Guest Editorial Human-Centric Communication and Networking for Metaverse Over 5G and Beyond Networks—Part II

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I. Introduction

METAVERSE, a hypothetical digital environment linking the cyber world and the physical world, is expected to revolutionize the way people interact. In the metaverse, people interact with objects, the environment, and each other through digital representations of themselves or avatars across time and space. For example, in the metaverse, people can have meetings with colleagues hundreds of miles away. They can also walk through the aisles of a store, find the best fit, and have it delivered to their doorstep. It is also possible to simulate the optimal process manufacturing line to adjust for product variation and minimize bottlenecks, or test an innovative aircraft wing design without building expensive prototypes.

By surveying recent work about metaverse supporting techniques, we find that many technical pieces (e.g., powerful chips, VR/AR, and artificial intelligence) of the metaverse puzzle are ready, but the communication and networking one is still missing. Metaverse is a new kind of virtual environment, which is supposed to be built upon a globally distributed computing infrastructure consisting of not only mobile end devices but also edge/cloud servers. A metaverse environment (including buildings, furniture, sky, etc.) shared by people could be built and maintained by edge/cloud servers, and people access this virtual environment using various end devices, e.g., VR/AR headsets or smartphones. The hyper-connectivity of the metaverse enables persistent personalized access to digital services and resources in real-time, without constraints of locations.

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A unique feature of the metaverse is that humans are the main players and it brings new challenges and opportunities to communication and networking research. In the metaverse, people would manifest and teleport across different virtual immersive landscapes. Successful experiences in the metaverse hinge on understanding and adapting to emerging customer behaviors and expectations. Moreover, as people journey through the metaverse traversing many ecosystems, security and trust will become even more important. All these activities need strong technical support from communication and networking infrastructure. For example, a user may have a meeting with colleagues and their connection quality should be guaranteed. After the meeting, this user may switch to online shops and the system needs to build virtual shopping scenarios and optimize the communication among people there. Such a kind of switching involves not only the change of peer-to-peer network settings among users but also associated data/service migration among cloud/edge servers over the core network. If people have payment activities, we need a strong network security guarantee and may invoke blockchain networks. Note that similar stories may happen to everyone in the metaverse at any time.

However, human activities and their influences on metaverse communication and networking have not been well understood and studied. If we can learn and predict human activities in the metaverse, we can better optimize our network settings and resource allocation. To achieve this, we need fundamental innovation of human-centric and hyper-connectivity communication and networking for metaverse, by integrating human behavior data analysis and prediction, dynamic network control, as well as privacy and security protection, so as to maximize system efficiency and improve user experiences. There are many open technical challenges, in both wireless access networks and core networks, from the physical layer to the application layer. We also need to rely on big data, machine learning, crowdsensing, social analytics, and other inter-disciplinary techniques to perceive, analyze and predict user behavior. Specifically, this Special Issue aims to attract research efforts from the following main fields.

- **Metaverse human behavior perception and analysis:** As the first step of human-centric design, it is important

to perceive and analyze user behaviors and activities in the metaverse. The extracted mobility and usage patterns can be used to optimize communication and networking infrastructure. Large-scale data, from both virtual and physical worlds, is the foundation of user behavior study and prediction. Incentive mechanisms are needed to motivate people for data sensing, acquisition, and sharing. Moreover, the collected data may be in different formats and contain errors, noises, and duplication. We also need to use distributed caching, computing, and communication capabilities for scalable and reliable data communication and analysis.

- **Intelligent metaverse network control and management:** After understanding human behavior, we need to integrate this knowledge into network control and management. Since human factors are difficult to be precisely modeled, we can use AI technology to enable intelligent network control. In addition, human activities are changing and we need to make the network adaptive to these changes. Many works about intelligent network designs and dynamic network control can fill this gap.
- **Metaverse network security and privacy enhancement:** Human-centric design may involve a lot of sensitive personal information and ecosystems (e.g., payments). Hence it is critical to guarantee security and privacy of the decentralized metaverse environment. Hence, we call for research efforts on network security and privacy protection for human-centric communication and networking in the metaverse.

This Special Issue has received over 100 high-quality submissions from researchers around the world. Based on a rigorous review process, 34 submissions are selected for publication in double issues. Every submission received at least three reviews, and each accepted paper went through two review rounds.

The second part of this Special Issue contains 14 papers, mainly focusing on security, privacy, as well as user interaction in the metaverse. In this guest editorial, we briefly review the research featured in this part. The papers included in this part are grouped into the following areas: security and privacy in the metaverse, blockchain and consensus in the metaverse, federated learning and unlearning in the metaverse, and user experience and interaction in the metaverse. The contributions of these papers are summarized in the following sections.

