國立清華大學電機資訊學院資訊工程研究所

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Master Thesis

低軌衛星與5G毫米波網路下之雲端虛擬實境遊戲串流體驗評估

Evaluating Cloud VR Gaming Experience over LEO Satellite and 5G mmWave Networks

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中文摘要

雲端 VR 遊戲將 VR 遊戲運算卸載至遠端雲端伺服器，並透過盡力而為的網際網路將渲染後的遊戲畫面串流至資源受限的頭戴式顯示器 (Head-Mounted Displays, HMDs)。居住在偏遠地區或市中心擁擠地帶的玩家，往往因為高延遲、低頻寬以及動態變化的網路狀況，無法順利享受此類服務。儘管新興的低軌衛星 (Low Earth Orbit, LEO) 以及 5G 毫米波 (millimeter Wave, mmWave) 網路為這些區域帶來更高品質的網路連線，這些技術是否能為當地玩家提供良好的使用者體驗 (Quality of Experience, QoE)，仍未被深入研究。本論文透過使用來自 Starlink 和商用 5G 行動網路之公開資料集中的多組具有挑戰性的網路追蹤記錄，進行詳細的使用者研究。研究結果顯示：相較於 5G mmWave 網路，LEO 衛星網路可提供更佳的雲端 VR 遊戲使用者體驗；網路延遲對於雲端 VR 遊戲 QoE 的影響尤為關鍵；快節奏遊戲在 LEO 衛星網路中表現較佳，而具備豐富紋理的遊戲則在 5G mmWave 網路中表現更佳。綜合而言，本論文證實，為居住在偏遠地區與市中心擁擠地帶的玩家提供高 QoE 的雲端 VR 遊戲服務是可行的。

Abstract

Cloud VR gaming offloads VR games to remote cloud servers and streams rendered game scenes over the best- effort Internet to resource-constrained Head-Mounted Displays (HMDs). Gamers living in remote regions and crowded down- towns cannot enjoy such services because of high network delay, low network bandwidth, and dynamic network conditions. Although emerging Low Earth Orbit (LEO) and 5G millimeter Wave (mmWave) networks bring better-quality Internet access to remote regions and crowded downtowns, whether they could enable good Quality of Experience (QoE) for gamers living there has never been studied. In this thesis, we conduct a detailed user study using a few challenging network traces in public datasets collected from Starlink and commercial 5G cellular networks. Our user study shows that: (i) LEO satellite networks achieve better cloud VR gaming QoE than 5G mmWave networks, (ii) delay plays a more critical role in ensuring good cloud VR gaming QoE, and (iii) fast-paced games work better in LEO satellite networks, while texture-rich games work better in 5G mmWave networks. In summary, this thesis confirms the feasibility of offering high-QoE cloud VR gaming services to gamers living in remote regions and crowded downtowns.

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我誠摯且衷心地感謝我的指導教授徐正炘教授，他在我研究生涯中的悉心指導，不僅深深影響了我的學術發展，也啓發了我的個人成長。除了持續地提供支持與具啓發性的技術指導外，徐教授還教會了我如何批判性思考、進行有意義的研究，以及以科學的方法撰寫論文。在他的細心回饋與耐心指導下，我學會了如何有邏輯地組織與表達自己的想法，並自信地在書寫與簡報中呈現研究成果。

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Chapter 1

Introduction

In the rapidly evolving digital entertainment landscape, Virtual Reality (VR) gaming immerses gamers with Head-Mounted Displays (HMDs) into virtual gaming worlds. Existing tethered HMDs such as Pimax 8K X, HP Reverb G2, and VIVE Pro 2 are connected to powerful rendering PCs via cables, which are expensive, stationary, and cumbersome. In contrast, standalone HMDs, such as Meta Quest 3, Pico 4, HTC Vive Focus Plus, and Apple Vision Pro, free VR gamers from cables but lack enough computational power for rendering high-quality virtual gaming worlds. To cope with the limitations, cloud VR gaming wirelessly shifts the computational burdens of standalone HMDs to cloud datacenters [2, 11, 27, 29] to stream high-quality, rendered game scenes from cloud servers to standalone HMDs, allowing VR gamers to access cutting-edge games using standalone HMDs. Cloud VR gaming, however, demands low delay[1], high bandwidth, and a manageable packet loss rate from the underlying networks for an appealing Quality of Experience (QoE). Because diverse and dynamic network conditions could negatively affect the cloud VR gaming experience, both open-source [29] and commercial [61] cloud VR gaming testbeds have been adopted in recent studies to evaluate the performance of cloud VR gaming systems [11, 27].

However, to the best of our knowledge, the QoE of cloud VR gaming over emerging LEO (Low Earth Orbit) and 5G mmWave (millimeter Wave) networks has not been rigorously investigated, although intuitively, they may allow gamers living in remote regions and crowded downtowns to play cloud VR games with high QoE. This is because, before the availability of these emerging network technologies, gamers living in remote areas either had terrestrial networks with limited bandwidth or Geosynchronous Earth Orbit (GEO) satellite networks with high network delay, while gamers living in crowded downtowns often suffered from congested cellular networks with insufficient capacity.

[1]Throughout this paper, we use delay for the time difference in the network layer, while latency for that in the application layer to avoid ambiguity.

We are therefore curious about the following two Research Questions (RQs).

- **RQ1**: How good is a LEO network for cloud VR gaming QoE?
- **RQ2**: How good is a 5G mmWave network for cloud VR gaming QoE?

One way to answer these two questions is to carry out a user study on a real cloud VR gaming testbed connected by these two emerging networks. Doing so, however, is tedious, expensive, and error-prone because of too many external factors that we couldn't control. Moreover, as networks are inherently dynamic, more subjects are needed for statistically meaningful user studies, while fair comparisons among different system parameters become more challenging, if possible at all.

To cope with this challenge, we adopt a network emulator to replay publicly available network traces in our testbed, built upon the open-source Air Light XR (ALXR) [31] project. To emulate the emerging networks, we analyze a LEO satellite dataset [59] and a 5G mmWave dataset [36] to select a few more challenging network traces for our user study. We only adopt these sample network traces to control the duration of the user study for fatigue avoidance. We adopt the single stimulus method [18] with integer Absolute Category Rating (ACR) between 1 (the worst) and 5 (the best). After each gaming session (at most 100 seconds), a subject answers the following five QoE questions: (i) overall quality, (ii) visual quality, (iii) interaction quality, (iv) immersive level, and (v) cybersickness. Mean Opinion Score (MOS) of each QoE question is calculated, reported, and analyzed.

Our user study, as the first of its kind, reveals the following key findings:

- Delay and bandwidth both affect the cloud VR gaming experience, but delay plays a more significant role.
- LEO satellite networks are more suitable for cloud VR gaming than 5G mmWave networks because of shorter and less fluctuating delay. Nonetheless, both LEO satellite and 5G mmWave networks provide acceptable MOS results of 3.75 and 3.59 (out of a scale of 1–5) in overall quality.
- LEO satellite networks offer a better gaming experience with fast-paced games, while 5G mmWave networks allow a better gaming experience with texture-rich games. These two networks can both support leisure games.

In summary, for RQ1, we find that LEO networks achieve a comparable cloud VR gaming experience to collocated VR gaming servers: no significant difference is observed. In contrast, for RQ2, we find that 5G mmWave networks deliver a worse cloud VR gaming experience than collocated VR gaming servers: a significant difference is found in overall quality, interaction quality, and immersive level. We emphasize that the user study was conducted with (top 10%) challenging network traces in these emerging networks, and their actual QoE gaps with collocated VR gaming servers in the field will be mostly smaller, showing the potential to bring cloud VR games to gamers living in remote regions and crowded downtowns.

1.1 Contributions

This thesis based on this work [24] and makes the following key contributions:

- **Testbed Setup:** We set up a cloud VR gaming testbed that integrates real-time frame capture, low-latency encoding (using NVIDIA NVENC), and frame streaming using the ALXR platform. A FreeBSD-based network emulator (Dummynet) was used to inject controlled network impairments.
- **Network Trace-Based Selection:** We carefully selected real-world network traces from LEO satellite (LENS dataset) and 5G mmWave (5GOrpher dataset), representing different performance conditions including low bandwidth, fluctuating bandwidth, high delay, and fluctuating delay.
- **User Study Design and Execution:** We conducted a comprehensive detailed user study with 16 participants who evaluated three cloud VR games under various network conditions. Subjective QoE metrics were collected using structured questionnaires.
- **QoE Analysis with Statistical Testing:** We statistically analyzed QoE results across networks using Dunn's post-hoc tests to identify significant differences. The analysis revealed that LEO provides more stable delay and better performance in time-sensitive games, while 5G mmWave offers higher throughput suitable for visually rich games.

1.2 Limitations

While the study offers meaningful insights into cloud VR gaming performance over emerging network technologies, some limitations must be acknowledged:

- **Controlled Laboratory Conditions:** Although real network traces were used for emulation, the evaluation was conducted in a controlled lab testbed. As such, it does not fully capture real-world unpredictability such as live congestion, user mobility, or environmental interference.
- **Limited Trace Diversity:** The selected network traces, although representative of challenging conditions, were drawn from specific geographical regions (E.g., Seychelles for LEO and U.S. cities for 5G mmWave). This may not encompass the full diversity of deployment environments globally.
- **mmWave Trace Characteristics:** The 5G mmWave traces used in this study did

not explicitly include transitions between Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) states or high-packet-loss events.

- **Application and Device Scope:** The evaluation focused on a specific cloud VR setup using the ALXR platform and a small set of representative games. Results may vary across different hardware configurations, interaction modalities, or content genres.
- **User Sample Size:** The user study involved 16 participants, which, while sufficient for statistical analysis, may not reflect the diversity of VR users across various age groups, gaming experience levels, or cultural backgrounds.

1.3 Organization

The remainder of this thesis is organized as follows:

- **Chapter 2: Background** — Reviews the foundational concepts of cloud VR gaming, Quality of Experience (QoE), and previous studies on emerging network technologies.
- **Chapter 3: Related Work** — Explores the related works of VR gaming Quality of Experience (QoE), cloud gaming Quality of Experience (QoE), and cloud VR gaming Quality of Experience (QoE).
- **Chapter 4: Testbed Setup** — Describes the architecture and implementation of the cloud VR testbed, and network emulation setup.
- **Chapter 5: User Study Design** — Details the network datasets and the procedure of the selection of representative network traces, user study procedure, evaluation metrics, and game configurations used in the study.
- **Chapter 6: Evaluation of User Study Results** — Presents the collected QoE data, statistical findings, and network trace-based network performance analysis. Interprets the findings, relates them to user experience, and explores implications for future cloud VR systems.
- **Chapter 7: Conclusion and Future Work** — Summarizes the key contributions and insights of this work and outlines directions for future research.

Chapter 2

Background

This chapter provides the necessary background knowledge on virtual reality, cloud gaming, cloud VR gaming, and the emerging network technologies like Low Earth Orbit (LEO) satellite networks and 5G millimeter Wave (mmWave) networks.

2.1 Virtual Reality

Virtual Reality (VR) refers to computer-generated environments that completely immerse users, providing a sense of presence in a virtual world that replaces their perception of the physical environment. According to Slater and Wilbur [44], VR fundamentally creates a psychological feeling of ”being there” despite physical absence from the depicted scene. As one component within the Extended Reality (XR) spectrum, VR occupies what Milgram and Kishino [34] identify as the ”complete virtuality” end of the reality-virtuality continuum. Unlike Augmented Reality (AR), which overlays digital elements onto physical environments, or Mixed Reality (MR), which creates interactive blends of real and virtual objects, Virtual Reality (VR) is designed to completely immerse users by replacing real-world sensory input with synthetic stimuli generated by computer systems [9]. Fig. 2.1 depicts the categories of Extended Reality (XR), which include Augmented, Virtual, and Mixed Reality.

The conceptual foundations of modern VR date back to Ivan Sutherland's work in 1968, when he created the first head-mounted display system [49], it was groundbreaking and offered immersive experiences, but it also posed technical challenges and risks for users, reflecting the complexities involved in developing early VR technology. After decades of development, VR began its transition toward consumer adoption with Palmer Luckey's Oculus Rift prototype in 2012, followed by Facebook's acquisition of Oculus in 2014. The global VR market is experiencing significant growth and was valued 16.32 billion USD in 2024 and is projected to increase to 123.06 billion USD in 2032 [12].

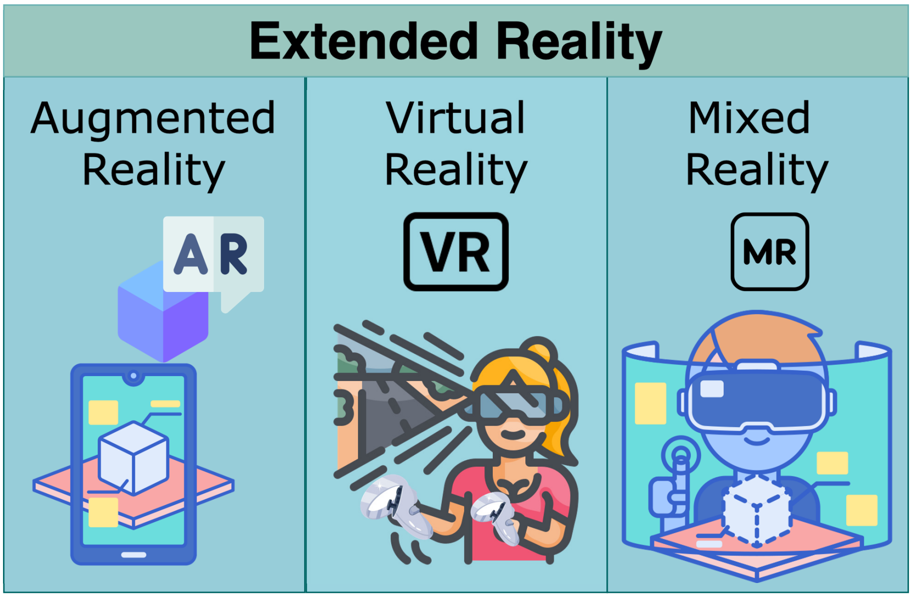


Figure 2.1: XR spectrum encompassing AR, VR, and MR technologies.

