RESEARCH ARTICLE

Digital-twin-enabled 6G network autonomy and generative intelligence: Architecture, technologies and applications

[version 1; peer review: awaiting peer review]

Min Shu1-3, wanfei sun1-3, jing zhang4, xiaoyan duan1-3, ming ai1-3

1 CICT Mobile Communication Technology Co., Ltd, Beijing, Beijing, 100083, China
2 State Key Lab of Wireless Mobile Communication, China Academy of Telecommunications Technology, Beijing, China
3 Datang Mobile Communications Equipment Co., Beijing, China
4 Mobile Communications Innovation Center, China Academy of Information and Communications Technology, Beijing, China

Abstract

Background: The 6G network provides on-demand services and efficient governance, which is an important capability of the 6G network in the future. Providing more flexibility, availability, and dynamicity in services and network function enablement face many challenges in the 6G network due to the system complexity. To fulfill the requirement of the new generation of a digital and intelligent network, the 6G architecture with digital twin as a new enabler technology, is expected to evolve in the network autonomy and generative intelligence properties, which could optimize and adapt the network and services themselves to a variety of scenarios and deployments.

Methods: To achieve 6G network autonomy and generative intelligence, we propose an architecture based on digital twin technology. This architecture integrates the digital twin network with the minimalist network and supports single-domain autonomous and cross-domain collaboration via centralized-distributed digital twin deployment, and defines the interactions between the digital twin and the service layer as well as the physical network.

Results: Based on the analysis of the architecture, we put forward the following design principles for the 6G digital twin network architecture: decoupling, interactions, endogenous AI, distribution, heterogeneity, autonomous, and closed-loop. In addition, we get the key technologies achieving collaboration efficiently between the network autonomy domain and generative intelligence domain in the distributed digital twin system. Important application directions of the 6G digital twin network architecture are also analyzed.

Conclusions: In this paper, the new digital-twin-enabled 6G architecture and 6G digital twin network architecture design principles are proposed. The key technologies and important application of
digital-twin-enabled 6G architecture are provided.

**Keywords**
Digital Twin, 6G, Network Autonomy, Generative Intelligence, Architecture
Introduction
The telecom industry continuously strives to explore digitalization, automation, and intelligence. In order to meet the diverse, highly dynamic and evolving requirements of applications, the 6G system must possess several key properties:

Network autonomy: 6G systems rely on creating a world where all things are sensing, connected, and intelligent, and so will need to become more autonomous. Network autonomy describes the system capability of network which is able to be governed by itself with minimal to no human intervention. A consequence of autonomy is the dramatic increase in complexity of ensuring the system works properly as expected.

Generative intelligence: 6G systems rely on a ubiquitous, and seamless connectivity and so they need to become more intelligent. In addition to serving as a connection infrastructure, the 6G system should also support AI from the architectural layer with the capability of generative intelligence. Generative intelligence refers to an innovative technology that can generate tasks, resource models, or systems for diverse services, based on information obtained from intelligent perception (such as scenarios, users, services, and network resources). Facing unknown new industries and new requirements in the future, it is even more necessary to intelligently generate and schedule AI use cases based on the method of endogenous AI in the network.

To efficiently enable the aforementioned properties of 6G systems, digital twin technology could be leveraged into the mobile network. A digital twin is a virtual representation of mobile network which can be created and updated with real-time data from the real network, dynamically adjusted and optimized to network performance, and then fed back its network parameters into the real network to achieve improvement.

