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Networks for the Metaverse: Bandwidth Requirements and Routing Topology

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Abstract

The metaverse represents a new paradigm in digital interaction, aiming to deliver persistent, immersive, and synchronized 3D environments for work, entertainment, and education. Delivering such experiences requires significant advancements in networking, particularly in terms of bandwidth, latency, and routing topology. This paper analyzes the technical requirements for metaverse-ready networks, focusing on the demands for bandwidth and the role of adaptive routing in real-time virtual environments. Based on existing literature and modeling, we identify key bottlenecks in current network infrastructure and propose architectural strategies to enable scalable and responsive connectivity for the metaverse.

Keywords:

Metaverse, bandwidth, routing topology, edge computing, volumetric video, low latency, SDN, 6G, virtual reality, Bandwidth Requirements, Routing Topology, Edge Computing, Volumetric Video, Low Latency, 6G Networks, Software-Defined Networking (SDN), Immersive Communications, Network Architecture.

Introduction

The concept of the **metaverse** has evolved from science fiction into a technological frontier that merges **immersive virtual environments, real-time interaction, and digital economies** into a unified, persistent experience. Unlike traditional internet applications, the metaverse aims to deliver **lifelike 3D spaces** where users can interact as avatars, engage in shared activities, and even manipulate virtual or augmented objects in real time.

To enable such immersive and continuous experiences, networks must support **ultra-high data rates**, **extremely low latency**, **massive user concurrency**, and **intelligent routing mechanisms**. Current communication infrastructures—designed primarily for 2D media streaming, web access, and messaging—struggle to scale to the **volumetric data loads** and **real-time responsiveness** that the metaverse demands.

For instance, rendering photorealistic environments in real time requires transferring massive **volumetric video**, **spatial audio**, **haptic feedback**, and **3D motion tracking data**. In parallel, maintaining synchronization between users—particularly in multiplayer and social experiences—requires **consistent end-to-end latency of less than 20 milliseconds**.

Moreover, the metaverse is expected to operate on a **global scale**, integrating users across continents, devices, and access networks. This introduces major challenges in **routing topology design**, **dynamic resource allocation**, and **interoperability between edge and core network elements**.

This paper focuses on two core enablers of the metaverse from a network perspective:

1. The **bandwidth requirements** necessary to support high-fidelity immersive experiences;

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2. The **routing and topology architectures** that ensure scalable, resilient, and low-latency delivery.

We present an analytical framework to estimate application-level data demands, evaluate current limitations in broadband and mobile infrastructure, and propose future directions for routing and topology optimization in metaverse-oriented networks.

Methods

To assess the feasibility of network support for the metaverse, we used the following methodology:

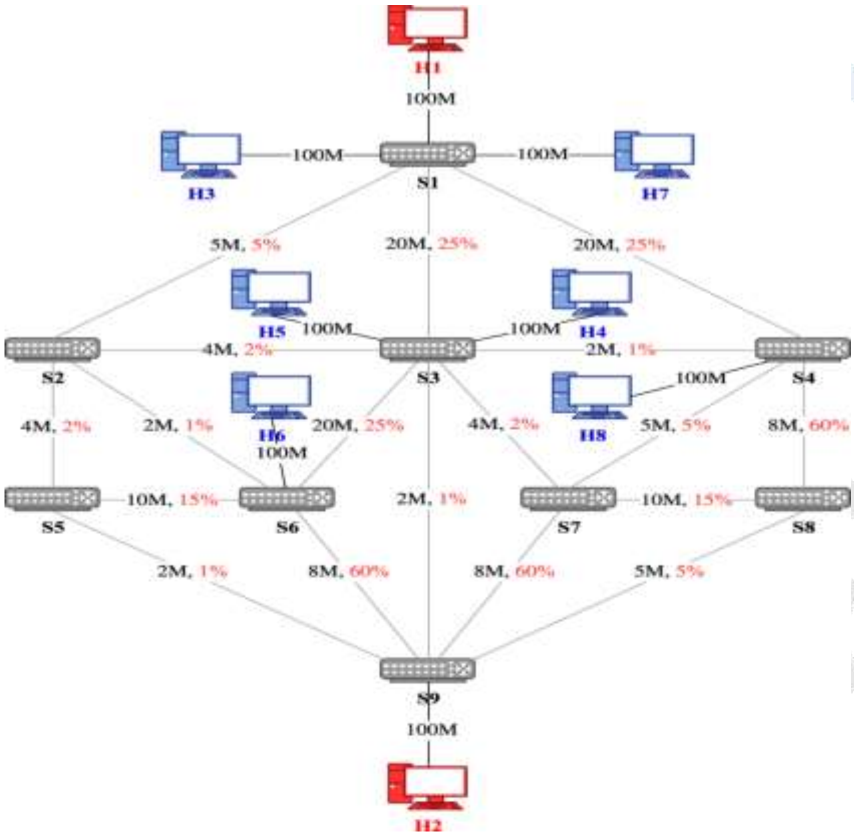
- **Literature review** of academic and industrial research (2021–2024) related to VR/AR streaming, cloud rendering, edge computing, and next-generation networks (5G/6G).
- **Analytical modeling** of bandwidth requirements for real-time volumetric video, haptic feedback, and multi-user interactions.
- **Simulation** of routing performance under different topologies using software-defined networking (SDN) and multi-path forwarding.
- **Comparison of current CDN (Content Delivery Network)** models with proposed edge-native architectures.