Contemporary VR systems comprise several essential components working in concert to create immersive experiences:

- **Head-Mounted Displays (HMDs):** These devices contain stereoscopic displays that present slightly different images to each eye, creating depth perception. HMDs can be classified into two primary categories:
  - *Tethered HMDs:* Connected to external computing systems via cables (e.g., Pimax 8K X, HP Reverb G2, VIVE Pro 2), offering superior visual fidelity but limited mobility.
  - *Standalone HMDs:* Self-contained units with integrated processing capabilities (e.g., Meta Quest 3, Pico 4, HTC Vive Focus Plus, Apple Vision Pro), prioritizing portability but traditionally delivering lower graphical quality.
- **Tracking Systems:** These technologies monitor user movement and position in physical space. For example, external sensors or cameras positioned around the play area track the user's movement, and cameras and sensors mounted directly on the HMD track movement relative to the surrounding environment.
- **Input Controllers:** Specialized controllers, gloves, and other interaction peripherals allow users to manipulate virtual objects and navigate digital environments. These controllers typically feature precise motion tracking, haptic feedback, and intuitive button layouts designed specifically for virtual interactions.
- **Spatial Audio:** Directional sound systems enhance immersion by providing audio cues that match visual stimulus locations, reinforcing spatial awareness within virtual environments. Three-dimensional audio creates a convincing soundscape that responds to head movements and source positioning, further strengthening the

sense of presence.

Researchers have developed various frameworks to categorize VR experiences based on their immersion levels. Perle Systems [38] categorizes virtual reality experiences into five distinct types based on their implementation and user experience characteristics:

- **Non-immersive VR:** This represents the most basic form of virtual reality, where users interact with a 3D environment through a standard display without head tracking. Typically experienced through desktop or laptop computers, non-immersive VR maintains users' awareness of their physical surroundings while providing a window into a virtual space. Common applications include traditional 3D modeling software, certain educational simulations, and early architectural visualization tools.
- **Semi-immersive VR:** These systems provide moderate immersion through large displays, specialized projection systems, or limited field-of-view headsets. Flight simulators represent classic examples of semi-immersive VR, where realistic controls combine with wide-screen visuals to create partial immersion while maintaining awareness of the physical environment. These experiences typically offer high graphical fidelity and specialized input devices but do not fully occlude the real world.
- **Fully immersive VR:** Representing the most common understanding of modern VR, fully immersive experiences utilize head-mounted displays that completely replace the user's visual field with computer-generated environments. These systems incorporate comprehensive motion tracking, specialized controllers, and often spatial audio to create a convincing sense of presence in the virtual world. Gaming, therapeutic applications, and professional training represent major application areas for fully immersive VR. Slater [43] argues these systems create a profound "place illusion" - the compelling sensation of being physically present within the virtual space.
- **Collaborative VR:** This category emphasizes multi-user virtual environments where multiple participants can interact with each other and shared virtual objects regardless of physical proximity. Enterprise training, social platforms, and remote collaboration tools employ collaborative VR to enable geographically distributed teams to work together in shared virtual spaces. These systems typically prioritize avatar representation, communication tools, and synchronized environments to maintain consistent experiences across all participants. Churchill and Snowdon [8] pioneered research into these "collaborative virtual environments" (CVEs), defining them as distributed digital spaces designed for multi-user interaction.
- **Augmented Reality (AR):** While technically distinct from VR, augmented real-

ity represents a related technology that overlays digital information onto the user's view of the physical world rather than replacing it entirely. Devices like Microsoft HoloLens, Magic Leap, and smartphone-based AR applications allow virtual elements to appear within and interact with the real environment. Industrial maintenance, retail experiences, and navigation assistance exemplify common AR applications.

Despite remarkable technological advances, VR still faces significant implementation challenges. Cybersickness greatly affects new users due to sensory conflicts between the visual and vestibular systems. Current hardware limitations include restricted field of view (90-120° versus human vision's 210°), visible pixel structures in displays, and high computational demands requiring high-performance hardware to maintain the 90Hz+ refresh rates necessary for comfort. Cloud-based VR applications introduce additional complexity with stringent requirements for bandwidth, latency under 20ms, and network stability.

Beyond entertainment, VR has established valuable applications across diverse professional domains. In healthcare, VR provides effective tools for pain management, exposure therapy for psychological conditions, surgical training, and rehabilitation. Educational implementations create experiential learning environments for abstract concepts, while design industries employ VR for prototyping and visualization that reduces development costs. VR social platforms enable natural collaboration through spatial presence and embodied interaction. Scientific applications leverage VR for data visualization and experimental environments impossible to create physically.

VR technologies have expanded well beyond entertainment into numerous professional domains:

- **Healthcare:** VR demonstrates proven efficacy in surgical simulation, pain management, exposure therapy, and rehabilitation protocols. Hoffman et al. [19] documented VR's effectiveness for pain management in burn patients, while Rizzo and Koenig [42] reviewed its applications treating PTSD and anxiety disorders.
- **Education and Training:** Freina and Ott [15] survey immersive learning environments across educational contexts, noting VR's particular value for teaching concepts difficult to visualize through traditional instructional methods.
- **Design and Manufacturing:** Berg and Vance [6] examined industry applications, finding widespread adoption for virtual prototyping, architectural visualization, and collaborative design reviews across manufacturing sectors.
- **Social Interaction:** Maloney and Freeman [32] investigate platforms designed for social engagement in virtual spaces, identifying key factors that create meaning-

ful shared experiences, including embodiment, spatial presence, and interpersonal connection.

- **Scientific Research:** Fox et al. [13] explore VR's applications for data visualization, experimental design, and psychological studies, emphasizing VR's capacity to create controlled conditions difficult or impossible to replicate in physical environments.

2.2 Cloud Gaming

Cloud gaming represents a paradigm shift in digital entertainment delivery, fundamentally altering how interactive content reaches end users. Unlike traditional gaming, where software executes locally on user hardware, cloud gaming offloads computation to remote servers while streaming the resulting audiovisual output to client devices. We can see a common structure of a cloud gaming platform in the figure 2.2.

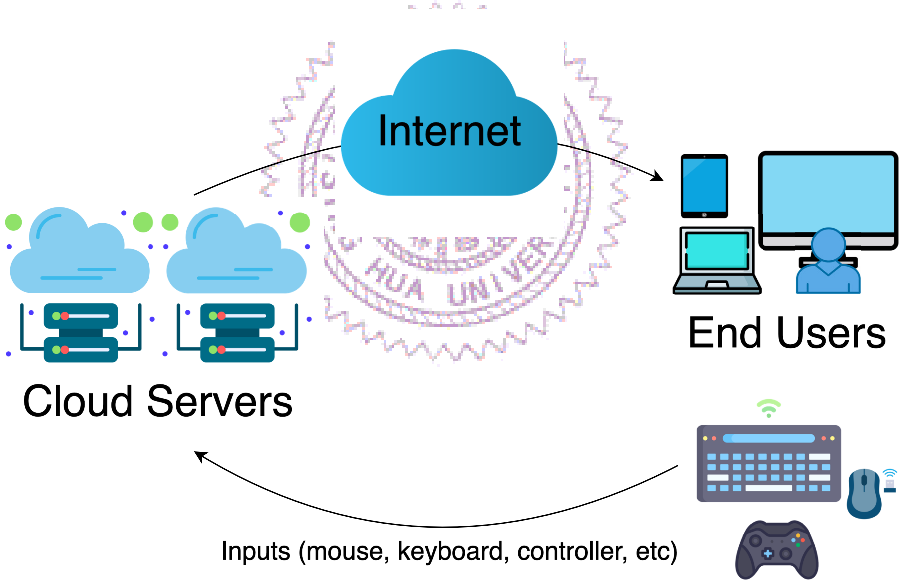


Figure 2.2: Overview of a general cloud gaming platform.

At its core, cloud gaming employs a client-server architecture where gameplay processing occurs entirely on remote servers. This architecture comprises several key components:

- **Server-Side Processing:** Game logic, physics calculations, and rendering occur on high-performance servers in datacenters. These servers handle all computational aspects that would traditionally execute on local hardware.
- **Video Encoding:** Rendered frames undergo real-time compression using advanced codecs to reduce bandwidth requirements. Encoder optimization specifically for gaming content significantly affects perceived quality.

- **Network Transmission:** Compressed video streams travel to clients while user inputs return to servers. This bidirectional communication creates a closed loop where minimizing latency becomes critical.
- **Client-Side Decoding:** Lightweight client applications decompress incoming video streams and display them while capturing user inputs. Client software can operate on devices with minimal computational capabilities.

This architecture effectively transforms interactive applications into video streams, making high-end gaming accessible on resource-constrained devices, essentially democratizing access to computationally intensive experiences by removing hardware barriers.

Despite significant progress in cloud gaming architecture, cloud gaming continues to face several persistent technical challenges:

- **Latency:** End-to-end latency remains the most significant barrier to cloud gaming adoption. Latency components include server processing, network transmission, and client decoding delays. Total latencies exceeding 100ms significantly degrade gaming experiences, particularly in fast-paced genres.
- **Bandwidth Requirements:** High-quality video streaming demands substantial network bandwidth.
- **Compression Artifacts:** Real-time video encoding introduces visual artifacts, particularly during high-motion sequences. Compression artifacts become more noticeable in scenes with rapid movement or complex textures, degrading perceived quality.
- **Network Instability:** Fluctuations in bandwidth, latency spikes, and packet loss significantly impact streaming quality. Even brief network disruptions can cause noticeable stutter, frame drops, or quality degradation that directly affects gameplay.
- **Scalability Challenges:** Server infrastructure must efficiently balance resources across multiple simultaneous users. GPU virtualization and dynamic resource allocation remain complex challenges for large-scale deployments.

These technical hurdles represent areas of active research, with academia and industry pursuing solutions through improved algorithms, adaptive streaming technologies, and novel system architectures. Several major commercial cloud gaming platforms currently operate, each employing distinct technical approaches and business models:

- **NVIDIA GeForce NOW:** Launched commercially in February 2020, this service provides access to users' existing game libraries purchased on platforms like Steam and Epic Games Store. GeForce NOW integrates with existing distribution platforms rather than creating a closed ecosystem.
- **Xbox Cloud Gaming (xCloud):** Microsoft's cloud service integrates directly with

Xbox Game Pass, offering a subscription library model. This integration with Microsoft's broader gaming ecosystem differentiates it from standalone services.

- **Amazon Luna:** Operating on a channel-based subscription model, Luna leverages Amazon's extensive AWS infrastructure. Luna benefits from Amazon's ownership of both content delivery networks and cloud computing resources.
- **PlayStation Plus (formerly PlayStation Now):** Sony's service focuses primarily on its proprietary game library. PlayStation has evolved from a standalone streaming service to integration with Sony's broader subscription offerings.

These implementations demonstrate different approaches to addressing cloud gaming's core challenges, each making distinct tradeoffs in terms of library access, pricing models, and technical performance. Network quality directly determines cloud gaming performance. Different game genres have varying latency tolerance, with first-person shooters may require 50 ms round-trip time, while turn-based strategy games may remain playable around 150 ms. Consistent bandwidth is often more important than peak throughput. Even minimal packet loss can severely impact perceived quality. Network conditions also affect subjective Quality of Experience (QoE). Cloud gaming research increasingly focuses on subjective factors that influence user acceptance beyond technical metrics.

Looking ahead, cloud gaming continues to evolve through several key technological advancements. Edge computing integration places processing resources closer to users, leveraging 5G networks to create hybrid rendering systems that significantly reduce latency. The technology increasingly serves as a cross-platform bridge, potentially transforming traditional gaming ecosystems into more interconnected experiences. Perhaps most significantly, cloud rendering for extended reality applications (VR/AR) represents an emerging frontier, though it introduces unique challenges, including stringent motion-to-photon latency requirements and the complexities of stereoscopic content delivery. These emerging directions suggest cloud gaming will continue expanding beyond its current implementation.

The intersection of cloud gaming with VR technology creates particularly interesting research opportunities, combining the inherent challenges of both domains and creating a unique set of technical requirements that push the boundaries of current network infrastructure.

2.3 Cloud VR Gaming

Cloud VR gaming represents the convergence of two transformative technologies: cloud gaming and virtual reality. This integration aims to overcome the computational limitations of standalone VR headsets while maintaining the mobility advantages they offer over tethered systems. By offloading rendering tasks to remote servers, cloud VR gaming promises to deliver high-fidelity virtual experiences on lightweight, untethered devices. Cloud VR gaming builds upon traditional cloud gaming architecture with additional requirements specific to immersive content. Fig. 2.3 illustrates a typical cloud VR gaming system, which has components like game providers, cloud servers, internet, and VR user clients. As described by Li et al. [29], the fundamental pipeline consists of several distinct stages:

- **Content Generation:** VR application logic and rendering occurs on powerful server hardware, generating stereoscopic frames at high resolution and frame rate.
- **Video Encoding:** Rendered frames undergo specialized compression optimized for stereoscopic content and motion characteristics unique to head movements.
- **Network Transmission:** Compressed video streams travel to the client device while motion tracking data flows in the opposite direction.
- **Client Processing:** The headset decodes incoming video, displays it with minimal latency, and continuously transmits precise head and controller tracking information back to the server.

Cloud VR gaming requires significantly more stringent performance parameters than traditional cloud gaming, particularly regarding motion-to-photon latency, the time between a user's physical movement and the corresponding visual update. Cloud VR gaming faces several distinct technical challenges beyond those of traditional cloud gaming, such as ultra-low latency requirements, high bandwidth requirements, quality consistency, and computational scaling requirements.

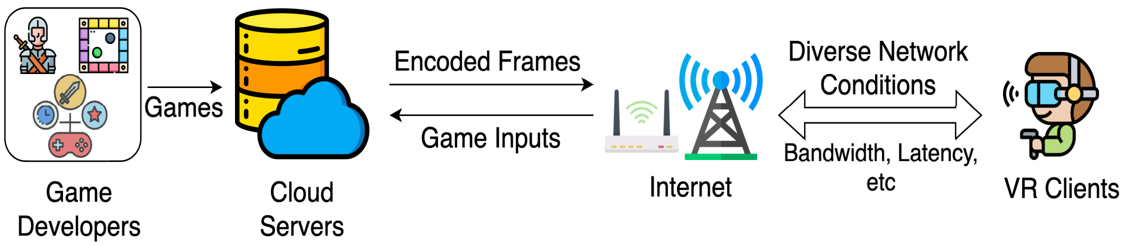


Figure 2.3: A typical structure of a cloud-based VR gaming system.

These challenges represent significant barriers to the widespread adoption of cloud VR gaming services. Current commercial implementations typically employ hybrid approaches, with varying degrees of processing occurring locally on headsets to compensate for network limitations. Several implementations of cloud VR gaming have emerged, spanning both commercial platforms and open-source solutions:

- **NVIDIA CloudXR:** This commercial solution extends NVIDIA's cloud gaming technologies specifically for VR/AR streaming. CloudXR implements specialized encoding techniques for stereoscopic content and provides SDK components for integration with existing VR applications.

