender groups 33% “Agree” and 67% “Strongly Disagree”.

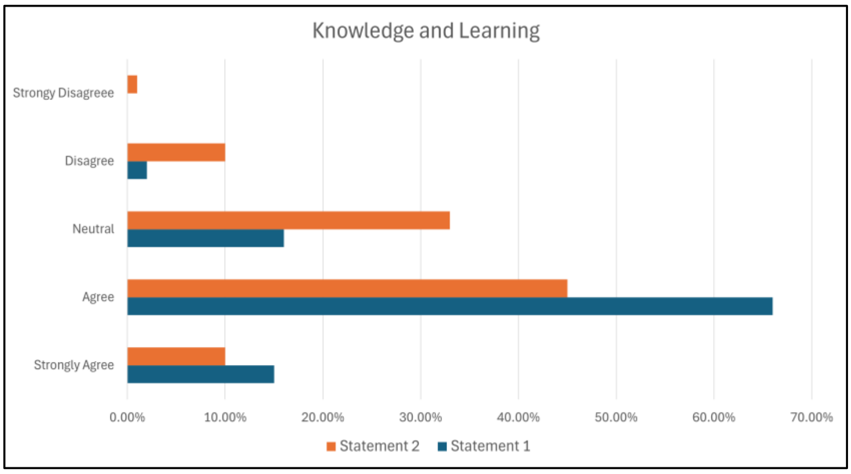



*Figure 62: Knowledge and Learning Category Trends.*

Figure 62 shows the trends for the knowledge and learning category. It is observed that approximately 81% of people across all age groups "Agree" or "Strongly Agree" that the system makes it easier to share knowledge with others in real time (Statement 1). By gender, 83% of males, 79% of females, and 33% in other gender groups responded similarly. However, around 78% of responders across all age groups responded "Agree" (45%) or "Neutral" (33%) towards the system's comparison with the existing collaboration tools (Statement 2). By gender, 43% of males "Agree" and 32% are "Neutral", 45% of females "Agree" and 38% are "Neutral", while for other gender groups 67% "Agree" and 33% "Disagree".

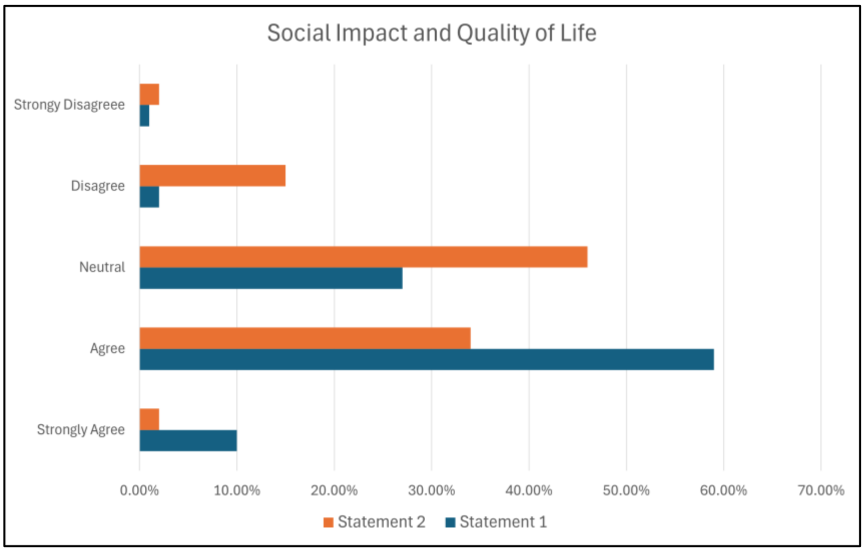



*Figure 63: Social Impact and Quality of Life Category Trends.*

Figure 63 presents the trend of responses under social impact and quality of life category. It is observed that approximately 68% of all the responders across all age groups "Agree" or "Strongly Agree" that the system improves quality of life by making communication tasks easier (Statement 1). By gender, 70% of males, 62% of females, and 67% in other gender groups responded similarly. On the other hand, all age groups responded either "Neutral" (46%) or "Agree" (34%) with system reducing the risk of unethical usage (Statement 2), totalling to around 80%. By gender, 49% of males are "Neutral" and

33% "Agree", 38% of females are "Neutral" and 34% "Agree", while for other gender groups 33% "Agree" and 33% are "Neutral".