There have been many achievements in the research of 6G-oriented digital twin network. In 4, P. Almasan et al. describe the general architecture of the digital twin network and exemplify the digital twin-based network optimization process. Y. Lu et al. studied the digital twin problem of base stations in wireless Mobile Edge Computing (MEC) networks, and proposed the architecture of wireless digital twin networks. The architecture is divided into access layer, digital twin layer and cloud layer. Y. Wu et al. concluded that communication in digital twin network includes physical to physical (P2P), physical to virtual (P2V) and virtual to virtual (V2V). Z. Wang et al. proposed the concept and framework of Mobility Digital Twin (MDT). The physical space of MDT includes three types of groups, namely Human, Vehicle, and Traffic. In the digital space, there are corresponding Digital Twins. Even though many researches recognize the digital twin as a key component of the future 6G telecommunication landscape, there are still various questions to be answered for proper architecture design. To support 6G network autonomy and generative intelligence, interaction with the service layer and the physical network, and collaboration between single-domain and cross-domain in the 6G network need to be studied. The extensive use of AI/ML requires incorporating the services and network function with flexible and reusable heterogeneous data integration pipelines in the architecture. Providing more flexibility, availability, and dynamicity in services and network function enablement, a specialized architecture to integrate the Digital twin as a new enabler technology is needed. In contrast to 1–7, we explore the role of digital twin in the autonomous system and the potential way to enable the capability of generative intelligence. An analysis of digital twin technology collaborations with network autonomy and generative intelligence in 6G network is also presented in this paper. Our main contributions are as follows:

- We propose a new architecture and design principles of digital twin-based system.
- We present the interaction between the digital twin-based system and network autonomous domain, as well as generative intelligence domain.
- We propose the applications and key technologies of digital twin enabled 6G network.

The rest of the paper is organized as follows. First we give an overview of research on digital twin network requirements and adaptability. Then we provide the architecture of the digital twin for supporting network autonomy and generative intelligence. Then we describe the applications of the digital twin and present the key technologies for the digital twin, and finally we draw the conclusion and provides an outlook on future research directions.

Overview of research on digital twin network requirements and adaptability
Overview of digital twin network
Digital twin has been applied in aerospace, industrial manufacturing, urban management, health care and other fields. Digital twin is established based on big data and AI (artificial intelligence) technology, and the development of physical entities is guided through verification and optimization in the digital twin space. Inspired by the use of digital twin in the above fields, mobile network operators and equipment vendors are now actively researching and promoting the use of digital twin technology in networks.

The Industry’s first digital twin based 5G engineering solution creates a digital replica of a physical site with enabling digital operations on the digital site, it completely overhauls the traditional delivery model and accelerates 5G rollout.

A “digital twin” of the carrier’s core network, combined with an AI-based application for designing optimal routes across a large, complex core network is used. The prerequisite for automation and intelligence of complex networks requires the creation of a digital twin of the complex network. When a network service request is initiated, the best path can be designed in the digital twin network for the network topology and flow based on AI technology, and alternative solutions can be designed for simulated faults.
Digital Twin performing predictive maintenance and demand simulation of an Enterprise IP Network\textsuperscript{11} is another use case. The digital twin network uses AI to identify potential events such as poor voice quality, longer web page loading time or longer latency and determine the impact of network performance on individual customers.

Digital twin network architecture with “three-layer, three-domain, double-closed-loop”\textsuperscript{12} and ubiquitous hyper-converged network architecture with the “three layers and three sides”\textsuperscript{13} have been proposed by the communication industry. They aim at the problems and challenges of large scale, complex compatibility, and high real-time requirements in building a digital twin network, and the corresponding key technologies to solve these problems are discussed.

Research difficulties and challenges in digital twin network
To realize a ubiquitous 6G network and fulfill the diverse service requirements, the main challenges that will be involved in digital-twin-enabled 6G network are how to define the scalable and reliable architecture and algorithms and clearly descript the interaction for digital twin between the service layer and the physical network.

Data-driven network architecture is also crucial for building the infrastructure for digital twins. However, training twin models for large datasets or distributed datasets faces many challenges, for instance, data changes may cause the deployed model performance to degrade below the score/accuracy it displayed in the training environment. To address these challenges, we can build flexible and reusable heterogeneous data integration pipelines and introduce real-time ML which trains a machine learning model by running live data through it and can continuously improve the model.

Digital twin architecture for network autonomy and generative intelligence
Digital twin interaction
In the 6G system, the goals of network autonomy and generative intelligence are to achieve efficient and intelligent network operation and maintenance and resource utilization. To achieve this, digital twin technologies, depicted in Figure 1 as a digital virtual mapping of physical network entities, will be a key driver to boost the transformation from traditional way to automated and intelligent network and service management. To carry out an autonomous and intelligent network, there is a need to deploy digital twin models with other enabler technologies for 6G network to better adapt to highly dynamic and evolving requirements of applications.