- **ALXR/ALVR:** These related open-source projects enable streaming VR content from PCs to standalone headsets. ALXR, an extension of the ALVR codebase, implements OpenXR compatibility for capturing rendered VR frames and transmitting them to mobile headsets.
- **Oculus Air Link:** Meta's proprietary streaming solution for Quest headsets emphasizes ease of use within a controlled ecosystem. Unlike platform-agnostic solutions, Air Link benefits from deep hardware integration but restricts usage to specific device combinations.
- **VRidge:** This commercial solution enables VR streaming across a wider range of devices, including smartphone-based headsets.

These existing implementations demonstrate varying approaches to addressing the core challenges of cloud VR gaming, each making different tradeoffs between performance, compatibility, and resource requirements. Network characteristics fundamentally determine cloud VR gaming feasibility. Traditional home broadband and public networks often struggle to meet the stringent requirements for latency and bandwidth stability.

Recent emerging network technologies suggest promising pathways toward making cloud VR gaming viable across diverse geographical contexts, though significant implementation challenges remain. Cloud VR gaming represents an important frontier in immersive computing, potentially enabling high-quality VR experiences on lightweight devices. While significant technical challenges persist, continued advancements in network technology and streaming algorithms suggest an increasingly viable pathway toward mainstream implementation.

2.4 Quality of Experience Evaluations

Quality of Experience (QoE) has become an important way to understand how users interact with and feel about multimedia systems. While Quality of Service (QoS) focuses on technical measurements like bandwidth and latency, QoE looks at the human side of technology use, giving us better insights into how satisfied users are with systems like cloud VR gaming.

2.4.1 Quality of Experience (QoE)

The International Telecommunication Union (ITU-T) formally defines Quality of Experience as "the degree of delight or annoyance of the user of an application or service" [22].

This definition represents a significant evolution from traditional Quality of Service (QoS) metrics, which primarily focus on objective network and system performance parameters. QoE extends beyond technical measurements to encompass the subjective, multidimensional nature of human perception and satisfaction.

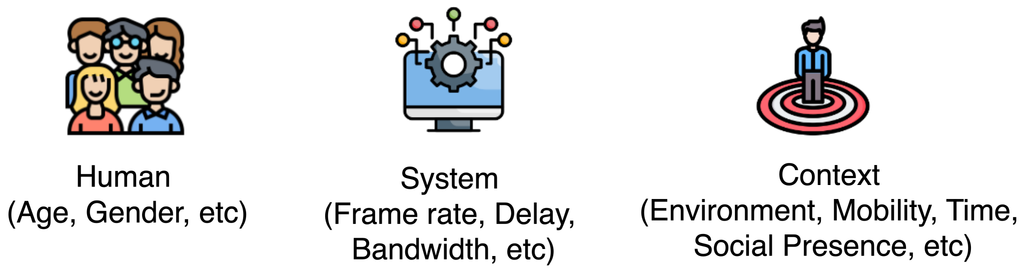


Figure 2.4: The factors that influence QoE evaluation.

The fig. 2.4 categorizes the key factors influencing Quality of Experience (QoE) into three groups. The QoE paradigm recognizes that user experience is not solely dictated by technical performance but emerges from a complex interplay of influences spanning system, human, and contextual dimensions. This multi-dimensional perspective is critical for accurately assessing and optimizing end-user satisfaction in interactive and immersive applications such as cloud VR gaming.

- **System Influence Factors:** These refer to the technical attributes of the service delivery chain, encompassing aspects such as network performance (e.g., latency, jitter, packet loss), hardware and device capabilities (e.g., display resolution, input responsiveness), and application-level parameters such as media compression, encoding settings, and frame rates. They directly impact the perceptual quality and interactivity of the application.
- **Human Influence Factors:** These include user-specific characteristics such as individual expectations, prior experience with similar technologies, cognitive and emotional states, attention levels, and sensory or perceptual abilities. These factors affect how users interpret and react to the system's performance, making QoE inherently subjective and user-dependent.
- **Context Influence Factors:** These capture the broader conditions under which the service is used, including the physical environment (e.g., lighting, noise), social context (e.g., shared or solo use), the nature of the activity or task (e.g., gaming, training, collaboration), economic considerations, and temporal aspects (e.g., time of day, duration of use). Such factors shape the relevance and perceived value of the experience beyond what technical metrics alone can explain.

This classification framework provides a holistic foundation for designing and evaluating immersive applications, ensuring that QoE assessments reflect real-world use conditions and diverse user profiles.

In immersive environments like virtual reality, the QoE conceptual framework requires further extension to address unique aspects of spatial media consumption. Slater and Wilbur [44] proposed an influential framework that identifies key dimensions of VR experience: presence (the psychological sense of "being there"), immersion (the objective fidelity of sensory stimulation), involvement (the user's engagement with content), and plausibility (the coherence of events within the virtual environment). These dimensions have been widely adopted in subsequent QoE research for immersive media. Also, to narrow the concept of QoE to gaming scenarios, particularly in the context of cloud VR, we can refer to this as gaming QoE, the player's perceived satisfaction or discomfort during interactive gameplay. There are additional factors that can influence more in the evaluation of gaming QoE, as shown in 2.5. First, technical factors such as network conditions, latency, responsiveness, and input delay directly affect interactivity and fluidity, especially critical in fast-paced or competitive games. Second, player-related factors include the user's skill level, fatigue, familiarity with VR systems, and cognitive state, all of which shape how a player perceives and reacts to the game environment. Lastly, game-specific factors, including genre, game mechanics, control intuitiveness, narrative engagement, and difficulty, influence how enjoyable or immersive the experience feels. These dimensions highlight the complexity and subjectivity of gaming QoE and its critical dependence on the interaction between the system, the user, and the game itself.

Figure 2.5: Additional factors that influence the gaming QoE evaluation.

QoE assessment methodologies span a spectrum from highly controlled experiments to ecological field studies in natural usage environments. Each approach offers distinct advantages and limitations for understanding user experience, particularly in complex interactive applications like cloud VR gaming. The ITU has developed standardized methodologies for conducting laboratory QoE evaluations across various media types like subjective assessment for video quality in multimedia applications, television picture quality, transmission quality in telephone, gaming QoE. These standards define specific environmental conditions, participant selection criteria, stimulus presentation methods, rating procedures, and statistical analysis techniques to ensure reproducibility and comparability of results across studies. However, laboratory settings may lack ecological validity, particularly for applications like VR gaming where context of use significantly impacts experience.

2.4.2 Subjective QoE Assessment Methods

Subjective assessment represents the most direct approach to QoE evaluation, capturing user perceptions and judgments through standardized protocols. The selection of appropriate assessment methods depends on research objectives, application characteristics, and practical constraints. Stimulus Presentation Methods Standardized methods for presenting stimuli in subjective quality assessments aim to gather consistent and reliable feedback on user-perceived quality across different conditions. These methods vary in how stimuli are delivered and evaluated by participants:

- **Single Stimulus (SS):** In this method, participants view or experience each test condition independently, without any accompanying reference. After each presentation, they provide a quality rating based solely on their immediate impression. This approach is straightforward and efficient, making it suitable for scenarios where reference conditions are unavailable or impractical to establish.
- **Double Stimulus (DS):** Also known as paired comparison methods, this approach involves presenting a test stimulus alongside a predefined reference stimulus. Participants evaluate the test condition relative to the reference, allowing for more direct comparison. This method is particularly useful when evaluating degradations or improvements relative to a known baseline.
- **Single Stimulus Continuous Quality Evaluation (SSCQE):** This method extends the single stimulus approach by asking participants to continuously rate the perceived quality of a stimulus over a longer duration. It is especially suitable for evaluating content with dynamic quality changes, such as streaming media or long gaming sessions, as it captures fluctuations in perceived quality over time.
- **Stimulus Comparison (SC):** In this method, two or more test conditions are presented either sequentially or simultaneously, and participants are asked to compare them directly. This approach helps in identifying relative preferences and is often used in experiments focused on optimization or preference-based tuning.

In the context of interactive applications like cloud VR gaming, single stimulus methods are most frequently used. This is largely due to the inherent challenges in defining a consistent and meaningful reference condition within dynamic, real-time environments where user interactions continuously alter the experience. The unpredictable and immersive nature of gameplay means that traditional reference-based methods may not capture the nuances of user perception effectively. Moreover, the temporal dynamics of gaming experiences introduce additional complexity. Users may experience momentary disruptions (e.g., latency spikes or quality drops) that significantly impact their perception of quality, even if the overall session recovers. Therefore, when designing QoE assessments for such applications, it's crucial to carefully structure test sessions to account for both short-term perceptual impairments and overall user satisfaction. This often involves selecting appropriate session lengths, ensuring realistic interaction scenarios, and possibly integrating continuous or post-session evaluations to reflect the complete experience.

Rating Scales and Methods

A variety of rating scales and methods are employed to capture different dimensions of user-perceived Quality of Experience (QoE). These methods offer structured frameworks for quantifying subjective impressions, enabling systematic analysis across different experimental conditions. The most commonly used rating approaches include categorical, continuous, and hybrid scales:

- **Categorical Scales:** These discrete rating systems prompt users to select a value from a predefined set of categories. They are widely used for their simplicity and interpretability.
  - **Absolute Category Rating (ACR):** A widely adopted 5-point scale where participants rate the overall quality of a single stimulus as *1-Bad*, *2-Poor*, *3-Fair*, *4-Good*, or *5-Excellent*. This method is suitable for quick evaluations of standalone conditions.
  - **Degradation Category Rating (DCR):** A 5-point scale used to assess the perceived level of impairment when a test condition is compared against a reference. Ratings range from *1-Very Annoying* to *5-Imperceptible*.
  - **Comparison Category Rating (CCR):** A 7-point scale that allows users to evaluate a test stimulus relative to a reference, with values ranging from *-3 (Much Worse)* to *+3 (Much Better)*, and 0 indicating no perceived difference.
- **Continuous Scales:** These scales allow users to express their perceptions on a continuum, often through slider interfaces or analog devices. Continuous scales can capture finer-grained differences in experience and are particularly useful in dynamic or long-duration assessments such as video streaming or gaming.
  - **Single Stimulus Continuous Quality Evaluation (SSCQE):** Participants continuously rate perceived quality over time as a stimulus plays. This method captures quality fluctuations, making it valuable for real-time applications.
- **Hybrid and Custom Scales:** Depending on the application domain, researchers may adopt or design hybrid scales combining elements of categorical and continuous scales to better capture specific aspects of experience, such as immersion,

comfort, or interactivity in VR environments.

In addition to selecting an appropriate scale, the method of rating collection, whether during or after stimulus presentation, affects the granularity and reliability of results. Real-time elicitation (e.g., continuous sliders) captures immediate perceptual changes, while post-session questionnaires offer insights into the holistic impression of the experience. Overall, the choice of rating scale and method should align with the nature of the application, the expected temporal dynamics of quality, and the specific QoE dimensions under investigation.

2.4.3 Objective QoE Assessment Methods

While subjective assessment remains the gold standard for measuring perceived Quality of Experience (QoE), objective methods are increasingly vital due to their ability to provide automated, reproducible, and scalable evaluations. Unlike subjective testing, which is time-consuming and dependent on human participants, objective approaches offer consistent and continuous monitoring capabilities, making them especially suitable for real-time and large-scale systems. Objective QoE assessment methods can be classified into three main categories, each addressing different aspects of the end-user experience:

- **Media-Based Metrics:** These methods rely on the analysis of audiovisual content to estimate perceived quality.
  - *Full-Reference (FR)* metrics, such as Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), and Video Multi-Method Assessment Fusion (VMAF), require both the original and the degraded versions of the content. They calculate objective scores based on pixel-level or perceptual differences.
  - *Reduced-Reference (RR)* metrics use a subset of the original data or a summary representation to evaluate quality, striking a balance between accuracy and resource requirements.
  - *No-Reference (NR)* metrics estimate quality based solely on the distorted content without any reference, making them ideal for live streaming and field deployments where ground truth is unavailable. However, NR models are typically less accurate and often require domain-specific training.
- **QoS-Based Estimation:** These methods infer QoE based on network- and system-level Quality of Service (QoS) indicators such as latency, jitter, throughput, packet loss, and buffering events.
  - While these parameters do not directly represent user experience, they have a known influence on perceived quality, especially in latency-sensitive and interactive applications like cloud gaming and video conferencing.

    - Machine learning techniques are increasingly employed to model the complex, often non-linear relationships between QoS indicators and QoE outcomes. Supervised models trained on annotated datasets can predict subjective quality scores with reasonable accuracy.
    - QoS-based methods are scalable and can be embedded in monitoring systems for proactive quality assurance and adaptive service management.
- **Psychophysiological Measurements:** These emerging techniques capture the user's physiological and behavioral responses to assess QoE at a more implicit and continuous level.
    - Signals such as heart rate variability (HRV), electroencephalography (EEG), galvanic skin response (GSR), pupil dilation, and eye-tracking data are used to infer cognitive load, emotional engagement, discomfort, or fatigue.
    - These methods offer deeper insights into user experience beyond traditional quality metrics, potentially enabling more personalized and adaptive content delivery.
    - However, they require specialized equipment, careful experimental control, and advanced signal processing techniques, limiting their use primarily to research contexts and high-end applications.

Each category presents its own advantages and limitations in terms of accuracy, generalizability, computational cost, and practical feasibility. In real-world applications, hybrid models that combine insights from multiple methods often deliver the best performance. For instance, a system might use media-based metrics to evaluate visual quality, QoS indicators for transport performance, and physiological data to monitor user comfort—all integrated to form a comprehensive QoE profile. The choice of objective assessment techniques should align with the nature of the application, available resources, and the specific dimensions of QoE that are most critical for user satisfaction. In the context of cloud VR gaming, combining VMAF scores with real-time latency tracking and potentially incorporating gaze or motion tracking data can provide a holistic understanding of the user's experience. As technologies and datasets evolve, the role of objective methods in QoE research and industry applications will continue to grow, complementing and, in some cases, replacing traditional subjective evaluations.

An essential challenge in objective QoE assessment is bridging the gap between measurable Quality of Service (QoS) parameters and subjective Quality of Experience (QoE) outcomes. QoS-to-QoE mapping aims to establish mathematical or data-driven models that can accurately predict user-perceived quality based on network and system performance indicators such as packet loss, latency, jitter, and bandwidth. Traditionally, early models used analytical or empirical formulas based on psychometric functions or curvefitting techniques. However, due to the inherent non-linearity and application-specific nature of the QoS-to-QoE relationship, machine learning approaches have become increasingly prevalent. These methods leverage statistical learning techniques to model the complex and often non-linear relationships between QoS features and QoE scores. Common algorithms include:

- **Random Forests:** An ensemble learning method that builds multiple decision trees and combines their outputs to handle complex interactions between QoS parameters and to prevent overfitting. Random Forests are known for their robustness and ability to capture non-linear effects.
- **Support Vector Machines (SVMs):** These models are effective for capturing non-linear relationships by projecting input features into higher-dimensional spaces using kernel functions. SVMs are particularly useful when the relationship between QoS parameters and QoE is not easily separable in the original feature space.
- **Neural Networks:** Deep learning models, especially feedforward neural networks and convolutional neural networks (CNNs), have demonstrated superior performance in learning complex, high-dimensional mappings from QoS features to perceived QoE. Recurrent neural networks (RNNs) and Long Short-Term Memory (LSTM) networks are also employed when modeling time-series QoS data.

