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

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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.

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

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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 first part of this Special Issue contains 20 papers that mainly focus on metaverse communication and networking architecture and operations. 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: wireless communication and networking for metaverse, metaverse network management, metaverse architecture and operations, and economic methods and marketing of metaverse. The contributions of these papers are summarized in the following sections.

II. Wireless Communication and Networking for Metaverse

In [A1], Zhao et al. formulate the optimization of the system utility-cost ratio (UCR) in metaverse wireless networks, which includes communication and computation resource allocation and virtual reality (VR) video resolutions, and develop a novel fractional programming technique to solve this problem. The proposed method is promising for improving the quality of service (QoS) of immersive applications in the human-centric metaverse.

In [A2], Ma et al. explore a terahertz (THz) network to enhance the quality of experience (QoE) in wireless VR systems. The authors propose a framework for an indoor multi-user, multi-RIS-assisted THz wireless VR system and formulate an optimization problem for maximizing QoE through beamforming, power allocation, and rendering capacity allocation. Extensive simulations demonstrate the improved QoE performance compared to baselines.

In [A3], Wang et al. propose a two-stage alternating optimization algorithm based on multi-task deep reinforcement learning (DRL) to jointly allocate charging time, schedule computation tasks, and optimize trajectory of UAVs and mobile devices in a wireless powered metaverse scenario. Theoretical analysis and performance results demonstrate that the proposed algorithm exhibits significant advantages over representative methods in terms of convergence speed and average computation efficiency.

In [A4], Zhang et al. propose a Neyman–Pearson criterion-driven approach integrating network functions virtualization (NFV) and software-defined network (SDN) architectures to address the challenges of efficiently supporting metaverse streaming with limited wireless resources and dynamic conditions. The proposed schemes are effective in meeting statistical QoS requirements for metaverse streaming in 6G networks.

In [A5], Xiao et al. address the challenge of optimizing information update frequency under limited wireless capacity. The authors focus on minimizing the statistical age-of-information (AoI) to catch varying wireless channels and the attention of users. The proposed methods effectively reduce statistical AoI, enhancing user experiences in the metaverse.

In [A6], Zhang et al. propose a reconfigurable intelligent surface (RIS)-aided multi-UAV cross-layer network system to improve seamless connectivity and user experience in 5G networks. The authors introduce an irregular RIS topology design, reducing channel acquisition costs and power consumption. The proposed method poses a promising solution for improving the QoS of human-centric metaverse services.

III. Metaverse Network Management

In [A7], Liu et al. propose a blockchain-based collaborative and verifiable virtualized network function (VNF) management scheme for metaverse, named BVNF+, which enables multiple network providers to abstract their services as VNFs and collaboratively manage end-to-end network slices for human-centric network services in metaverse. The authors conduct security analysis and extensive experiments based on a real-world blockchain testing network to demonstrate the efficacy of the proposed methods.

In [A8], Chen et al. introduce a human-aware hierarchical SDN architecture, integrating a metaverse cloud layer, a mobile edge computing (MEC) server-empowered edge layer, and a distributed terminal layer. The authors propose a novel spatial reuse framework for bandwidth optimization and a Lyapunov optimization-based decentralized partially observable Markov decision process (Dec-POMDP) problem to maximize spectral efficiency, latency, and reliability. A multi-agent hierarchical deep reinforcement learning algorithm is developed to tackle this complex problem, showing significant performance improvements over traditional methods in enhancing real-time immersive experiences.

In [A9], Zheng et al. focus on enhancing content delivery for delay-sensitive metaverse users through a cache-enabled, unmanned aerial vehicle (UAV) base station (UBS)-assisted cellular network. they present analytical models to evaluate network performance, considering the success probability and average content delivery delay for metaverse users. Then, the authors develop a base station association strategy based on received power and cache hit probability. This method offers theoretical guidance for deploying UBSs in metaverse applications.

In [A10], Li et al. address the challenge of reconfiguring cellular networks, crucial for applications like the metaverse. Traditional data-driven methods are limited by their lack of precision and difficulty in handling new, unobserved base stations. The authors introduce an innovative intent-driven configuration synthesis approach using satisfiability modulo theory (SMT) to achieve precise solutions. To overcome scalability issues, they design sampling-based constraint verification and domain-specific optimizations, demonstrating effectiveness across various network sizes.