II. Federated Learning and Unlearning for Metaverse

In [A1], Zhou et al. propose a Personalized Federated Learning with Model-Contrastive Learning (PFL-MCL) framework to enhance communication and interaction in humancentric metaverse environments. They develop a multi-center aggregation for learning multiple global models and a hierarchical neural network structure for addressing data and model heterogeneity. They also adopt a contrastive learning scheme to accelerate convergence while reducing communication overhead.

In [A2], Wang et al. focus on challenges in training machine learning models for the human-centric metaverse using federated learning (FL), particularly due to extensive data communication and user unreliability. The authors propose MetaFul, a federated unlearning solution that operates without data transmission. MetaFul comprises three components: Low-throughput federated learning (LT-FL) to reduce model transmission size, Loss-based model quality assessment (LM-QA) to evaluate user data quality, and Non-communicative federated unlearning (NC-FUL) to revoke the impact of low-quality data on the model.

In [A3], Hou et al. propose to use FL to enhance user experience in the metaverse and develop an efficient FL scheme with dynamic user selection, gradient quantization, and resource allocation, considering the limitations of wireless communication resources and user demands. Experiments show this scheme outperforms conventional methods in dynamic network settings.

In [A4], Guo et al. developed a multi-view synthesizing framework to address the data and computation intensity of virtual reality (VR) transmission. The framework introduces a 3D-aware generative model that processes single-view images for users with overlapping fields of view, significantly reducing content transmission volume. The authors then adopt a federated learning approach to enhance training efficiency with a large latent feature space and low-latency communication through fewer transmitted parameters. Simulation results confirm the efficacy of the proposed framework in VR content delivery.

III. Blockchain and Consensus in Metaverse

In [A5], Liu et al. introduce a blockchain-based spatial crowdsourcing (SC) system (BlockSC) for the metaverse, addressing challenges in centralized server reliability and location privacy in task assignments. The authors develop a novel ciphertext-based task-matching scheme to grant task location access only to designated workers, using geographic coordinate transformation and bilinear mapping. This approach preserves location privacy for workers and requesters, as demonstrated through a case study.

In [A6], Cheng et al. propose an adaptive, modular blockchain architecture for a decentralized metaverse, which includes an adaptable consensus/ledger protocol based on a modular blockchain structure, reducing resource consumption while ensuring a secure environment. The authors also introduce the concept of Non-Fungible Resource (NFR) for virtualizing and renting idle resources. Results on XuperChain demonstrate the effectiveness of the proposed methods in addressing the metaverse's dynamic needs and resource challenges.

In [A7], Paing et al. introduce a counterfactual quantum Byzantine fault tolerance (CQ-BFT) protocol for multipartite networks in the blockchain-based metaverse, utilizing counterfactual unitary telecomputation with chained quantum Zeno gates. The protocol enables parties to reach a consensus without physical particle transmission. The use of this counterfactual BFT design in quantum blockchain promises the next phase of blockchain, leading to the secure human-centric metaverse.

In [A8], Liu et al. propose to enhance real-time immersive experiences through vehicular edge computing by incorporating the metaverse into vehicular networks. The authors introduce a reputation model to score vehicles to select those with high reputations for participating in a practical Byzantine fault tolerant (PBFT) consensus, increasing success and credibility without expanding the number of participants. Simulations confirm the scheme's effectiveness in achieving efficient, low-latency, and low-energy PBFT consensus in the vehicular metaverse.

IV. Security and Privacy in Metaverse

In [A9], Yang et al. introduce a virtual-real identity link (VRIL) attack model that links users' real and virtual identities using observed information. To address VRIL risk predictions, the authors develop a tuple frequency-based VRIL prediction (TupPre) model and improve prediction accuracy by incorporating attribute value correlation knowledge. This research is promising to construct the foundation of identity privacy frameworks in the metaverse.

In [A10], Yu et al. focus on the efficiency and security of behavior-oriented decision-makers in the metaverse from the perspective of autonomous driving (AD). The authors propose a novel neural backdoor attack against deep neural network-based decision-makers, using spatiotemporal driving behaviors instead of immediate states. The adversary acts as a normal driver and triggers attacks through specific driving behaviors. Extensive experiments reveal that this backdoor attack is highly stealthy and effective.