### 7.2.2 Impact Assessment of KVI Dimensions

Referring to the KVI dimensions established in Section 6.4, the development of handprints and footprints for each category enables an assessment of the emerging trends. The findings suggest the potential benefits of the system appear to outweigh its harmful impacts, as respondents confirmed the system delivers the expected benefits as compared to its negative consequences.

Generally, a positive reception of the 3D DT System is identified for most of the categories. Respondents reacted positively, acknowledging significant benefits such as improved productivity, enhanced knowledge sharing, reduced carbon footprint, and easier communication. These findings are consistent with the identified handprints in Table 8 for each dimension. Consequently, certain areas require refinement, particularly regarding the privacy, security, and risk of unethical usage, where the responses tend to concentrate around a neutral stance. This reflects a slight presence of footprints evident in Table 8, such as ethical misuse of data and privacy concerns, suggesting that while the system is perceived as inclusive and accessible, further measures can be done to address digital trust.

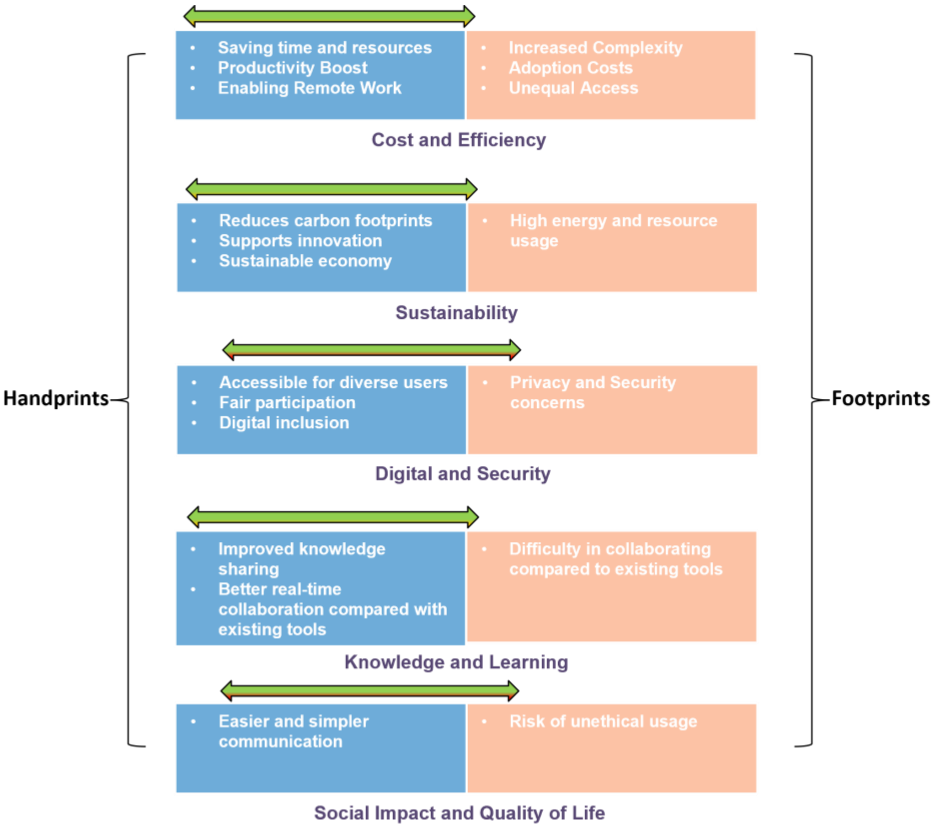



*Figure 64: Alignment of the user's responses.*

Figure 64 shows the alignment of the user's responses mapped more towards the handprints indicating potential benefits are recognized more strongly than the drawbacks. Nonetheless, areas of privacy, security, and unethical usage of data require further developments as trends show a slight shift towards the footprints.

# 8 RESULTS ANALYSIS

This section analyses the results obtained from the validation and testing of the 3D DT system. It highlights findings from use case implementation, the functional and the non-functional requirements of the system, and the KPI and KVI validations.

