Programmable Network Testbed for QoS/QoE Assessment of Holographic Media Delivery

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***Abstract*—Transmitting holographic media is one of the driving applications in the field of immersive media, demanding moving beyond 5G capabilities. The effective delivery of Holographic-Type Communications (HTC) presents challenging network and computational requirements to meet the end user's expected Quality of Experience (QoE). This demo showcases ongoing efforts on a programmable testbed to facilitate research on the impact of network Quality of Service (QoS) parameters on Point Cloud video QoE metrics at the Head Mounted Device (HMD).**

I. Introduction

The rapid growth in recent communication technologies has driven a new era of immersive media experiences. Holographic-Type Communications (HTC) represents a paradigm shift in immersive media delivery. It enables the transmission of volumetric/holographic content like Point Cloud and Light Field Videos, as well as multi-sensory media (Mulsemedia) across communication networks to remote locations [1]. HTC is expected to be an essential application for next-generation communication networks, including beyond 5G and future 6G networks, and in various domains such as entertainment, education, and healthcare [2].

Despite the immense potential of holographic-type immersive experiences, the realization of HTC poses significant challenges to the network's ability to meet stringent Quality of Service (QoS) requirements. The immersive nature of holographic media, characterized by six degrees of freedom (6DoF), requires a delicate balance between ultra-low latency (within a few milliseconds) and massive bandwidth (up to hundreds of gigabits per second). These demanding network requirements are key to provide satisfactory Quality of Experience (QoE) in holographic streaming.

On the other hand, cutting-edge technologies such as Software-Defined Networks (SDN), Network Function Virtualization (NFV), and network programmability will play a pivotal role in enabling HTC transmission in next-generation network scenarios. These technologies are expected to meet specific Key Performance Indicators (KPIs) related to QoE directly and indirectly in HTC realm [3]. In this context, network programming languages like P4, a domain-specific language for network devices, can be leveraged to achieve data plane network programmability. State-of-the-art research efforts have explored the potentiality of SDN and NFV for HTC, focusing on simulating in-network computing and slicing [4], network delay and packet loss for QoE analysis [5]. However, existing emulation and simulation tools often have limitations due to local devices' processing capabilities, particularly in terms of maximum throughput, which can result in a shortfall in accurately representing the demanding network conditions required for holographic media transmission.

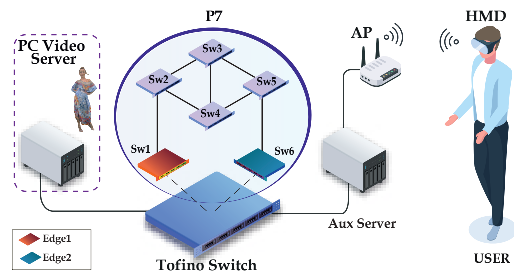


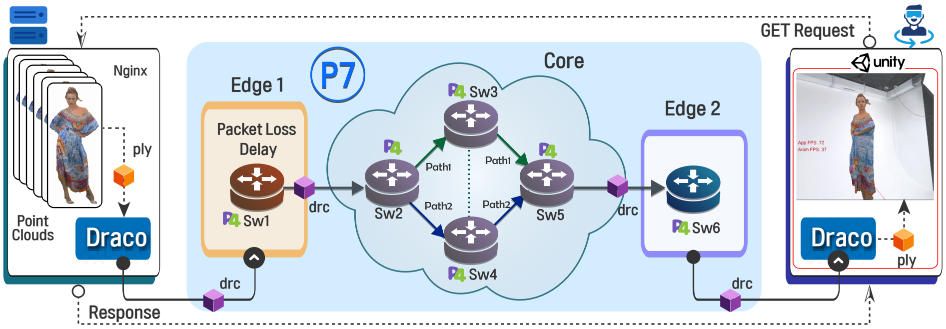
Fig. 1: Overview of the proposed testbed.

Understanding the impact of network QoS metrics on QoE KPIs in immersive holographic media is a key step for optimizing the delivery of next-generation services. To this end, we employ P4 Programmable Patch Panel (P7) [6], [7], a high-end, affordable network emulation platform that uses high-performance programmable hardware to emulate network topologies. Our demonstration uses P7 to analyze how various network QoS metrics affect QoE, mainly focusing on performance indicators like Frames Per Second (FPS) in Head Mounted Devices (HMD) for holographic projections, aiming to comprehend their smoothness and quality.