Machine learning-based QoS-to-QoE models often require a substantial amount of labeled training data, typically obtained from controlled subjective experiments. Feature engineering is critical in these models, as the relevance and quality of input QoS parameters significantly influence prediction accuracy. Beyond traditional supervised learning, newer approaches explore semi-supervised, unsupervised, and reinforcement learning paradigms to reduce the need for labeled data and adapt dynamically to varying network and application contexts. Furthermore, explainability and interpretability of the models are becoming increasingly important, particularly in operational environments where understanding how QoS factors influence QoE can inform network management, optimization strategies, and service-level agreements (SLAs). In cloud VR gaming and immersive applications, where user experience is highly sensitive to subtle variations in latency, frame loss, and throughput, accurate and dynamic QoS-to-QoE estimation models are vital for maintaining service quality and enabling real-time network adaptation.
Physiological measurements offer potential insight into users' unconscious responses to quality variations without requiring explicit subjective ratings:

- **Electroencephalography (EEG):** Brain activity measurements correlating with cognitive load and attention
- **Electrodermal Activity (EDA):** Skin conductance reflecting arousal and stress levels

- **Heart Rate Variability (HRV):** Cardiac rhythm variations indicating emotional state
- **Eye Tracking:** Pupil dilation, fixation patterns, and blink rate as indicators of visual attention and cognitive processing
- **Facial Expression Analysis:** Automated recognition of emotional responses

While promising for continuous, unobtrusive assessment, psychophysiological approaches remain primarily research tools rather than standardized QoE metrics. Their application to VR evaluation introduces additional complexity due to the encumbering nature of many measurement devices when used with head-mounted displays. As cloud VR gaming continues to develop, these evaluation methods will play a key role in both understanding user needs and optimizing system performance across different network environments and applications.

2.5 Next Generation Network Technologies

Current and emerging network technologies are revolutionizing the capabilities of internet connectivity, particularly for applications with demanding requirements like cloud VR gaming. This section explores two critical next-generation networking approaches: satellite-based connectivity and 5G millimeter wave technology.

2.5.1 Satellite Network Technologies

Satellite networks have become essential for delivering communication services in remote and underserved regions. In the study, Vatalaro et al. [53] compare Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) systems, focusing on how signal degradation and interference affect performance. LEO satellites, due to their closeness to Earth, offer reduced signal delay and improved reception but require frequent handovers as they move quickly across the sky. MEO satellites offer a balance between delay and coverage area, while GEO satellites, though affected by higher latency, benefit from fixed positioning and extensive coverage.

LEO Satellite Networks

Satellite networks, a.k.a. Non-Terrestrial Networks (NTNs), have the potential to provide ubiquitous coverage and significantly impact the performance of latency-sensitive and bandwidth-intensive use cases such as cloud VR gaming. They can serve as a complementary component to 5G terrestrial networks, extending service availability to underserved areas and providing redundancy for network-critical applications. Zhao and

Pan [60] conducted a comprehensive measurement study on the Starlink access network and also conducted a latency target-based measurement and analysis of three state-of-the-art video streaming ABR algorithms over Starlink networks. It provides insights into how newer networks could support real-time applications like cloud gaming. The integration of LEO satellites by Starlink offers a promising alternative to traditional network infrastructures, potentially reducing latency due to the lower orbit compared to geosynchronous satellites. This diminished latency plays a pivotal role in optimizing real-time applications, such as video conferencing and online gaming, by substantially enhancing responsiveness and user experience. LEO satellite Starlink dataset [59] explores these aspects in depth, presenting a dataset that helps to understand Starlink's performance across various global locations. This work [61] studied VR gaming traffic characteristics such as frame size, inter-arrival time, and latency, the researchers built a testbed to study the Quality of Service (QoS) in cloud-based VR gaming. The study reveals how different network conditions and encoding schemes affect VR gaming performance, providing essential information on managing VR traffic and optimizing cloud gaming systems. However, Zhao et al. [61] worked on VR gaming traffic evaluation, not in the scope of exploring various networks in the cloud VR gaming. Besides, Laniewski et al. [25] mount a Starlink FHP dish on a car, conduct continuous measurements of Starlink's performance while the car is driving, and analyze the resulting network traces dataset [10]. This work [25] measures Starlink's performance over the span of two months, including all relevant network parameters such as download and upload throughput, RTT, and packet loss, as well as detailed power consumption data.

In addition to their potential for reducing latency, LEO networks exhibit distinct architectural and operational characteristics that differentiate them from traditional terrestrial or GEO satellite systems. One major advantage is their global mobility support. Due to the moving nature of LEO satellites across the Earth's surface, users can maintain continuous coverage even in remote or mobile scenarios such as maritime operations, rural telemedicine, or vehicular communication. However, this mobility comes with challenges. The need for frequent handovers between satellites, often every few minutes, can introduce jitter and brief service disruptions if not carefully managed. Maintaining seamless connectivity under these dynamic topologies demands advanced handover protocols and predictive scheduling algorithms.

LEO constellations, such as Starlink, OneWeb, and Amazon's Project Kuiper, are designed with thousands of satellites to ensure dense coverage and minimize coverage gaps. However, their performance is influenced by ground station density, inter-satellite links (ISLs), and orbital dynamics. Unlike terrestrial infrastructure, where signal paths are relatively static, LEO-based routing must account for time-varying topology, which complicates latency and throughput estimation. While some LEO systems employ ISLs to route data through space, others rely on terrestrial backhauls, which can introduce inconsistent round-trip times depending on ground station proximity and backhaul congestion.

Recent measurement studies emphasize these nuances. For example, Mohan et al. [35] demonstrated that Starlink experiences periodic latency and throughput variations caused by globally synchronized 15-second reconfiguration intervals, rather than terminal obstructions or satellite handoffs; these variations can affect performance during active gaming or video streaming sessions. Furthermore, Liu et al. [30] evaluated the impact of orbital altitude and inclination on bandwidth fluctuation, showing that network variability increases in regions with sparse ground infrastructure or during satellite transitions over the horizon. These findings highlight the importance of designing LEO-aware application-layer strategies, such as adaptive bitrate control or latency-resilient game mechanics, especially for applications like cloud VR gaming that are sensitive to even short disruptions.

In terms of deployment challenges, LEO systems face scalability concerns in spectrum coordination and satellite management. Coordinating thousands of fast-moving satellites requires significant control-plane intelligence, while spectrum sharing with terrestrial networks raises policy and interference concerns. Moreover, the total bandwidth per user may fluctuate based on satellite load and geographic contention, which introduces fairness issues in user experience.

2.5.2 5G mmWave Networks

Fifth-generation (5G) cellular networks represent a significant advancement in wireless communication technology, providing enhanced bandwidth capacity and data transmission rates compared to previous generations. While 5G encompasses various frequency bands and implementations, the millimeter wave (mmWave) spectrum stands out as a transformative component that enables unprecedented wireless performance in appropriate deployment scenarios.

The mmWave spectrum refers to radio frequencies between approximately 24 GHz and 100 GHz, a dramatic leap upward from traditional cellular bands that typically operate below 6 GHz. This higher frequency spectrum offers several key advantages and characteristics:

- **Bandwidth Availability**: The mmWave bands provide substantially more bandwidth than all cellular allocations below 6 GHz combined. This expanded bandwidth directly translates to proportionally higher data rates, enabling multi-gigabit throughput potential.
- **Propagation Limitations**: mmWave signals experience higher path loss and are

more susceptible to blockage by obstacles (including human bodies), building materials, and environmental factors such as rain. These signals typically cannot penetrate buildings and have limited diffraction around obstacles.

- **Directional Transmission**: Due to the short wavelengths, mmWave systems implement large antenna arrays in compact form factors, enabling highly directional beamforming to overcome path loss and increase network capacity through spatial reuse.

These fundamental characteristics create both challenges and opportunities for 5G mmWave deployments, requiring specialized implementation approaches to realize their potential, particularly in dense urban environments.

5G mmWave networks demonstrate distinctive performance characteristics that differentiate them from conventional sub-6 GHz cellular systems:

- **Throughput**: Commercial 5G mmWave deployments have demonstrated peak throughput exceeding 1 Gbps and average rates between 200-750 Mbps under favorable conditions [36]. This represents a significant improvement over 4G LTE performance, enabling new classes of bandwidth-intensive applications.
- **Latency**: While theoretical minimum latency for 5G systems can approach 1 ms, practical implementations achieve end-to-end latency typically in the 15-30 ms range [39]. This represents an improvement over 4G but still presents challenges for the most demanding real-time applications.
- **Coverage**: Due to propagation limitations, mmWave cells typically provide coverage within 100-200 meters from the base station, necessitating much denser deployment compared to conventional cellular networks.
- **Connection Stability**: The directional nature and blockage sensitivity of mmWave signals can cause rapid fluctuations in connection quality. This characteristic creates challenges for applications requiring consistent bandwidth and latency.

Research by Narayanan et al. [36] provided one of the first comprehensive real-world performance evaluations of commercial 5G mmWave networks, measuring performance across three major U.S. cities. Their findings revealed impressive peak performance but highlighted significant variability based on environmental factors, user mobility, and network load.

Further investigations by Ghoshal et al. [16] specifically examined uplink performance in mmWave networks, an aspect particularly relevant for interactive applications like cloud VR gaming that require bidirectional communication. Their systematic study across multiple cities and mobile operators revealed the performance characteristics of uplink connections, which often differ substantially from downlink due to power constraints and antenna configurations.

The performance profile of 5G mmWave networks creates both opportunities and challenges for cloud VR gaming applications:

- **Bandwidth Advantages**: The multi-gigabit capacity of mmWave links substantially exceeds current cloud VR streaming requirements (typically 15-50 Mbps per stream), providing headroom for future increases in resolution, frame rate, and visual complexity.
- **Multi-User Capacity**: The high throughput and spatial reuse capabilities of mmWave enable multiple users in close proximity to simultaneously access high-bandwidth applications without mutual interference, an advantage for location-based VR entertainment or collaborative applications.
- **Latency Considerations**: While significantly improved over previous generations, the practical end-to-end latency of mmWave networks still consumes a substantial portion of the maximum acceptable latency budget for VR applications, leaving minimal margin for additional processing and rendering delays.
- **Reliability Challenges**: The susceptibility of mmWave to blockage and the resulting throughput variability can cause disruptive visual artifacts in VR streaming if not properly managed through adaptive streaming techniques.

Research by Peñaherrera-Pulla et al. [39] specifically investigated cloud VR performance over 5G networks in industrial scenarios. Their findings suggest that 5G can support cloud-based VR applications with performance comparable to local Wi-Fi connectivity in many scenarios, though with some limitations in the most demanding use cases.

Cloud-based virtual reality gaming demands high bandwidth and minimal latency to deliver a highly immersive user experience. The potential of 5G mmWave to fundamentally change where and how VR experiences can be delivered remains significant, particularly as mmWave coverage expands beyond initial limited deployments in dense urban areas.

Chapter 3

Related Work

In this chapter, we survey related works of cloud gaming, cloud VR gaming user experience evaluations. Despite significant technological progress, several persistent challenges can affect VR gaming user experience. Below are the possible factors that can affect user experience:

- **Cybersickness:** This phenomenon resembles motion sickness but results from sensory conflicts between visual and vestibular systems during VR exposure. LaViola [26] provided an early comprehensive analysis of this issue, while Rebenitsch [41] later documented that approximately 80% of users experience some degree of discomfort during initial VR sessions.
- **Field of View Limitations:** Human peripheral vision spans approximately 210 degrees horizontally, while most current VR headsets offer only 90-120 degrees. Xiao and Benko [56] demonstrate that this limitation creates a ”tunnel vision” effect that reduces immersion and spatial awareness.
- **Display Resolution:** The proximity of displays to the eyes in HMDs can reveal individual pixels, creating what Beams et al. [5] term the ”screen door effect,” which diminishes visual comfort and text legibility within virtual environments.
- **Computational Requirements:** Abrash [1] notes that generating convincing VR experiences demands extraordinary computational resources to maintain high frame rates (typically 90Hz or higher) necessary to prevent discomfort, requiring ”performance levels significantly beyond traditional 3D gaming.”
- **Wireless Streaming Challenges:** For cloud-based VR applications, Li et al. [29] identify specific technical hurdles in streaming VR content, including extreme bandwidth requirements, latency sensitivity, and network stability concerns.

3.1 Cloud Gaming QoE Evaluations

Cloud gaming has been studied with both open-source and commercial platforms. GamingAnywhere [20] is the first open-source cloud gaming platform designed to deliver low-latency and high-quality gaming experience, which was used in various studies. For example, Huang et al. [21] carried out a user study using GamingAnywhere, comparing satisfaction levels between mobile and desktop platforms and assessing how various system parameters, such as resolution, frame rate, bitrate, and network delay, affect the overall gaming QoE in cloud gaming. Although commercial platforms are harder to experiment with, Graff et al. [33] examined Google Stadia and NVIDIA GeForce Now to understand their adaptation mechanisms to cope with fluctuating network delay and packet loss rate. These works [20, 21, 33] only considered traditional rather than cloud VR games in HMDs. Additionally, Zadtootaghaj et al. [57] investigated the effects of frame rate and bit rate on the Quality of Experience (QoE) in cloud gaming through subjective experiments. Their findings suggest that a frame rate of 25 fps is sufficient for maintaining acceptable quality levels in low bandwidth scenarios, while their proposed structural model aims to predict overall QoE based on technical parameters. This study emphasizes the trade-off between video quality and interaction quality, providing valuable insights for optimizing cloud gaming services. Moreover, Jumani et al. [23] introduced the EmotionNET model, a deep learning-based framework for real-time QoE assessment in cloud gaming environments. Their user study involved 30 participants who played the game Fortnite for 20 minutes under different network conditions.This integration of facial emotion recognition offers a dynamic approach to understanding user experiences in cloud gaming, particularly in low-latency environments, addressing limitations found in earlier studies that relied primarily on technical metrics or subjective feedback. In a novel contribution to the field, Carvalho et al. [7] improved QoE estimation across different cloud gaming services by employing transfer learning techniques. Their study included a user assessment on a mobile cloud gaming platform, showing that transfer learning significantly enhances QoE predictions by adapting a pretrained model from wired gaming contexts. This work highlights the versatility of transfer learning in addressing QoE evaluation challenges in diverse gaming environments and emphasizes the need to consider various network conditions and game types when assessing user experiences.