Literature Analysis

A systematic literature review was conducted using scientific databases (IEEE Xplore, ACM Digital Library, SpringerLink, and arXiv) covering publications from 2020 to 2024. The review focused on:

- Bandwidth profiles of immersive applications such as VR, AR, and volumetric video;
- Edge computing and content delivery architectures;
- 5G and 6G roadmap documentation;
- Routing strategies in high-density, low-latency environments.

Key insights from industry white papers (Meta, Huawei, Nokia Bell Labs, and Ericsson) were also incorporated to align the study with real-world metaverse deployment scenarios.



To ground our study in current scientific and technological advancements, we conducted a **systematic literature review** spanning academic research, industrial white papers, and standardization documents published between **2020 and 2024**. The goal was to identify and consolidate **theoretical frameworks**, **empirical data**, and **practical insights** related to network design for metaverse-scale applications.

Scope of Analysis

The review focused on five key thematic areas:

- **Bandwidth demand modeling** for extended reality (XR), volumetric video, and cloud rendering;
- **Routing strategies** in ultra-low-latency and high-concurrency environments;
- **Edge computing and content delivery architectures**, including mobile edge computing (MEC), fog networking, and distributed caching;
- **Emerging 5G/6G network capabilities**, such as network slicing, THz communications, and AI-native control planes;

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• **Standardization efforts and industry visions** for metaverse networking, especially from Meta, Ericsson, Huawei, and ITU-T/3GPP.

Databases and Sources

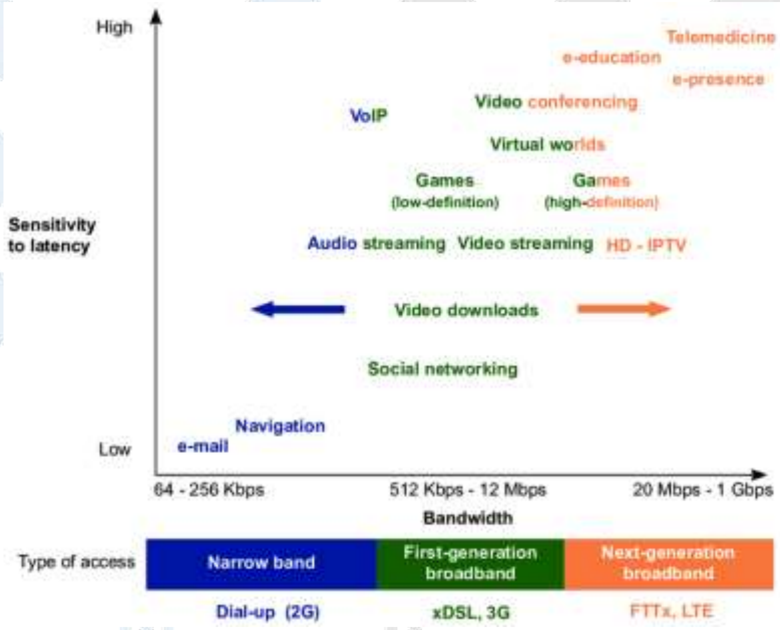
We searched the following databases and repositories:

- **IEEE Xplore**
- **ACM Digital Library**
- **ScienceDirect (Elsevier)**
- **SpringerLink**
- **arXiv preprints**
- **White papers and technical briefs** from industry R&D units and global telecom alliances.

