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Edge-Enabled Metaverse: The Convergence of Metaverse and Mobile Edge Computing

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Abstract: Metaverse is a virtual environment where users are represented by their avatars to navigate a virtual world having strong links with its physical counterpart. The state-of-the-art Metaverse architectures rely on a cloud-based approach for avatar physics emulation and graphics rendering computation. The current centralized architecture of such systems is unfavorable as it suffers from several drawbacks caused by the long latency of cloud access, such as low-quality visualization. To this end, we propose a Fog-Edge hybrid computing architecture for Metaverse applications that leverage an edge-enabled distributed computing paradigm. Metaverse applications leverage edge devices' computing power to perform the required computations for heavy tasks, such as collision detection in the virtual universe and high-computational 3D physics in virtual simulations. The computational costs of a Metaverse entity, such as collision detection or physics emulation, are performed at the device of the associated physical entity. To validate the effectiveness of the proposed architecture, we simulate a distributed social Metaverse application. The simulation results show that the proposed architecture can reduce the latency by 50% when compared with cloud-based Metaverse applications.

Key words: industrial Metaverse; edge computing; Blockchain; virtual environment; task offloading; fog computing

1 Introduction

Metaverse has emerged as a powerful alternative to the Internet as we know it today. Instead of navigating through web pages via 2D flat devices like smartphones or laptops, Metaverse allows users to interact with 3D virtual worlds using their avatars where they can work, study, or have fun. With virtual visualisation technologies such as Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and Extended Reality (XR), users can enjoy immersive virtual experiences enriched with realistic feedback sensors. Metaverse has received much attention, with many multi-billion companies willing to invest in its applications. Meta, previously called Facebook, revealed its plan to invest 10 billion US dollar in the Metaverse technology[1]. Similarly, Microsoft spent 70

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billion US dollar in the acquisition of Activision Blizzard company to develop its Metaverse[2].

The Metaverse is expected to revolutionize the traditional Internet and dominate all aspects of our lives. It has promising applications in virtual education, virtual workplace, and a real estate, to name a few. However, to fulfill the potential of a massive virtual universe, the Metaverse applications must address some requirements, such as ultra-low latency, high demands of resources, interoperability between applications, and security and privacy issues[3].

Current Metaverse implementations use a cloud-based centralized approach for avatar physics emulation and graphical rendering. Such a centralized design is not suitable, as it suffers from several drawbacks caused by the relatively long latency required for cloud access, such as low-quality visualisation. For instance, Second Life has many virtual worlds that depend on a centralized architecture[4]. Each virtual world is divided into regions managed by their dedicated servers. Most computations required for running the virtual world simulation, such as physics emulation, 3D animation, and collision detection, are performed by the region's centralized server. Therefore, the number of users that can access each region is limited by the server's computational power and communication capacity. Such limitation defeats the purpose of a universal virtual world, which is supposed to accommodate as many avatars as the number of people in the real world. Fog computing[5] and mobile edge computing[6] have been proven to tackle the issues of cloud-based systems by moving the computationally heavy load near the end-user and distributing it among edge devices. Such an approach can significantly reduce the system's latency and optimize system's performance.

In this paper, we propose a Fog-Edge hybrid computing architecture for Metaverse applications that leverage an edge-enabled distributed computing paradigm, which leverages edge devices to fulfill the required computation for heavy tasks, such as collision detection in a virtual universe and 3D physics computations. The computational cost of each entity, such as collision detection or physics emulation, is performed at the end device of that physical entity. For example, for every avatar in Metaverse, the users of edge devices are responsible for performing computational tasks related to the avatar's physical movement, such as its momentum, mass, and physical forces of the surrounding entities. Our contribution can be summarized as follows:

• Investigate the Metaverse development trends, its similarities with Blockchain development history, and the possibility of converging to multi-fragmented Metaverses rather than a distributed universal Metaverse.

• Propose a hybrid Fog-Edge architecture for Metaverse applications that leverages the physical entities' end-devices computing resources to perform the computational tasks required to run the Metaverse.

• Simulate the proposed architecture in a distributed social Metaverse application scenario to evaluate the improvements with respect to a centralized approach.