3.2 VR Gaming QoE Evaluations

Some earlier works considered networked VR applications, which were not hosted in the cloud. For example, Van Damme et al. [52] explored how latency impacts user perceptions during collaborative tasks in multi-user VR environments. Similarly, Vlahovic et al. [55] conducted two user studies to understand how network delay affects the VR gaming QoE of a multiplayer game. These networked VR applications [52, 55] periodically exchange short state-update messages rather than numerous large video packets carrying complex rendered scenes in cloud VR gaming. Slivar et al. [45] investigated the effects of various network types, latency levels, and social context on QoE in competitive multiplayer VR games through a user study involving different player pairings and network conditions. Zhang et al. [58] studied QoE-oriented mobile VR gaming in distributed edge networks, proposing an algorithm to optimize the placement and rendering levels of multiple VR objects to meet stringent delay and visual quality requirements. Their work evaluated QoE comprehensively through simulation with real-world VR game data, demonstrating significant improvements in visual QoE and system performance across various metrics.

Other studies emphasize user experience in controlled or application-specific VR scenarios, such as game design, training, or education. Amaral and Rodriguez [4] reviewed various approaches to analyzing QoE in serious VR games, highlighting methodologies for real-time control, industrial training, and collaborative medical education. The work by Sudakova [48] performed early user experience testing in VR game development which demonstrate the benefits of user experience evaluation outweigh the associated costs. Additionally, Vlahovic et al. [54] examined the aftereffects of VR gaming on user comfort and cognitive performance by comparing three VR games with different natural interaction mechanics. Their study revealed that discomfort sources extend beyond cybersickness, including muscle fatigue and device-related pain, and highlighted how different interaction types can variably impact reaction time and cognitive workload.

3.3 Cloud VR Gaming QoE Evaluations

Researchers have recently looked into the implications of hosting VR games in the cloud. For instance, based on an open-source platform, several of our prior works improved the gaming QoE from different aspects, such as encoding rate control to adapt to bandwidth dynamics [28] and foveation techniques to allocate more resources to areas closer to HMD gamer gazes [11]. A study by Godoy et al. [17] investigated the impact of network latency on user-perceived Quality of Experience (QoE) in cloud-based VR systems using NVIDIA CloudXR and a latency-controlled experimental setup. Commercial platforms have also been used to study the QoE of cloud VR gaming, e.g., Rossi et al. [46] employed NVIDIA CloudXR for a user study, specifically focusing on how network conditions affect gaming QoE in a first-person shooter game. These papers [11, 28, 46] failed to consider HMD gamers living in remote regions and crowded downtowns, who may not have good access networks for cloud VR gaming services.

Chapter 4

Testbed Setup

This chapter details the experimental infrastructure we constructed to evaluate cloud VR gaming performance across emerging network technologies. We first outline our technical implementation approach and then describe the set up configuration of our evaluation platform.

4.1 Implementation

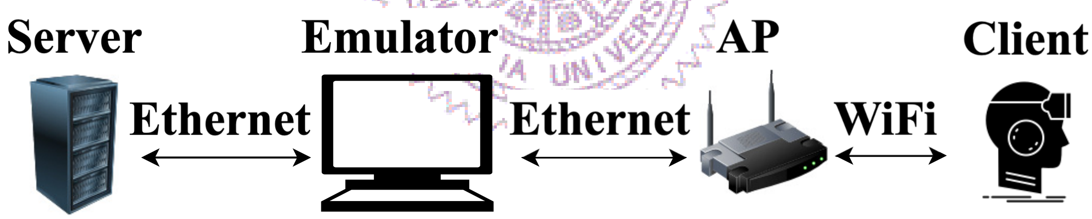


Figure 4.1: Our cloud VR gaming testbed for the user study.

To facilitate empirical assessment of cloud VR gaming over novel network architectures, we established a custom experimental framework built upon the Air Light XR (ALXR) project [31]. This approach provides a non-invasive testing environment for commercial VR applications without code modifications, thereby preserving authentic application behavior and yielding insights applicable to real-world deployment scenarios. Our implementation adopts a black-box streaming architecture with distinct server and client components functioning in coordinated fashion. At the server side, the system leverages the OpenXR API to intercept rendered frames directly from the graphics pipeline. This method ensures minimal processing overhead while maintaining broad game compatibility. The captured visual data undergoes hardware-accelerated H.264 compression through NVIDIA's NVENC technology, which achieves an effective balance between visual fidelity and encoding latency, a crucial aspect for maintaining responsive VR experi-

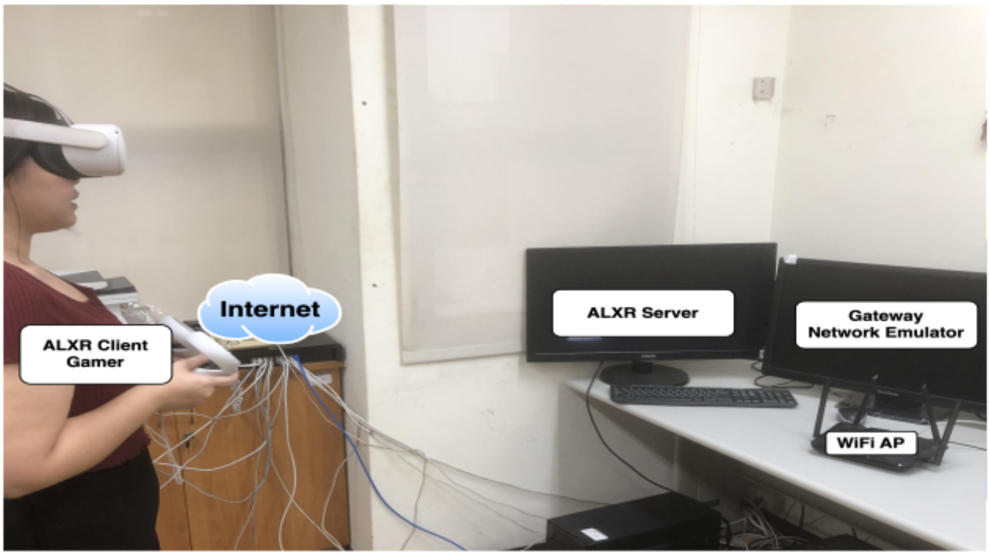


Figure 4.2: User playing with our system for the user study.

ences.

For network transmission, a custom UDP-based protocol is implemented with application-level reliability mechanisms optimized for real-time VR content. Rather than employing standard TCP reliability that might introduce excessive delays during congestion, our system incorporates adaptive prioritization that favors current frame delivery when network conditions deteriorate. This design principle acknowledges that in immersive contexts, temporal continuity often outweighs perfect visual reproduction when faced with bandwidth constraints.

The client component, derived from the ALXR/ALVR codebase [3], operates directly on the standalone headset. This software layer manages both the reception and presentation of streaming visual content while simultaneously capturing motion tracking data for return transmission. To preserve the critical action-response loop, tracking information traverses dedicated communication channels configured for expedited delivery, helping maintain the tight temporal relationship necessary for comfortable immersive experiences.

A central element of our implementation is the network emulation subsystem built around Dummynet [14]. After evaluating several potential emulation technologies, we selected Dummynet for its exceptional precision and flexibility in reproducing complex network behaviors. Key advantages of this approach include:

- **Kernel-level implementation:** Operating within the FreeBSD network stack, Dummynet provides highly accurate traffic management with minimal overhead, avoiding the performance limitations of user-space solutions.
- **Temporal precision:** The system offers millisecond-level scheduling granularity essential for replicating the distinctive delay patterns of satellite and millimeter

wave communications.

- **Dynamic parameter adjustment:** Unlike static emulation tools, Dummynet permits real-time modification of network parameters without connection interruption, enabling faithful reproduction of fluctuating conditions observed in mobile contexts.
- **Bidirectional traffic shaping:** The ability to independently control upstream and downstream characteristics allows precise emulation of asymmetric network profiles common in emerging wireless technologies.
- **Complex condition modeling:** Beyond basic bandwidth and latency constraints, Dummynet excels at reproducing packet reordering, duplication, and stochastic loss patterns that significantly impact streaming applications.

Our implementation extends Dummynet's native capabilities through a custom trace playback mechanism that translates empirical network measurements into dynamic configuration adjustments. This component updates emulation parameters at one-second intervals, reconfiguring traffic management policies with current bandwidth constraints, propagation delays, and loss probabilities derived from our dataset of real-world network observations.

To facilitate comprehensive performance analysis, we integrated instrumentation at multiple stages within the processing pipeline. Server-side telemetry captures frame generation times, encoding durations, and packet transmission events. The client component similarly records video reception timestamps, decoding completion points, and display presentation moments. These temporal markers enable precise measurement of both component-specific latencies and end-to-end system responsiveness.

4.2 Set Up

The physical configuration of our experimental environment comprises carefully selected hardware and software components designed to isolate network performance as the primary variable under examination. Our server platform utilizes a high-performance computing node with an AMD Ryzen 7 5700G processor (3.8 GHz), 32GB of DDR4-3200 memory, and an NVIDIA GeForce RTX 3070 graphics accelerator. This configuration provides sufficient computational headroom to eliminate processing bottlenecks during content generation and encoding, ensuring that observed performance variations stem from network conditions rather than rendering limitations.

Between the server and client segments, we positioned a dedicated network emulation node running FreeBSD 13.1. This system implements the traffic management policies necessary to reproduce specific network characteristics of interest. The emulation device features multiple network interfaces: one connected via Gigabit Ethernet to the server segment, and another linking to the client distribution network. This arrangement ensures all experimental traffic traverses the controlled emulation environment.

For wireless distribution, we deployed a D-Link WiFi 6 access point operating in an isolated frequency band. This high-capacity local connection ensures that final-hop wireless transmission does not introduce unintended performance limitations. Channel selection and power settings were optimized for our testing environment through preliminary signal mapping to minimize interference.

The client endpoint utilizes a Meta Quest 2 standalone VR headset featuring a Qualcomm Snapdragon XR2 processor, Adreno 650 GPU, and 6GB of system memory. By selecting widely-adopted consumer hardware rather than specialized research equipment, our findings maintain direct relevance to practical deployment scenarios.

Chapter 5

User Study Design

To enable reproducible evaluation of cloud VR gaming over emerging network architectures, we thoroughly designed a detailed user study procedure and utilized empirical network traces collected from operational deployments of LEO satellite and 5G mmWave networks. These datasets provide realistic network behavior patterns that cannot be adequately represented by synthetic models or simplified parameter distributions.

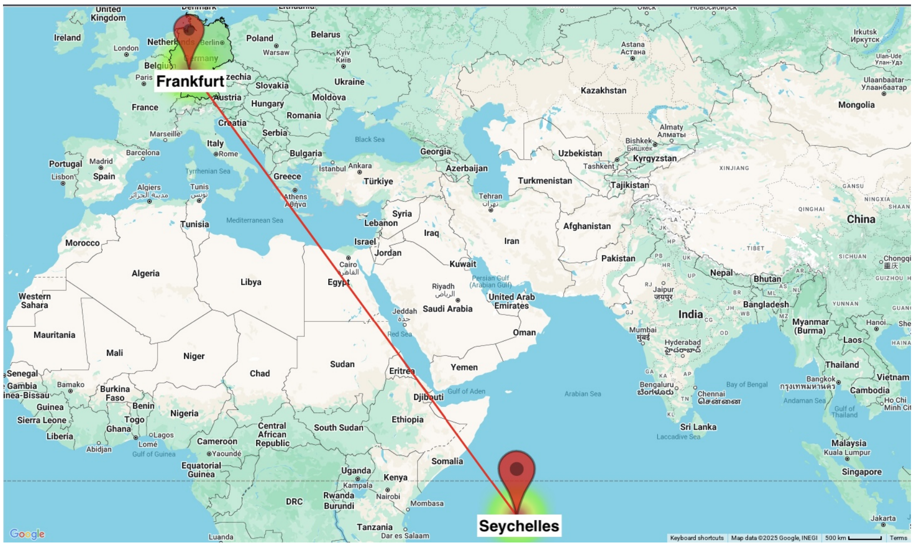
5.1 Datasets

To evaluate the Quality of Experience (QoE) of cloud VR gaming under realistic network conditions, we adopted a laboratory testbed environment in which network behavior is emulated using trace-driven datasets. This approach offers controlled, repeatable, and safe testing conditions that would be difficult to achieve with live network deployments. While real-world experimentation with operational LEO satellite or 5G mmWave networks could provide valuable insights, such an approach is impractical due to variability in network availability, uncontrollable environmental factors, and high equipment and access costs.

Moreover, emulating networks using real-world datasets allows us to isolate and examine specific performance bottlenecks such as delay spikes, bandwidth drops, and jitter, while maintaining a consistent experimental framework across subjects. This ensures fairness and comparability across user sessions and eliminates inconsistencies introduced by external network dynamics, such as congestion or handover unpredictability in the field.

In this study, we utilize two publicly available datasets: one collected from Starlink's LEO satellite network and another from commercial 5G mmWave cellular networks. By replaying network traces from these datasets in our testbed, we are able to rigorously compare the impact of each network type on cloud VR gaming QoE.

5.1.1 LEO Satellite Networks



(a)

Figure 5.1: LEO satellite network connection between Seychelles and Frankfurt PoP.

LEO satellite networks, such as Starlink, represent a transformative connectivity option for remote and underserved regions, offering global coverage with substantially lower propagation delays compared to traditional GEO satellite systems. To understand the QoE of cloud VR gaming over LEO satellite networks, we leveraged the comprehensive LENS dataset [59], which captures real-world performance characteristics of operational Starlink connections. The LENS dataset represents one of the most extensive and geographically diverse collections of LEO satellite network measurements available to the research community. It comprises continuous network performance readings collected from seven distinct geographical locations across three continents over a period spanning January 2022 to December 2023. Each measurement point in the dataset includes timestamps, throughput (both uplink and downlink), round-trip time (RTT), sampled at one-second intervals. For our study, we focused specifically on the traces collected between Seychelles and Germany (Frankfurt). This particular connection was selected because it is a remote and geographically isolated region, and this setting provides a valuable opportunity to evaluate the performance and user experience of cloud VR gaming in challenging network conditions typical of remote areas, where reliance on inter-satellite links and limited ground infrastructure may impact latency and stability. Fig. 5.1 shows the map of LEO satellite network trace PoP connection we used in our work, which is between Seychelles and Frankfurt. The dataset revealed several key characteristics of LEO satellite connectivity:

- Latency variation patterns: The Seychelles-to-Frankfurt connection exhibited periodic latency fluctuations due to satellites moving in and out of optimal alignment, with RTT values varying significantly and often reaching several hundred milliseconds during orbital cycles.
- Throughput stability: Despite the significant distance, the connection maintained surprisingly stable throughput during non-congested periods, for downstream and upstream.
- Weather impact signatures: The dataset includes periods of adverse weather conditions, allowing us to observe performance degradation patterns during precipitation events, which manifest primarily as increased packet loss rather than bandwidth reduction.
- Inter-satellite handover effects: Clear performance signatures are visible during satellite handovers, typically appearing as brief latency spikes followed by stabilization periods.

