Quality of Experience Modelling and Analysis for Live Holographic Teleportation

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***Abstract*—Holographic media offers a more engaging experience than 2D or 3D media, making it a promising technology for future applications. However, producing high-quality holographic media requires meeting demanding requirements such as low latency, high bandwidth, significant computing resources, and intelligent adaptation. Unfortunately, the current network infrastructure falls short of meeting these requirements. The increasing popularity of holographic media and the demand for more immersive experiences make it essential to consider user QoE and factors that influence it. This work focuses on latency sensitive network conditions and examines impactful factors and performance metrics as it relates to the user's QoE. The impact of disruptive factors is systematically quantified through subjective quality assessment evaluations. Additionally, the work presented proposes a QoE model for evaluating network-based QoE for live holographic teleportation.**

***Index Terms*—Quality of Experience, Holographic Teleportation, Immersive Media, Volumetric Media.**

I. INTRODUCTION

HOLOGRAPHIC teleportation [1] provides more immersive user experience by enabling unrestricted user view of the teleported object with free movement and six degrees of freedom (6DoF) in the extended reality (XR) space. This type of emerging technology application has been recently facilitated by the 5G paradigm, and is considered as a killer application for future media streaming services [1]–[3]. The realization of this type of volumetric media for highly interactive, large scale use is still restricted due to limitations of current networks to support requirements such as powerful computing resources, high bandwidth, low latency, and adaptability [4].

The capabilities of 5G networks and mobile edge computing (MEC) technology makes live holographic teleportation feasible. This allows users to have a more immersive experience by providing photo-realistic interactivity which was not possible with standard 2D video. Although at a stage that could be considered low level or low scale, such immersive experiences indicate that a high potential exists for achieving much higher quality and more immersive holographic applications. This is further supported by advancements by Moving Picture Experts Group (MPEG) in compressing point clouds [5], which is an underlying technology that enables holographic and volumetric communication. However, there are several factors that limit the realization of high quality and highly immersive holographic media applications such as holographic teleportation for large scale use. These factors such as powerful computing resources, high bandwidth, low latency, and adaptability, limit scalability [4], with research efforts expected to contribute towards the prevalence of these applications [6]. Moreover, factors such as bandwidth, latency, and quality representation are of significant importance as they also impact the user Quality of Experience (QoE) for live holographic applications [2].

The importance of such factors especially network conditions such as latency and packet loss rate (PLR) represents the need to investigate the impact of these factors on the user QoE. This is particularly of significant importance in live streaming cases. The reason for this is that network related parameters have an impact on standard performance metrics of holographic teleportation, including frames per second (FPS) and playback latency, which are directly perceived by the end user [7]. In this paper, we define playback latency as the time gap between the action taking place at the source's side and the time point the user sees that action. Whilst QoE and subjective studies [8]–[10] on holographic media exist, it is necessary to investigate the impact of rigid network requirements on user QoE as such requirements are important for highly interactive holographic applications. Therefore, subjective analysis of the impact of network based factors is required to investigate the influence of such factors and their extent on user QoE. This will provide insight into future highly immersive and interactive holographic applications.

Moreover, with regard to quality assessment for 6DoF volumetric based immersive media, a variety of traditional objective metrics have been previously applied, with such metrics classed into geometric and rendered Field-of-View (FoV) based metrics [11]. For example, PSNR based metrics such as point-to-point and point-to-plane geometry distortion metrics [12] and more visually perceptive metrics such as structural similarity index measure (SSIM) and video multimethod assessment fusion (VMAF) have been previously utilized. Such metrics, although valuable for assessing the compression performance of techniques such as point cloud

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compression (PCC) [5], fail to account for several important factors and performance metrics with regards to user QoE for live application cases and as such are not suitable for assessing user QoE under live network conditions.

Furthermore, user oriented performance metrics such as playback latency which is an essential metric for live holographic teleportation as it relates to performance and user experience [7] are not considered by such objective metrics, resulting in the ineffectiveness of such objective metrics for live streaming scenarios. This issue is further compounded by the lack of relevant literary works on the impact of playback latency and its significance for live holographic teleportation, under strict network conditions, which is the focus of this research work. As such, usage of such objective metrics is not suitable for subjective quality assessment as they lack network awareness. Hence, in order to address these constraints, this paper explores the influence of different network conditions, specifically latency and packet loss, on standard performance metrics of holographic teleportation. These metrics encompass FPS and playback latency, which are perceptible to the user, ultimately affecting the user's QoE during live holographic teleportation.