In [A11], Nan et al. introduce the Spatio-temporal Identity Multi-graph convolutional network Framework (SIMF) for efficient metaverse traffic prediction. SIMF's novel layer and module capture node correlations, reducing dependence on topology, and better reflecting avatar interactions. SIMF shows high accuracy and low complexity, ideal for metaverse traffic prediction.

In [A12], Liu et al. focus on network modeling for allocating resources efficiently and configuring networks to satisfy the demands of diverse applications and users. The authors propose a weakly supervised learning method for network modeling to reduce the costs of collecting large datasets. This method utilizes low-cost queuing theory-based labels and combines them with a small amount of simulation data to create accurate models. The proposed method is promising to achieve efficient, high-performing human-centric networks in the expanding metaverse.

IV. Metaverse Economic and Marketing Models

In [A13], Xu et al. introduce the Enhanced second-score auction-based Physical-Virtual SynchronizAtion (EPViSA) mechanism for effective entity allocation in the vehicular metaverse's synchronization service market. EPViSA improves total social welfare by determining synchronizing autonomous vehicles (AVs) and metaverse billboard providers (MBPs) and protecting participants from adverse selection against adverse selection, as validated by analysis and simulations, achieving near-optimal social welfare.

In [A14], Lotfi et al. develop a novel iterative contract design and use a variant of multi-agent reinforcement learning (MARL) to solve the modeled multidimensional contract problem in the metaverse. Extensive simulations validate the contract's effectiveness in ensuring truthful interactions and maximizing VSP profit while minimizing individual rationality and incentive compatibility violations.

In [A15], Liu et al. introduce the Budgeted-pricing Blocking Bandit (B^2-bandit) problem, considering virtual service providers (VSPs)' blocking constraints and unknown non-identical VSPs' attributes. They then propose a pricing policy for known VSP information with a near-optimal approximation ratio, and an online learning algorithm for unknown information, achieving low accumulated regret. Real dataset experiments show a significant improvement over baseline pricing algorithms in value accumulation.

V. Metaverse Architecture and Operation

In [A16], Su and Li propose human-centric continuous integration in the metaverse, using accumulated labeled data from interactive behaviors like VR or AR headset usage to fine-tune deep learning models over a sustained period of time. The proposed scheme is effective in adapting machine learning models to dynamic metaverse environments.

In [A17], Meng et al. present a cross-system design framework aimed at minimizing the packet rate for effectively modeling a robotic arm in the metaverse. The framework utilizes a novel Constraint Proximal Policy Optimization (C-PPO) algorithm, which integrates system-specific knowledge into the Proximal Policy Optimization reinforcement learning method. Experiments with a real-world robotic arm show a 50% reduction in convergence time and packet rate, surpassing a baseline in packet rate efficiency and modeling error distribution.

In [A18], Chen et al. focus on the inherited security vulnerabilities and susceptibility to interference attacks in the human-centric communication metaverse. The authors introduce an intelligent game anti-interference collaborative computing model for metaverse 5G environments and design an intelligent Stackelberg Game-theoretic Policy-based Learning (SGPL) algorithm for jamming resistance. Numerical results demonstrate the SGPL algorithm's effectiveness in metaverse anti-jamming, suggesting potential applicability in other multi-user metaverse applications.

In [A19], Ye et al. consider a new quality-of-information (QoI)-aware mobile crowdsensing (MCS) campaign by UAVs that move around and collect data from mobile users wearing metaverse devices. The authors then introduce MetaCS, a multi-agent deep reinforcement learning framework for MCS by UAVs, which enables UAVs to select the most informative partners to communicate with. MetaCS outperforms six baselines in overall QoI with experiments on real-world mobility datasets.

In [A20], Cai et al. introduce SMSS, a stateful model inference service on a serverless platform supporting GPU sharing for human behavior prediction. SMSS utilizes a log-based workflow and a two-layer GPU sharing mechanism. Experiments demonstrate SMSS's effectiveness in ensuring stateful task execution and reducing cold start times for inference tasks, which provides a promising solution for enhancing human-centric metaverse services.

