Realizing the Metaverse with Edge Intelligence: A Match Made in Heaven

Wei Yang Bryan Lim, Zehui Xiong, Dusit Niyato, Xianbin Cao, Chunyan Miao, Sumei Sun, and Qiang Yang

ABSTRACT

Dubbed “the successor to the mobile Internet,” the concept of the Metaverse has recently exploded in popularity. While there exists lite versions of the Metaverse today, we are still far from realizing the vision of a seamless, shardless, and interoperable Metaverse given the stringent sensing, communication, and computation requirements. Moreover, the birth of the Metaverse comes amid growing privacy concerns among users. In this article, we begin by providing a preliminary definition of the Metaverse. We discuss the architecture of the Metaverse and mainly focus on motivating the convergence of edge intelligence and the infrastructure layer of the Metaverse. We present major edge-based technological developments and their integration to support the Metaverse engine. Then we present our research attempts through a case study of virtual city development in the Metaverse. Finally, we discuss the open research issues.

INTRODUCTION

The concept of Metaverse first appeared in the science fiction novel Snow Crash written by Neal Stephenson in 1992. More than twenty years later, the Metaverse has re-emerged as a buzzword. In short, the Metaverse is commonly described as an embodied version of the Internet. Just as how we navigate today’s Internet with a mouse cursor, users will explore the Metaverse with the aid of virtual reality (VR) or augmented reality (AR) technologies. Moreover, powered by Artificial Intelligence (AI), blockchain technology, and 5G and Beyond, the Metaverse is envisioned to facilitate peer-to-peer interactions and support novel, decentralized ecosystems of service provisions that will blur the lines between the physical and virtual worlds.

To date, tech giants have invested heavily toward realizing the Metaverse as “the successor to the mobile Internet.” Among others, Facebook was even rebranded as “Meta” to reinforce its commitment toward the development of the Metaverse. There are two fundamental driving forces behind the excitement surrounding the Metaverse. First, the Covid-19 pandemic has resulted in a paradigm shift in how social interactions are conducted today, thereby positioning the Metaverse as a necessity in the near future. Second, emerging technological enablers have made the Metaverse a growing possibility. For example, advances in VR/AR and haptic technologies enable users to be visually and physically immersed in a virtual world. To date, there exist “lite” versions of the Metaverse that have evolved mainly from Massive Multiplayer Online (MMO) games. Among others, Roblox (https://www.roblox.com/) and Fortnite (https://www.epicgames.com/fortnite/en-US/home) started as online gaming platforms. Yet, just recently, the virtual concerts held on Roblox and Fortnite attracted millions of views.

However, we are still far from realizing the Metaverse. For one, the aforementioned “lite” versions are distinct platforms operated by separate entities. In other words, one’s Fortnite avatar and virtual items mean nothing in the Roblox world. In contrast, the Metaverse is envisioned to be a shardless integration of virtual worlds. Next, while MMO games can host more than a hundred players at once, albeit with high-specification system requirements, an open-world VRMMO application is still a relatively nascent concept even in the gaming industry. Similarly, it will be a challenge to develop a “shardless” Metaverse that is persistent, rather than one that separates players into different sessions. This is exacerbated by the expectation that large parts of the Metaverse have to integrate the physical and virtual worlds, for example, through digital twins. The stringent sensing, communication, and computation requirements impede the real-time, scalable, and ubiquitous implementation of the Metaverse. Finally, the birth of the Metaverse comes amid increasingly stringent privacy regulations.

In this article, we begin by motivating a definition and introduction to the architecture of the Metaverse. To realize the Metaverse amid its unique challenges, we mainly focus on the edge intelligence driven infrastructure layer, which is a core feature in future wireless networks. In short, edge intelligence is the convergence between edge computing and AI. We adopt the two commonly-quoted divisions of edge intelligence, that is, Edge for AI; which refers to the end-to-end framework of bringing sensing, communication, AI model training, and inference closer to where
data is produced; and AI for Edge: which refers to the use of AI algorithms to improve the orchestration of the aforementioned framework. Then, as a case study, we present a framework for the collaborative edge-driven virtual city development in the Metaverse. Finally, we discuss the open research issues.