The study presented focuses on network delay and PLR for latency sensitive network conditions as the two primary influential factors on user QoE for live holographic teleportation. In addition to this, the quality representation is also factored in the study. It should be noted that highly interactive holographic teleportation is still at an early phase with significant improvements expected in the future. The work presented aims to inform on the user QoE for such holographic applications for current and future cases in 5G, 6G networks and beyond. Thus the main contributions highlighted are:

- First and foremost, extensive experiments accounting for performance metrics such as playback latency and interactivity for a subjective quality assessment study on the impact of disruptive network factors on user QoE for live holographic assessment are conducted. This study particularly focuses on latency sensitive network requirements, with various network conditions emulated, robustly informing on the user quality of experience in such scenarios.
- Secondly, a detailed evaluation of systematic performance and definitive analysis of network influenced system dependent metrics in the context of various latency sensitive network conditions is presented. This further facilitates the investigation of possible existing correlations between such deterministic factors particularly as they relate to user quality of experience in live holographic teleportation.
- Finally, A network aware QoE model which accounts for the impact of latency sensitive network conditions based on subjective user experimental data is developed and proposed. The proposed QoE model is adapted for multiple quality representations for subjective quality assessment for live holographic teleportation. As such, network based factors and user oriented performance metrics are accounted for in user awareness and experience.

II. LITERATURE REVIEW

In holographic communication based applications, such as holographic teleportation, several factors associated with the rendering and delivery of holographic media can significantly impact user quality of experience. Research has sought to understand how factors such as network latency, packet loss, bandwidth constraints, device capabilities, compression techniques, immersiveness, interactivity, and content complexity affect the QoE of holographic communication and volumetric media [2], [3], [8]–[10], [13], [14]. As such, numerous studies have been conducted to evaluate the influence of these factors on the quality of experience for holographic communication and volumetric media. In [9], the authors conduct subjective experiments with regard to holographic augmented reality (AR). They propose a QoE evaluation framework and subsequently design a QoE evaluation model for holographic AR. The work focuses on content quality, hardware quality, environment understanding, and user interaction as the key influential factors. The authors in [11] conduct experiments to analyze the accuracy and correlation of FR and NR objective metrics as it relates to subjective evaluation. They report that VMAF is suitable as an objective benchmark for volumetric based subjective evaluations. Likewise, the authors in [8] carry out objective and subjective quality evaluations for adaptive point cloud streaming. They investigate the impact of content, streaming, and network related factors primarily bandwidth on user QoE and carry out objective assessments to evaluate the suitability and correlation of objective metrics as they relate to subjective evaluation. The work presented in [14] focuses on factors such as buffering and introduces a framework for enabling internet-scale holographic-type communications with experiments conducted for guaranteed QoE. Moreover, in [15], subjective studies are conducted to evaluate the impact of User-Centered Adaptive techniques such as tiling adaptive mechanisms for streaming of dynamic point clouds. Similarly, the authors in [16] focus on the impact of distance, occlusion, and screen resolution on QoE. A QoE model based on planar geometric projections is subsequently proposed and applied for adaptive streaming. In [17], the authors conduct experiments to investigate subjective and objective factors as they relate to QoE for point cloud based volumetric media. The work focuses on compressed point cloud video streaming, with subjective experiments carried out using head mounted displays (HMDs). They further propose a QoE model based on multiple parameters that they report can accurately assess user perceived quality. Furthermore, the authors in [18] study the impact of distance and quality switching on user perception. The results indicate that a combination of shorter distances and lower quality representation degrades the perceived user quality. Likewise, in [19] the focus of the investigation is on immersive and interactive subjective quality assessment based on dynamic quality changes and viewer distance. A novel subjective evaluation methodology for point cloud content in a 6DoF environment is also proposed.

In the realm of holographic communication and volumetric media, despite the extensive research conducted on various parameters influencing QoE, there are three fundamental issues that have not received adequate attention. Firstly, there is a scarcity of research studies focusing on live streaming scenarios. The second issue pertains to the limited investigation of erroneous network factors, such as packet loss and latency, and other key user oriented performance metrics such as playback latency, especially in latency sensitive network conditions, which are crucial for holographic communication. Finally, there is a dearth of works on network-based QoE models specifically tailored to live holographic streaming applications.

