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Editorial:

Artificial-intelligence-empowered digital-twin-based network autonomy

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With the rapid acceleration of global digitalization, the sixth-generation (6G) mobile network is poised to play a pivotal role in advancing industrial intelligence, fostering high-quality economic development, and enabling comprehensive societal digital transformation. Confronted with the increasing complexity and cost pressures of maintaining and optimizing existing fifth-generation (5G) mobile networks, as well as the limitations of added-on or patched artificial intelligence (AI), 6G networks must integrate AI into their design from the outset. On one hand, native AI can provide on-demand computing power, data, and algorithmic support, systematically enabling AI in the entire life cycle of the network. On the other hand, the digital twin (DT) of wireless networks further bolsters network simulation, dynamics prediction, and performance verification capabilities, tremendously reducing trial-and-error costs. Research on integrating native AI and DT technologies into 6G mobile networks is inspiring, and potential key technical benefits of the development of 6G network autonomy include:

1. The architectures and deployment for 6G autonomous networks

Architectural design and deployment are crucial to better support autonomy in 6G networks. The service-based radio access network (RAN) architecture is a promising approach that leverages AI to enable dynamic resource allocation and hierarchical deployment, meeting diverse task requirements while improving network flexibility. Additionally, autonomous RAN frameworks that integrate AI with network DT (NDT) technologies can significantly enhance network autonomy, equipping networks with enhanced sensing, analysis, and optimization capabilities. Furthermore, with the rise of large model technologies, studying their deployment and optimization in 6G networks has emerged as a new focal point.

2. DT-enabled AI learning and 6G network optimization

Integrating AI and DT technologies brings intelligent enhancements to 6G networks while introducing new optimization challenges. The precise modeling and future network state prediction capabilities of DT networks (DTNs) not only enable high-fidelity reconstruction of communication environments but also enhance the network's adaptability to dynamic changes. Furthermore, the collaborative optimization of pricing strategies and task offloading in 6G networks empowered by native AI and DT technologies can promote high-level network autonomy while optimizing the AI training process.

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3. Leveraging AI to enhance 6G network performance

AI technologies play a significant role in improving 6G network performance. By optimizing resource allocation and network configuration, AI can boost system capacity and significantly enhance communication efficiency. Additionally, integrating DT with AI facilitates the development of more efficient wireless network management solutions, fostering sustainable development in 6G networks.

Nevertheless, the future application of 6G network autonomy still encounters various challenges. In this context, the journal *Frontiers of Information Technology & Electronic Engineering* organized a special issue on AI-empowered DT-based network autonomy. This special issue covers basic theories, hardware design, system architecture, algorithm optimization, and application technologies related to 6G network autonomy. It is intended to promote the industry consensus on the 6G wireless network architecture as well as the standardization and implementation of related technologies. After rigorous review, eight papers have been selected, including one position paper, five research articles, and two correspondences.

To address the challenges of low service efficiency and high operational costs stemming from the added-on AI in 5G networks, 6G networks must natively support new functionalities such as sensing, computing, AI, big data, and security while promoting Everything as a Service (XaaS). Guangyi LIU and collaborators proposed a framework for a 6G autonomous RAN empowered by AI and NDT technologies. Their work outlined the progression from 5G to 6G through the integration of native cloud, native AI, and NDT to enhance network autonomy, intelligence, and agility. A microservice-based architecture was introduced to enable flexible orchestration and customization of services in a cloud-native manner. A native AI framework was developed to efficiently manage AI use cases in network operations, ensuring quality of service for AI applications. Additionally, the implementation of a DTN served as a virtual environment for training and tuning AI models, mitigating potential risks associated with poorly trained models. The integration of AI and NDT facilitates closed-loop management and optimization, ultimately advancing the autonomy of RANs.

Incentive-based task offloading for DTs in 6G native AI networks is crucial for enabling high-level network autonomy and optimizing AI training processes. Tianjiao CHEN and collaborators established a Stackelberg game to model the interaction between base station operators (acting as leaders) and resource-limited network entities (acting as followers) to balance pricing strategies and offloading decisions. They analyzed the Stackelberg equilibrium to derive optimal solutions and further employed a deep reinforcement learning (DRL) algorithm to handle the dynamic nature of wireless network environments, achieving adaptive pricing and task offloading. The feasibility and effectiveness of the proposed scheme were validated with numerical results.