Among them, we carefully selected four 100-second representative traces with the following challenging conditions:

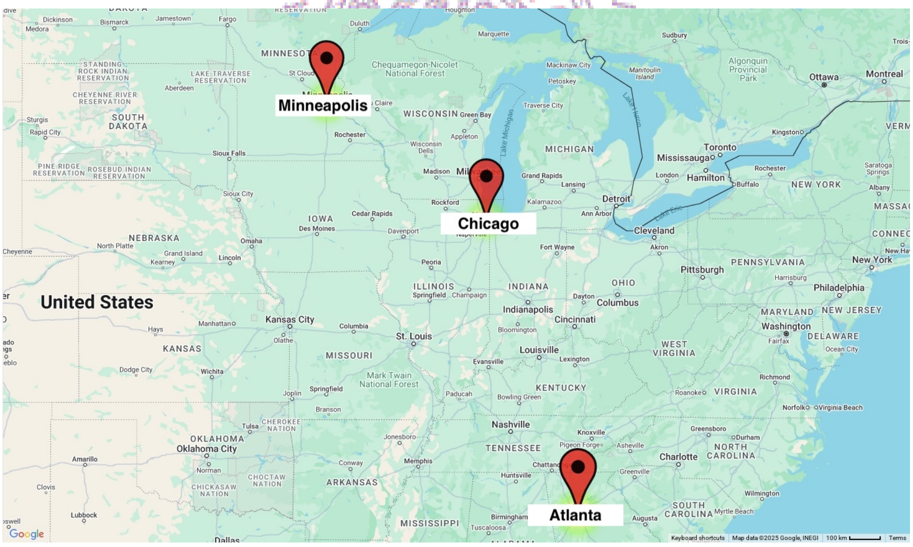
- **Low Bandwidth (LB)**, which is the 10th percentile of the average throughput. This trace characterizes persistently constrained bandwidth environments, representative of rural links where sustained low throughput can lead to severe video degradation and stalling.
- **Fluctuating Bandwidth (FB)**, which is the 90th percentile of the throughput variance. This trace captures highly dynamic bandwidth conditions, which can stress adaptation algorithms and induce visual instability due to frequent bitrate switching in real-time streaming.
- **High Delay (HD)**, which is the 90th percentile of the average delay. This scenario emulates network paths with elevated propagation or processing latencies, such as those observed in satellite or cross-continental connections, posing a significant challenge for latency-sensitive VR games.
- **Fluctuating Delay (FD)**, which is the 90th percentile of the delay jitter. This trace reflects inconsistent latency, which can result in temporal distortions, delayed feedback, and degraded interaction fluidity in immersive applications.

Table 5.1 gives the average throughput and delay of the LEO satellite network traces. These trace segments were selected after extensive analysis of the complete dataset, isolating periods that exemplify particular network challenges while remaining representative of actual conditions encountered in real-world deployments. The LENS dataset's comprehensive nature was invaluable for this purpose, as it allowed us to identify not just average performance characteristics but also challenging edge cases that stress gaming systems. Table 5.1 summarizes the key network characteristics of these representative trace segments, which serve as the foundation for our LEO satellite network emulation.

Table 5.1: Average Statistics of Representative Network Traces

Trace	LEO Networks		mmWave Networks	
	Throughput	Delay	Throughput	Delay
LB	51.68 Mbps	49.75 ms	409.22 Mbps	29.68 ms
FB	52.68 Mbps	51.84 ms	750.98 Mbps	166.15 ms
HD	123.66 Mbps	119.38 ms	237.25 Mbps	188.26 ms
FD	90.11 Mbps	87.51 ms	195.94 Mbps	227.61 ms

5.1.2 5G mmWave Networks



(a)

Figure 5.2: 5G mmWave network collected locations in United States.

5G mmWave networks operate at higher frequency bands (24 to 53 GHz) to achieve dramatically increased bandwidth capacity compared to sub-6 GHz cellular systems, enabling theoretical throughput up to 20 Gbps, roughly 100× improvement over 4G LTE. This makes mmWave particularly suitable for bandwidth-intensive applications in dense urban environments, despite its limited propagation characteristics such as high attenuation, vulnerability to blockage, and pseudo-optical signal propagation. mmWave signals require highly directional beamforming using phased-array antennas, which are sensitive to environmental factors including physical blockages (e.g., human body, vehicles), UE orientation, and even small perturbations, causing significant variations in throughput and connection stability.

To understand how these networks perform with cloud VR gaming workloads, we utilized a comprehensive 5Gophers dataset of 5G mmWave performance measurements [36] collected from commercial smartphones (Samsung Galaxy S10 5G) operated on mmWave networks of Verizon and T-Mobile in Minneapolis, Chicago, and Atlanta. This dataset encompasses over 15 TB of cellular traffic across diverse urban environments, capturing detailed performance metrics such as throughput, latency, signal strength, handover events between 4G/5G (highlighting frequent, rapid handoffs due to mmWave's sensitivity), and line-of-sight (LoS) versus non-line-of-sight (NLoS) dependencies. Unlike previous datasets focused on sub-6 GHz or early-stage 5G deployments [40, 47] and VR performance studies conducted on conventional 5G networks [39], the 5Gophers dataset represents one of the first large-scale empirical studies capturing real-world commercial 5G mmWave performance under realistic mobility patterns, various times of day, weather conditions, and blockage scenarios. This facilitates an unprecedented understanding of mmWave's benefits, such as up to 10× throughput gain over 4G under clear LoS conditions, as well as its challenges, including high throughput variability, susceptibility to blockages, and the need for adaptive network-layer and application-layer mechanisms to optimize user experience. Key characteristics of the 5G mmWave dataset include:

- **Throughput dynamics:** The dataset reveals extreme throughput variability (ranging from 100 Mbps to over 1.5 Gbps) based on factors such as distance from base stations, presence of obstacles, and mobility patterns.
- **Latency profiles:** The measurements show that while 5G mmWave can achieve very low latencies (as low as 15ms) under optimal conditions, real-world deployments frequently experience higher and more variable latencies (50-250ms) due to network congestion, handovers, and backhaul limitations.
- **Beam management effects:** The dataset captures the performance impact of beam tracking and switching operations, which are unique to mmWave deployments and can cause brief but significant interruptions in connectivity.
- **Mobility impact:** Performance metrics during pedestrian and vehicular mobility reveal distinct degradation patterns as users move through the coverage area, including sudden throughput drops during beam switches.

From this dataset, we extracted four representative 100-second trace segments that characterize challenging but realistic network conditions:

- **Low Bandwidth (LB):** Representing the 10th percentile of average throughput performance. This trace simulates scenarios where users experience poor connectivity or congestion, helping us understand how cloud VR performance degrades under severely limited bandwidth.

- **Fluctuating Bandwidth (FB):** Representing the 90th percentile of throughput variance with significant fluctuations. This trace represents highly unstable bandwidth conditions, which can frequently occur in mobile or congested networks. Such fluctuations may result in frequent bitrate adjustments and visual artifacts.
- **High Delay (HD):** Representing the 90th percentile of observed latency. This trace reflects conditions with consistently high latency, often encountered in long-distance communications or networks with inherent propagation delays. High delay is particularly critical for evaluating interaction-heavy VR applications.
- **Fluctuating Delay (FD):** Representing the 90th percentile of delay variation. This trace can lead to inconsistent responsiveness and motion-to-photon delays. This can also be one of the key factors influencing user comfort and immersion in VR environments.

These traces capture the distinctive performance characteristics of 5G mmWave networks, particularly the high throughput potential coupled with significant variability based on environmental factors and mobility.
Table 5.1 also gives the average throughput and delay of the 5G mmWave network traces. The combination of both LEO satellite and 5G mmWave network traces allows us to compare these two promising but fundamentally different connectivity approaches for cloud VR gaming applications, representing both rural/remote (satellite) and dense urban (mmWave) deployment scenarios.

5.2 User Study Procedure

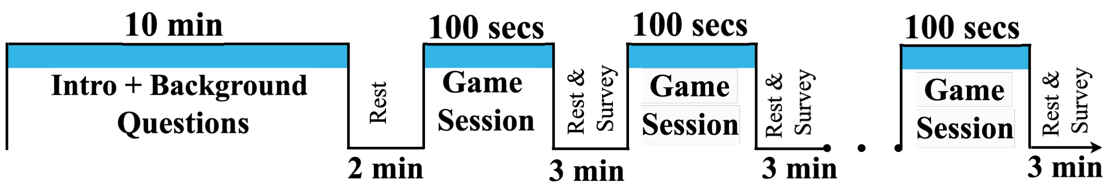


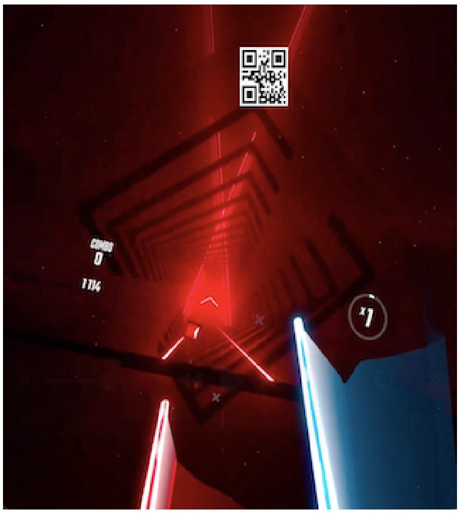
Figure 5.3: User study procedure for each subject.

We selected three VR games spanning diverse gameplay characteristics to comprehensively evaluate Quality of Experience (QoE) under varying network conditions:

- **Beat Saber** represents a latency-sensitive game. It demands highly responsive interactions synchronized with rhythmic cues, making it an ideal candidate for as-

(a)

(b)



(c)

Figure 5.4: User playing three games: (a) AngryBird, (b) ArtPuzzle, and (c) BeatSaber.

sessing the impact of network delay and jitter.

- **Art Puzzles** exemplifies a texture-rich, visual quality-sensitive game. It involves solving puzzles composed of detailed, static imagery. While it is not interaction-intensive, it requires high visual fidelity for a satisfying experience, making it suitable for evaluating the effects of bandwidth and compression artifacts.
- **Angry Birds** falls under the category of a leisure or casual game. It involves moderate user interaction and visual complexity, with less stringent demands on latency or throughput. This makes it useful as a baseline for comparing user tolerance to network impairments in non-time-critical scenarios.

By covering a range of latency sensitivity, visual complexity, and interaction intensity,

Table 5.2: Survey Questions Used in Our User Study

Question	Description
Overall Quality (OQ)	How would you rate the overall quality of this game session?
Visual Quality (VQ)	How would you rate the visual quality of this game session?
Interaction Quality (IQ)	How responsive was the game session to the actions that you performed?
Immersive Level (IL)	How would you assess the sense of immersion during this game session?
Cybersickness (CS)	Are you feeling any sickness or discomfort now?

Table 5.3: Demographic Information of User Study Participants

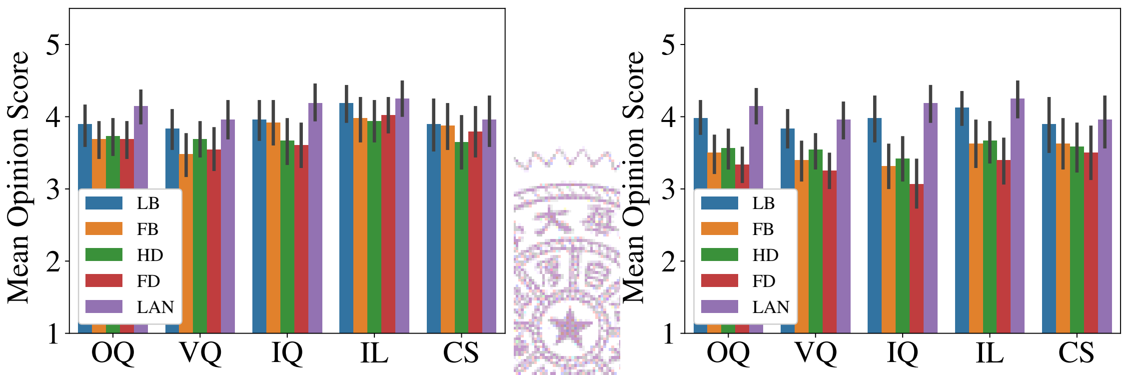
Category	With VR Experience	Without VR Experience	Total
Gender			
Male	7	2	9
Female	2	5	7
Eyesight			
Normal	5	2	7
Near-sighted	4	5	9
Age Group			
Below 25	5	3	8
Above 25	4	4	8

these games allow for a nuanced, game-aware analysis of how network conditions affect cloud VR gaming QoE. Fig. 5.4 visually illustrates three example game scenes that participants played during the study. In this study, Quality of Experience (QoE) refers to the degree of delight or annoyance of user experience, as defined by ITU-T [22]. We consider five QoE questions [37, 50], detailed in Table 5.2. We employ the Single Stimulus method for ACR [18] between 1 and 5, where 1 is the least, and 5 is the most comfortable experience. In our study, we also measured the following Quality of Service (QoS) metrics: (i) latency, (ii) throughput, and (iii) packet loss rate, which allow us to cross-reference the QoE results from the HMD gamers for root cause analysis. We note that these measurements were done in the application layer, i.e., between the ALXR server and the client.

Fig. 5.3 reveals the user study procedure for each subject. We consider two emerging networks, four representative traces, and three games, leading to 24 game sessions. For comparisons, we also perform baseline sessions (one for each game) with no incurred network delay and bandwidth limit, which are referred to as the LAN baseline. Before these 27 game sessions, each subject answers a background questionnaire following an ITU-T recommendation [51]. For example, we ask each subject about his/her eyesight and experience of VR gaming. The demographic breakdown of participants is summarized in Table 5.3. We recruited 16 subjects aged 21 to 32 years old, with a mean age of 25.75 and a standard deviation of 2.66. The gender distribution is: nine males and seven females. Nine subjects reported having previous exposure to VR experiments, whereas seven were novices to VR technology. Regarding visual acuity, 9 participants reported near-sightedness, while 7 participants had normal vision. This balanced distribution of demographic characteristics allowed us to investigate potential differences in QoE perception based on gender, age, visual acuity, and prior VR exposure.