This paper aims to address these gaps by providing a subjective quality assessment to evaluate the impact of erroneous network conditions in latency sensitive live streaming scenarios. It seeks to shed light on the influence of these factors in latency sensitive conditions. Additionally, the paper proposes a network-based QoE model for assessing QoE based on network channel conditions. It is important to note that the focus of this work is not on point cloud compression or its effect on user QoE; rather, it strictly considers the impact of erroneous transmission.

III. METHODOLOGY

In order to tackle the issues highlighted in the literature, it is essential to conduct subjective assessments to evaluate user satisfaction and perception in holographic and volumetric media applications, specifically in scenarios involving latency sensitive conditions, such as holographic teleportation. A comprehensive and carefully designed methodology is paramount to gain a deeper understanding of the user experience and effectively capture the nuances of their subjective evaluation. This section details the methodology adopted to assess subjective QoE for holographic and volumetric media, with a specific emphasis on accounting for user oriented performance metrics and examining the influence of diverse conditions on user QoE.

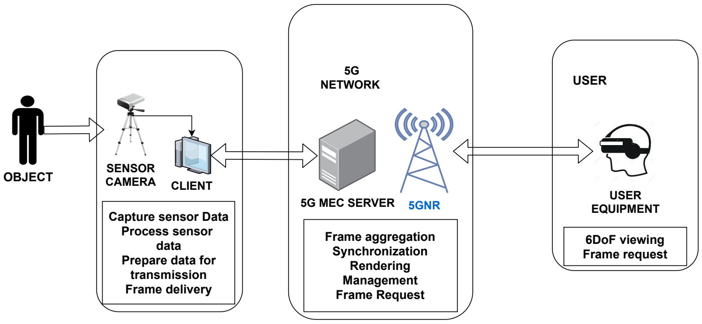

Fig. 1. Holographic teleportation platform with 5G MEC

A. Experiment Configuration

In order to assess the subjective quality for live holographic teleportation, the basic system setup in Fig. 1 depicting remote production in 5G networks facilitated via a 5G MEC framework for satisfactory performance [1] was adapted and modified for multi camera erroneous holographic teleportation depicted in Fig. 2. Here, four cameras are used to capture the source or object for a complete photo realistic representation of the source. The frames captured by the client are transmitted to the server which handles the necessary aggregation, synchronization and transmits the complete 3D hologram to the UE. Network links with a bandwidth capacity of 1 Gbps are utilized to provide the necessary connectivity within the setup.

Each client has a unique calibration, with the aggregation of all camera frames providing a complete capture of the source. This allows the user to view the complete hologram of the source from multiple angles. To facilitate erroneous transmission for latency sensitive network conditions, a network emulator, Netem [20] is utilized via a middle box. Moreover, re-transmission is enabled to facilitate controlled experimentation for effective subjective assessment. Furthermore, a range of different packet loss and delay values are used to alter the erroneous network conditions of the transmission channel. Here, delay and packet loss values impact the transmission of all four clients in the experiment setup. The values of the erroneous parameters used are listed in Table I

TABLE I
PARAMETERS FOR EVALUATION

Delay(ms)	0	10	50	100
PLR(%)	0	0.01	0.1	-
Quality representation	Q1	Q2	Q3	-

In order to more aptly factor latency sensitive erroneous conditions, the values have been selected based on proposed literary and technical specifications [21]–[23]. Three distinct quality representation levels are considered for assessment. These quality representations are characterized as various resolutions and directly translate to point densities. Furthermore, the combination of all these parameters results in the generation of 36 unique test case scenarios for subjective assessment.

Moreover, to assess the subjective quality for live holographic teleportation, a double stimulus approach is employed for improved assessment. This facilitates the consideration of user oriented performance metrics. Here, the user was briefed on the experiment and provided the necessary instructions. After the instructions had been read and consent was obtained, the user was equipped with a HMD for a test evaluation trial. After successful completion of the trail, the user carried out assessment of the 36 test cases for live holographic teleportation. Upon completion of the subjective assessment, the user was provided with a questionnaire complete and allowed to provide any feedback or comments. Assessment of the subjective quality was conducted based on interactivity, quality, and playback latency, which is the time difference between the source action and relayed hologram action under the erroneous network conditions for live holographic teleportation. The generation of the photo realistic hologram in the XR space coupled with the use of HMDs allowed for interactivity and immersive 6DoF viewing experience whilst providing freedom of movement in the physical space. As such, the assessment conducted under the varying network conditions was not limited to a single point of view. Furthermore, in order to quantify the subjective quality, a mean opinion score (MOS) [24] scale was utilized.