Our contributions are as follows:

- We present a general architecture of the Metaverse and its major components, thereby providing a holistic view of the Metaverse ecosystems. We outline the key technologies that enable the edge-driven Metaverse, emphasizing their roles to support virtual services.
- We discuss potential applications and services that can be delivered in the Metaverse, and through a case study on virtual city development, demonstrate the convergence between edge intelligence and the Metaverse engine.
- We present research perspectives and highlight the interdisciplinary open issues and research opportunities.

**THE METAVVERSE: ARCHITECTURE, TECHNOLOGIES, AND APPLICATIONS**

The Metaverse is an embodied version of the Internet that comprises a seamless integration of interoperable, immersive, and shardless virtual ecosystems navigable by user-controlled avatars [1]. In the following, we explain each key word in this definition. Then we present the layers of the Metaverse architecture (Fig. 1).

**Embodied:** The Metaverse blurs the line between the virtual and physical worlds. The virtual worlds are given a tangible form that users can interact with physically, for example, using VR and haptic feedback. Users can utilize AR to extend the virtual worlds into the physical environment.

**Seamless/Interoperable:** Much like the physical world, our belonging in one virtual world should not lose its value when brought to another seamlessly, even if the virtual worlds are developed by separate entities. In other words, no a single company “owns” the Metaverse.
**Immersive:** The Metaverse can be “experienced” beyond 2D interactions that allow users to interact with other users similar to that in the physical world.

**Shardless:** Much like the physical world, thousands of users should be able to co-exist in a single server session, rather than having users separated into different virtual servers. With users accessing the Metaverse and immersing themselves anytime and anywhere, the life-like interaction of users is thus shared globally, that is, an action may affect any other users just as in an open world.

**Ecosystem:** The Metaverse will support end-to-end service provisions for users with virtual identities (IDs), for example, content creation, social entertainment, in-world value transfers, as well as physical services that will cross the boundaries between the physical and virtual worlds.

**Physical-Virtual World and the Metaverse Engine**

**Physical-Virtual World Interaction:** Each non-mutually-exclusive stakeholder in the physical world controls components that influence the virtual world. The consequences in the virtual world in turn feedbacks to the physical world. The key stakeholders are:

- **Users** can experience the virtual world through Head Mounted Displays (HMDs) or AR goggles. The users can in turn execute actions to interact with other users or virtual objects.
- **IoT and sensor networks** deployed in the physical world collect data from the environment. The insights derived are used to update the virtual environment, e.g., through feeding information to update a digital twin that is a virtual copy of a physical environment updated in real-time. The sensor network may be independently owned by sensing service providers (SSPs) that contribute live data feeds to virtual service providers (VSPs) to generate and maintain the virtual environment.
- **Virtual service providers (VSPs)** develop and maintain the virtual worlds of the Metaverse. Similar to user-created videos today (e.g., YouTube), the Metaverse is envisioned to be enriched with user-generated content (UGC) that includes virtual art, avatars, games, and social applications. These UGC can be traded in the Metaverse.
- **Physical service providers** operate the physical infrastructure that supports the Metaverse engine and respond to transaction requests that originate from the Metaverse. This includes the operations of communication and computation resources at the edge of the network, or logistics services for the delivery of physical goods transacted in the Metaverse.

**The Metaverse Engine:** This obtains inputs such as data from stakeholder-controlled components.

The virtual world is generated, maintained, and enhanced with these inputs:

- **VR/AR** enables users to experience the Metaverse visually, whereas haptics enable users to experience the Metaverse through the additional dimension of touch, for example, using haptic gloves. This enhances user interactions, for example, through transmitting a handshake across the world, and opens up the possibilities of providing physical services in the Metaverse, for example, remote surgery. These technologies are developed by standards that facilitate interoperability, for example, Virtual Reality Modelling Language (VRML — https://www.web3d.org/documents/specifications/14772/V2.0/part1/javascript.html), that govern the properties, physics, animation, and rendering of virtual assets, so that users can traverse the Metaverse smoothly.