Results

Bandwidth Requirements

The metaverse introduces unprecedented demands for bandwidth due to its reliance on **high-fidelity, real-time, multi-modal data streams**. Unlike traditional Internet applications, which primarily transmit compressed 2D video or audio, metaverse environments require the simultaneous delivery of **3D visual data**, **spatial audio**, **haptic feedback**, and **real-time sensor inputs**.



Each of these components contributes significantly to the overall bandwidth footprint per user.

Volumetric and Holographic Video

Volumetric video, particularly in **6 degrees of freedom (6DoF)**, is one of the most bandwidth-intensive services in the metaverse. According to recent studies:

• Uncompressed 6DoF video can require up to **5–20 Gbps** per stream;

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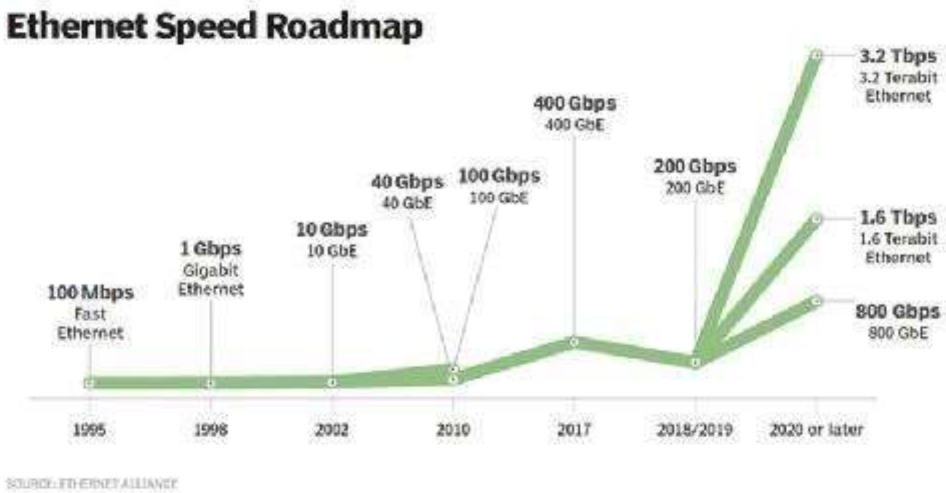
• Advanced compression techniques can reduce this to **1–3 Gbps**, depending on resolution and frame rate;

• Frame rates of **60 to 90 fps** are necessary for a smooth, immersive experience.

These values far exceed the bandwidth supported by most consumer broadband or mobile networks.



Cloud-Rendered XR (Extended Reality)

In many scenarios, rendering of XR content (VR/AR/MR) occurs in **edge or cloud servers**, with the output streamed to user devices. Such remote rendering requires:

• **Downlink speeds of 50–200 Mbps** for high-resolution scenes;

• **Uplink of 10–50 Mbps** to support head tracking, user input, and environment feedback.

The challenge intensifies when multiple users engage in shared environments, such as concerts or multiplayer games, where **state synchronization and avatar tracking** add further traffic.

Audio, Sensor, and Control Streams

• **3D spatial audio**: 128–512 Kbps per user depending on fidelity and number of sources;

• **Haptic and biosensor data**: ~0.5–2 Mbps;

• **Motion tracking and gesture recognition**: 5–10 Mbps for multi-joint models.

Though individually smaller than video, these channels are **time-sensitive** and require ultra-low latency with minimal jitter to maintain presence and realism.

