Guest Editorial
Digital Twins for Mobile Networks—Part I

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I. Background and Motivation

DIGITAL twins (DTs), defined as the virtual representation of a real-world entity or system, act as a mirror to provide a way to simulate, predict physical behaviors, and possibly control the real-world entity where applicable. Originating in the industry, advances in computing capacity and recent progress in artificial intelligence (AI)-based analytics make DTs attractive to a broader set of use cases including mobile networks.

Today, mobile networks provide access to a wide range of communication services, from essential infrastructure to more specialized functions in all aspects of the modern world. Due to their massive geographical coverage scale and complex environment, the consequences will be severe if mobile networks encounter downtime or failure. DTs for mobile networks, or DTMNs can add value to both the development and operational phases of mobile networks and therefore have started to make their way into some existing mobile network solutions, such as in network planning and site management optimization tools. By providing a virtual copy of mobile networks, DTMNs can help mobile network providers predict and assess network incidents, test, and offer network updates.

With the new advances in mobile networks, DTMNs can be instrumental in enabling a much wider variety of services. Service requirements can be projected by analyzing current trends and adding expected developments so DTMNs can serve different future scenarios. A replica of the current network state can be deployed and tested using DTMNs, simulating, and analyzing the new service performance and its impact on other existing services, and the new service can be launched after passing the test. The resulting insights can also be used to optimize investments in services and direct them to where they have the greatest economic value.

What is more, DTMNs can unlock the huge potential of recent AI developments in mobile networks. Indeed, most AI algorithms require large amounts of realistic data. DTMNs can be used to develop algorithms when real networks do not provide sufficient data or when applying AI algorithms under development to real networks is risky. The case of reinforcement learning is an example of this.

DTMNs can be helpful when applying new configurations and function changes to mobile networks, as it is essential to know how the function or configuration performs before introducing it to the whole network. Using DTMNs, the impact of the changes can be tested in safer environments. For example, evaluating the planned steps for deploying the new software in the cloud environment can ensure that the available resources are sufficient to do the test and, if successful, roll out the new version.

Finally, with the ongoing deployment of 5G and the expected evolution to 6G, mobile networks will be denser and more responsive, and small changes in the network can have a cascading effect in a short period of time. Therefore, the effective implementation of DTMNs will contribute to the success of mobile networks in their evolution toward 6G by giving a complete virtual copy to simulate different scenarios and test solutions, facilitate network analysis, and find optimal solutions.

While DTMNs can bring immense benefits to mobile networks, issues and challenges need to be addressed to build compelling DTMN architectures and use DTMNs effectively for future mobile network planning, network optimization, fault diagnosis and prediction, including security-related faults, and intelligent operation and management.

In this timely Special Issue, the aim is to bring together researchers from academia and industry with various backgrounds to present current advancements in algorithms, frameworks, and technologies for DTMNs to address these issues and challenges.

We have received 180 submissions on the above topics, of which we have selected 50 papers. This is the first edition, containing 25 papers; the remaining 25 papers will appear in the second part of this Special Issue. The papers included in this edition are grouped into the following areas: network planning and optimization, technologies and architecture, security, and machine learning. Each paper in subject areas is summarized hereafter.

II. Network Optimization

Van Huynh et al. [A1] introduced a fairness-aware latency minimization framework in DT-aided mobile edge computing (MEC) with ultra-reliable and low latency communications (URLLC), which jointly optimizes various communication

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and computation parameters, including bandwidth allocation, transmission power, task offloading, and processing rate of user equipment and edge servers.

Hao et al. [A2] investigated the task offloading problem in DT-assisted URLLC-enabled mobile edge networks, which considered the uncertain deviation between the physical layer and the DT layer. The authors formulated latency and energy consumption minimization problems to optimize task offloading, resource allocation, and power management.

Zhang et al. [A3] proposed a DT-driven intelligent task-offloading framework for collaborative MEC. DT maps the collaborative MEC system into a virtual space and optimizes the task offloading decisions.

Cao et al. [A4] proposed to model task offloading in vehicular edge computing networks as a constrained five-objective optimization problem that includes minimizing the downlink delay, computation delay, and energy consumption while performing load balancing. To obtain more accurate vehicle location and other information, DT was proposed for low-cost trials in task offloading.

Xu et al. [A5] proposed a DT-driven edge-end collaborative scheduling algorithm for heterogeneous tasks and computing/communication resource allocation. The authors formulated a job completion time minimization problem to jointly optimize the edge-end task division, transmit power control, and computing resource type matching and allocation.

III. Network Planning

Guo et al. [A6] proposed the construction a UAV-assisted mobile network to provide efficient communication for mobile users in high-density and high-traffic environments with a DT-empowered dynamic resource allocation strategy based on online training with low communication overhead.

Jia and Wang [A7] proposed a new virtual network topology-based DT to reduce the complexity of load-balanced user association in 6G heterogeneous networks. The authors considered more stable communication performance indicators and physical statistics to effectively reflect the real-time link quality and environmental dynamics in the DT. To assist overall network operation, fast update of the DT for the networks is achieved by adopting principal component analysis to discover specific network areas with changes.