In [A11], Zhang et al. propose a privacy-preserving identity-based data governance (IDRG) scheme for blockchain-empowered metaverse communications. IDRG enables users to cryptographically control content readability and editability, utilizing polynomial functions to extend traditional identity-based encryption to multiple users. They enrich chameleon hash-based redactable blockchains for comprehensive rights governance and support user accountability and revocation. Experiments on the FISCO blockchain show significant computational efficiency improvements of IDRG over existing solutions.

V. User Experience and Interaction in Metaverse

In [A12], Chai et al. focus on metaverse video streaming and investigate how super-resolution (SR) model granularity affects system performance and optimal SR model selection for different video contents under diverse environmental conditions. The authors then introduce a novel 360-degree video streaming framework with saliency-driven dynamic super-resolution (SDSR), using model predictive control for bitrate adaptation and SR model selection. Extensive experiments demonstrate SDSR's superiority over existing algorithms.

In [A13], Hu et al. propose a low-cost, high-precision system for head motion tracking, termed HeadTrack, which is essential in virtual reality and the metaverse for human-computer interaction applications. The system emits inaudible chirps from smartphones, using the earphones as receivers. Time-of-flight measurements from the smartphone to each earphone microphone deduce the user's face orientation and distance. Experiments show HeadTrack accurately tracks head direction with an average error below 6.3° in pitch and 4.9° in yaw.

In [A14], Huang et al. introduce an interest-aware semantic communication scheme designed for lightweight point cloud video (PCV) streaming, termed ISCom. This scheme consists of a region-of-interest (RoI) selection module, a lightweight encoder-decoder, and a deep reinforcement learning-based scheduler, to optimize real-time PCV decoding and rendering on resource-constrained devices. Extensive experiments show that ISCom can outperform existing methods in improving the rendering frame rate and reducing data volume as well as memory usage, offering a promising solution to improve immersive experiences for metaverse applications.

Appendix: Related Articles

[A1] X. Zhou et al., "Personalized federation learning with model-contrastive learning for multi-modal user modeling in human-centric metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 817–831, Apr. 2024.

[A2] P. Wang et al., "Mitigating poor data quality impact with federated unlearning for human-centric metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 832–849, Apr. 2024.

[A3] X. Hou, J. Wang, C. Jiang, Z. Meng, J. Chen, and Y. Ren, "Efficient federated learning for metaverse via dynamic user selection and gradient quantization and resource allocation," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 850–866, Apr. 2024.

[A4] Y. Guo, Z. Qin, X. Tao, and G. Y. Li, "Federated multi-view synthesizing for metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 867–879, Apr. 2024.

[A5] Y. Liu et al., "BlockSC: A blockchain empowered spatial crowdsourcing service in metaverse while preserving user location privacy," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 880–892, Apr. 2024.

[A6] Y. Cheng, Y. Guo, M. Xu, Q. Hu, D. Yu, and X. Cheng, "An adaptive and modular blockchain enabled architecture for a decentralized metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 893–904, Apr. 2024.

[A7] S. N. Paing et al., "Counterfactual quantum Byzantine consensus for human-centric metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 905–918, Apr. 2024.

[A8] L. Liu, J. Feng, C. Wu, C. Chen, and Q. Pei, "Reputation management for consensus mechanism in vehicular edge metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 919–932, Apr. 2024.

[A9] Z. Yang, X. Cao, H. Wang, D. Wu, R. Wang, and B. Yang, "VRIL: A tuple frequency-based identity privacy protection framework for metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 933–947, Apr. 2024.

[A10] Y. Yu, J. Liu, H. Guo, B. Mao, and N. Kato, "A spatiotemporal backdoor attack against behavior-oriented decision makers in metaverse: From perspective of autonomous driving," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 948–962, Apr. 2024.

[A11] C. Zhang, M. Zhao, W. Zhang, Q. Fan, J. Ni, and L. Zhu, "Privacy-preserving identity-based data rights governance for blockchain-empowered human-centric metaverse communications," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 963–977, Apr. 2024.

[A12] B. Chai et al., "SDSR: Optimizing metaverse video streaming via saliency-driven dynamic super-resolution," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 978–989, Apr. 2024.

[A13] J. Hu, H. Jiang, Z. Xiao, S. Chen, S. Dustdar, and J. Liu, "HeadTrack: Real-time human–computer interaction via wireless earphones," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 990–1002, Apr. 2024.

[A14] Y. Huang et al., "ISCom: Interest-aware semantic communication scheme for point cloud video streaming on metaverse XR devices," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 4, pp. 1003–1021, Apr. 2024.

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