By using a digital twin, a replica of the current network state can be created as a “twin”. The digital twin entity, as an independent network subsystem or a network function, can provide service-based interfaces for the network autonomous domain and the generative intelligence domain. New services with different requirements on performance and their related service-level agreements (SLAs) could be generated and deployed in the digital twin, by using analytics models to simulate and analyze the service performance within closed-loop environments, the network can achieve self-organizing and self-optimizing.

Architecture and design principles of digital twin
We propose the notion of architecture and design principles of digital twin for network autonomy and generative intelligence to enable various services such as radio resource management, mobility management, whose overview is given in Figure 2. The architecture aims at integrating the digital twin network with the minimalist network and supporting single-domain autonomous and cross-domain collaboration via centralized-distributed digital twin deployment. The minimalist network infrastructure provides the physical network resources with embedded AI/ML entities integrated. The infrastructure includes radio functions and base stations with AI capabilities. The service layer is expected to provide the compatible interface to enable interoperation between the digital twin network and 6G service layer. The tasks and service requirements generated by 6G system can be transformed into intent and distributed to the digital twin network. By using analytics models to simulate and analyze the service performance in centralized and distributed digital twin domains, the 6G system will achieve automatic closed-loop control and implement simplified control of complex networks or services.

We next present a general description on digital-twin-based 6G architecture principles given in Table 1 and a detailed discussion on key techniques and future applications.

The overall objective of digital twin networks is to enable end-to-end autonomous network for telecom services. Digital twin uses machine learning, data analytics, and multiphysics.
simulation to study the dynamics of a given system, which can efficiently enable the 6G systems to simplify procedures and deliver valuable information\textsuperscript{14}. To apply real-time monitoring and dynamically optimize the 6G system, which incorporated digital twin technology, new architecture principles are proposed in this paper and provide insights about future system architecture. These architecture principles could be considered on the path to design the 6G system with digital-twin-enabled 6G network autonomy and generative intelligence. In current stage, 6G could carry out further PoC (proof of concept) and verification of some principles based on 5G systems to fulfill the backward compatibility (e.g., decoupling, distribution, autonomous), as well as explore a future-proof architecture with a clean slate (e.g., Endogenous-AI, Heterogeneous data integration pipelines).

1) Decoupling: Decouples physical object and digital twin object for operational flexibility

The overall architecture should comply with the layered architecture pattern. The transformation of a physical system into a digital twin is primarily based on decoupling, which can be divided into information decoupling and system function decoupling. Each system and layer runs in self-operating mode and hides the details of domain information, whereby the system function and common data repositories of the 6G network are delivered in a distributed way.

2) Interactions: Supports interactions between Minimalist Network and Digital Twin Network

Minimalist Network decomposes network functions into microservices, so that the network runs on a micro-service centric architecture. The interface between Minimalist Network and Digital Twin Network should provide simplified interaction capabilities for exchanging perception data and information, mapping digital space, and real-time feedback.

3) Endogenous-AI: Supports endogenous intelligence as basic capability

Endogenous intelligence applied locally is a core principle for the internal models of Minimalist Network and Digital Twin Network. More real-time sensing components and AI inference capabilities are introduced to both Minimalist Network and Digital Twin Network to improve observability or digital awareness of resources, services, and surrounding environments.

4) Distribution: Supports Distributed ML and Real-time ML

There are many challenges when training twin models for large datasets, a distributed digital twin system with distributed ML can improve model performance, increases model accuracy, and scale to larger input data sizes. Multiple models can be trained at distributed locations to reduce the model training
In model inference phase, the performance of the models could be enhanced by combining the predictions from multiple contributing models. Moreover, federated learning that enables machine learning models obtain experience from different data sets in different locations with security protections can be a promising solution to enable scalable, distributed machine learning-based twin model.

Real-time ML is the process of training a machine learning model by running live data through it, to continuously improve the model. It provides a more immediate level of accuracy for physical objects and digital twin objects by recognizing new patterns and adapting to reflect those.