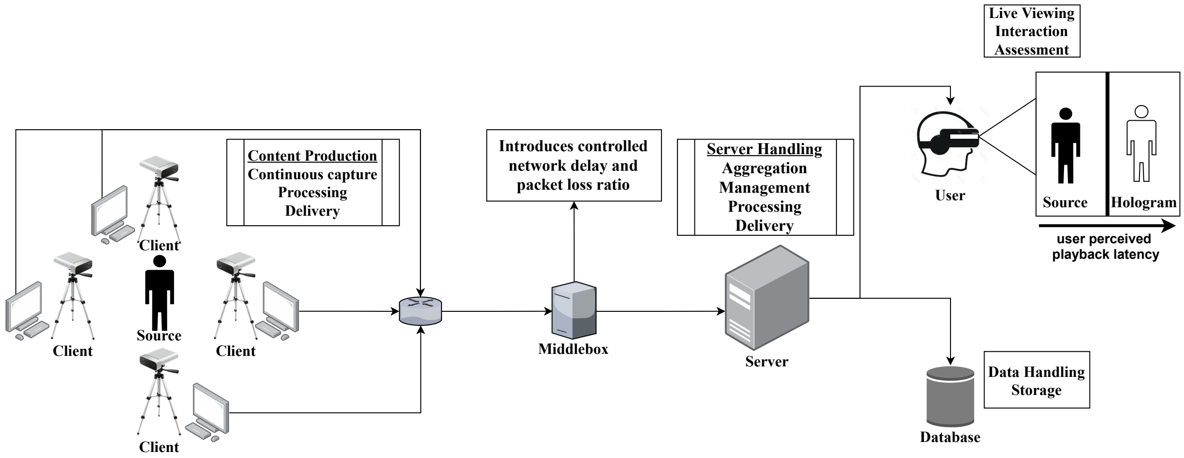

Fig. 2. Experiment system setup for subjective assessment

The scale which was provided in the instruction paper ranges from 1-5 with a description for each score. The description of the MOS used is shown in Table II.

TABLE II
MEAN OPINION SCORE SCALE

MOS	Quality
5	Excellent
4	Good
3	Fair
2	Poor
1	Bad

IV. EXPERIMENT RESULTS AND ANALYSIS

The impact of erroneous latency sensitive network conditions on live holographic teleportation is evaluated in terms of QoE and system based QoE metrics.

A. *QoE Analysis*

For subjective assessment, ITU-T P.919 [25] and ITU-R BT.500 [26] were adopted as recommendations. A total of 29 people participated in the subjective evaluation, with both male and female representation contributing to the total participant number. Further variation is present in the participant pool with ages ranging from 21 to 60 years old. Following outlier prerequisites similar to ITU-R BT.500, the result of four participants were excluded, resulting in a total participant count of 25 with each participant evaluating 36 test cases using the MOS scale listed in Table II.

Fig. 3 displays the plots of average MOS against varying delay and packet loss values for the different quality representations. As such, the impact of delay and packet loss for latency sensitive live holographic teleportation can be inferred. The patterns observed indicate that the maximum average MOS is achieved when no delay and pack loss is introduced. However, it is evident that the maximum average MOS of approximately four is only achieved at the lowest quality representation of Q1 which is the HD resolution. This is in contrast to the quality representation of Q2 which displays a similar pattern and peak to the quality representation of Q3 which are the FHD and WQHD resolutions respectively. Thus, it can be inferred that in a live streaming for low latency network conditions, FPS and interactivity which is significantly impacted by latency is much more important for user experience in holographic teleportation. This is further supported by comments from participants indicating that lower quality is much more tolerable provided that the object motion is continuous and uninterrupted.

Fig. 4 depicts the detailed distribution of the MOS scores. Similarly to Fig. 3, it is evident that reducing latency is optimal for user experience. This is characterized by higher maximum and median MOS scores observed with lower latency values. Furthermore, the figure also indicates that lower quality representations are preferable for user experience for latency sensitive network conditions. This is due to the significant increase in bandwidth requirements for higher density quality representations, without any adaptation mechanisms applied, resulting in less tolerable perceivable playback latency in the live stream. Moreover, the patterns indicate that network delay values in the experiment can have a greater influence than lower packet loss values even when retransmissions occur. This trend can be attributed to the onset and progressive severity of motion misalignment between multi client frames, and subsequent playback latency, which is significantly impacted by delay [7].

