Guest Editorial Special Issue on Cybertwin-Driven 6G: Architectures, Methods, and Applications

INTERNET of Everything (IoE) brings unprecedented challenges regarding scability, mobility, availability, and security to wireless communications. Cybertwin emerges as a promising paradigm for the next-generation mobile network, i.e., 6G. Basically, it serves as the communication anchor of a user at the edge and performs fundamental authentication and network resources control functionalities. Cybertwin is also an indispensable enabler of the cloud native network paradigm and can efficiently support the digital twin and metaverse. With cybertwin, heterogeneous access networks can be easily exploited in a synergic manner, such that advanced applications, such as multiscreen multistream rich media delivery, can be realized with guaranteed QoS. Furthermore, a user's activities in cyberspace can be recorded naturally which becomes his/her/its digital asset. In the future, cybertwin may become the personal assistant and even an immortal second life of the user.

The implementation of cybertwin calls for novel architectural designs, methods, and applications, so as to make the next-generation network more flexible, scalable, reliable, and secure. The cross-layer and cross-discipline nature of cybertwin requires substantial research from relative fields, including communications, networking, AI, security, and economics. This special issue aims to invite researchers to present their creative thoughts and outstanding works on the cybertwin-driven 6G and to promote and develop the great potentials of cybertwin.

Although the concept of cybertwin is new, the special issue attracted over 40 quality submissions from distinguished researchers from all over the world. The review was conducted through a multiround process, with qualified reviewers expertizing each paper, and the final decisions were made in a discreet manner. Thanks to the great support from the current Editor-in-Chief, Prof. Honggang Wang, and the former Editor-in-Chief, Prof. Xuemin (Sherman) Shen, and the dedicated work of all reviewers, we were able to accept 16 excellent research works covering various topics in cybertwin-driven 6G. In the following, we will introduce these articles and highlight their main contributions.

In the article "Efficient and privacy-preserving speaker recognition for cybertwin-driven 6G," Li and Lin propose an efficient and privacy-preserving speaker recognition scheme for cybertwin-driven 6G, referred to as NEATEN, to address challenges like voiceprint disclosure in vehicle scenarios. Two novel algorithms are proposed and applied to achieve efficient and accurate speaker recognition without leaking the voiceprint data. NEATEN has high accuracy, efficiency, and security, and can be flexibly deployed in a real cybertwin-driven 6G vehicle environment.

In the article "Reliable cybertwin-driven concurrent multipath transfer with deep reinforcement learning," Yu *et al.* investigate the data scheduling issue to alleviate the packet out-of-order problem in concurrent multipath transfer (CMT). A CMT with deep reinforcement learning (CMT-DRL) algorithm is proposed to determine the data scheduling decisions. Experimental results indicate that CMT-DRL outperforms the existing benchmarks in terms of the number of out-of-order packets, roundtrip time, and throughput.

The article "Adaptive edge association for wireless digital twin networks in 6G" examines unique and complex challenges at the edge of 6G network. A wireless digital twin edge network model is presented to enable new functionalities, such as hyperconnected experience and low-latency edge computing. Moreover, a deep reinforcement learning (DRL)-based algorithm is developed to find the optimal solution to the digital twin placement problem.

The article "Application of cybertwin for offloading in mobile multiaccess edge computing for 6G networks" exploits the multiaccess edge computing (MEC) technology for the future IoT network. A mathematical model of the total service delay of a cybertwin-based MEC system is presented. Algorithms for guiding the operation of cybertwins and the control plane in a MEC scenario are proposed. Simulations demonstrate that cybertwin brings significant improvement for the MEC scenario in the form of a faster overall service due to the higher cooperation.

In the article "Toward privacy-preserving cybertwin-based spatiotemporal keyword query for ITS in 6G era," Guan *et al.* consider a cybertwin-based spatiotemporal keyword query service over a dynamic message data set in intelligent transportation systems (ITS). A layered index based on segment trees to dynamically organize messages is designed. A two-server privacy-preserving spatiotemporal keyword query scheme is presented to achieve privacy preservation and efficient computation.

In the article "Multiagent deep reinforcement learning for task offloading and resource allocation in cybertwin-based networks," Hou *et al.* present a hierarchical task offloading strategy for delay-tolerant and delay-sensitive missions

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to guarantee user Quality of Experience (QoE), low latency, and ultrareliable services. Numerical results demonstrate that the proposed strategy can improve system efficiency and task completion ratio compared to the benchmark schemes.

The article "Adaptive artificial intelligence for resource-constrained connected vehicles in cybertwin-driven 6G network" presents an adaptive AI framework based on efficient feature selection to cooperate with cybertwins resource allocation. Then, an efficient algorithm is proposed and employed in order to obtain accurate interaction measures for adaptive feature selection to balance the tradeoff between modeling accuracy and computational overhead.