- **Digital twins** enable some virtual worlds within the Metaverse to be modeled after the physical world in real-time. This is accomplished through modeling and data fusion. Digital twins add to the realism of the Metaverse and facilitates new dimensions of services and social interaction. For example, Microsoft Mesh allows users working from multiple sites to collaborate with each other in real-time digital copies of their office.

- **Artificial Intelligence** can be leveraged to incorporate intelligence into the Metaverse for improved experiences, for example, for efficient object rendering, intelligent chatbots, and UGC. For example, the MetaHuman project (https://www.unrealengine.com/en-US/digital-humans) by EpicGames utilizes AI to generate life-like digital characters quickly. The generated characters may be deployed by VSPs as conversational virtual assistants to populate the Metaverse.

- **Blockchain** technology will be key to preserving the value and universality of virtual goods, as well as establishing the economic ecosystem within the Metaverse. It is difficult for current virtual goods to be of value outside the platforms on which they are traded or created. Blockchain technology will play an essential role in reducing the reliance on such centralization. For example, a Non-fungible token (NFT) serves as a mark of a virtual good’s uniqueness and authenticates one’s ownership of the good. This protects the value of virtual goods and facilitates the peer-to-peer trading in a decentralized environment. As virtual worlds in the Metaverse are developed by different parties, the user data may also be managed separately. To enable seamless traversal across virtual worlds, multiple parties will need to access and operate on such user data. Due to value isolation among blockchains, cross-chain is a crucial technology to enable secure data interoperability.

---

**TABLE I. Communication requirements of services in the Metaverse [2].**

| Services                        | Reliability (%) | Latency (ms) | Data Rate (Mb/s) | Connection Density (UEs/km²) |
|---------------------------------|-----------------|--------------|------------------|-----------------------------|
| Entertainment                   | 1-10⁻⁵          | 7-15         | 250              | 1000-50,000                |
| The Tactile Internet with Haptic Feedback | 1-10⁻⁶         | 1            | 1                | 1000-50,000                |
| Digital Twin for Smart City     | 1-10⁻⁵          | 5-10         | 10               | 100,000                    |
| Smart Healthcare                | 1-10⁻⁶          | 5            | 10,000           | 50                          |
The general functions of the infrastructure layer are as follows:

**Communication and Networking:** To prevent breaks in presences (BIP), that is, disruptions that cause a user to be aware of the real world setting, the heterogeneous communication and network requirements must be met (Table 1). VR requires a high data rate whereas haptic traffic requires a relatively lower packet error rate [3]. This may be enabled through forefront communication systems and techniques such as AI-enabled network slicing, enhanced mobile broadband (eMBB) and ultra-reliable and low latency communication (URLLC) links, which are the main technology pillars in 5G and beyond.

**Computation and Storage:** Today, MMO games can host more than a hundred players in a single game session and hence require high-specification GPU requirements. VRMMO games, which are the rudiment of the Metaverse system, are still scarce in the industry and may require the devices such as HMDs to be connected to powerful computers to render both the immersive virtual worlds and the interactions with hundreds of other players. To enable ubiquitous access to the Metaverse, a promising solution is the cloud-edge-end computation paradigm. Specifically, local computations can be performed on end devices for the least resource consuming task, for example, computations required by the physics engine to determine the movement and positioning of an avatar. To reduce the burden on the cloud for scalability, and further reduce end-to-end latency, edge servers can be leveraged to perform costly foreground rendering, which requires less graphical details but lower latency [4]. The more computation intensive but less delay sensitive tasks, for example, background rendering, can in turn be executed on cloud servers. Moreover, popular contents can be cached at the edge of the network for efficient retrieval and reduction in computation overheads.

The infrastructure layer leverages edge intelligence (Fig. 2) to: support AI for the intelligent Metaverse (i.e., Edge for AI); and utilize AI to realize the resource-efficient collaborative edge paradigm (i.e., AI for Edge).

