6G Digital Twin

未来移动通信论坛
FuTURE MOBILE COMMUNICATION FORUM

· Abstract

- Digital twin, with emerging potential 6th generation (6G) technology, can be a new driving force for 6G. It can benefit widely in the scenarios of networks, industry, agricultural and human bodies. Digital twin technology is an organic combination of many supporting technologies. Moreover, some solutions to the adoption of digital twin are presented, such as mobile network, intelligent transportation, and Internet of things (IoT). Intent aware digital twin 6G networks can be a full life-cycle solution, driven by the knowledge graph.

- Keywords: digital twin，6G， Digital twin 6G networks .

Table of Contents

1. *Overview*

1.1. History of Digital Twin

The "twin" concept was originated from NASA in its Apollo program in 1970. NASA attempted to create a mirror system to monitor physical spaces that are not accessible to people, that is, to build two identical spaceflight vehicles, one launched to the space for missions and one left on the Earth (mirror system) to reflect the working state of the vehicle in space so that engineers could analyze and handle emergencies occurred in space [1]. For example, by simulation of the mirror system, astronauts were instructed to rebuild oxygen tanks that exploded in outer space [2]. These two spacecraft were real physical entities.

In 2002, Professor Grieves of the University of Michigan for the first time proposed the idea of Digital Twin (DT) in the course of Product Lifecycle Management. Later he elaborated in a whitepaper [3] that the digital twin was mainly composed of three parts: physical objects, virtual objects, and information flow between physical objects and virtual objects, as shown in Figure 1. In 2003, Främling proposed an agent-based system structure where each product was associated with a virtual counterpart or agent, and the agent kept pace with the physical counterpart via the Internet for a one-to-one correspondence between the digital twin and the physical twin (bijection) [4].

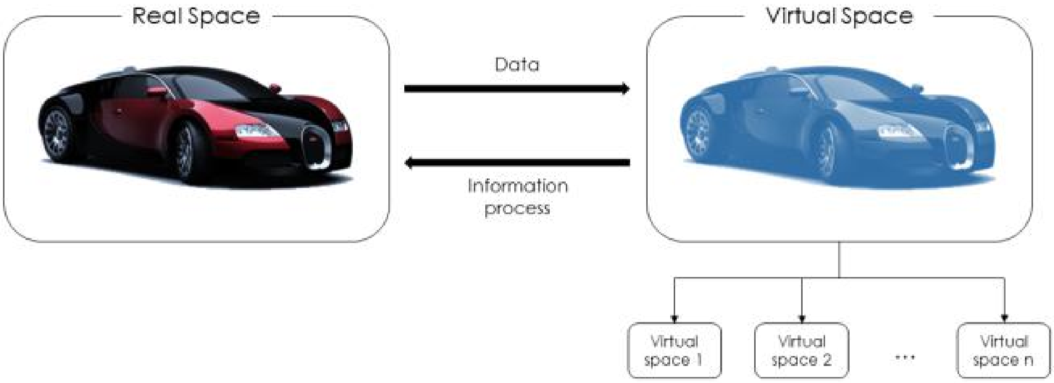

Figure 1 Digital Twin Model Proposed by Grieves

In 2010, the term "Digital Twin" was officially used by NASA in its technical report and defined as "an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system" [5]. In 2012, NASA and the U.S. Air Force jointly published a paper on the digital twin, pointing out that the digital twin would be one of the key technologies driving the development of future spaceflight vehicles. In the same year, Främling put forward a conceptual model showing how to use the digital twin as a virtual sensor to predict the life of a spaceflight vehicle and ensure its structural integrity [6].

In recent years, with the development of new generations of information technologies such as the Internet of Things (IoT), big data, cloud computing, and artificial intelligence (AI), the implementation of digital twins has gradually been implemented in place. At this stage, the digital twin application is relatively mature in aerospace, intelligent manufacturing, smart city, and some other fields, and remains at the growing phase in healthcare, agricultural development, etc. Governments, enterprises, and organizations in different countries value the digital twin highly that it is becoming a new driver to national digital transformation, a new direction for the business layout of multinational enterprises, and a new focus of global IT development [7].

1.2. Current Researches on Digital Twin

Currently, there is no consensus among the academic and industrial circles regarding the definition and connotation of the digital twin. Their respective understandings of the digital twin connotations are given in Table 1.