Chapter 6

Evaluation of User Study Results



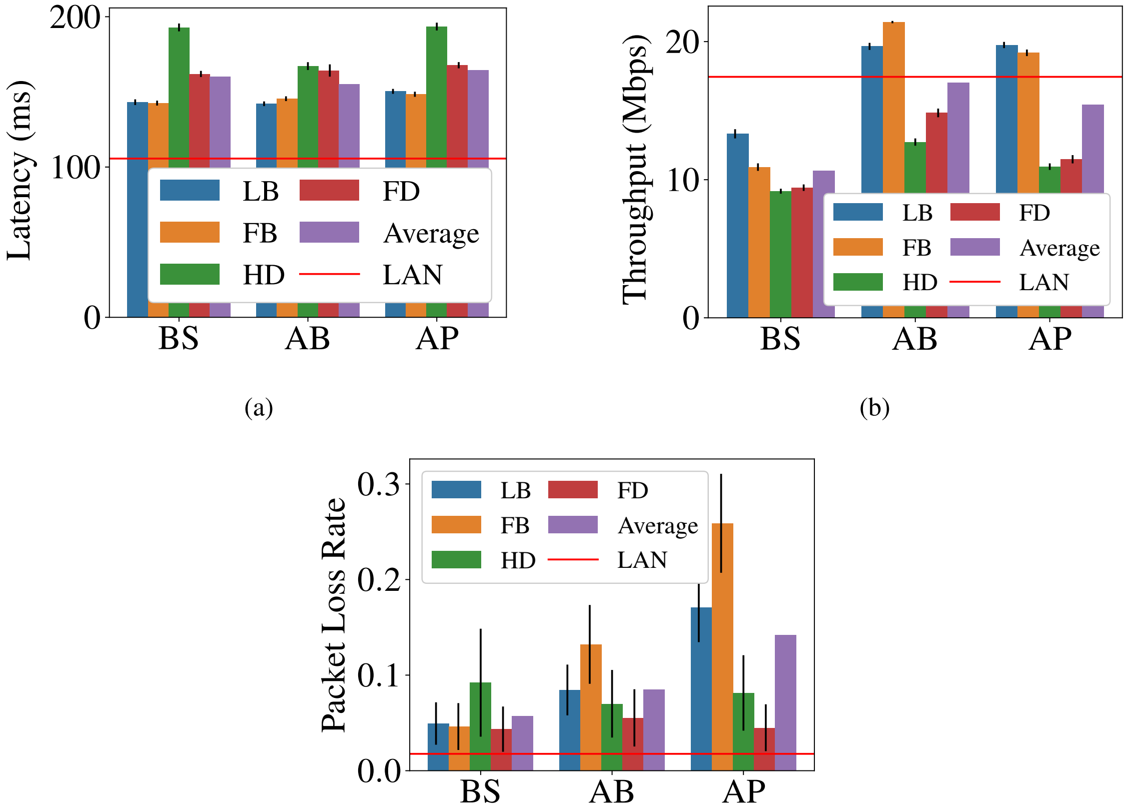
(a) (b)

Figure 6.1: MOS results of individual network traces from: (a) LEO satellite, and (b) 5G mmWave networks.

6.1 Impact of Network Parameters on QoE

In this section, we discuss the analysis and results of our user study and how different networks affect the QoE of the cloud VR gaming experience. We first analyze the impact of delay versus bandwidth in LEO satellite networks and 5G mmWave networks, then compare the overall performance between these network types, and lastly investigate how different game genres perform across different networks.

Delay is more crucial than bandwidth in LEO satellite networks. Fig. 6.1(a) shows the average MOS results over all subjects in LEO satellite networks. We make the following observations. First, LB outperforms all other traces (except the baseline LAN) in all five questions, which is counter-intuitive. Hence, we plot the measured latency, throughput, and packet loss rate in Fig. 6.4. This figure reveals that LB gives the lowest

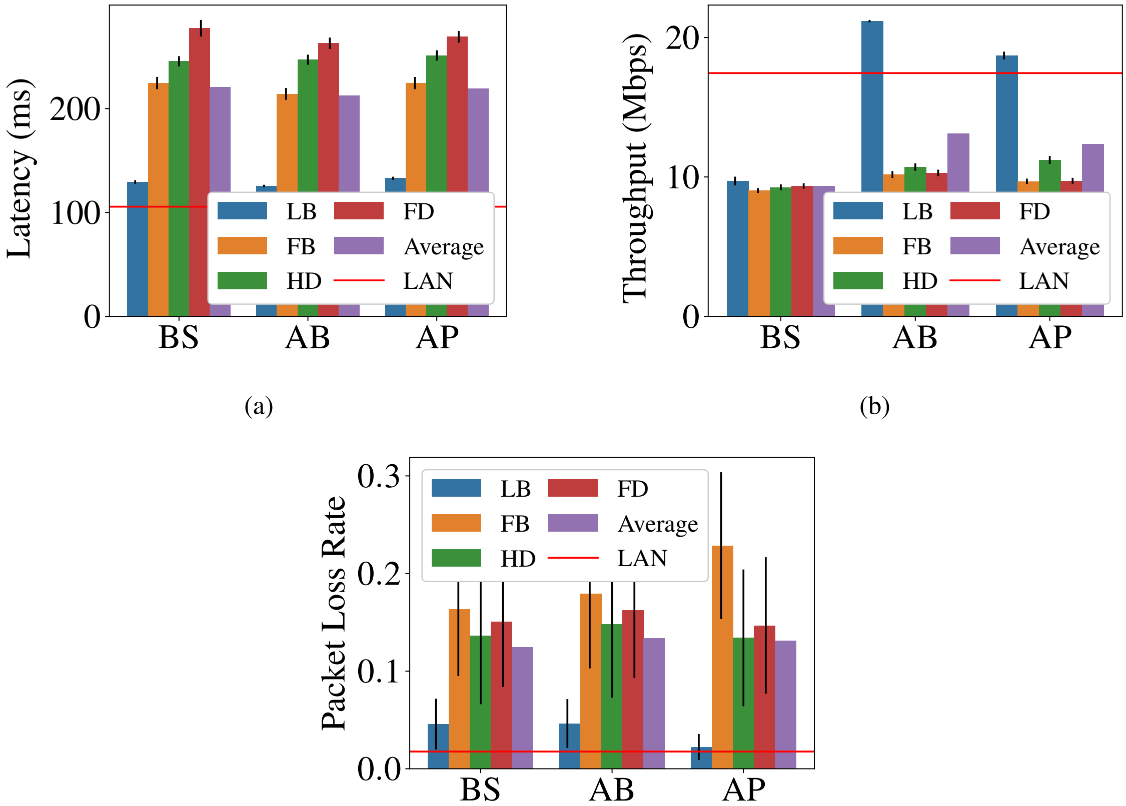


(a) (b) (c)

Figure 6.2: Gamewise QoS measurements for LEO satellite network.

average latency and packet loss rate, as well as the highest throughput, which justifies the superior performance of LB. In fact, Table 5.1 confirms that LB has a lower delay than other traces from LEO satellite networks. Second, Fig. 6.1(a) reveals that compared to LB, FB leads to lower OQ, VQ, and IL, which can be attributed to more fluctuating delays, leading to higher 46.08% more packet loss rate, as shown in Fig. 6.4. With that said, FB still performs well in terms of interaction quality and cybersickness because its bandwidth and latency are comparable to those of LB, as demonstrated in Table 5.1. Last, while HD and FD offer higher bandwidth, Fig. 6.1(a) illustrates that they both perform badly in all five questions, which can be explained by their higher latency, shown in Fig. 6.4: 26.55% and 13.30% longer latency, compared to LB, respectively. This is also consistent with the delays reported in Table 5.1. In summary, we find that LEO satellite networks offer enough bandwidth for cloud VR gaming, and delay plays a more critical role in ensuring high cloud VR gaming QoE to gamers living in remote regions.

Delay is also more crucial than bandwidth in 5G mmWave networks. Fig. 6.1(b) shows the average MOS results over all subjects in 5G mmWave networks. Observations similar to those in LEO satellite networks are made in this figure, and the root causes



(a)

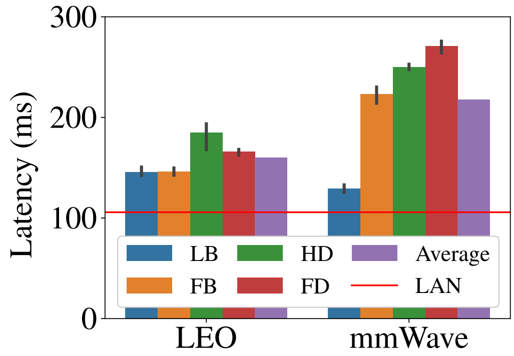
(b)

(c)

Figure 6.3: Gamewise QoS measurements for 5G mmWave network.

can be shown in Fig. 6.4 as well. For example, LB outperforms all other traces (except the LAN baseline) because of the lower and less fluctuating delay. Among the other three traces, HD and FB have similar delays and higher bandwidth, which lead to higher MOS results. FD has the highest latency according to the fig. 6.4, hence it leads to bad MOS scores in all QoE metrics as shown in the fig. 6.1(b). These application-layer measurements are inline with those network-layer ones reported in Table 5.1. In summary, we find that 5G mmWave networks can provide sufficient bandwidth, but lower and more stable delays improve QoE for cloud VR gamers living in crowded downtowns.

To further investigate the role of both average performance and stability of network parameters, we plotted the Cumulative Distribution Functions (CDFs) of delay of both networks, focusing on both average values and variance across trace segments. Fig. 6.5(a) and 6.6(a) present the CDFs of delay for both networks, showing that while average delay remains moderate, the delay variance is notably higher. This supports our earlier finding that fluctuating delay in both networks leads to the lower QoE, as instability in delay introduces perceptual inconsistency in the gaming experience.



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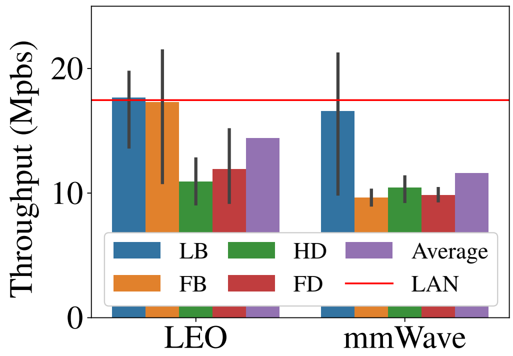

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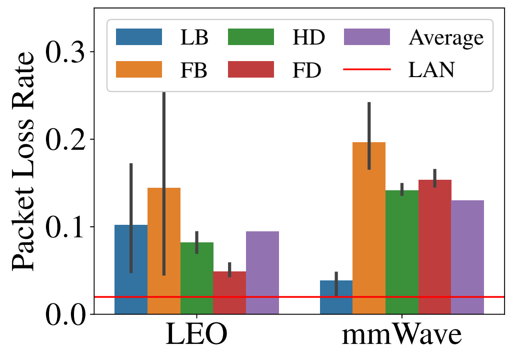
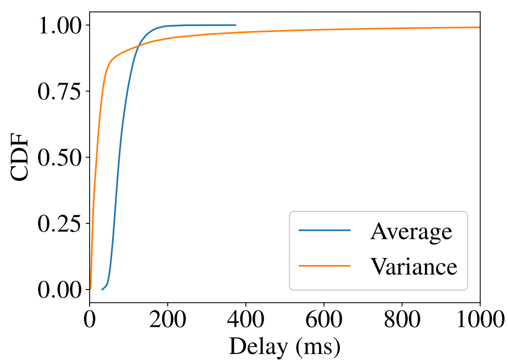
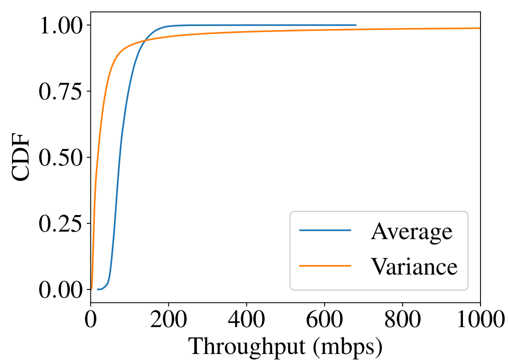


(c)

Figure 6.4: QoS measurements from different networks: (a) latency, (b) throughput, and (c) packet loss rate.



(a)

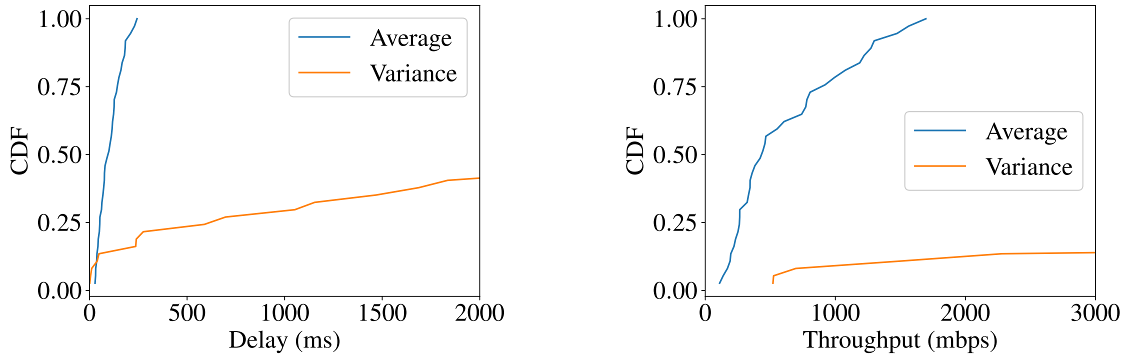


(b)

Figure 6.5: CDF of LEO satellite network of average and variance of (a) delay and (b) throughput.

6.2 Comparative Network Performance

LEO satellite networks offer better cloud VR gaming QoE than 5G mmWave net-



(a) (b)

Figure 6.6: CDF of 5G mmWave network of average and variance of (a) delay and (b) throughput.

works. Next, we aggregate the results from all four representative traces and report the overall MOS results in Fig. 6.7. This figure reveals that LEO satellite networks achieve better MOS results than 5G mmWave networks in cloud VR gaming: e.g., a gap of 0.57 (out of 1–5 scale) in IL is observed. Next, we compare these two emerging networks with the LAN baseline using post-hoc Dunn's tests. We see no significant difference between the MOS results offered by LEO satellite networks and the LAN baseline, which is quite impressive, considering our four representative traces are challenging ones. In contrast, we identify significant differences in OQ, IQ, and IL between 5G mmWave and the LAN baseline with p-values of 0.0440, 0.0049, and 0.0249, respectively. A deeper investigation of Fig. 6.4 shows that 5G mmWave networks result in longer latency, higher packet loss rate, and lower throughput, contributing to the significant difference in overall experience as well as interactability and immersion. In summary, we find that LEO satellite networks are more promising for cloud VR gamers living in remote areas than 5G mmWave networks for those living in crowded downtowns. Similarly, Fig. 6.5(b) and Fig. 6.6(b) display the CDFs for throughput. They confirm that 5G mmWave networks offer higher throughput on average but also highlight greater variance. This aligns with our earlier observation that high throughput does not always guarantee better QoE, particularly if the throughput fluctuates widely. Therefore, these CDF plots reinforce the key insight that temporal stability (low variance) is just as important as absolute performance (high average) in supporting consistent cloud VR gaming experiences.