5) Heterogeneity: Supports data fabric for flexible and reusable heterogeneous data integration pipelines, services, and semantics

Data Fabric is defined as a design concept that serves as an integrated layer (fabric) of data and connecting processes. Data fabric utilizes real-time data, historical data, network resource models (NRM) and machine learning to unify data across various types and endpoints in digital twin system.

6) Autonomous: Supports single-domain autonomous and cross-domain collaboration

The digital twin should have the capability of independence and self-governing, which is a core principle of Autonomous Network. The autonomous domain is an atomic unit with autonomous capabilities in the autonomous network architecture.

7) Closed-loop: Supports closed-loop automation with Intent-driven interface

Closed-loop automation is the overseeing eye of a network’s automation. The control loop adjusts and adapts itself via the cycle of Awareness, Analysis, Decision, Execution, keeping both the physical system and digital twin system in the desired state without any intervention. The intent driven interface may utilize closed-loop automation mechanisms, in intent driven closed-loop, intent is used for controlling of closed-loop automation, which means intent can be translated to policies and management tasks to execute the closed-loop automation.

The architecture in this paper has the following features compared to other architectures.

1) More precise orientation to native intelligent 6G networks. Compared with the general architecture of the DTN, a novel architecture is proposed in this paper for 6G networks and native intelligent networks, realizing the separation of service twin and network twin and the independent autonomous closed loops of the two types of twin domains.

2) The applicable network scenarios are wider. The architecture in this paper is applicable to 6G end-to-end networks, which is a more expanded applicable scenario compared to the wireless MEC scenario in literature and the mobile digital twin network in literature.

3) The combination of distributed twin and cloud twin. Wireless MEC digital twin network architecture and cloud digital twin network architecture have their own advantages and disadvantages. In this paper, the architecture adopts a combination of distributed twin and cloud twin, and proposes 6G digital twin network collaboration by distributed digital twin network framework.

4) Efficient data interaction. Based on the more real-time interaction of distributed network, distributed AI and distributed twin data, it is the first time to propose the application of digital fabric technology to 6G digital twin network, which makes data interaction and usage more efficient compared to digital thread.

5) Refinement of communication methods. the communication in DTN is further refined beyond P2P, P2V, and V2V to the physical service layer, network facility layer, twin service body, distributed network twin, and cloud network twin. And realize the small closed-loop of physical twin of service layer, small closed-loop of physical twin of network facility, and large closed-loop of service layer, network facility layer and their twin domains.

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<td>02: Interactions</td>
<td>Supports interactions between Minimalist Network and Digital Twin Network.</td>
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Applications of digital twin enabled 6G network
Dynamic network management and control

The Digital Twin Network (DTN) can be built mirroring the real communication network to realize dynamic network management and control by using digital twin technology. The same “input” as those to the real network can be fed into the DTN, and then the performance of the DTN can be evaluated and further optimized by adjusting the network parameters in the DTN to reach the target. To achieve this, the DTN needs to build models that could reflect the real network structure and realize real-time interaction with the physical network, intention verification and closed-loop control also need to be implemented in DTN to get the result of the feasibility check. The optimized network parameters in the DTN can then be applied to the real network and verified with the performance data collected from the real network. Ideally, 1) the real network and DTN render the same operation status and performance, and 2) parameters testified in the DTN to reach the optimum network performance can be applied to the real network in real time, so that the best performance of the real network can be achieved synchronizing with the DTN.

Here, the “input” of the DTN can be service requirements (e.g., Quality of service (QoS)) for specific scenarios or new use cases, network status (e.g., load), abnormality (e.g., Distributed denial-of-service (DDoS) attack), etc. The “output” of the DTN (i.e., optimized network parameters) can be parameters for network configuration (e.g., number, capacity, and service area of network functions), network function control (e.g., policy control and session management parameters), radio resource control, etc. The “target” can be, besides the optimum network performance, the optimum service experience, maximum of resource efficiency, etc, or a combination of those targets (e.g., a balance between optimum network performance and service experience).