The rest of the paper is organized as follows. Section 2 reviews recent research on Metaverse technologies. Section 3 presents Metaverse architecture and its enabling technologies. Section 4 investigates the similarities between Metaverse and Blockchain development history and the possibility of converging to multi-fragmented Metaverse solutions rather than a distributed universal Metaverse. The proposed hybrid Fog-Edge architecture for Metaverse applications is featured in Section 4. In Section 5, we present the simulation results of a use-case of distributed social Metaverse application that uses the proposed Fog-Edge architecture. Finally, we conclude the paper and outline future research directions in Section 6.

2 Related Work

Recently, we have witnessed unprecedented research development on Metaverse technologies. In this section, we review the Metaverse's most recent research works and show the difference with our current work.

Ning et al.[7] surveyed recent Metaverse development trends from five perspectives: network infrastructure, enabling technologies, services management, VR objects virtualization, and virtual VR convergence. Wang et al.[8] surveyed Metaverse literature with a special focus on security and privacy threats facing Metaverse application, and reviewed the state-of-the-art privacy preserving solution for Metaverse applications. Similarly, Huynh-The et al.[9] explored the role of Artificial Intelligence (AI) in Metaverse development, furthermore they discussed the application of machine learning and deep learning algorithms in Metaverse applications. Whereas Cheng et al.[10] briefly reviewed virtual reality social platforms that can be viewed as early prototypes of social Metaverse.

Yang et al.[11] surveyed the convergence of AI and Blockchain technologies for Metaverse applications. They discussed how AI can empower Blockchain-based Metaverse applications such as virtual currency trading. Likewise, Jeon et al.[12] discussed how AI and Blockchain can affect Metaverse development in post COVID-19 era. Similarly, Gadekallu et al.[13] discussed the potential applications of Blockchain in Metaverse, specifically, data storage and acquisition, data interoperability, and Blockchain for data privacy preservation.

Nguyen et al.[14] introduced MetaChain, a Blockchain-based architecture that deals with usage of smart contracts operating on Blockchain to manage and automate complex interactions between the Metaverse users and virtual service providers. Xu et al.[15] discussed the potentials of AI, edge computing, and Blockchain for ubiquitous and seamless access to the Metaverse. In the same vein, Lim et al.[16] presented the infrastructural architecture required for Metaverse with special focus on the convergence of edge intelligence and the infrastructure layer of the Metaverse. However, none of the above-mentioned works showed the potential of Fog-Edge computing for Metaverse application through practical use case as we will show in the rest of this paper.

3 Metaverse Architecture, Technology, and Application

In this section, we discuss the main components of Metaverse applications and its enabling technologies.

3.1 Architecture

The Metaverse is a future big revolution of the Internet and can be viewed as 3D version of the current Internet. As users navigate and teleport in virtual worlds represented by their avatars, this requires the seamless mapping of users in the physical world and their counterparts in the virtual universe. The concept of physical-cyber mapping is not a unique feature of Metaverse, and it has been used in many other technologies, such as cyber-physical-systems, digital twin[17], human-in-the-loop[18], hybrid human-artificial intelligence[19], and human-robot interaction[20], to name a few, which will be inseparable with Metaverse. The Metaverse takes this concept to a broader level, encompassing the mapping and simulation of all our daily life activities into cyberspace. It enhances this mapping by providing a rich and engaging user experience that is immersive and interactive. To achieve this purpose, the Metaverse operating in multi-layer architecture is depicted in Fig. 1.

Physical space: The access point to the Metaverse includes any device that enables a user to interact with the Metaverse. General-purpose mobile devices and