6.3 Game-Specific Performance Analysis

Different emerging networks are better suited for different cloud VR games. The

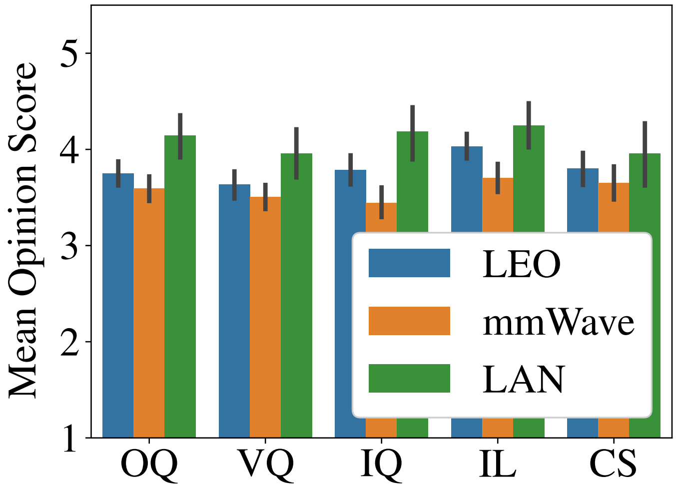


Figure 6.7: Average MOS results of all traces in three networks.

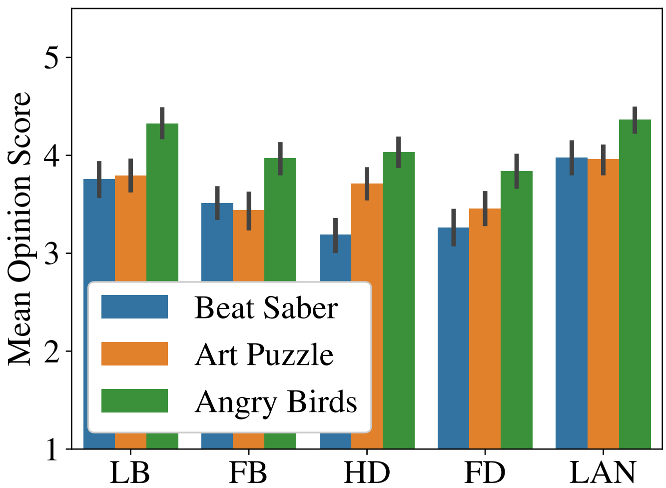


Figure 6.8: Average MOS results from different games.

above analyses did not distinguish between game types, that is, the results were aggregated across all games. We now examine the impact of game type on performance across different emerging networks. Specifically, Fig. 6.9 presents the average MOS scores for each individual game. We made the following observations:

- Fast-paced **Beat Saber**: According to the MOS results shown in Fig. 6.9(a), FB in LEO satellite networks outperforms others by at most 4.0 and 4.2 MOS results in OQ and IQ, which can be attributed to the lowest latency achieved by FB. A similar observation is also made in 5G mmWave networks in Fig. 6.9(d), LB enhances the OQ and IQ by at most 3.63 and 3.5 MOS results compared with other traces. This can also be attributed to the low latency achieved by LB. In contrast, FD in 5G mmWave networks get only 2.06 MOS results in IQ, which is the lowest across all gaming sessions. This can be attributed to FD's high latency. We conclude that

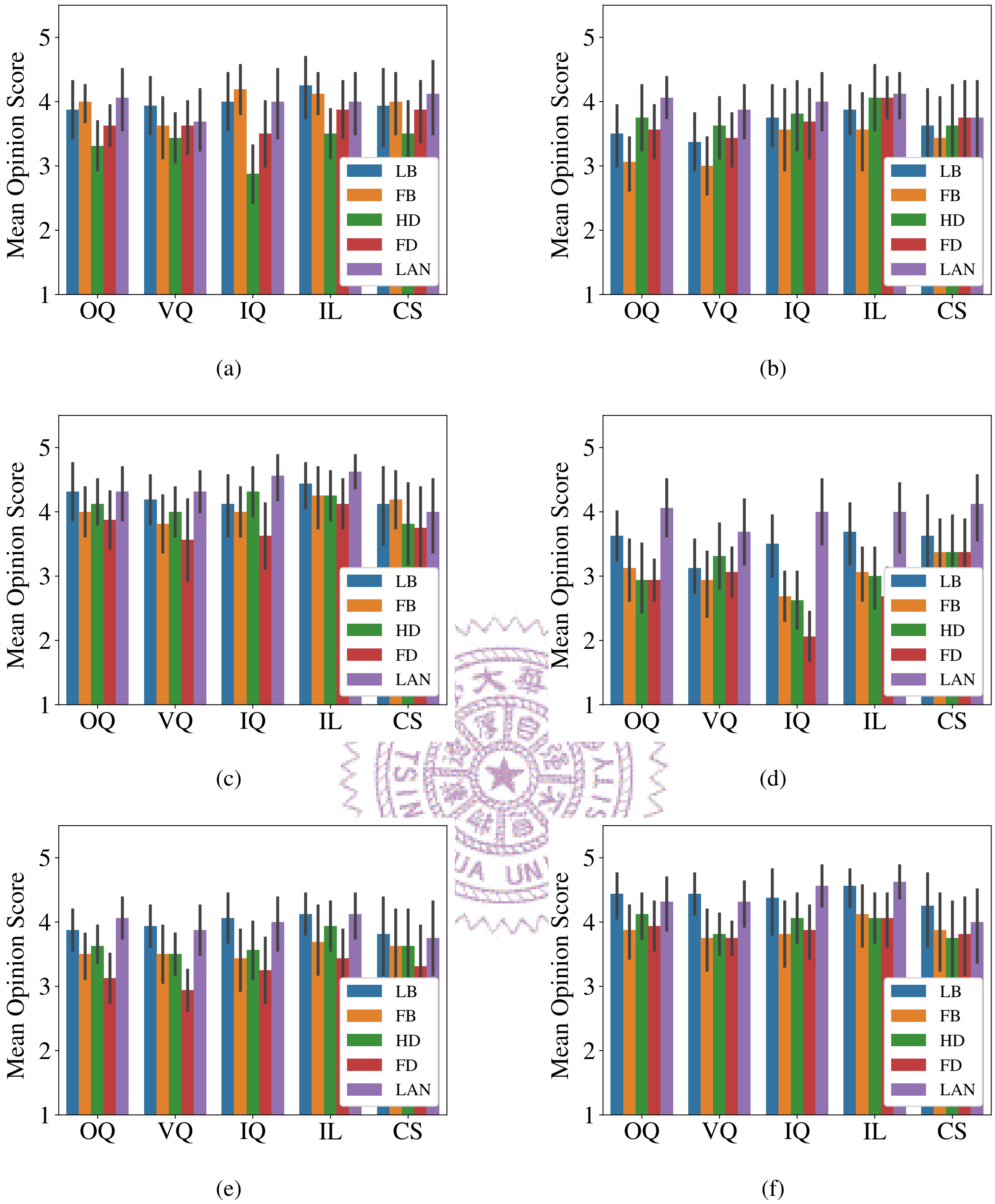


Figure 6.9: MOS results from different games: (a), (d) Beat Saber, (b), (e) Art Puzzle, (c), (f) Angry Birds; over different networks: (a)–(c) LEO satellite and (d)–(f) 5G mmWave networks.

Beat Saber works better in LEO satellite networks thanks to lower delay.

- Texture-rich **Art Puzzle**: Comparing Figs. 6.9(b) and 6.9(e), we find that all four network traces in LEO satellite networks lead to inferior MOS results in general, compared to the network traces in 5G mmWave networks. A closer look shows that

HD trace in 5G mmWave networks performs well in MOS results, largely due to the ample bandwidth compared to the traces from LEO satellite networks. In contrast, FD in 5G mmWave networks suffers from high and fluctuating delay, leading to lower MOS results. With that said, overall, Art Puzzle works better in 5G mmWave networks, thanks to higher bandwidth.

- Leisure **Angry Birds**: As shown in Figs. 6.9(c) and 6.9(f), most traces lead to acceptable MOS results. Despite low bandwidth FD in LEO satellite networks, we still observe fairly good MOS results of 3.90 in OQ. Moreover, with high latency FD in 5G mmWave networks, we observe an even better MOS result of 3.94 in OQ. We conclude that Angry Birds works well in both LEO satellite and 5G mmWave networks.

Fig. 6.8 reports the overall MOS results aggregated from all challenging traces in two emerging networks, along with those from the LAN baseline. This figure confirms the following findings: (i) fast-paced Beat Saber doesn't work well in 5G mmWave networks due to longer and more fluctuating delay, (ii) texture-rich Art Puzzle doesn't work well in LEO satellite networks due to lower bandwidth, and (iii) leisure Angry Birds work well in both emerging networks. Adding to that, the figure also reveals that traces with lower delay, such as LB and FB, give higher MOS results for fast-paced Beat Saber, while traces with higher bandwidth traces, such as HD and FD, achieve higher MOS results for texture-rich Art Puzzle. Last, for leisure Angry Birds, even low-bandwidth and high-delay FD of both emerging networks perform reasonably well.

To better understand how underlying network conditions contributed to these game-specific QoE results, we examined the corresponding Quality of Service (QoS) metrics for each game under both LEO satellite and 5G mmWave networks, as shown in Figures 6.2 and 6.3.

Figure 6.2 presents the latency, throughput, and packet loss observed for each game under the LEO satellite network. Notably, the Low Bandwidth (LB) trace exhibits the lowest delay and packet loss rate across all games, contributing to the highest Mean Opinion Score (MOS) in fast-paced games like Beat Saber. This supports our earlier conclusion that LEO networks are particularly well-suited for delay-sensitive VR applications. In contrast, the High Delay (HD) and Fluctuating Delay (FD) traces show increased variance in latency, degrading performance for time-critical gameplay.

Figure 6.3 reveals that while 5G mmWave traces especially for HD, it performs well due to high throughput, but for the FD trace, it exhibits larger delay variation, leading to bad performance. This explains why Art Puzzle, which emphasizes visual quality, scores well under the higher throughput condition, while Beat Saber suffers due to its sensitivity to delay spikes. The Low Bandwidth (LB) trace again demonstrates a better balance of stable latency and good throughput, resulting in favorable performance even in interaction-intensive games.

Together, these figures highlight that the optimal network condition for a VR game depends not only on average QoS metrics but also on their temporal stability, aligning with our broader conclusion that different VR content types require tailored network strategies.

To further investigate the role of both average performance and the stability of network parameters, we plotted the Cumulative Distribution Functions (CDFs) of delay for both networks, focusing on both average values and variance across trace segments. Fig. 6.5 and 6.6 illustrate the CDFs of delay and throughput metrics, capturing both the central tendency and variability for LEO satellite and 5G mmWave networks.

For the LEO satellite network, the delay CDF shows a steep rise in the average curve in the fig. 6.5(a), indicating that most delay values are tightly clustered, generally below 200 ms. This suggests stable and predictable latency. Although the variance curve is slightly more spread out, it remains consistently lower than that of mmWave in the fig. 6.6(a), confirming greater delay stability. This stability is crucial for interaction-sensitive VR games. Our user study confirms this insight: in Beat Saber, a fast-paced, interaction-heavy game, participants gave higher scores for interaction quality (IQ) and overall quality (OQ) under LEO conditions. This alignment between delay stability and user-perceived responsiveness underscores LEO's suitability for time-critical cloud VR experiences.

In contrast, 5G mmWave networks exhibit higher average throughput, with many values exceeding 1 Gbps, as shown in fig. 6.6(b). However, the delay CDF in fig. 6.6(a) is flatter and more widely distributed, indicating greater delay variance. These latency spikes are primarily due to environmental obstacles and signal disruptions between the base station and the user equipment (UE) panel, which were present during trace collection. Such Line-of-Sight (LoS) interruptions or partial blockages are inherent challenges in real-world mmWave deployments. Despite its high bandwidth, this delay instability makes 5G mmWave less reliable for games with strict latency requirements.

In summary, the CDF plots reinforce our earlier findings: LEO satellite networks offer more consistent latency, making them ideal for interaction-centric applications like Beat Saber, whereas 5G mmWave provides superior throughput, which benefits visual fidelity in applications like Art Puzzle, but suffers in scenarios where delay consistency is critical.

Chapter 7

Conclusion

In this chapter, we will make the conclusion of our work and outline potential future works for the current thesis.

7.1 Key Take-Away Messages

We investigated the QoE of cloud VR gaming in emerging LEO satellite and 5G mmWave networks. To our knowledge, even though these two networks may enable gamers living in remote regions and crowded downtowns to access cloud VR gaming, the actual QoE results have never been quantified and analyzed. Through a carefully designed user study, we strive to answer two RQs and find that gamers living in remote regions and crowded downtown can enjoy cloud VR gaming through these two emerging networks. More specifically, our user study shows that: (i) LEO satellite networks achieve better cloud VR gaming QoE than 5G mmWave networks, (ii) delay plays a more critical role in ensuring high cloud VR gaming QoE, and (iii) fast-paced games work better in LEO satellite networks, while texture-rich games work better in 5G mmWave networks.

7.2 Future Work

Based on our findings, we suggest that content providers developing real-time streaming applications should consider: (i) optimizing for delay consistency rather than purely minimizing average delay, (ii) adapting content complexity based on network characteristics, simpler interactions for high-latency networks and richer content for high-bandwidth networks, (iii) implementing application-specific adaptation techniques that consider for both network conditions and content requirements. These insights extend beyond cloud VR gaming to other latency-sensitive applications, such as live sports streaming, remote operations, and telehealth services.

While LEO satellite and 5G mmWave networks hold great promise for expanding access to cloud VR gaming, several research directions remain open for the community to explore. These include, but are not limited to: (i) incorporating additional network trace datasets that capture a wider range of geographic locations and network characteristics; (ii) evaluating cloud VR games with high-motion content, social interactions, or multiplayer functionality; (iii) selecting additional representative network traces exhibiting high or fluctuating packet loss rates, which may occur during transitions between Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) conditions in 5G mmWave networks; and (iv) developing QoE models grounded in measurable QoS metrics, which can be leveraged by cloud VR gaming systems to adapt to dynamic server/client and network conditions.

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