Guest Editorial Signal Processing for Digital Twin in 6G Multi-Tier Computing Systems

I. Introduction

DIGITAL twin (DT) has become a game-changing technology in many smart applications, including smart cities, manufacturing, automotive, gaming, entertainment and climate resilience. DTs help push the boundaries of system reliability and are used to support a wide range of func- tions such as diagnostics and fault prediction. Keeping DT up-to-date requires communication means with low latency, high reliability, and high data security protection. The digital virtual twins of physical systems are then used to optimize performance of the system in real time, and one example for such systems is the sixth-generation (6G) wireless networks. There are many challenges in representing a physical system virtually, such as true *reflection* of attributes, *entanglement* and *composability*. Entanglement refers to the truly complete exchange of information between physical objects and their logical twins, while composability deals with using the ex- isting twins of different entities to enable a complete twin- based service. A typical 6G service can be deployed using either a single or multiple twin objects. Multi-tier computing enables the distributed smart devices using the signal pro- cessing and wireless communication techniques to share their idle computing and storage resources, realising the efficient utilisation of multi-tier resources. The sharing of computing, communication and caching resources in multi-tier computing systems is maturing with the continuous development of signal processing and wireless communication technology to create an intelligent interconnected world for the metaverse.

This special issue has received a strong response and has attracted submissions from researchers around the world. This is a testament to the widespread interest in digital twin signal processing in 6G multi-tier computing research. Based on a rigorous review process, a total of 11 papers were selected for publication in the special issue. Every submission received at least three reviews, and each accepted paper underwent at least one round of revisions.

In this guest editorial of our special issue, we briefly review the research presented in the issue and focus on the research development of signal processing for digital twin in multi-tier computing. The special issue begins with a paper by the guest editors, which highlights the major challenges of DT and provides an overview of an important research topic, multi-tier computing enabled DT. The remaining papers are categorised as follows.

The paper "Multi-Tier Computing-Enabled Digital Twin in 6G Networks" investigates a vision for multi-tier computing enabled DT, focusing on its interactions with various wireless techniques and performance enhancements. Future research directions and open issues are discussed, covering DT appli- cation scenarios based on multi-tier computing.

The paper "A Joint Communication and Computation Framework for Digital Twin over Wireless Networks" [A1] in- vestigates the problem of low-latency communication and computation resource allocation for digital twin (DT) over wireless networks. In this paper, multiple physical devices in the physical network (PN) need to frequently offload the computation task related data to the digital network twin (DNT), which is generated and controlled by the central server. This joint communication and computation problem is formulated as an optimization problem whose goal is to minimize the overall transmission delay of the system under total PN energy and DNT model accuracy constraints.

The paper "Data Augmentation for Predictive Digital Twin Channel: Learning Multi Domain Correlations by Convo- lutional TimeGAN" [A2] investigates data augmentation for the DT channel to improve the prediction accuracy and enhance the capability of tackling channel aging problem, where the convolutional time-series generative adversarial network (TimeGAN) approach is proposed for generating the dataset having the same channel coefficient distribution and correla- tions in time, frequency and space domain as the original one. The paper "Multi-Tier Caching for Statistical-QoS Driven Digital Twins Over mURLLC-Based Next-Generation Mobile Networks Using FBC" proposes to integrate multi-tier caching with finite blocklength coding (FBC) for supporting massive ultra-reliable and low latency communications (mURLLC)- based DT by developing multi-tier 6G mobile networks. The authors develop the efficient inter-tier and intra-tier collabora-tive multi-tier caching mechanisms, where popular DT data is selectively cached at different wireless network caching tiers. The paper "ESQFL: Digital Twin-Driven Explainable and Secured Quantum Federated Learning for Voltage Stability Assessment in Smart Grids" introduces an Explainable and Secured Quantum Federated Learning (ESQFL) method for voltage stability assessment, an innovative solution combining quantum techniques, differential privacy (DP), and Shapley value calculation. ESQFL, by leveraging the continuous in- sights from DT, emphasizes localized data analytics in a decentralized framework, integrating a Gaussian-based DP mechanism for enhanced data privacy

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and leveraging quantum teleportation for efficient Shapley value transmission.

The paper "Digital Twin-assisted Space-Air-Ground Integrated Networks for Vehicular Edge Computing" [A4] investigates a framework that integrates DT technology into space-air-ground integrated networks (SAGINs) to enhance vehicular edge com- puting. The objective is to offload tasks in ultra-reliable low- latency communications-enabled vehicular networks, focusing on minimizing overall latency for requested tasks by reducing transmission time for task offloading and edge processing requirements.

The paper "Intelligent Reflecting Surface Aided Multi-Tier Hybrid Computing" [A5] propose a novel DT edge network frame- work by considering the mutual effect of DT and mobile edge computing (MEC) functionalities. Specifically, the tasks from MEC user equipment (UE) can be either locally processed, or offloaded and then computed in the servers located in higher tiers. Besides, the server in the middle tier is also served as a fusion center to aggregate data from distributed UEs via the over-the-air computation technique.

The paper "Integration of 6G Signal Processing, Communication, and Computing based on Information Timeliness-aware Digital Twin" [A6] addresses model training problem of DT empowered electric vehicle energy management from the perspective of age of information (AoI) optimization. The proposed algorithm achieves network resource management of 6G signal processing, communication, and computing integration through AoI-optimal DT assistance and AoI-aware learning.