## 8.1 USE CASE IMPLEMENTATIONS

The use case implementation of the 3D DT application over the 5G sliced network and Wi-Fi TSN was successfully completed, fulfilling the requirements for a collaborative 3D DT workspace with multiple users and enabling coordinated control of the physical Fab Lab facility, including the 3D printer. The heterogeneous traffic generated by the 3D DT application combined voice, video, and motion streams into a single 5G user for KPI validation. Wi-Fi TSN achieved deterministic communication with the robot arm, where time-aware scheduling operated effectively. Even under mixed traffic conditions, including video streaming, ROS2 messages, and deterministic heartbeat signals, the scheduling maintained stable and synchronized robot operation.

ROS2 DDS communication makes it difficult to achieve deterministic timing in TSN networks. Therefore, Wi-Fi TSN validation was conducted using 200 ms safety heartbeat signals in the robot arm. ROS2 remains in high demand for robotics and industrial applications, and its adoption will continue to grow. The DDS protocol performs internal communication control, which prevents precise time management under IEEE 802.11Qbv time-aware scheduling. Because of this black-box behaviour, QoS control for ROS2 is likely better suited to AI/ML-based methods. Similar to the dynamic resource allocation for 3GPP-based 5G slices demonstrated in this work, such AI-driven optimization can adapt to changing traffic conditions and represents a promising direction for future research.

## 8.2 SYSTEM PERFORMANCE AND KPI ANALYSIS

The test specifications were designed to cover all functional, non-functional, and qualitative KPI metrics, ensuring extensive validation of the performance. A V-Model validation approach was followed, encompassing all validation requirements and objectives, execution of test cases, collection of data flows and metric values, classification of the data, reporting of results, and finally analysis and conclusions based on the obtained results.

With respect to the functional and non-functional requirements outlined in Section 5.3, the 3D DT system was observed to operate normally, with all the components functioning as intended. The results for test cases outlined under subsections 7.1.1, 7.1.2, 7.1.3 and 7.1.7 verified correct file handling, successful session scheduling, VR headsets compatibility, clear communication and visualization for both remote user and instructors, interaction with the virtual objects, and proper operation of 3D printing process. Additionally, wireless network functionality was validated by ensuring connectivity through the configured UE slices via trial controller and successful interaction within the 3D environment. All the scenarios were executed successfully, with no issues observed, confirming the system met intended functional and non-functional requirements.

For the qualitative KPI metrics specified under Section 5.1, the measurement data obtained from multiple test runs indicate that all KPI thresholds were met. Specifically, the camera stream bitrates were achieved ≥ 2 Mbps, while VR headset 3D, audio, and control data, as well as 3D printer virtual user interface data, each exceeded required 1 Mbps. The wireless link accommodated VR headset traffic peaks around 400 Mbps, and the wired link towards the edge server in 5GTN has capacity of 10

Gbps. 5G traffic tests confirmed downlink and uplink channel have the required capacities of 400 Mbps and 50 Mbps, respectively, with latency within the target limits ≤ 10ms for downlink and ≤ 14ms for uplink. The 3D DT edge server maintained processing times of ≤ 16.6ms (60 fps), and packet reliability for the targeted latency was measured at 99.9% for the downlink channel. For the uplink channel, one test run experienced packet losses, but the overall average across three test runs met the required threshold. These results are outlined under subsection 7.1.4. In addition, the obtained Wi-Fi TSN test case results under subsection 7.1.6 demonstrate accurate time synchronization between the AP and STA clocks which is ≤10 µs, latency bounds for the 200ms cyclic signal from the robot arm within 1-10ms, and video payload from the camera at 1Mbps (30 fps), confirming that relevant KPI thresholds were successfully met. Below Table 9 shows the target vs achieved values for qualitative KPI metrics derived from multiple test cases.

*Table 9: Target vs Measured KPI Values*

| KPI Category | Target Values | Measured Values |
|---|---|---|
| Link Capability | 3D Printer monitoring video ≥ 2 Mbps | Combined data rate for camera stream data, 3D Virtual environment, audio, and control data, Virtual browser UI data average across three test runs 15.32 Mbps. |
| | VR Glasses (3D data + audio + control) ≥ 1 Mbps | |
| | Virtual browser UI Data ≥ 1 Mbps | |
| | Wireless Traffic from VR Glasses up to 400 Mbps | Wireless traffic average from VR headsets across three test runs 45.59 Mbps with peak values reach across 500 Mbps. |
| | Wired traffic towards 5GTN link capacity 10 Gbps | Link capacity of the uplink towards 5GTN is 10 Gbps with maximum traffic peaks reaching around 500 Mbps so the link is sufficient enough. |
| | 5G Downlink channel up to 400 Mbps | Downlink throughput average across three test runs 280.33 Mbps. |
| | 5G Uplink channel up to 50 Mbps | Uplink throughput average across three test runs 46 Mbps. |
| Latency | 5G Downlink channel ≤ 10 ms | Downlink delay average across three test runs 8.50 ms. |
| | 5G Uplink channel ≤ 14 ms | Uplink delay average across three test runs 11.53 ms. |