The dynamic management and control on the network (including network architecture, functionality, resources and etc.) enabled by the interactions between the DTN and real network, can play an important role in network autonomy and generative intelligence. Following are four key aspects of such dynamic network management and control: accurate mirror of the real network (i.e., building the DTN for the real network with great accuracy), accurate input to the DTN (i.e., providing the same stimulus to the DTN as those to the real network), quick responding and convergence in the DTN (i.e., optimizing network parameters in the DTN quickly to reach the target), and real-time feedback to the real network (i.e., providing the optimized network parameters to the real network in real time). AI technologies, e.g., GAN (Generative Adversarial Networks) and Deep Reinforcement Learning, can be used to realize and further optimize these key aspects.

Network failure prediction and diagnosis

As a digital mirror that accurately simulates the real network, the digital twin network can provide early warning of operational failures or errors in the real network, such as warnings for network congestion. This can be achieved by collecting the network operational data in the DTN and using AI for analyzing, monitoring and forecasting. Compared with collecting and analyzing data from the real network, the data collection and analysis in the DTN can be more real-time, and the DTN can adjust the network parameters according to prediction with early warning and output the adjusted parameters to the real network in time. In this way, the occurrence of operational failures in the real network can be avoided, thereby saving a large number of social resources and network resources that are consumed by corrections after failures occur.

Of course, the DTN may not be able to predict all possible network failures (such as network paralysis caused by external attacks). When a fault occurs in the real network, the DTN can be used to locate and diagnose the faults of network and assist to find the root cause more quickly and accurately, than previous methods, and to provide the best rapid recovery solution for the network via testing and comparison (e.g. rapidly reorganizing the network to offer additional communication coverage/capacity while isolating the faulty network). The corresponding method and parameters can then be applied quickly to the real network for rapid self-healing and performance improvement, achieving network autonomy and generative intelligence in network failure scenarios.

Collaboration between network autonomous domain and generative intelligence domain

The DTN, as an independent network subsystem or a network function, can provide service-based interfaces for the network autonomous domain and the generative intelligence domain, to offer e.g., real-time network status exposure or performance verification services based on the service requests.

For the generative intelligence domain, a request containing the intelligently generated network resource allocation or scheduling command can be invoked towards the DTN for network performance verification service. The DTN executes the network resource allocation/scheduling command and feeds back the evaluation and analysis on the resulted network status (such as performance, service experience) to the generative intelligence domain. Based on this, the generative intelligence domain determines whether the network resource allocation/scheduling decision is correct and feasible, updates the decision if necessary, and invokes network performance verification service to the DTN again. Finally, the generative intelligence domain can make the decision on the optimal network resource allocation/scheduling strategy.

For the network autonomous domain, similarly, a request containing the autonomous network management command can be invoked towards the DTN for network performance verification service. The DTN executes the autonomous network management command, and feedback on the evaluation and analysis of the resulted network status of the network autonomous domain. Based on this, the network autonomous
domain determines whether the autonomous network management decision is correct and feasible, updates the decision if necessary, and invokes network performance verification service to the DTN again. Finally, the network autonomous domain can decide the optimal autonomous network management strategy.

The DTN can also execute the network resource allocation/scheduling commands provided by the generative intelligence domain and the autonomous network management commands provided by the network autonomous domain simultaneously, and feed back the evaluation and analysis on the resulted network status to the generative intelligence domain and the network autonomous domain for decision assessment and possible updates. In this way, the collaboration between the generative intelligence domain and the network autonomous domain is formed to achieve optimal network performance and/or business goals.

**Key technologies of digital twin enabled 6G network**

**Distributed digital twin system collaboration**

The 6G digital twin network is a virtual digital network with real-time status of the whole domain of the communication network, including users, access network, transmission network, core network, management system, etc. However, training digital twin models for large datasets may face many challenges, for instance, the need to deal with extraordinary complexity models of large size datasets and high computing power for training, as well as the collection of large datasets. Moreover, this may lead to slow and inefficient when digital twin systems conduct inference.