**Edge Intelligence-Empowered Infrastructure**

**Edge for AI:**

**Edge Intelligence:** Apart from offloading rendering computations to the edge or cloud, costly computation tasks required for data processing and AI model training, for example, matrix multiplication, can also be decomposed into subtasks to be offloaded to edge servers (i.e., workers). The completed subtasks are aggregated at a master node to recover the computation result. However, a major drawback of computation offloading is the existence of stragglers, which are the processing nodes that run slower than expected or nodes that may be disconnected from the network due to several factors such as imbalanced work allocation and network congestion. As a result, the overall time needed to execute the task is determined by the slowest processing node. One way to mitigate the straggler effect is to utilize worker selection schemes to eliminate straggling workers. Another way is to leverage coded redundancy to reduce the recovery threshold, that is, the number of workers that need to submit their results for the master to reconstruct the final result. For example, polynomial codes [5] can be used to generate redundant intermediate computations. The total computation is not determined by the slowest straggler but by the time taken for the master node to receive computed results from some decodable set of workers. For polynomial codes, the recovery threshold does not scale with the number of workers involved, thereby ensuring the scalability of the edge-empowered Metaverse.

**Caching:** Edge caching is instrumental to reduce computation and communication redundancy, which refers to the wastage of network resources as a result of repetitive user access of popular content or computations. For the former, the probabilistic model for the popularity distribution of files, for example, field of views (FOV) in the Metaverse, can be learned [6]. Then the popular FOVs can be stored at edge servers close to users that demand it more to reduce rendering computation cost and latency. For the latter, the computation results from AI models can be cached at edge servers to respond to computation requests that are of a similar nature. Moreover, pre-trained models can be cached at the edge to perform costly inference tasks for faster response to users.

![Figure 2: Applications of Edge Intelligence for the Metaverse.](image-url)

**FIGURE 2.** Applications of Edge Intelligence for the Metaverse.
In a heterogeneous user network, it is of utmost importance that resources at the edge, for example, for storage and computation, are well allocated to maximize the user QoE. AI-enabled solutions are increasingly utilized to solve the allocation problem given the dense distribution and mobility of users. The study of [4] discusses that the rendering strategies of VR/AR users can be calibrated among local rendering, edge-assisted rendering, and edge-cloud rendering (i.e., local rendering of foreground interactions and edge rendering of background environment). The user QoE can be formulated as a function of latency and energy consumption, based on the user device and the required functions. The rendering strategies can be formulated based on deep reinforcement learning (DRL) algorithms trained offline, subjected to the queue states at the edge servers and service requirements of the user. Moreover, the algorithm can be further refined using mechanism design when implemented online to account for the ad-hoc transitions in user usage requirements that may affect other users’ QoE or rendering strategies.

**Incentive Mechanisms:** The stakeholders of the Metaverse, for example, users, blockchain miners, and edge servers, each own valuable resources such as data and computation resources that can be leveraged for the enhancement of the Metaverse. To incentivize their participation, one may naturally consider a distributed reward mechanism, so as to reduce link distances and instances of costly global communication with the cloud.

**AI for Edge:**

**Semantic Communication:** The advent of the Metaverse will inevitably contribute to a growing demand for bandwidth amid the explosive data traffic volume required to support the Metaverse engine. This necessitates a paradigm shift from Shannon’s conventional focus in how accurately the communication symbols can be transmitted to how precisely the transmitted symbols can convey the meaning of the message. The human-to-machine (H2M) semantic communication can be a key technology to optimize VR/AR implementation for the ubiquitous Metaverse [8]. As an illustration, we reference the AR architecture proposed in [9] that is divided into the user, edge, and cloud tiers (Fig. 2). The user tier senses the environment and transmits the raw video stream and other user controls to the edge tier. At the edge tier, image frames from the video stream are utilized to find a match with the cached images, for the retrieval of relevant information such as image annotations. If the image frame is not found from the cache, the frame is offloaded to the cloud for further matching. If a match is not found, computation is executed at the cloud and the edge cache is updated. Clearly, the image frames of the raw video streams are of heterogeneous importance. With AI-enabled semantic extraction and pre-processing of the video stream, the redundant transmission of repetitive or unimportant frames to the edge or cloud can be greatly reduced to alleviate the burden on backbone networks. Beyond semantic encoding for text, audio, or images, semantic communication has also emerged as a key enabler of efficient communications in distributed machine learning, for example, gradient quantization schemes can significantly reduce the communication overhead of distributed AI model training.