Guo et al. [A8] proposed DT in aerial computing networks. They studied the problem of intelligent unmanned aerial vehicles (UAV) deployment and resource allocation. The authors proposed a DT-assisted UAV deployment strategy and modeled the data interdependence among subtasks. After that, two DT-assisted hybrid binary and partial task offloading schemes were proposed using heuristic greedy and deep Q network-based schemes.

IV. Technologies and Architectures

Liao et al. [A9] proposed an ultra-low age of information (ULAoI) information timeliness metric which determines DT consistency and energy management precision. Compared with age of information (AoI), ULAoI further considers the occurrence of extreme events and higher order statistical characteristics of excess AoI value.

Zhang et al. [A10] proposed a DT architecture for terahertz (THz) networks, which maps a THz physical network into a virtual network DT where the DT network is represented as a graph structure. On this basis, a distributed message propagation algorithm was also proposed, which uses a graph neural network to provide a solution for the resource management problem.

Zheng et al. [A11] proposed betweenness centrality (BC) to find the critical nodes (vertices) in kinds of DTMN applications, such as delay tolerant networks. To reduce BC computing memory consumption, they proposed a path-merging-based algorithm called Galliot to calculate the BC values to minimize memory consumption and enable BC computation of large-scale graphs on graph processing units.

Ruah et al. [A12] presented a Bayesian framework for DT-based control, monitoring, and data collection in wireless systems. A general Bayesian framework was used to quantify and account for model uncertainty at the DT caused by limitations in the amount and quality of data available from the physical twin. In the proposed framework, the DT builds a Bayesian model of the communication system, which is leveraged to enable core DT functionalities such as control via multiagent reinforcement learning, monitoring of the physical twin for anomaly detection, prediction, data-collection optimization, and counterfactual analysis.

Qi et al. [A13] proposed DT-enabled mobile network video streaming using mobile crowdsourcing. Crowdsourcing technology is used to attract mobile users to follow the specified path and share their network resources with other users. The authors leverage the DT as a centric controller. The design of the specified path is formulated as a problem of user recruitment optimization with cost constraint, for which a graph-partition-based approach is proposed.

V. Machine Learning

Cui et al. [A14] proposed a learning framework that maximizes the sum rate by jointly optimizing the access point and user association (AUA), power control, and reconfigurable intelligent surface (RIS) beamforming in DT-assisted, RIS-based user-centric cell-free systems.

Zhou et al. [A15] addressed the problem of designing lightweight model training and real-time processing in high-speed mobile networks. They introduced an end-edge-cloud structured three-layer federated reinforcement learning framework, incorporating a DT system.

Chen et al. [A16] proposed a traffic prediction-assisted federated deep reinforcement learning scheme to efficiently migrate services and improve the cost efficiency of DT-enabled MEC networks.

Mu et al. [A17] proposed communication-assisted sensing with federated learning in DT-empowered mobile networks. Two communication-assisted sensing architectures were proposed to improve the communication efficiency of mobile networks, namely, a centralized architecture of federated transfer learning (FTL) and a decentralized architecture of FTL.

Hu et al. [A18] proposed a masked 1-D convolutional autoencoder for bearing fault diagnosis based on DT-enabled industrial Internet of Things.

Xu et al. [A19] proposed joint optimization for nonorthogonal multiple access and multitier hybrid cloud-edge computing in industrial IoT and leverage meta reinforcement learning to improve the generalization and fast adaptation of learning models for DT empowered industrial IoT.

Sun et al. [A20] proposed a class-driven graph attention network learning framework for multi-label classification of mobile health data in DTMN. The framework uses a temporal context attention module to generate class representation vectors by fusing multidimensional features of time and class. The framework the dynamically models different relevances among the class representation vectors through a dynamic graph attention module, improving the multilabel time series classification performance while maintaining a smaller parameter size and lower computational complexity.

VI. Security

Zhang et al. [A21] proposed a moving target defense (MTD) solution for DTMN. The authors considered two MTD schemes, namely host address mutation (HAM) and route mutation (RM), which adjust network properties and invalidate different stages of the cyber kill chain. The authors formulated a semi-Markov decision process (SMDP) to model time-varying security events and dynamic deployment of multiple MTD schemes.

Li et al. [A22] proposed a trust management strategy for DTs in vehicular ad hoc networks. The scheme is embedded with blockchain, and considers identity authentication to detect malicious DT vehicles.

Xiong et al. [A23] present the problem faced to adopt revocable attribute-based encryption (RABE) schemes in DTs in terms of balancing the efficiency, security, and scalability simultaneously. To address this problem, the authors propose an unbounded and efficient direct RABE scheme with adaptive security.

Wei et al. [A24] proposed a blockchain-based multiuser oblivious data sharing scheme (MODS) for DTs in the context of industrial IoT. MODS supports confidentiality, obliviousness, and access control for the DT data stored on the blockchain.

Fang et al. [A25] proposed an IDRes identity-based system for DT-enabled healthcare. This system employs mobile devices to generate a high-frequency sonar signal to complete respiration detection and identity recognition.