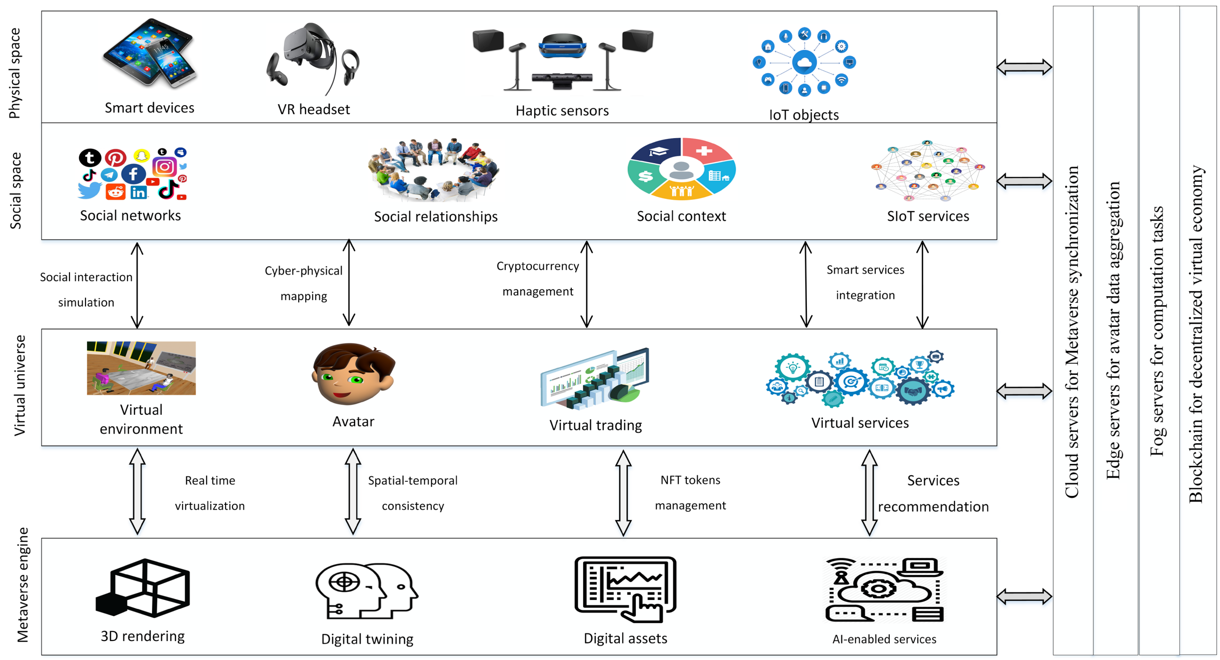

Fig. 1 Physical-social-cyber mapping supported by Fog-Edge computing and Blockchain decentralized virtual economy.

computers can serve as Metaverse access points, but when accessing from such devices, the users cannot benefit from many services and features offered by Metaverse applications. An immersed and interactive user experience can be offered only through XR devices and haptic sensors, which include sensors and headsets of virtual reality, augmented reality, mixed reality, and extended reality. Metaverse applications are connected to Internet of Things (IoT) smart services, and actions that take place in Metaverse may trigger IoT smart services in the physical space. For instance, the temperature in the current position of Metaverse avatar can be mapped with the temperature of IoT-enabled smart home air conditioning system to simulate the Metaverse weather.

Social space: Among the criticism of Metaverse, some may claim that the Metaverse is just a 3D social network enhanced by VR technologies. While such a claim is valid up to some extent, in the sense that the Metaverse will transform the way we interact with social networks, from single access point interaction to 3D world navigation accessed by VR technologies. However, Metaverse incorporates many concepts that go beyond traditional social networks, such as virtual assets trading, virtual learning environment, virtual military training, and telepsychiatry[21, 22], to name a few. In addition to the conventional social networks, the Metaverse is integrated with users' social context provided by Social Internet of Things (SIoT) services[23]. SIoT services are customized according to the user's social features[24, 25].

Virtual universe: The physical and social space entities are mapped into virtual space. The users are represented by avatars, while other physical entities are represented by digital assets. The map of the virtual world might be a representation of real world map, such as the world map, a specific building map, or an imaginary map like the maps used in multiplayer online games. Cyber-physical and digital twin applications are integrated with the Metaverse application to offer a realistic cyber representation of the physical world.

Metaverse engine: It performs computations required to run virtual universe simulation, which includes computationally heavy tasks such as collision detection in virtual universe, computation of 3D physics, and other aspects of the virtual universe that demand high computational power. For example, the validation of Non-Fungible Token (NFT) trading transactions requires tremendous computational power, not to mention data processing of digital twin applications and AI-enabled services like storytelling and recommendation services that empower the virtual universe simulation. Current state-of-the-art Metaverse implementations perform computation on the cloud, which limits simulation capacity and increases access latency.

3.2 Enabling technology

Metaverse is the next version of 3D Internet that realizes a seamless integration of immersive and interoperable ecosystems navigable by user-controlled avatars. That requires large-scale mapping of entities from physical and social spaces to a virtual universe. To do that, Metaverse relies on plethora of services backed by various cutting-edge technologies. In the following, we present and discuss Metaverse enabling technologies.

