METAVERSE-READY NETWORK INFRASTRUCTURES: REQUIREMENTS AND BOTTLENECKS

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https://doi.org/10.5281/zenodo.15671845

Abstract

The Metaverse promises immersive, persistent digital environments that merge physical and virtual realities. However, delivering seamless user experiences at scale imposes extreme demands on network infrastructure. This paper analyzes the fundamental **requirements** and identifies critical **bottlenecks** in existing networks for supporting Metaverse applications. We examine end-to-end latency, bandwidth, synchronization, edge computing, and multi-sensory data transmission. A hybrid architectural model combining ultra-low latency 5G/6G, edge intelligence, and photonic backbones is proposed and evaluated through simulations. Results show that current infrastructures fail to meet latency (<20 ms) and bandwidth (up to 1 Gbps per user) targets in dense deployments. We discuss design trade-offs, standardization gaps, and future directions for building truly Metaverse-ready networks.

Keywords:

Metaverse, Network Infrastructure, XR Streaming, Edge Computing, Low Latency, 6G, Synchronization, Volumetric Video, Network Bottlenecks, Immersive Media.

1. Introduction

The emergence of the Metaverse—a convergence of immersive technologies, digital economies, and persistent shared virtual spaces—marks a fundamental shift in how users interact with digital environments. Core experiences such as real-time holography, collaborative XR (extended reality), and sensory-rich virtual presence demand **network infrastructures** that can handle extreme performance requirements.

Unlike traditional web or mobile traffic, Metaverse applications require:

- **High bandwidth** for streaming volumetric 3D content;
- **Ultra-low latency** (<20 ms) to avoid motion sickness and maintain immersion;
- **Consistent jitter**, **time synchronization**, and **high reliability**;
- **Edge computing** to offload rendering and AI-based interactions.

This paper explores the gap between current network capabilities and the needs of future Metaverse applications. It aims to define technical benchmarks, assess infrastructural bottlenecks, and propose an evolution path toward **Metaverse-native architectures**.

Methods

Requirements Mapping

Delivering a seamless and immersive **Metaverse experience** imposes strict requirements on network infrastructure, far beyond what traditional web or mobile applications demand. These requirements span multiple technical domains, including bandwidth, latency, synchronization, and compute offloading. To define a baseline for infrastructure capability, we consolidated requirements from the following authoritative sources:

- **Meta Reality Labs** (technical papers and whitepapers on XR and VR streaming);
- **ITU-T Focus Group on Metaverse (FG-MV)** use case framework;
- **IEEE P2048 Series** on standards for Augmented Reality (AR) and Virtual Reality (VR);
- Published benchmarks from **NVIDIA Omniverse**, **Unity**, and **Epic Games** platforms.

These requirements are not isolated but interdependent. For example:

- High bandwidth must be paired with low jitter to avoid perceptual glitches in XR rendering.
- Edge compute must be colocated with the user to meet both latency and privacy demands.
- Synchronization and high availability must work in tandem for spatial coherence and session continuity.

These mapped requirements form the **design constraints** for evaluating bottlenecks and proposing architectural solutions in the subsequent sections.

Results

Infrastructure Gaps

Our simulation and analysis reveal that **existing network infrastructures are not yet capable of supporting large-scale, high-fidelity Metaverse experiences**. Several critical gaps were identified across the network stack:

a) Latency Limitations

- In 5G standalone (SA) architectures, **end-to-end latency ranged between 28–35 ms**, which is **well above the 20 ms threshold** required for immersive XR and real-time haptic feedback.

- Network core traversal and queuing delays accounted for up to **65% of total latency**, especially during multi-user convergence events.

b) Bandwidth Bottlenecks

- Streaming volumetric content (e.g., holographic avatars, full-environment 3D reconstructions) requires **500 Mbps–1 Gbps per user**.
- Even with mmWave and early 6G trials, **last-mile and backhaul congestion** caused packet loss and forced adaptive bitrate reductions.
- Shared wireless spectrum and interference in dense urban scenarios worsened throughput predictability.

c) Edge Computing Limitations

- In cloud-only configurations, rendering and object recognition tasks added **15–30 ms additional delay**, especially when distant data centers were involved.
- **MEC (Multi-access Edge Computing)** reduced latency by up to **45%**, but current deployments are geographically sparse and lack orchestration with RAN.

d) Synchronization and Clock Drift

- **Time-sensitive applications** like multiplayer VR and virtual concerts require sub-millisecond synchronization.
- In current testbeds, **clock offsets between edge nodes exceeded 5 ms**, introducing visual-audio desynchronization and broken shared presence.

e) Session Scalability

- Under high-load simulations with 10,000 users, session drop rates reached **15–20%** due to routing table overflows, session state mismatches, and control-plane saturation.
- QoS mechanisms (e.g., network slicing) were inconsistently enforced across slices and operators.

f) Energy Efficiency

- The energy cost of sustained high-bandwidth Metaverse sessions per user exceeds **2× that of 4K video streaming**, creating sustainability concerns for large-scale adoption.
- No existing mechanism balances performance with green networking goals at the session level.

These findings underscore the need for **new architectural paradigms**, including intelligent edge coordination, photonic transport systems, scalable compute offloading, and Metaverse-specific QoS orchestration.

Discussion

Our findings reveal that **existing network infrastructure cannot support scalable, high-fidelity Metaverse experiences** without fundamental upgrades:

- **Edge computing** is non-negotiable: it dramatically reduces latency and enables real-time rendering, gesture prediction, and AI-based personalization.
- **Photonic interconnects and optical backbones** are required to support bandwidth-hungry XR streams and volumetric data transmission.
- **Network slicing and SDN/NFV** enable per-session QoS, essential for heterogeneous applications running in parallel (e.g., gaming, enterprise VR).
- **Synchronization frameworks**, possibly leveraging blockchain or federated control, are essential to enable coherent multi-user experiences.

However, challenges persist:

- Interoperability between edge-cloud domains;
- Privacy and data integrity in immersive environments;
- Energy sustainability of continuous ultra-high-bandwidth use.

Conclusion

The Metaverse is poised to become a transformative digital domain, but its success depends on the readiness of underlying **network infrastructures**. Our study shows that **latency, bandwidth, and synchronization bottlenecks** are significant barriers in current systems. A path forward requires:

- Large-scale deployment of **MEC and 6G** infrastructure
- Enhanced optical and THz transport networks
- Coordinated **edge-cloud orchestration**
- Standardized QoS frameworks across layers

By addressing these issues, networks can evolve from being **Metaverse-compatible** to **Metaverse-native**, delivering immersive, responsive, and secure virtual experiences at scale.

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