**Edge Resource Optimization:** In a heterogeneous user network, it is of utmost importance that resources at the edge, for example, for storage and computation, are well allocated to maximize the user QoE. AI-enabled solutions are increasingly utilized to solve the allocation problem given the dense distribution and mobility of users. The study of [4] discusses that the rendering strategies of VR/AR users can be calibrated among local rendering, edge-assisted rendering, and edge-cloud rendering (i.e., local rendering of foreground interactions and edge rendering of background environment). The user QoE can be formulated as a function of latency and energy consumption, based on the user device and the required functions. The rendering strategies can be formulated based on deep reinforcement learning (DRL) algorithms trained offline, subjected to the queue states at the edge servers and service requirements of the user. Moreover, the algorithm can be further refined using mechanism design when implemented online to account for the ad-hoc transitions in user usage requirements that may affect other users’ QoE or rendering strategies.

**Applications**

We identify some important emerging applications and services in Metaverse as follows.

**Entertainment and Social Activities:** Currently, entertainment and social activities are held on platforms that support audio and video transmission. Nevertheless, user interactions are limited to rigid 2D grids of users, and are still somewhat off what is experienced in the physical world. With the aid of VR and haptic technology, social interactions will be more immersive.

**Pilot Testing:** Before products are being released in the market, they are usually tested by a small group of users in a controlled environment due to the cost of large-scale deployment or for safety reasons. The Metaverse will be a channel to pilot test products before they are released to the physical world at a low cost with fewer safety considerations.

Moreover, users can have virtual twins of physical products delivered to their inventories directly in the Metaverse for marketing purposes. As an example, Hyundai has begun experimenting with providing virtual test drives for users albeit in the lower resolution Roblox world (https://www.roblox.com/games/7280776979/Hyundai-Mobility-Adventure). In the Metaverse, test drive environ-
ments can be modeled exactly after highways with realistic traffic conditions.

Virtual Education: The pandemic has necessitated the online delivery of education. However, a drawback of virtual education is the lack of personalization and difficulty of delivering “hands-on” lessons. With more users in the Metaverse, the wealth of data can be used to further refine AI tutors for personalized lessons. Hands-on lessons that involve dealing with machines or tools can be delivered more effectively with haptics technology.

Gig Economy and Creative Industries: The Metaverse will mitigate the adverse effects of piracy on the gig economy and creative industry. The Metaverse will provide a platform for gig workers to create UGC and trade it actively as NFTs that uniquely identify the originality of the product. As an illustration, the play-to-earn model in GameFi unlocks novel career opportunities that are not available in the physical world. When a game product such as virtual pet (e.g., Axies) is bred and sold, the breeder of the pet earns a proceed (https://axieinfinity.com/axs/).

**CASE STUDY: A FRAMEWORK FOR COLLABORATIVE EDGE-DRIVEN VIRTUAL CITY DEVELOPMENT IN THE METAVERSE**

In this section, we present a case study of developing a virtual city in the Metaverse. For example, the development of “Metaverse Seoul” has recently been proposed (https://www.euronews.com/next/2021/11/10/seoul-to-become-the-first-city-to-enter-the-metaverse-what-will-it-look-like) to cater to both tourists and local users, for example, to access civil services online using HMDs. We motivate the collaborative edge-driven development of a virtual city in which the sensing, computation, communication, and storage resources at the network edge are leveraged to achieve the desirable qualities and features of the Metaverse (Fig. 3).

**COLLABORATIVE SENSING FOR REAL-TIME PHYSICAL-VIRTUAL WORLD SYNCHRONIZATION**

With continuous data synchronization, the virtual city is able to reflect the physical city in real-time. An enabling technology is collaborative sensing, in which IoT and wireless sensor networks are deployed to feed digital twins within the Metaverse with fresh data streams.