Blockchain. The Metaverse economy involves trading virtual assets and in some cases involves interaction with real economy. Securing and managing the big data resulting from virtual goods and virtual services trading require persistent and transparent trading mechanisms. Blockchain technology can play an essential role in this regard. Blockchain can be leveraged to secure virtual trading and preserve the value of digital assets and services. Blockchain as a distributed solution can overcome the drawback of a centralized trading paradigm. One of the most promising applications of Blockchain in Metaverse is NFT trading. NFT is used to mark the ownership of digital goods and assets. Utilizing Blockchain in NFT trading can facilitate peer-to-peer digital assets exchange in a distributed and decentralized manner.

AI. AI technologies empower Metaverse in many aspects. Deep learning and machine learning algorithms have been proven effective in tackling complicated problems. These algorithms perform the best when they learn from large amounts of data, and in this regard, Metaverse activities can generate very large data. AI plays an essential role in creating realistic virtual 3D worlds and automating the content generation of the Metaverse. For instance, NVIDIA introduced GANverse3D, an AI-based framework that allows content creators to take photos of real objects, and automatically generate virtual replicas with lights, physics models, and Physics-Based Rendering (PBR) materials. Furthermore, deep learning libraries like

Facebook's PyTorch3D or NVIDIA's TensorRT can be used for 3D object rendering, which accelerates virtual scene creation and minimizes computational cost. Facebook recently created AI Research Supercluster (RSC)[26], which is considered among the largest AI-enable supercomputer dedicated to the applications of AI for creating Metaverse scenes and content.

B5G/6G. Navigating the Metaverse smoothly through VR technology depends mainly on network latency. As VR technologies are delay-sensitive and require very short latency, communicating with Metaverse servers plays a pivotal role in this regard. Metaverse activities generate massive big data such as social communications between millions of users and the transmission of high-resolution interactive 3D animations, which requires high network bandwidth. Therefore, beyond 5G (B5G) and 6G networks might partially fulfill Metaverse communication requirements. B5G and 6G enable a real-time, ubiquitous, and ultra-reliable communications for massive Metaverse devices with support for device-mobility, which can reach 1020 Gbps[27].

XR technologies. XR refers to virtual visualization technologies that include virtual reality, mixed reality, and augmented reality. XR head-mounted helmets and displays are the main access point to Metaverse. XR devices allow users to enjoy real-time immersive and interactive experience through multi-sensory large-scale 3D modeling[28]. XR devices and haptic sensors create a visually realistic virtual environment, while IoT smart sensors carry out environment digitization by sensing the surrounding objects. In this way, the users are not limited to screen-based devices like laptops or smartphones to access the Metaverse.

4 Proposal for a Distributed Metaverse

4.1 Universal Metaverse or interconnected Metaverse

Most of the recent propositions of Metaverse design do not come in line with the vision of a universal Metaverse. It is rather several independent and fragmented Metaverse that rely on different hardware and software technologies. The isolated implementations of independent Metaverse jeopardise its integration, and make it extremely difficult to interconnect these independent Metaverses to form a universal Metaverse. This scenario is analogous to the history of Blockchain development. The early vision is a universal Blockchain, where the authority is distributed among public nodes and anyone can participate in the decision-making process. The universal Blockchain is proposed to solve the drawbacks of the centralized authority model. However, since the launch of the first cryptocurrency Bitcoin Blockchain, we have witnessed a proliferation of thousands of independent cryptocurrency Blockchains. Some of them offer the ability to host other cryptocurrencies or other distrusted applications to operate in their Blockchain platform. Such as Ethereum open-source and decentralized Blockchain[29], which allow third parties to host immutable and decentralized applications into its Blockchain, these applications are governed by smart-contract. This Blockchain service model is known as Blockchain-As-A-Service (BAAS)[30]; however, it is far from being a universal Blockchain, as it is still always dependent on the Blockchain provider. Moreover, many organizations have their own controllable Blockchains. This kind is known as private Blockchain due to the fact that it is controlled by a single authority or/and being accessible but limited entities. As one can notice, the development trend of Blockchain has diverted from the original vision of a unified universal Blockchain. Even though in the last few years, there are several attempts to interconnect all the public Blockchains into a single Blockchain, but up to nowadays there is no prominent technology that allows such integration. That is due to the homogeneous algorithms and technologies that manage these independent Blockchains. The current development of Metaverse is taking a similar track. Various companies possess their exclusive centralized Metaverse, accessible solely to their user base. However, unlike Blockchain, in these private Metaverses the users do not participate in the decision-making process. And it is barely a virtual social world that replaces traditional social networks, rather than a universal Metaverse that replaces the physical world.