The diversity of tasks poses significant challenges for future 6G networks, necessitating dynamic and customizable RAN architectures. Chunjing YUAN and collaborators proposed a service-based RAN architecture that enables decoupled RAN functions tailored to specific tasks, driven by AI optimization. Leveraging graph theory and a minimum spanning tree approach, they developed a decoupling scheme for the RAN control plane, achieving high cohesion and low coupling among functions. Additionally, an integration decoupling scheme for the RAN and core network was introduced to address signaling bottlenecks in the Ng interface. This architecture offers flexibility and efficiency comparable to that of monolithic RANs while enhancing capabilities in service scheduling, handovers, and security.

Xing ZHANG and collaborators proposed a DT-empowered satellite-terrestrial integrated network (STIN) to address challenges in dynamic resource allocation stemming from network complexity and user mobility, facilitating seamless global communication coverage. The proposed model features multi-layer DT deployment to enhance flexibility and reduce system latency. By employing a multi-agent RL (MARL) algorithm, they optimized the deployment strategy, achieving significant latency reduction under varying network conditions. The potential of DT-driven solutions for dynamic network optimization was effectively demonstrated.

The DT channel (DTC) can accurately describe the electromagnetic wave propagation of the air interface and is the underlying foundation of DTN. However, environmental information is multi-dimensional, making its relationship with the channel highly complex. Jianhua ZHANG and collaborators proposed a unified method for constructing radio environment knowledge inspired by electromagnetic wave properties, with the aim of simplifying the relationship between the environment and channel for 6G DTNs. Their approach effectively reduced environmental information redundancy through a scatterer determination scheme based on random geometry and quantified electromagnetic wave contributions such as reflection, diffraction, and blockage. Their lightweight convolutional neural network (CNN) based path loss prediction task demonstrated the method's effectiveness, with a small prediction error and a short testing duration. This work enhances the construction of DTCs by addressing environmental complexities.

Optimizing the deployment of large language models (LLMs) in edge computing environments is essential for enhancing privacy and computational efficiency. Rongpeng LI and collaborators presented an innovative model-based RL (MBRL) framework for dynamically optimizing the splitting point of LLMs in edge computing environments. They analyzed the impact of various splitting points in mainstream open-source LLMs and proposed a reward surrogate model to mitigate computational costs associated with frequent performance evaluations. The proposed framework significantly improved the balance between inference performance and computational load under varying network conditions. This work provides a structured approach to LLM deployment across heterogeneous devices, offering promising applications for smart cities and the industrial Internet of Things.

Yannan YUAN and collaborators proposed a unified data collection framework based on the 6G data plane (DP) to tackle the inefficiencies of fragmented data collection in 5G. They demonstrated the uplink efficiency of the DP protocol stack using a 6G user equipment (UE) prototype and highlighted the increasing efficiency gains with larger data packets. The two-sided data collection mode incentivizes providers, enabling DT UE to reduce DT network resource overhead. By integrating ASN. 1 for small datasets and ProtoBuf for large ones, the framework ensures scalability.

Accurate prediction of future network status is crucial for DTNs to facilitate proactive decision-making. Nengwen ZHAO and collaborators proposed TSNet, a Transformer-based foundation model tailored for time-series data, to address the limitations of traditional statistical and learning-based methods. TSNet adapts the Transformer architecture for network prediction tasks by incorporating frequency learning attention and time-series decomposition blocks. They also validated TSNet's achievement of superior zero-shot prediction accuracy by comparison with fully supervised methods, with further improvements attainable through fine-tuning.

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Jiangzhou WANG is a professor and former head of the School of Engineering and Digital Arts, University of Kent, UK. He has published more than 300 articles in international journals and conferences and four books in the areas of wireless mobile communications. He is a fellow of the Royal Academy of Engineering, UK, and a foreign member of the Chinese Academy of Engineering. He was a recipient of the Best Paper Award at IEEE GLOBECOM 2012. He was the Technical Program Chair of the 2019 IEEE International Conference on Communications (ICC 2019), the Executive Chair of IEEE ICC 2015, and the Technical Program Chair of IEEE WCNC 2013. He has served as an editor for a number of international journals, including *IEEE Trans Commun* from 1998 to 2013. He was an IEEE distinguished lecturer from 2013 to 2014.

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