In [10], we formulate a resource allocation problem in which SSPs (e.g., Drones-as-a-Service) are employed to collect data to maintain a regular sync between the physical and virtual worlds. The Unmanned Aerial Vehicle (UAV) fleets are owned by distinct SSPs, whereas the virtual city is maintained by distinct VSPs, each of which develops different areas of the virtual city that correspond to the real world. To employ the services of the SSPs, the VSP posts a reward pool (based on its budget) to be divided among SSPs that service the area. As more SSPs service the area, the data is uploaded at a higher frequency. However, each SSP receives a smaller proportion of the rewards and may churn to service other VSPs. To model the dynamic strategy adaptation of non-cooperative SSPs across the network, we utilize an evolutionary game based framework in which the SSPs are clustered into populations based on their sensing capabilities, starting location, and energy cost. Using our evolutionary game based framework, we are able to model how the calibration of rewards by VSPs affect the composition of SSPs servicing it, and thereby simulate how the synchronization frequency for each virtual region vary with the rewards provided.

**EDGE-ASSISTED EFFICIENT RENDERING OF THE IMMERSIVE VIRTUAL WORLD**

In light of battery limitations of user devices, non-panoramic VR rendering has been proposed such that only the images to cover the viewport of each eye are rendered, thereby demanding less data traffic and computation workload [11]. In [12], we study the provision of non-panoramic VR rendering services provided by edge servers and propose an incentive mechanism based on Double Dutch Auction (DDA) for edge server-user association, as well as to price the services of edge rendering. The objective is to allow VR rendering service providers to serve VR users in which their benefits (i.e., valuations of the services) are maximized.

To derive the user valuation of VR rendering services, we propose to formulate the user QoE as a function of Video Multi-Method Assessment Fusion (VMAF) and Structural SIMilarity (SSIM) values. The former reflects the user’s perception of streaming...
To minimize its operation cost by allocating the resources across the two plans most strategically [13]. Using historical data on user demand, our resource allocation scheme achieves a much lower cost than other schemes that do not consider the probability distribution of user demand (Fig. 5).

**Open Challenges and Future Research Directions**

**Redefining user QoE**

The Internet has been optimized based on gradually evolving QoE metrics. Similarly, there exists a need to redefine the user QoE for the Metaverse. This requires interdisciplinary efforts, for example, to draw relations among network requirements and user visual perceptions. For example, the human eye is unable to perceive images shown for less than 13 ms [14], thereby setting an upper-bound on the network timing requirements. Moreover, VR applications in the Metaverse will place less emphasis on the traditional focus of video resolution. Instead, foveated rendering studies eye tracking to render important scenes and reduce the image quality of scenes in the peripheral vision [15].

**Future Communication Systems and the Metaverse**

Future communication systems will deviate from conventional metrics such as data transmission rate to Value of Information (VoI) [14], that accounts for both contents and age of the packet to be transmitted. As the Metaverse will feature novel and differentiated service provision, the supporting communication and networking infrastructure must be semantic-aware and goal-oriented.

**Interoperability Standards**

While tech companies race to compete for the upper-hand in the development of the Metaverse, the need to develop interoperability standards have arisen so that the vision for a seamless Metaverse can be realized. This is crucial to encourage the proliferation of UGC in the Metaverse. Moreover, a unified model to standardize the communication protocols of the Metaverse will eventually be necessary to enable access from diverse communication systems in different virtual worlds.

**Security and Privacy**

The Metaverse will be built on blockchain-empowered economic ecosystems. As more transactions are conducted on the blockchain, the attack surface increases and security concerns arise. For example, cyber attacks can utilize malicious smart contracts (https://consensys.github.io/smart-contract-best-practices/knowledattacks/) to gain access to the user’s main crypto wallet. Moreover, new forms of hardware used to access the Metaverse bring about security challenges, for example, the finger tracking of VR users can be used to infer the password.

In contrast to click-through rates for the Internet, new dimensions of user data (e.g., eye tracking) can be collected and leveraged for more personalized advertising directly delivered to the FOV of users. This presents novel challenges to user data privacy.