4.2 Distributed Metaverse

The main driving factor behind Blockchain fragmentation mentioned-above is the seeking of authority and the benefits that such authority brings along. For instance, the inventor of Bitcoin, Satoshi Nakamoto, possesses around 1 million bitcoins, with a net worth of 73 billion US dollar, making it the 15th richest person worldwide. Similarly, although a cloud-based Metaverse is unfavorable in term of visualization quality and also does not serve the vision of a universal Metaverse. However, such a design gives organizations that have launched their own Metaverse the upper hand by controlling users' Metaverse data in their servers, and we will end up with thousands of separated Metaverses rather than a universal Metaverse. For example, Second Life has many virtual worlds that are using centralized architecture, where a virtual world is divided into smaller regions, each managed by dedicated servers. Most of the computation required for running the virtual world simulations such as physics emulation, 3D animation, and collision detection is performed by the region's centralized server. Therefore, the number of users that can access each region is limited by the server's computation and communication capacity. Such limitation defeats the purpose of a virtual world, which is supposed to accommodate avatars as much as the real-world location can physically accommodate people. The Metaverse fragmentation problem and computational bottleneck can be resolved by considering a universal Metaverse where the data control and computation requirement of each entity in the virtual world are the responsibility of its corresponding entity in the physical space. In this context, we propose a distributed architecture that can achieve a universal Metaverse and solve the computational bottleneck.

The generic data of the Metaverse such as virtual world spatial data and environment context information is publicly accessible by any entity, while any personal data about virtual entities is managed by its counterpart in the physical world. Furthermore, the computational cost of each entity such as collision detection or physics emulation is performed at the end-device of that physical entity. For example, for each avatar in the Metaverse, the user's edge devices are responsible to perform computation tasks related to the avatar's physical movement such as its momentum, mass, and physical forces of surrounding entities. Such distributed architecture requires reliable independent infrastructure that manages the virtual world, and synchronizes and updates events to all related entities' end devices. In Fig. 2, cloud servers are dedicated to virtual universe simulation, while the edge servers are leveraged to perform computational tasks of specific regions of the virtual world grid. These areas might depict a mid-tier entity, such as a Metaverse application emulating virtual workplaces, where the

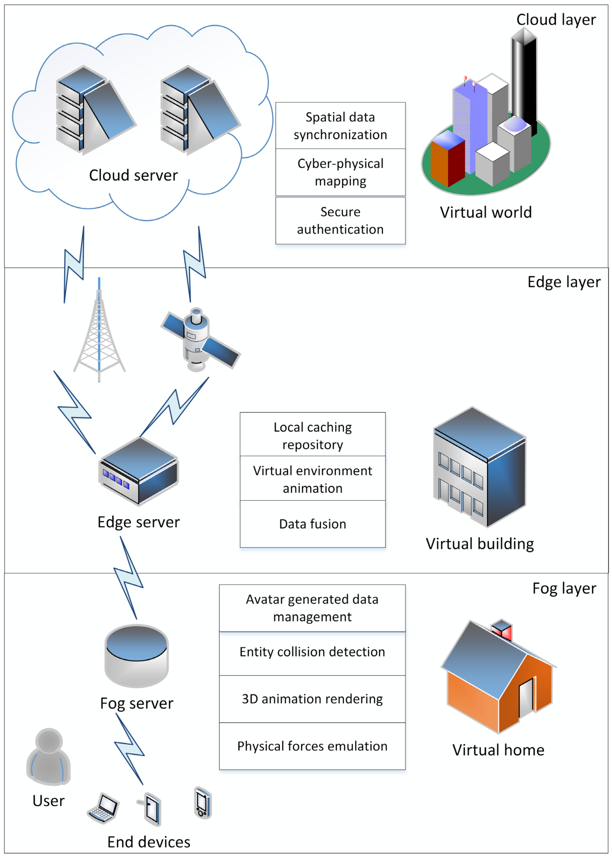

Fig. 2 Proposed hybrid Fog-Edge architecture for Metaverse applications.

company oversees employees' data. Finally, fog servers perform computational tasks near end users in a smart home environment for instance. The advantage of layered architecture is twofold. Firstly, the users control their data, which enables organizations to access a universal Metaverse rather than multiple separated Metaverses. Secondly, the computational bottleneck is resolved by distributing the computational cost of heavy tasks.