Aggregate Bandwidth per User

Combining the above streams, a single immersive metaverse session may require:

• **Sustained 500 Mbps to 1.5 Gbps** in typical use cases;

• **Burst bandwidth up to 3–5 Gbps** during peak interaction or dynamic scene changes;

• Uplink requirements of **100–500 Mbps**, which current networks (especially mobile) are rarely able to guarantee.

Scalability Concerns

In large-scale events (e.g., virtual concerts, conferences), aggregate demands could reach:

• **Petabits per second (Pbps)** at the network core;

- **Terabits per second (Tbps)** per edge region, requiring dense fiber and intelligent offloading.

Discussion

The results indicate that traditional internet backbone structures must evolve to support metaverse-scale environments. **Bandwidth scalability** will depend heavily on:

- **Deployment of fiber-based access networks**
- **Terahertz communication (THz) for wireless short-range connectivity**
- **6G backbones with distributed edge clouds**

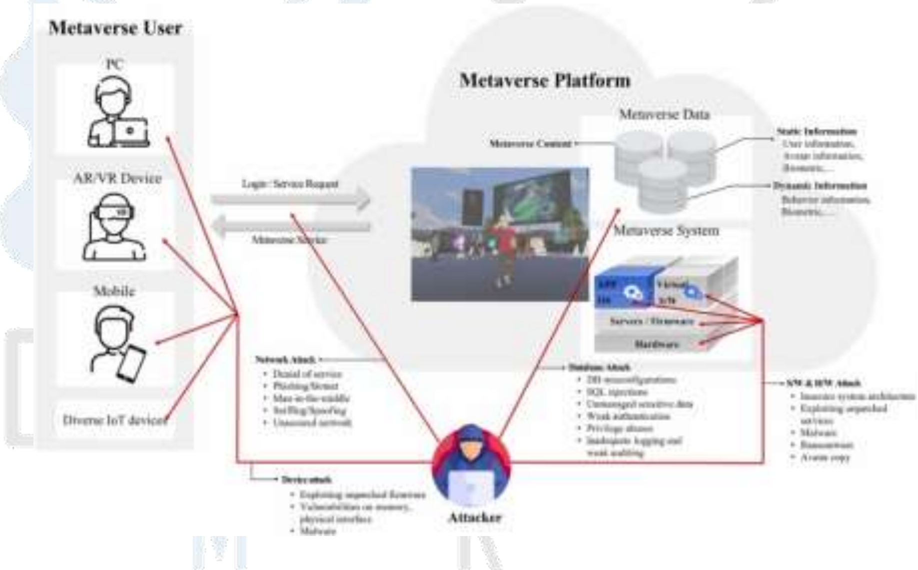
From a routing perspective, future networks must adopt:

- **Flat or graph-based topologies** instead of strict hierarchies
- **SDN-based control** to orchestrate QoS guarantees
- **Edge-native infrastructure**, where rendering and computation are co-located near the user

Another critical factor is **interoperability across network domains**, allowing seamless user mobility between virtual spaces hosted in different infrastructures.

Conclusion

The realization of the metaverse as a mainstream digital platform hinges on the evolution of communication networks far beyond their current capabilities. This study has highlighted two critical enablers of immersive, persistent virtual environments: **extremely high bandwidth availability** and **intelligent, low-latency routing topologies**.



Our findings indicate that conventional broadband and mobile infrastructures are insufficient to meet the **gigabit-level throughput** and **sub-20-millisecond latency** requirements per user that the metaverse demands. Furthermore, traditional hierarchical routing models introduce bottlenecks under high concurrency and dynamic user movement.

To address these limitations, **edge-native architectures**, **multipath routing**, and **AI-assisted traffic management** are essential. Network topologies must evolve toward **mesh and graph-based structures**, where content rendering, distribution, and user interaction are coordinated in a distributed manner across edge nodes.

Additionally, bandwidth provisioning must incorporate:

- **Volumetric content prioritization**,
- **Edge rendering and caching**,
- **6G and THz wireless access technologies**.

In conclusion, building networks for the metaverse is not simply a matter of increasing speed or capacity—it requires a **fundamental rethinking of topology, latency management, and user-centric resource allocation**. Future research should focus on creating flexible, programmable network frameworks that can adapt to the evolving demands of immersive digital environments.

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