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Appendix: Related Articles

[A1] D. Van Huynh, V.-D. Nguyen, S. R. Khosravirad, G. K. Karagiannidis, and T. Q. Duong, “Distributed communication and computation resource management for digital twin-aided edge computing with short-packet communications,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3008–3021, Oct. 2023.

[A2] Y. Hao, J. Wang, D. Huo, N. Guizani, L. Hu, and M. Chen, “Digital twin-assisted URLLC-enabled task offloading in mobile edge network via robust combinatorial optimization,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3022–3033, Oct. 2023.

[A3] Y. Zhang, J. Hu, and G. Min, “Digital twin-driven intelligent task offloading for collaborative mobile edge computing,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3034–3045, Oct. 2023.

[A4] B. Cao, Z. Li, X. Liu, Z. Lv, and H. He, “Mobility-aware multiobjective task offloading for vehicular edge computing in digital twin environment,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3046–3055, Oct. 2023.

[A5] C. Xu, Z. Tang, H. Yu, P. Zeng, and L. Kong, “Digital twin-driven collaborative scheduling for heterogeneous task and edge-end resource via multi-agent deep reinforcement learning,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3056–3069, Oct. 2023.

[A6] Q. Guo, F. Tang, and N. Kato, “Resource allocation for aerial assisted digital twin edge mobile network,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3070–3079, Oct. 2023.

[A7] P. Jia and X. Wang, “A new virtual network topology based digital twin for spatial–temporal load-balanced user association in 6G HetNets,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3080–3094, Oct. 2023.

[A8] H. Guo, X. Zhou, J. Wang, J. Liu, and A. Benslimane, “Intelligent task offloading and resource allocation in digital twin based aerial computing networks,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3095–3110, Oct. 2023.

[A9] H. Liao et al., “Ultra-low AoI digital twin-assisted resource allocation for multi-mode power IoT in distribution grid energy management,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3122–3132, Oct. 2023.

[A10] H. Zhang, X. Ma, X. Liu, L. Li, and K. Sun, “GNN-based power allocation and user association in digital twin network for the terahertz band,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3111–3121, Oct. 2023.

[A11] Z. Zheng, B. Du, C. Zhao, and P. Xie, “Path merging based betweenness centrality algorithm in delay tolerant networks,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3133–3145, Oct. 2023.

[A12] C. Ruah, O. Simeone, and B. Al-Hashimi, “A Bayesian framework for digital twin-based control, monitoring, and data collection in wireless systems,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3146–3160, Oct. 2023.

[A13] L. Qi, X. Xu, X. Wu, Q. Ni, Y. Yuan, and X. Zhang, “Digital-twin-enabled 6G mobile network video streaming using mobile crowdsourcing,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3161–3174, Oct. 2023.

[A14] Y. Cui, T. Lv, W. Ni, and A. Jamalipour, “Digital twin-aided learning for managing reconfigurable intelligent surface-assisted, uplink, user-centric cell-free systems,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3175–3190, Oct. 2023.

[A15] X. Zhou et al., “Digital twin enhanced federated reinforcement learning with lightweight knowledge distillation in mobile networks,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3191–3211, Oct. 2023.

[A16] X. Chen et al., “Traffic prediction-assisted federated deep reinforcement learning for service migration in digital twins-enabled MEC networks,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3212–3229, Oct. 2023.

[A17] J. Mu, W. Ouyang, T. Hong, W. Yuan, Y. Cui, and Z. Jing, “Digital twin-enabled federated learning in mobile networks: From the perspective of communication-assisted sensing,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3230–3241, Oct. 2023.

[A18] H.-X. Hu, Y. Feng, Q. Hu, and Y. Zhang, “A masked one-dimensional convolutional autoencoder for bearing fault diagnosis based on digital twin enabled industrial Internet of Things,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3242–3253, Oct. 2023.

[A19] H. Xu, J. Wu, Q. Pan, X. Liu, and C. Verikoukis, “Digital twin and meta RL empowered fast-adaptation of joint user scheduling and task offloading for mobile industrial IoT,” *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3254–3266, Oct. 2023.

[A20] L. Sun, C. Li, B. Liu, and Y. Zhang, "Class-driven graph attention network for multi-label time series classification in mobile health digital twins," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3267–3278, Oct. 2023.

[A21] T. Zhang et al., "When moving target defense meets attack prediction in digital twins: A convolutional and hierarchical reinforcement learning approach," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3293–3305, Oct. 2023.

[A22] B. Li et al., "Trust management strategy for digital twins in vehicular ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3279–3292, Oct. 2023.

[A23] H. Xiong, Z. Qu, X. Huang, and K.-H. Yeh, "Revocable and unbounded attribute-based encryption scheme with adaptive security for integrating digital twins in Internet of Things," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3306–3317, Oct. 2023.

[A24] W. Wei, B. An, K. Qiao, and J. Shen, "A blockchain-based multi-users oblivious data sharing scheme for digital twin system in industrial Internet of Things," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3318–3332, Oct. 2023.

[A25] K. Fang et al., "IDRes: Identity-based respiration monitoring system for digital twins enabled healthcare," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 10, pp. 3333–3348, Oct. 2023.

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