5 Use Case: Distributed Social Metaverse

To show the effectiveness of a distributed Metaverse architecture described in the last section, we have implemented a distributed social Metaverse application where the user data and computational tasks are performed at edge devices. In the proposed distributed social Metaverse, the users navigate a virtual map and communicate with nearby users through text messaging. Additionally, they can place orders to buy digital assets. To simulate the network architecture, we have used iFogSim simulator[31] to simulate devices and fog/edge/cloud servers. To support application-specific scenarios such as social network simulation or Blockchain management, we have extended iFogSim to simulate our Metaverse application. Specifically, we have created user class to simulate users and their properties through a contextual spatial information in the Metaverse. Blockchain/Block/Transaction classes are used for digital assets trading in Metaverse, and a few other classes are used for events management. Every user's personal information such as messages and Metaverse navigation history is stored in its end-devices. The digital asset trading history is stored in public Blockchain. To simulate the required computational cost for 3D simulation, each user is associated with computational tasks. In our proposed architecture, these tasks are performed at the local fog server for spatial navigation and at the edge server for social interaction management. We set cloud-based architecture as a baseline, where all the computation and data management are performed at the cloud server.

Figure 3 shows the latency difference between the two schemes with various Metaverse users count. As we can clearly observe, the latency significantly increases in cloud-based Metaverse with the increase of user count, unlike Fog-Edge Metaverse, which maintains lower latency, even when the user count increases. That is because in the latter, spatial navigation and collusion detection tasks are performed near the end-user, whereas in the former these tasks are performed on the cloud server, which increases the latency. Similarly, in Fig. 4, we see that latency exponentially increases in cloud-based Metaverse along with the increase of digital assets purchases transaction count. Fog-Edge Metaverse maintains a relatively low latency even with a high transaction count, as the transactions are validated in the edge server.

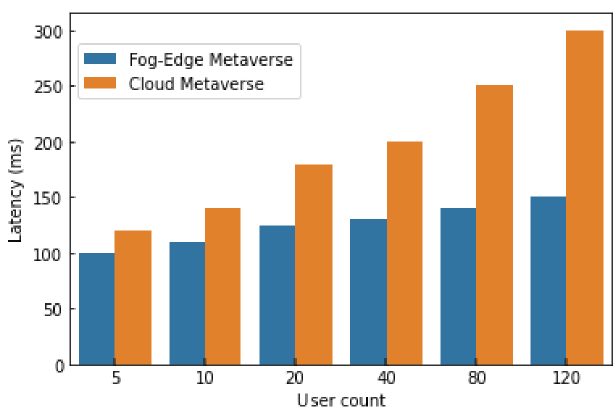

Fig. 3 Metaverse access latency with various user count.

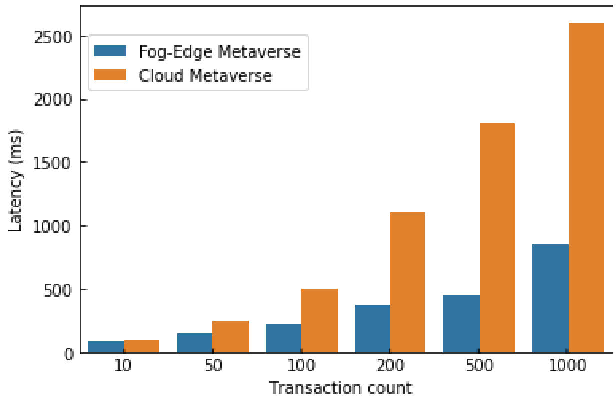

Fig. 4 Metaverse access latency with various transaction count.

6 Discussion and Open Issue

With the expected widespread of Metaverse applications, there are many challenges that face Metaverse development.