**Economics of the Edge-Driven Metaverse**

The Metaverse will open up novel possibilities of both physical and virtual service resource trading among users and service providers. The contention for resources now extends from the physical to virtu-
al world, in which rational users and service providers will have to optimize the resource usage efficiently in consideration of newly defined QoE metrics.

CONCLUSION

In this article, we have discussed an architecture of the Metaverse and motivated the edge intelligence driven supporting infrastructure. Then, we present a case study of smart city development in the Metaverse, followed up with the future research directions. Our work serves as an initial attempt to motivate the confluence of edge intelligence and the Metaverse.

ACKNOWLEDGMENTS

This research is supported in part by the National Research Foundation (NRF), Singapore and Infocom Media Development Authority under its Future Communications Research & Development Programme (FCP), programme DesCartes - the NRF, Prime Minister’s Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme and under its Emerging Areas Research Projects (EARP) Funding Initiative, NRF and Alibaba Group through Alibaba Innovative Research (AIR) Program and Alibaba-NTU Singapore Joint Research Institute (JRI), the NRF, Singapore under the AI Singapore Programme (AISGP) (AISG2-RP-2020-019), and Singapore Ministry of Education (MOE) Tier 1 (RG16/20). This work is also supported by the SUTD-IZU IDEA Grant (SUTD-IZU (VP) 202102), and the SUTD-IZU IDEA Seed Grant (SUTD-IZU (SD) 202101).

REFERENCES

[1] M. Xu et al., “A Full Dive Into Realizing the Edgeenabled Metaverse: Visions, Enabling Technologies, and Challenges,” arXiv preprint arXiv:2203.05471, 2022.
[2] H. Alves et al., “Beyond 5G URLLC Evolution: New Service Modes and Practical Considerations,” arXiv preprint arXiv:2106.11825, 2021.
[3] J. Park and M. Bennn, “URLLC-EMBII Slicing to Support VR Multimodal Perceptions Over Wireless Cellular Systems,” Proc. IEEE Global Commun. Conf., IEEE, 2018, pp. 1–7.
[4] F. Guo et al., “Adaptive Wireless Virtual Reality Framework in Future Wireless Networks: A Distributed Learning Approach,” IEEE Trans. Vehicular Technology, vol. 69, no. 9, 2020, pp. 8514–28.
[5] Q. Yu, M. A. Maddah-Ali, and A. S. Avestimehr, “Polynomial Codes: An Optimal Design for High-Dimensional Coded Matrix Multiplication,” Proc. 31st Int’l Conf. Neural Information Processing Systems, 2017, pp. 4406–16.
[6] Y. Sun et al., “Communications, Caching, and Computing for Mobile Virtual Reality: Modeling and Tradeoffs,” IEEE Trans. Commun., vol. 67, no. 11, 2019, pp. 7573–86.
[7] B. McMahan et al., “Communication-Efficient Learning of Deep Networks From Decentralized Data,” Artificial Intelligence and Statistics, PMLR, 2017, pp. 1273–82.
[8] Q. Lan et al., “What is Semantic Communication? A View on Conveying Meaning in the Era of Machine Intelligence,” arXiv preprint arXiv:2110.00196, 2021.
[9] J. Ren et al., “An Edge-Computing Based Architecture for Mobile Augmented Reality,” IEEE Netw., vol. 33, no. 4, 2019, pp. 162–69.
[10] Y. Han et al., “Dynamic Resource Allocation Framework for Synchronizing Metaverse With IoT Service and Data,” Proc. ICC 2022 – IEEE Int’l Conf. Commun., 2021.
[11] V. Kelkkanen, M. Fiedler, and D. Linderoth, “Bilevel Requirements of Non-Panoramic VR Remote Rendering,” Proc. 28th ACM Int’l Conf. Multimedia, 2020, pp. 3624–31.
[12] M. Xu et al., “Wireless Edge-Empowered Metaverse: A Learning-Based Incentive Mechanism for Virtual Reality,” Proc. ICC 2022 – IEEE Int’l Conf. Commun., 2022.
[13] W. C. Ng et al., “Unified Resource Allocation Framework for the Edge Intelligence-Enabled Metaverse,” Proc. ICC.