In the article "Performance study of cybertwin-assisted random access NOMA," Chen *et al.* develop a cybertwin-assisted nonorthogonal random access system and analyzed the system performance of a p-persistent slotted CSMA system with NOMA. Nonconvex optimization problems are then formulated to maximize successful transmission probability and the sum data rate. An effective iterative algorithm with fast convergence is designed to tackle the nonconvexity and obtain the optimal transmission probabilities for the devices.

The article "Post-quantum secure ring signatures for security and privacy in the cybertwin-driven 6G" proposes post-quantum secure ring signatures to enhance security and privacy in cybertwin-driven 6G (PRSG for short). A double authentication preventing ring signature (DAPRS) is constructed based on the accumulator and the constructed zero-knowledge argument of knowledge. Then, the authors present how to use DAPRS to build a secure and efficient privacy-preserving scheme in cybertwin-driven 6G.

In the article "Digital twin for federated analytics using a Bayesian approach," Chen *et al.* focus on the applications of the digital twin technique, which emulates the resource-limited physical/end side while utilizing the rich resource at the virtual/computing side, to address the challenge of limited computing resources at the data generating devices. A federated Markov chain Monte Carlo with a delayed rejection (FMCMC-DR) method is developed to estimate the representative parameters of the global distribution. A rejection–acceptance sampling technique and a delayed rejection technique are combined, allowing the FMCMC-DR method to be able to explore the full state space.

In the article "Joint virtual network topology design and embedding for cybertwin-enabled 6G core networks," Li *et al.* propose a network virtualization (NV)-based network architecture in cybertwin-enabled 6G core networks to efficiently allocate heterogeneous resources for customized services. An optimization problem is formulated to minimize the VN embedding cost while satisfying the end-to-end packet delay requirements. An adaptively weighted heuristic algorithm is developed to determine a set of near-optimal solutions for large-scale networks.

In the article "Learning-based transmission protocol customization for VoD streaming in cybertwin-enabled next-generation core networks," a learning-based transmission protocol customized for Video-on-Demand (VoD) streaming services is designed for a cybertwin-enabled next-generation core network, providing caching-based congestion control and throughput enhancement functionalities at the edge of the core network based on traffic prediction. A comprehensive operation framework is also presented with in-network congestion control and throughput enhancement modules.

In the article "Deep-reinforcement-learning-based cybertwin architecture for 6G IIoT: An integrated design of control, communication, and computing," Xu *et al.* introduce the architecture of the machine-learning-based cybertwin for 6G-enabled Industrial Internet of Things (6G-IIoT) and leveraged DRL to conduct the integrated design via systematic trial and error in the cybertwin model. The adaptive observation window for deep Q-network (AOW-DQN) is invented, which generates system states adaptive to the control system's physical dynamics. Experimental results demonstrate the effectiveness and efficiency of this approach.

The article "A combinatorial auction resource trading mechanism for cybertwin-based 6G network" proposes a progressive adaptive user selection environment (PAUSE)-based combinatorial auction resource trading mechanism to allocate the resource efficiently and securely. The user's privacy can be well protected and its cost can be saved due to the transparency of this mechanism. Simulation results validate the effectiveness of the proposed mechanism in comparison with the centralized benchmark.

In the article "GraphComm: Efficient graph convolutional communication for multiagent cooperation," Yuan *et al.* explore a graph convolutional communication method (GraphComm) for multiagent cooperation to eliminate the communication bottleneck. A variational information bottleneck is used to encode the observations and intentions compactly. A graph information bottleneck with an attention-based neighbor sampling mechanism is utilized to improve the effectiveness and robustness of the multiround communication process. Experimental results show that GraphComm can improve the effectiveness, robustness, and efficiency of communication in multiagent cooperative tasks as compared with baseline methods.

In the article "Joint placement of UPF and edge server for 6G network," Li *et al.* study how to minimize the latency with cost limitation by means of jointly deploying edge servers and user plane functions (UPFs) in 6G scenario. The problem is simplified by analyzing the placement relationship between edge servers and UPFs and prune the solution space of the problem. To solve the problem effectively, a UPF and edge server placement algorithm is proposed. The evaluation results show that the proposed algorithm outperforms the benchmarks.

We would like to express our sincere thanks to all the authors for submitting their papers and to the reviewers for their valuable comments and suggestions that significantly enhanced the quality of these papers. We are also grateful to Prof. H. Wang, the current Editor-in-Chief, and Prof. X. Shen, the former Editor-in-Chief of IEEE INTERNET OF THINGS JOURNAL, for their great support throughout the whole review and publication process of this special issue, and, of course, all the editorial staff. We hope that this special issue will serve as a useful reference for researchers, scientists, engineers, and academics in the field of cybertwin-driven 6G.

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