B. *Metric Analysis*

Metric analysis informs on metric performance in relation to the impact of erroneous latency sensitive network conditions on live holographic teleportation, providing performance and systemic based examination with regards to QoE.

Fig. 5 exhibits the results of the FPS performance under varying erroneous conditions for latency sensitive network transmission. The plots indicate a deterioration pattern for FPS with increasing delay and packet loss. This is observed in the reduction of the lowest FPS with increments in delay and packet loss. Particularly, under the defined experiment conditions, the results indicate that the impact of delay is more significant than packet loss. This corresponds with the results

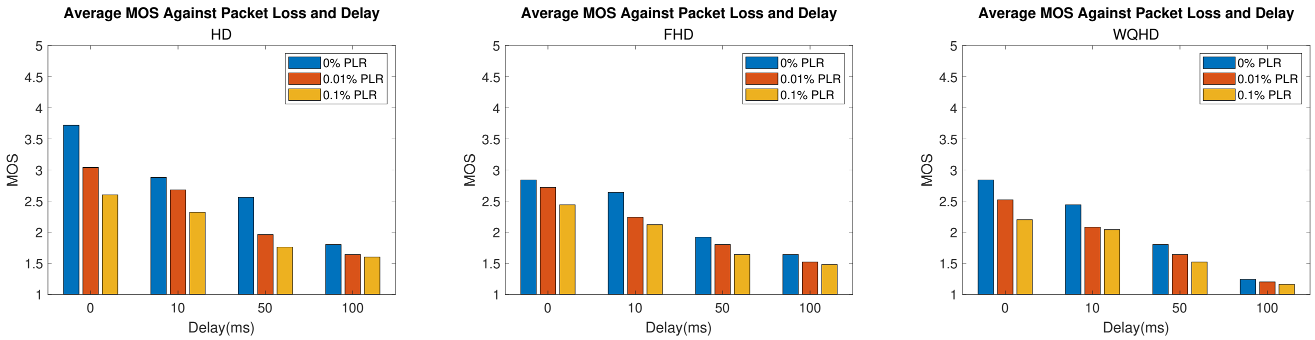

Fig. 3. Average MOS distribution for various delay and packet loss states

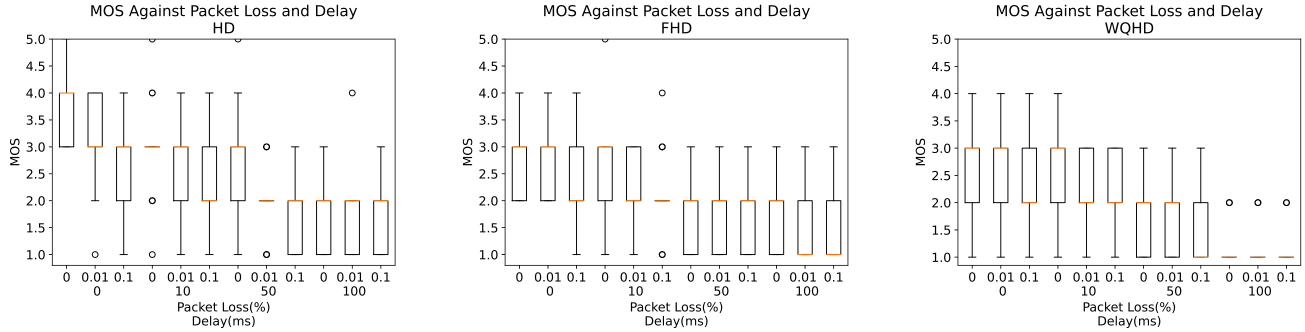

Fig. 4. MOS distribution for various delay and packet loss states

from the subjective tests. Moreover, it is evident that increasing quality representation or point density results in reduced performance and subsequently worse QoE performance. The degraded performance is associated with the absence of any utilized adaptive mechanisms for live transmission. This is because increases in quality representation result in significant increases in data to be transmitted [1], [7] and as such if no adaptations are employed to handle the increased requirements and with all transmission mechanisms kept constant, the time and subsequent computational resources required for transmission and rendering significantly increases. Thus, visual distortions such as motion misalignment and playback latency become much more perceivable, resulting in less optimal user experience.