| | | |
|---|---|---|
| | Game engine processing time 16.6 ms (60fps) | Processing time on average across three test runs 16.66 ms. |
| Packet Reliability | 99.9% | Downlink 0.00137% , Uplink 0.093%. |
| Wi-Fi TSN between VR and Robot arm | Time Synchronization ≤ 10µs | Average offset of slave clock to synchronize with master clock is 0.253µs. |
| | Latency for 200ms cyclic signal from robot arm between 10-1 ms | Average across three test runs 0.61 ms. |
| | Video Payload from robot arm camera 1 MBps (30fps) | 1 MBps video payload achieved throughout the measurement. |

Given that all KPI metric thresholds, as well as functional and non-functional requirements, were satisfied, the 3D DT system can be considered effective in its current state. However, opportunities for network-level enhancements remain, and future improvements could focus on further optimizing latency and throughput under large-scale and high-load conditions, for integration with larger organizations, ensuring seamless scalability as the number of connected devices increase. Enhancement mechanisms for fault tolerance to minimize disruptions in critical operations also provide areas of further development, and these measures would not only maintain system performance under evolving demands but also ensure long-term reliability of the 3D DT system deployment.

## 8.3 KVI ANALYSIS

The responses gathered from the designed questionnaire provided insights into all the KVI categories which are established in Section 5.2. The findings across different age groups indicate general agreement on the ability of the system to improve collaboration and productivity, to facilitate the completion of daily tasks, to reduce carbon footprint, to support future innovations and economic models, to ensure accessibility for people from different backgrounds, to enable real-time knowledge sharing, to compare with existing collaboration tools, and to simplify communication. Consequently, a neutral stance across all age groups was observed regarding privacy, security, and unethical usage risks connected to the system, indicating this area requires further development and education.

The analysis of the KVI dimensions under subsection 7.2.2 indicate the perceived benefits of the system surpass the associated drawbacks. Participants consistently showed consensus with the ability of the system to deliver value across key areas such as collaboration, sustainability, efficiency, and knowledge sharing; whereas impact related to privacy, security, and knowledge sharing were less strongly expressed. This highlights that, while the 3D DT system demonstrates significant potential to achieve its intended benefits, targeted measures are necessary to strengthen data protection mechanisms, implementing access control policies, and further enhancement in data handling. These measures would reinforce increase user trust, thereby ensuring a more balanced impact across all the KVI dimensions.

## 8.4 EXPECTED IMPACT

The lessons learnt from this work highlight both the technical feasibility and the challenges of deploying 3D DT applications over advanced networking infrastructures. From a technical perspective, the integration of 3D DT applications with 5G slicing and Wi-Fi TSN proved feasible, achieving deterministic performance for collaborative VR and real-time robotic control. While KPI targets such as throughput, latency, synchronization, and reliability were successfully met, challenges were identified in handling ROS2 traffic. Because ROS2 DDS operates as a black box, time-aware scheduling could not be directly applied, underscoring the need for complementary approaches such as safety heartbeat signals and AI/ML-driven dynamic QoS optimization.

In terms of broader impact, the outcomes of this work are expected to extend beyond the current use case to other industries and societal domains. The demonstrated integration of 3D DT applications with deterministic networking enables not only collaborative manufacturing scenarios, but also potential applications in healthcare, education, logistics, and smart cities, where immersive collaboration and real-time control are equally critical. These results therefore provide a transferable framework that can accelerate the adoption of 3D DT concepts in diverse industrial and societal contexts.

Finally, the work contributes to ongoing efforts in standardization and European research strategies. Insights on the challenges of deterministic networking with robotics, the role of Wi-Fi TSN, and the potential of AI/ML-driven 5G slice optimization are directly relevant to discussions in 3GPP, IEEE TSN, and related bodies. Moreover, the validation methodology and findings are expected to support other EU projects in aligning with 6G strategies, providing evidence for scalability, reliability, and user-centric service design in DT and XR applications.

