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# A survey on Digital Twins for Multi-User Synchronization in Human-centered IRs

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**Abstract**—Multi-user extended reality (XR) is an advanced technology that immerses users simultaneously into the metaverse, aiming to provide a real-time interaction experience in different scenarios. However, different users’ network conditions cause data transmission to be asynchronous. It forces users’ behavior in the metaverse to go out of sync, seriously impacting the user experience. This paper presents a framework for *human-centred* synchronization of networks and metaverse applications, often denoted as Intelligent Realities, using *Digital Twin (DT)* technologies for the networks (network DTs) as well as for the individual users’ XR parts (XR DTs). Our framework uses users’ attention as a key input to dynamically allocate network resources and align content, thereby keeping widely distributed users in sync. To motivate this framework, we surveyed recent DT-based XR and network systems and found a significant gap: few studies work on synchronizing systems between *network DTs* and *XR DTs*. This highlights the need to explore integrated solutions for networked real-time multi-user interaction in the metaverse.

**Index Terms**—HCI, XR, digital twin, multi-user, network resource allocation

## I. INTRODUCTION

With the continuous advancement of XR technology, there is a growing focus on delivering immersive multi-user experiences. Unlike single-user scenarios, multi-user networks place greater emphasis on user synchronization. We propose a framework of Multi-User Human-Centered Intelligent Realities (HC-IRs), which integrates Human-Computer Interaction (HCI), Software Defined Networks (SDN), Machine learning (ML), and other XR techniques to support user interaction in a real-time virtual environment. However, it needs to coordinate multiple users, XR devices, and network conditions, introducing significant synchronization and resource management challenges. In addition, ensuring all users receive a consistent and timely experience remains a challenge, particularly in distributed and heterogeneous network conditions.

Digital Twins are dynamic virtual representations of real-world systems [1]. They replicate structural features and mirror behaviors, enabling simulation and remote control. In our context, we maintain two types of DTs: Network DTs that mirror real-time network performance (e.g., latency, bandwidth for each user) and XR DTs that mirror each user’s virtual state (e.g., position, viewpoint, and attention focus). By linking these twins via a synchronization module, we can simulate and control the joint network application behavior in real

time. However, as we will discuss, existing works investigate network and XR digital twins separately. There is a need for an integrated solution that puts the network and XR as parts of a unified system. In the following section, we will present the framework and review recent research on XR and network digital twins to highlight the lack of integration between them.

## II. PROPOSED FRAMEWORK AND A MINI SURVEY

We propose a multi-user Digital Twin framework in Figure 1 to manage synchronization in Multi-User HC-IRs. The design consists of two tightly integrated DT modules: one for real-time response to actual network conditions and the other for response to the positions and orientations of multiple users in the real world, bridged by a synchronization module. These modules virtualize real-world users and systems, maintaining state consistency through real-time feedback loops.

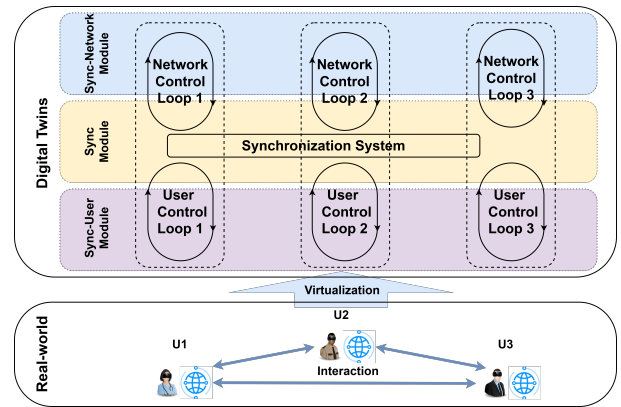


Fig. 1. Digital twins for Multi-User HC-IRs

1. **Sync-Network Module:** This module contains network control loops (one per user), each realized as a Network DT. These DTs continuously track and model user-specific network conditions, such as latency, packet loss rate, and bandwidth.

2. **Sync-User Module:** This module consists of several user control loops. Advanced sensors collect user behavior information (such as movement, electrocardiogram, and even thoughts) and map it to the DT, enabling real-time synchronization and prediction of user behavior.