6.1 User safety

Social media companies still struggle to provide a safe online environment and protect their users from online threats, including sexual harassment, cyber-bullying, and identity theft. Metaverse is no exception to online threats. Furthermore, the interactiveness of 3D virtual world has aggravated the situation, as the perpetrators can now access more sensitive information that they cannot get on traditional social networks. One of the most serious threats in Metaverse is sexual harassment, which has always existed in social networks, but Metaverse adds an extra layer of realistic visualization that worsens the situation. Metaverse users that experience sexual harassment in the virtual universe can suffer from psychological effects as a result of such virtual harassment. For example, the Belgian police have investigated a case of a woman that has been virtually raped in Second Life[32]. Another instance involves a 7-year-old girl being subjected to gang rape by two male avatars within the platform of Roblox[33]. Some may claim that what happened in the virtual universe is not real after all. However, recent studies showed that cyber sexual violence is strongly associated with symptoms of anxiety, stress, depression, and post-traumatic reactions[34]. Metaverse companies have already imposed restrictions to contain sexual harassment. Setting restrictive measures can help prevent virtual sexual harassment incidents, however, it would defeat the purpose of social

Metaverse where the avatar can interact without restrictions. For example, Meta has introduced a personal boundary feature[35], if activated, other avatars cannot approach your avatar less than two feet distance. Sexual harassment has never been limited to physical assaults in the real world, and it will neither be in Metaverse. An AI-based solution is required to tackle this problem, without limiting social contacts, yet being capable to detect and stop sexual harassment. In this context, Artificial Social Intelligence (ASI)[36] can play an important role, as it is more focused on users' social behaviors rather than their avatar movement patterns. In this regard, the edge-enabled Metaverse can accelerate the computational tasks required by AI models to detect user safety issues.

6.2 Information privacy

The Metaverse incorporates rich data about users more than traditional social media. A user's virtual identity is a mapping of its real identity in the virtual world[37], and therefore protecting the information of an avatar in the virtual universe is as important as in the physical world. Since the Metaverse leverages many technologies, a weakness in any technology threatens the entire system. For example, public Blockchain transactions of digital asset purchases can be analysed to guess the identity of buyers and sellers, which gives a golden chance for privacy intruders and hackers to target profitable victims. Any leaking of the personal information of avatars can lead to potential identity theft. Implementing multi-layer identity management for Metaverse users is a paramount requirement to ensure avatars' security and privacy. Edge devices can handle the computational requirement for privacy-preserving schemes such as avatar disguise or avatar stalking prevention.

6.3 Metaverse addiction

The excessive use of technology, specifically online gaming and the internet, can lead to an addiction disorder. The Metaverse faces the same issue, furthermore, recent studies showed that XR technologies can increase the risk of internet addiction by 44% compared to traditional access devices such as smartphones or laptops[38], as many activities will take place in the Metaverse, ranging from virtual education and virtual workplace to virtual parties. Spending long hours wearing XR helmets and glasses that are a few inches from users' eyes will cause severe eye problems. Users may find it difficult to separate reality from the virtual universe, let alone the impact of light-intensive images on our eyes. A recent study[39] showed that kids who used VR glasses for 20 min had difficulties in distinguishing the distances of objects in reality as a result of the vergence-accommodation conflict. Addition control and usage time limit can be put in place by the Metaverse service provider. However, users can get around such measures using various techniques, such as accessing the service using multiple accounts or accessing the services through a Virtual Private Network (VPN). Edge-enable Metverse design offers more control over usage time, as the edge device is close to the end-user and can be used to monitor usage time.

6.4 Evaluation of user experience

In the proposed solution we envision the execution of some Metaverse components in the Fog-Edge servers and in the end-device instead of in the central cloud. These are mostly related to user avatar data management, collision detection, and rendering and management of the interaction with the physical world. This approach requires the transmission of real-time data from other Metaverse physical entities (objects and users) for the relevant processing. This is the case, for instance, in the case of interaction among avatars of people located at quite far ends of the Internet. Where to process and store the data, which part of the required processing to execute, and at which temporal and spatial accuracy has to be decided by taking into account the final quality delivered to the users. This calls for appropriate experience models that estimate the delivered quality on the basis of introducing latency and rendering quality influencing factors. These models still have to be studied as only preliminary solutions have been defined for VR/AR communications[40].

7 Conclusion

The Metaverse will replace the traditional Internet and dominate all aspects of our lives. The state-of-the-art cloud-based Metaverse architecture can limit the virtualization experience. In this paper, we have proposed a hybrid Fog-Edge computing architecture for Metaverse applications, and the proposed architecture makes use of edge devices to perform the required computation for heavy tasks such as collision detection in the virtual universe and computation of 3D physics. The computational tasks related to a virtual entity are performed at the end device of that physical entity. Simulation results show that the proposed architecture can reduce visualization latency by 50% compared to the cloud-based Metaverse applications.

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