# 9 SUMMARY

This deliverable has presented the implementation and validation of the 6G-XR UC4, developed as part of WP6, to demonstrate the integration of 3D DT technology with advanced networking enablers. The work focused on showcasing immersive multi-user collaboration, remote 3D printing, and robotic arm control within VR environment, supported by 5G slicing, edge services, and WI-FI TSN.

**3D DT Application:** A Babylon.js–based VR application was implemented, enabling immersive design review and remote operation of a 3D printer in a shared VR environment. Integration with 5G slicing and edge services ensured controlled QoS and low-latency communication.

**Wireless TSN:** A Wi-Fi 6–based TSN system was deployed to enable real-time control of a UR10 robot arm while simultaneously streaming video from a surveillance camera. RT robot control data and BE video traffic were scheduled and prioritized to demonstrate deterministic performance over Wi-Fi.

**Validation:** KPVI based evaluation was carried out to assess the performance of overall implemented 3D DT System, and all the related components. The testing encompassed performance aspects, including network capability and application-specific functionalities. Beyond the technical validation, the assessment also considered broader implications for society and the impact on people, highlighting potential benefits and identifying areas of refinement of the DT system.

Overall, this deliverable confirms the feasibility of combining 3D DT applications with 5G slicing, edge computing, and Wi-Fi TSN technologies to achieve deterministic QoS for VR-enabled collaboration and industrial use cases. Moreover, the evaluation confirms the promising role of 3D DT in advancing immersive digital technologies, verifying the 6G-XR high-level Objective 7: Develop and deploy 3D Digital Twin with XR remote control capability.

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# 11 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:** | *NOKIA Airscale, Ericsson, USRP….* | **5G Core:** | OAIBOX, Cumucore, SA/NSA, … | **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 behavior/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** | *logfile A* | *logfile D* | *logfile G* | Refer to the relevant diagram below and explain verdict | Pass/Fail |
| **Checkpoint ID #2** | *logfileB* | *logfile E* | *logfile H* | | |
| **Checkpoint ID #3** | *logfileC* | *logfileF* | *logfileI* | | |
| **Final Diagrams** | | | | | |
| *insert here the main diagrams explaining the verdict* | | | | | |

# 12 ANNEX B – KVI QUESTIONNAIRE

Below is the questionnaire covering each KVI category, the responses collected from this are then mapped to the required KV enablers required by the 3D DT system.

## Questionnaire UOULU 3D Digital Twin XR UC4

### DEMOGRAPHICS AND BACKGROUND

**Indicate your gender:**

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

**Indicate your age range:**

- 0-10 ☐
- 10-20 ☐
- 20-40 ☐
- 40-60 ☐
- Over 60 ☐
- I prefer to not disclose ☐
- I prefer to specify my age: ___________

**Indicate your level of familiarity with immersive technologies, like Virtual Reality (VR), Extended Reality (XR), Augmented Reality (AR)**

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

**Indicate your level of familiarity with network technologies, like 5G, 6G**

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

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## COST AND EFFICIENCY

**Q1. The 3D Digital Twin Environment improves collaboration and productivity across different locations.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

**Q2. The system helps in completing daily tasks more efficiently.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

**Q3. The system helps in reducing resource usage (time, travel, materials)**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

## SUSTAINABILITY

**Q4. The system contributes to environmental sustainability by reducing the carbon footprint.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

**Q5. The system helps in future innovations.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

**Q6. The system supports more sustainable economic models – by helping organisations reduce operating costs, resources optimization and long-term efficient planning by the insights provided by the 3D Digital Twin**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

## DIGITAL AND SECURITY

**Q7. The system is accessible for people having different backgrounds, abilities and skills.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

**Q8. I am concerned that when using this system my privacy and data would not be protected.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

## KNOWLEDGE AND LEARNING

**Q9. The system makes it easier to share knowledge with others in real time.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

**Q10. Compared to existing collaboration tools (e.g., Instagram, Snapchat, Email, Teams, etc.) the system makes it easier to collaborate with others in real time.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

**6G XR** | Questionnaire

## SOCIAL IMPACT AND QUALITY OF LIFE

**Q11. Using this system improves quality of life by making task communication simple and easier.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

**Q12. The system reduces the risk of unethical usage.**

Strongly Agree ☐; Agree ☐; Neutral ☐; Disagree ☐; Strongly disagree ☐

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