Fig. 6 shows the throughput performance under varying erroneous conditions for latency sensitive network transmission. The patterns observed from the plots indicate increased throughput with higher quality representation. Furthermore, at the least erroneous state, the throughput is greater with the effective range decreasing with increasing network delay and packet loss. This is associated with increased transmission time and retransmissions which get increasingly worse for a given period. As such, it is evident that the impact of playback latency on the user QoE at these erroneous states is significantly more perceptible and far more severe. This further diminishes user experience as the ability for user interactivity is greatly reduced under such conditions. Moreover, this pattern together with the results observed in Fig 4 indicates that interactivity is of more significance to user experience under such network conditions.

V. QOE MODELLING

To assess and facilitate optimal user QoE for live holographic teleportation under latency sensitive network conditions, there is a need to model the impact of such network parameters on QoE. As such, expanding upon the discoveries outlined in Section IV-A, a QoE model is proposed for live holographic teleportation. In pursuit of this objective, the connection between QoE and fluctuations in latency and packet loss is leveraged.

A. *Network compliant QoE Model*

As the impact of erroneous network conditions on QoE is evident from Fig. 4, to derive a network conformable QoE model, multiple combinations of delay, packet loss, and for quality representations are considered. Thus, the subjective assessment scores accounting for the impact of such factors are used in developing the proposed QoE model, therefore providing compliance at the network level. Furthermore, employing statistical analysis the relationship between QoE, delay, and packet loss can be derived for the three quality representations. As such, the derived relationship can be represented with Eq (1).

$$\begin{gathered} QoE = a \cdot exp^{b \times D} + c \cdot exp^{d \times PL} + e \\ QoE = Clip(1, 5, QoE) \end{gathered} \tag{1}$$

where QoE represents the predicted QoE, D, and PL represent delay and packet loss, and a, b, c, d, and e are the proposed model coefficients. Clipping is utilized to limit any atypical occurrences with the derived models. Moreover, non linear regression analysis is the statistical modeling technique