II. Testbed Architecture

In order to create a testbed environment capable of programmable data plane functionality for holographic streaming, we employed P7, which allowed us to emulate complex network topologies realistically. The high-level overview of the proposed test environment is illustrated in Fig. 1. It consists of an `Nginx` proxy server running on Ubuntu 22.04 LTS, a `Tofino` programmable switch (3.2 Tbps Wedge 100BF-32X), and an auxiliary server connected to an access point. This access point connects the `Meta Quest-3` mixed-reality HMD to the network via Wi-Fi at up to 840 Mbps bandwidth.

A core feature of our setup is P7's ability to emulate scenarios representing multiple interconnected autonomous systems, service providers, or edge networks, each with distinct characteristics and metrics. P7 relies on a P4 program compiled into `Tofino` hardware pipelines to perform forwarding actions



Scenario	PL (%) DL(ms)	QoE Rating
Ideal	0 0	Q1
Minimal PL	0.1 0	Q1
Moderate DL	0 4	Q2
High DL	0 10	Q3
Low PL, High DL	0.1 10	Q3
High PL	2.0 0	Q2

Fig. 2: Point Cloud (PC) video transmission setup (left) and test scenario parameters with QoE scores (right).

over links parameterized with packet loss, delay, and bandwidth. Besides, the data plane programmability of P7 allows for defining various network paths and the creation of network slices, each tailored for specific services or priority levels.

As depicted in Fig. 2 (left), the transmission architecture within the `Tofino` switch is organized into three distinct network areas: two network edges (*Edge1* and *Edge2*) and a core network. For this experiment, QoS metrics, including packet loss and delay, were applied at the emulated switch *Sw1*, representing *Edge1*. The remaining emulated switches ($Sw2 \cdots Sw5$) make up the core network, which, along with the *Edge2* switch *Sw6*, remained unaffected by disruptions in this demonstration. Note that no bandwidth limitations were enforced throughout the experiment.

We utilized Point Cloud (PC) video for holographic media, specifically the `Long Dress` PC video from a publicly available dataset[1]. Due to the large size and complexity of PC content, it is important to compress the videos before transmission to optimize network bandwidth usage. To achieve this, we used Google `Draco`[2] library for PC compression and decompression. We developed a PC video player using the `Unity` engine, designed to run on the HMD. Each point cloud file is compressed on the server and made available for transmission. The `Unity` application running on the `Meta Quest-3` requests these files using the GET method. Once received, the `Draco` library embedded in the `Unity` application on the HMD decodes the files, and the player projects the `Long Dress` video in the immersive environment.

III. Demonstration

The primary objective of this demo is to analyze the impact of network QoS on the QoE for PC content transmitted in a real HMD. This practical implementation enables us to evaluate how adverse network conditions influence the immersive experience of holographic content in real-world applications. To evaluate the effects of network anomalies, we conduct six test scenarios under varying conditions on *(Edge1)*, each test characterized by different packet loss percentages and delay times (measured in milliseconds). These parameters were systematically applied to assess their impact on the PC video playback and FPS in the `Meta Quest-3` projection. The rendered PC video was categorized into three quality levels: *Q1* for excellent, *Q2* for mild, and *Q3* for poor, based on subjective visual assessment of playback smoothness. The recorded demonstration video, which highlights the results, can be accessed in this link[3]. A table (see Fig. 2, right) summarizes the quality levels corresponding to the applied packet loss (PL) and delay (DL) configurations for six distinct scenarios. We observed that network conditions significantly influenced PC video quality; performance remained smooth under the ideal, even with minimal PL scenarios. However, the quality deteriorated as PL and DL increased, leading to stuttering and compromised performance.

IV. Final Remarks

To enhance holographic transmission and perform comprehensive QoE assessments for HTC, ongoing efforts focus on mitigating quality deterioration due to packet loss by exploring the implementation of Forward Error Correction and addressing delays through decoding/rendering at the nearest edge, furthermore investigating dynamic network slicing and integrate advanced features like In-band Network Telemetry by leveraging the current P7-based programmable testbed.

Acknowledgment

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