To address these challenges, we can adopt distributed twin models architecture. In the architecture as shown in Figure 3, the centralized digital twin entity can build digital twin models with a global view, by collecting datasets from other distributed digital twin systems via data fabric technology, generating physical-based models and implementing digital simulation. Distributed digital twin entity can also generate the digital models itself with local datasets or the necessary data from other digital twin entities, to achieve digital twin simulation in its own domain. In terms of 6G digital twin network, distributed small digital twin systems are constructed by dividing physical regions and functional domains. In comparison, the number of devices and information of the digital twin system in the distributed domain will be greatly reduced, and the information collection of the physical network and the synchronization of physical network and twin information will be more real-time. Distributed digital twin systems collaboration can achieve global digital twin network functionality by transmitting network model descriptions, or specific description information, and greatly compressing the amount of data required to be transmitted. As a result, the latency and overhead of the central digital twin network to obtain the global physical network state synchronously are greatly improved.

**Feature network model construction**

In addition to reflecting the real-time state of the physical network, the 6G digital twin network can also build digital
twin network models with network-specific features. The network features required for different scenarios of services have variability, and network states with different characteristics, not necessarily the real-time state of the network, are often required for creation, verification, and optimization in twin networks\(^}\text{15}\). Based on this requirement, constructing a feature network model based on the network model description will be a key technology in 6G digital twin networks.

In the 6G digital twin network, a network model with the characteristics of the scenario’s network requirements can be constructed as the starting network state for the network verification of that scenario, then a series of subsequent studies can be implemented. In the generative intelligence process, the network model description can be used as the starting network state and the target network state based on the digital twin network for the verification of network optimization. The geographic location of the network verification environment and the scope of the functional domain can be selected in the network model construction, and a certain expansion is carried out based on involving the local area, which in turn is optimized from the regional optimum and gets rid of the chimney optimization. Further, the network model with various features is continuously optimized according to the 6G digital twin network.

**Efficient data management technology.** Among the various definitions and elements of digital twin networks, data is a recognized element. The data of the digital twin network is complex and huge, and the whole life cycle management of data involves acquisition, transmission, storage, use and destruction, etc. Therefore, the accurate use of data elements is related to the success of the digital twin network\(^}\text{18}\).

a) Digital thread technology: Digital thread can cover all aspects of the system life cycle and value chain, and realize the fusion of multi-view model data, which is a key technology in digital twin networks, and can realize the efficient and accurate use of data between physical devices and twins, between twins and twins, and between layered twin systems\(^}\text{19}\). It has the function of “pushing the right information, in the right way, to the right place at the right time”.

b) Data Fabric Technology: Data fabric technology is a data architecture that supports the design, deployment, and use of data systems across platforms by continuously analysing existing, discoverable, and inferable metadata to achieve flexible data delivery. Data fabric technology has core capabilities including data enhancement catalogues, semantic knowledge graphs, active metadata, recommendation engines, data preparation and data delivery, data orchestration, and DataOps\(^}\text{20}\).

Data fabric technology has not been applied to digital twin and mobile communication networks yet. However, its powerful data management capabilities will probably be used in future research to address the large and complex data management of 6G native intelligent networks and digital twin networks.

**Conclusions and future work**

In this paper, we have presented a vision of digital-twin enabled 6G network autonomy and generative intelligence and proposed a digital-twin-based architecture and design principles. The architecture aims at enabling the synergy of the physical network and the digital twin network, as well as exploring the technology enablers to achieve automatic closed-loop control and implement simplified control of complex networks or services. Furthermore, we have provided key technologies and applications of digital-twin enabled 6G network.

We have concluded that a digital twin will serve as a critical enabler of 6G services. Our proposed underlying general rules and guidelines for digital twin architecture, key technologies, and applications will offer 6G AI-Native network scalability and reliability by using real-time ML and distributed deployment.

Based on the architecture we propose in this paper, to guarantee the performance of different digital twin entities, there is a need to propose novel optimization schemes for the distributed digital twin sub-network, as well as to study the scenarios and requirements for communication between them, and then design efficient communication methods. Besides, we propose to apply data fabric technology to 6G networks and the digital twin networks. Thus, in the network autonomy domain, we will further investigate how to build flexible and reusable heterogeneous data integration pipelines as well as a real-time machine learning training mechanism for training machine learning models by running live data.

**Data availability**

No data are associated with this article.

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**References**