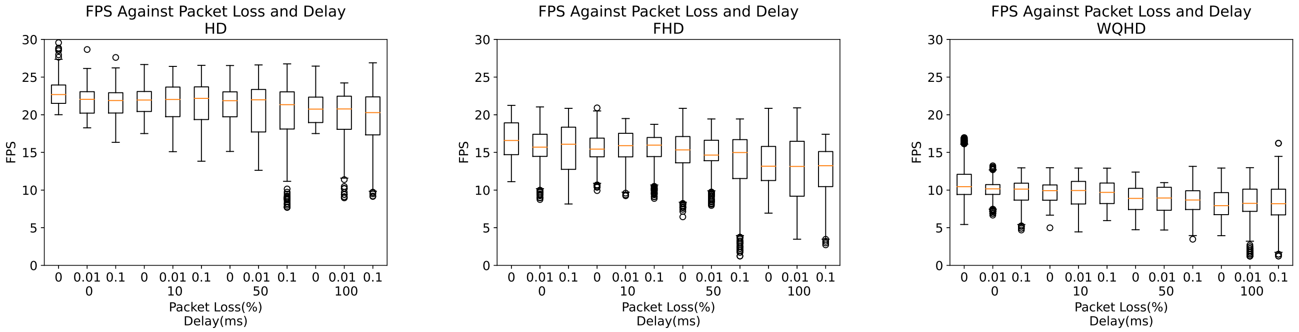

Fig. 5. FPS distribution for various delay and packet loss states

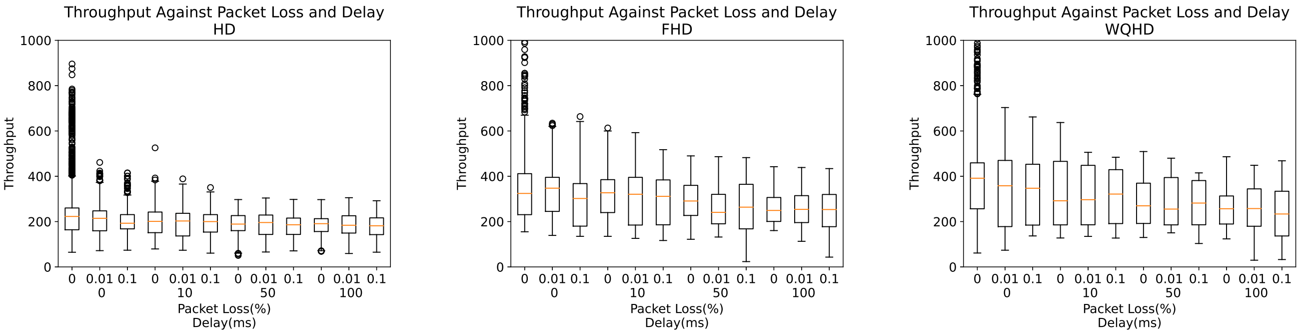

Fig. 6. Throughput distribution for various delay and packet loss states

utilized for deriving the models with 95% confidence bounds. Furthermore, Table III displays the model coefficients, a, b, c, d, and e for various quality representations.

B. Accuracy Evaluation

To precisely assess the models, the accuracy of each variant was evaluated. To this effect additional subjective assessment data is obtained, facilitating the generation of test QoE scores. The test QoE scores are utilized for evaluation against the model generated scores for the same network conditions. Thus, Table IV list various correlation metrics, with metrics such as Pearson Linear Correlation Coefficient (PLCC), Spearman Rank Order Correlation Coefficient (SROCC), Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE), all employed to appropriately examine the correlation and errors of the respective model variants.

It is evident from the correlation analysis that the predicted scores of the model variants display a correlation with the test QoE scores. This indicates that the proposed models can suitably reflect the user QoE. Although various factors could impact QoE for holographic applications, with correlation scores of approximately 0.6 and 0.66 for the Q1 and Q3 variants respectively, it can be inferred that the models can adequately support live holographic teleportation for latency sensitive network conditions.

VI. CONCLUSION AND FUTURE WORK

The rise in popularity of volumetric and holographic communications, coupled with the introduction of more powerful and user-friendly devices and resources, has opened up a new frontier in communication. This frontier emphasizes immersiveness and interactivity. In line with these advancements, this paper focuses on applications like holographic teleportation, which has specific and demanding requirements. It evaluates the impact of network-related factors on user quality of experience for latency sensitive live holographic teleportation.

Extensive double stimulus subjective assessments were carried out to evaluate the influence of delay and packet loss on user QoE, considering interactivity, quality, and playback latency under latency sensitive conditions. Additionally, a comprehensive analysis of multiple metrics was performed to establish a clear relationship between these factors and user QoE. Results and feedback from participants indicate that the double stimulus approach enables more effective assessment, especially for latency sensitive scenarios.

Furthermore, when exposed to erroneous network conditions in live holographic communication, interactivity takes precedence over quality for users, highlighting the necessity for adaptations to meet user demands. Leveraging the subjective data, various models were developed to represent the corresponding quality for QoE evaluation. These models demonstrate satisfactory correlation compared to subjective ground truth QoE scores, achieving Pearson correlation scores of up to 0.66. Consequently, these models provide a viable alternative for QoE evaluation in the context of latency sensitive live holographic teleportation.

In the forthcoming work, the scope of experiments will be broadened to encompass a larger participant pool and additional factors for evaluation. Additionally, the model's performance will be evaluated, with various statistical techniques and

TABLE III
MODEL COEFFICIENTS FOR THE QUALITY REPRESENTATION VARIANTS OF THE PROPOSED QOE MODEL

Quality Representation	a	b	c	d	e	a_{bounds}	b_{bounds}	c_{bounds}	d_{bounds}	e_{bounds}
Q1	1.442	-0.03097	0.5715	-87.52	1.342	1.165 1.719	-0.04995 -0.012	0.3543 0.7887	-167 -8.057	1.042, 1.641
Q2	0.9869	-0.03073	-1322	0.001737	1324	0.7291 1.245	-0.05628 -0.005183	-1.607×10^7 1.607×10^7	-21.11 21.11	-1.607×10^7, 1.607×10^7
Q3	1.571	-0.0147	0.3691	-94.9	0.656	0.7923 2.35	-0.02974 0.0003462	0.1658 0.5724	-219.3 29.48	-0.1736, 1.486

TABLE IV
MODEL ACCURACY

Quality Representation	PLCC	SROCC	RMSE	MAE
Q1	0.58	0.59	0.90	0.67
Q2	0.57	0.59	0.80	0.64
Q3	0.66	0.66	0.79	0.64

transmission conditions considered. Moreover, a comparative analysis will be conducted, comparing it with similar models, and exploring adaptation and intelligent adaptation techniques.

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