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JOURNAL ON SELECTED AREAS IN COMMUNICATIONS for their support and guidance.

APPENDIX: RELATED ARTICLES

[A1] J. Zhao, L. Qian, and W. Yu, "Human-centric resource allocation in the metaverse over wireless communications," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 514–537, Mar. 2024.

[A2] Y. Ma, K. Ota, and M. Dong, "QoE optimization for virtual reality services in multi-RIS-assisted terahertz wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 538–551, Mar. 2024.

[A3] X. Wang, J. Li, Z. Ning, Q. Song, L. Guo, and A. Jamalipour, "Wireless powered metaverse: Joint task scheduling and trajectory design for multi-devices and multi-UAVs," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 552–569, Mar. 2024.

[A4] X. Zhang, Q. Zhu, and H. V. Poor, "Neyman–Pearson criterion driven NFV-SDN architectures and optimal resource-allocations for statistical-QoS based mURLLC over 6G human-centric metaverse mobile networks using FBC," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 570–587, Mar. 2024.

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[A6] X. Zhang, H. Zhang, K. Sun, K. Long, and Y. Li, "Human-centric irregular RIS-assisted multi-UAV networks with resource allocation and reflecting design for metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 603–615, Mar. 2024.

[A7] D. Liu, C. Huang, L. Xue, W. Zhuang, X. S. Shen, and B. Ying, "Collaborative and verifiable VNF management for metaverse with efficient modular designs," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 616–628, Mar. 2024.

[A8] Q. Chen, R. Li, X. Xu, J. Wu, H. Jiang, and M. Qiu, "Human-aware dynamic hierarchical network control for distributed metaverse services," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 629–642, Mar. 2024.

[A9] J. Zheng, Q. Zhu, and A. Jamalipour, "Content delivery performance analysis of a cache-enabled UAV base station assisted cellular network for metaverse users," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 643–657, Mar. 2024.

[A10] F. Li, C. Hei, J. Shen, Q. Li, and X. Wang, "Human-intent-driven cellular configuration generation using program synthesis," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 658–668, Mar. 2024.

[A11] H. Nan, R. Li, X. Zhu, J. Ma, and K. Xue, "Spatio-temporal identity multi-graph convolutional network for traffic prediction in the metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 669–679, Mar. 2024.

[A12] J. Liu et al., "Practical network modeling using weak supervision signals for human-centric networking in metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 680–693, Mar. 2024.

[A13] M. Xu et al., "EPVISA: Efficient auction design for real-time physical-virtual synchronization in the human-centric metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 694–709, Mar. 2024.

[A14] I. Lotfi, D. Niyato, S. Sun, D. I. Kim, and X. S. Shen, "Semantic information marketing in the metaverse: A learning-based contract theory framework," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 710–723, Mar. 2024.

[A15] X. Liu et al., "B^2-bandit: Budgeted pricing with blocking constraints for metaverse crowdsensing under uncertainty," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 724–736, Mar. 2024.

[A16] N. Su and B. Li, "MLOps in the metaverse: Human-centric continuous integration," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 737–751, Mar. 2024.

[A17] Z. Meng et al., "Task-oriented cross-system design for timely and accurate modeling in the metaverse," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 752–766, Mar. 2024.

[A18] M. Chen, A. Liu, N. N. Xiong, H. Song, and V. C. M. Leung, "SGPL: An intelligent game-based secure collaborative communication scheme for metaverse over 5G and beyond networks," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 767–782, Mar. 2024.

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[A20] Z. Cai, Z. Chen, R. Ma, and H. Guan, "SMSS: Stateful model serving in metaverse with serverless computing and GPU sharing," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 3, pp. 799–811, Mar. 2024.

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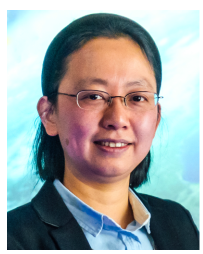

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