The paper "Digital Twin Based User-Centric Resource Management for Multicast Short Video Streaming" [A3] proposes a user-centric resource management scheme based on the DT technique, which aims to enhance user satisfaction as well as reduce resource consumption. A low-complexity resource scheduling algorithm has been designed to determine the joint bandwidth and computing resource reservation.

The paper "Distributed Digital Twin Migration in Multi-tier Computing Systems" [A7] investigates the DT migration and resource management problem in the multi-tier computing system to minimize the data synchronization latency from users to their corresponding DTs. To enable distributed resource management and DT migration, the optimal communication and computation resource management policies are derived for each edge server using convex optimization methods.

The paper "Cooperative End-Edge-Cloud Computing and Resource Allocation for Digital Twin Enabled 6G Industrial IoT" [A8] proposes a DT-assisted cooperative computing framework for task hierarchical offloading in End-edge-cloud (EEC). The framework consists of two layers that provide flexible offloading modes and reduce the computational load on edge servers (ESs). One layer is the user ends, ESs, and cloud server in IIoT, and the other layer is the digital representation of various entities. These DTs interact with their physical counterparts in real time, allowing for seamless information exchange and decision-making.

II. Conclusion

The guest editors hope that this special issue will provide valuable insights into current and future research areas on signal processing for DT-enabled multi-tier computing tech- nologies. Meanwhile, the guest editors would like to thank both Prof. Xiao-Ping Zhang and Mikaela Langdon for their timely assistance in preparing the special issue. Last but not the least, we would also like to take this opportunity to thank all the authors and reviewers for their efforts in ensuring that this is a quality and relevant special issue.

III. Appendix Related Articles

[A1] Z. Yang, M. Chen, Y. Liu, and Z. Zhang, "A joint communication and computation framework for digital twin over wireless networks," *IEEE J. Sel. Top. Signal Process.*, vol. 18, no. 1, pp. 6–17, Jan. 2024, doi: 10.1109/JSTSP.2023.3347931.

[A2] G. Liang, et al., "Data augmentation for predictive digital twin channel: Learning multi-domain correlations by convolutional timegan," *IEEE J. Sel. Top. Signal Process.*, vol. 18, no. 1, pp. 18–33, Jan. 2024, doi: 10.1109/JSTSP.2024.3358980.

[A3] X. Huang, W. Wu, S. Hu, M. Li, C. Zhou, and X. Shen, "Digital twin based user-centric resource management for multicast short video streaming," *IEEE J. Sel. Top. Signal Process.*, vol. 18, no. 1, pp. 50–65, Jan. 2024, doi: 10.1109/JSTSP.2023.3343626.

[A4] A. Paul, K. Singh, M.-H. T. Nguyen, C. Pan, and C.-P. Li, "Digital twin-assisted space-air-ground integrated networks for vehicular edge computing," *IEEE J. Sel. Top. Signal Process.*, vol. 18, no. 1, pp. 66–82, Jan. 2024, doi: 10.1109/JSTSP.2023.3340107.

[A5] Y. Zhao, et al., "Intelligent reflecting surface aided multi-tier," *IEEE J. Sel. Top. Signal Process.*, vol. 18, no. 1, pp. 83–97, Jan. 2024, doi: 10.1109/JSTSP.2023.3332455.

[A6] H. Liao, Y. Shu, J. Lu, Z. Zhou, M. Tariq, and S. Mumtaz, "Integration of 6G signal processing, communication, and computing based on information," *IEEE J. Sel. Top. Signal Process.*, vol. 18, no. 1, pp. 98–108, Jan. 2024, doi: 10.1109/JSTSP.2023.3341353.

[A7] Z. Chen, W. Yi, A. Nallanathan, and J. A. Chambers, "Distributed digital twin migration in multi-tier," *IEEE J. Sel. Top. Signal Process.*, vol. 18, no. 1, pp. 109–123, Jan. 2024, doi: 10.1109/JSTSP.2024.3359009.

[A8] Y. Wang, J. Fang, Y. Cheng, H. She, Y. Guo, and G. Zheng, "Cooperative end-edge-cloud computing and resource allocation for digital twin enabled 6G industrial IoT," *IEEE J. Sel. Top. Signal Process.*, vol. 18, no. 1, pp. 124–137, Jan. 2024, doi: 10.1109/JSTSP.2023.3345154.

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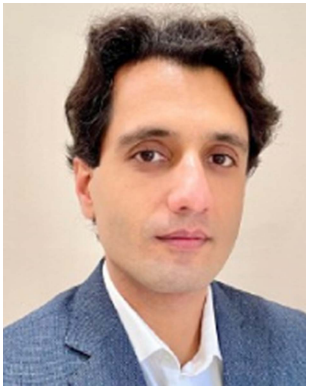

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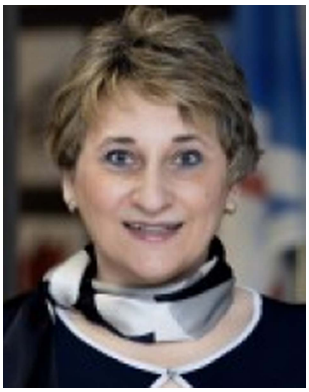

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