3. **Sync Module:** The synchronization system exchanges data and coordinates policy between the Network DTs and

TABLE I  
TECHNICAL FEATURE COMPARISON OF PAPERS WITH NETWORK AND XR DIGITAL TWINS

Paper	Network System			XR System			Sensors Used for Data Collection
	Network DT related to XR	Monitoring	Resource Allocation	Network Prediction	XR DT related to Network	Multi-user Interaction	
[2]	✓	✓	✓	✓	✓	✓	Telescope sensors (e.g., orientation, temp)
[3]	✓	✓	✓	✓	✓	✓	Quantum clocks, entangled photon sensors
[4]	✓	✓	✓	✓	✓	✓	Eye tracking, motion capture, biometric sensors
[5]	✓	✓	✓	✓	✓	✓	IoT machine sensors, cameras
[6]	✓	✓	✓	✓	✓	✓	Environmental IoT sensors (for XR overlay)
[7]	✓	✓	✓	✓	✓	✓	Wi-Fi AP telemetry, robot state feedback

XR DTs. This core aligns application interaction needs with network capabilities. Simultaneously, it is also responsible for synchronizing users' network conditions. For example, users with high-priority roles can trigger network adaptive resource allocation components that ensure fairness in user experience.

The innovative aspect of our framework is that the network synchronization is no longer static or purely network-triggered; instead, it is driven by users' behaviors in the virtual environment. We enable a closed-loop system by virtualizing both user behavior and network state as twins. For example, when a user looks at something, the system's network twin immediately reacts to ensure that "something" is consistently delivered to all relevant users with minimal delay.

To understand the state of our framework, we conducted a mini-survey to identify the DT systems in both network and XR application domains, highlighting their relevance for synchronization tasks. We began by formulating a search string to retrieve papers whose titles or keywords simultaneously include digital twin, XR, and network. The search was conducted using the Scopus database and yielded 17 results. After a thorough review, six publications were identified as directly related to our research. We analyzed their technical features, summarized in Table I. The comparison spans key capabilities on the network side (monitoring, resource allocation, and network prediction) and on the XR side (multi-user interaction and user behavior prediction). We also note the types of sensors each approach uses for data collection (e.g., eye trackers, IoT sensors) since sensor inputs indicate what user or environment data the system considers.

Table I shows a clear research gap. None of the surveyed solutions provides a comprehensive integration of network DTs and XR DTs for synchronization. For example, only one work [7] implements all three network DT technical features (monitoring, resource allocation, and network prediction). However, that work does not address multi-user behavior integration. On the XR side, only two studies [2], [5] explicitly consider multi-user interaction, and only one [4] mentions user behavior prediction to enhance real-time responsiveness. Moreover, several works develop separate digital twins for network and XR systems without achieving real-time collaboration between the two domains. Our mini-survey shows that current DT-based Network-XR systems lack a cross-domain synchronization mechanism. This insight directly motivates our proposed framework.

### III. CONCLUSION AND FUTURE WORK

To achieve this framework, it still faces many challenges: 1)Synchronization algorithm, 2)Prediction and resource allocation algorithm, 3)DT modeling, and 4)Evaluation metrics.

To address these challenges, we conducted a survey to summarize recent research on XR and network digital twins and proposed an XR–Network Digital Twin framework to support Multi-User HC-IRs synchronization and adaptive prediction. This contribution offers guidance for future research focusing on immersive, interactive, and intelligent Digital Twin systems.

In future work, we aim to use DT technology to virtualize network and user behavior data, enabling real-time modeling and simulation of multi-user environments. Based on this, we plan to develop a behavior-aware synchronization algorithm that dynamically uses behavior similarity to allocate network resources. This approach aims to adapt effectively to evolving user interactions and fluctuating network conditions, thereby supporting multi-user real-time synchronization.

A full performance evaluation of the proposed framework is also a part of future work. For example, the inter-user synchronization error is the time difference between when two users see the same event or update in XR. Our framework aims to minimize this error, keeping it below human-perceptible thresholds (e.g., <20 ms frame offset). We can also track fairness and latency to measure if any user experiences consistently higher lag and whether the adaptive resource allocation improves or worsens fairness. Additionally, if predictive models are used, we can evaluate their accuracy. These metrics can help show whether the synchronization works better than static or network-only methods.

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