Table 1 Comparison of Understandings of Digital Twin Connotations by the Academic and Industrial Circles

Source	Institution	Connotation of Digital Twin
A Survey on Digital Twin: Definitions, Characteristics, Applications, and Design Implications	Brescia University, Italy	DTs can be defined as (physical and/or virtual) machines or computer-based models that are simulating, emulating, mirroring, or “twinning” the life of a physical entity, which may be an object, a process, a human, or a human-related feature[2].

Digital Twin and Its Potential Application Exploration	Beihang University, etc.	Digital twin, as a technology of integrating multi-physics, multi-scale and multidisciplinary attributes, characterized by real-time synchronization, faithful mapping, and high fidelity, could realize interaction and integration between physical space and virtual world [7].
Digital Twin Whitepaper	China Center for Information Industry Development	The digital twin refers to a comprehensive application of information technologies such as perception, computing, and modeling to describe, diagnose, predict, and make decisions on physical spaces through software definitions, thus achieving the interactive mapping between the physical space and cyberspace [8].
White Paper of Digital Twin Application	China Electronics Standardization Institute, Rootcloud Technology Co. Ltd.	The digital twin is a digital expression of a special physical entity or process with data connections that ensure the convergence between the physical state and the virtual state at the same rate and provide an integrated view of the entire lifecycle of the physical entity or process, helping to optimize the overall performance [1].
Digital Twin Computing	DTC Innovation Forum	Digital twin computing is a new computing model that, by executing various operations and combining digital twins freely, reproduces the real world in an unprecedented, new, large-scale, and high-precision way and makes new interactions true in cyberspace, including interactions within human beings, surpassing the physical copy in the real world [9].
White Paper for Digital Twin of 5G Cities	AsiaInfo, Migu, Digital Twin Consortium	The digital twin is an integrated multi-disciplinary, multi-physical quantity, multi-scale, and multi-probability simulation process for mapping in digital space upon the full use of physical

		models, sensor updates, operation history, and other data, to reflect the lifecycle process of the physical counterpart. The digital twin is a concept beyond reality and can be regarded as a digital mapping system for one or more important and interdependent device systems [10].

According to the definitions listed in Table 1, the digital twin has the following typical characteristics:

1) **Bidirectional precise mapping** (bi-mapping) means that the data flow is bidirectional between physical objects and twins. Physical objects input data to twins for modeling; while twins give feedback to physical objects for prediction, control, and decision-making. Precise mapping is to fully present, accurately express, and dynamically monitor physical objects on twins.
2) **Real-time** means that a real-time relation between physical objects and twins can be established so that twins characterize physical objects as the time axis varies and enable the real-time mapping of physical objects.
3) **Lifecycle** refers to the whole process of a product in which the digital twin can run through, including design, development, manufacturing, service, maintenance, scraping, and recycling.

1.3. Digital Twin + 6G Fusion and Development

The digital twin will be closely integrated and mutually promoted with 6G technologies.

On the one hand, 6G technologies enable the data and feedback transmission with ultra-large capacity and ultra-low latency for the digital twin at the interaction layer, promoting better applications of the digital twin technology.

On the other hand, the digital twin gives new ideas and solutions for the research of 6G key technologies. For example, in the digital twin network, the digital twin technology is applied to the network field, through the virtual expression of the physical network, to analyze, diagnose, simulate, and control the physical network based on data, models, and interfaces. This yields low-cost network optimization, intelligent network decision-making, efficient network innovation, and closed-loop management of the network throughout its lifecycle [11]. The digital twin technology is employed to model the indoor environment, by virtue of tunable metasurfaces of graphene, to control the propagation paths of indoor THz signals and reduce the probability of blocking THz signals [12]. The edge network-based digital twins reduce the average offloading latency, offloading failure rate, and service migration rate of the edge network [13].

This white paper addresses the application scenarios of the digital twin in Chapter 2, key technologies of the digital twin in Chapter 3, the digital twin-enabled 6G network and solutions for some vertical industries in Chapter 4, and the outlook to the future development of the digital twin in Chapter 5.

2. *Application Scenarios of Digital Twin in 6G*

2.1. Twin Network

In the 6G era, the digital twin technology will be widely applied to communication networks. With up-and-up perception + modeling technologies, virtual digital twins of real physical networks will be built to offer capabilities in the query in the real world + prediction in the virtual world + interaction between real and virtual worlds.

The network digital twin will be implemented by virtue of many technologies such as perception, modeling, data processing, and control, including the constantly developing technologies for network measurement and data collection; more refined network awareness technology to perceive the network state; unified data platform technologies providing underlying data supports for the internal and external by building unified and reliable data platforms through cloud-based technologies; network model technologies for NE & topology modeling and simulation of network operation through digital approaches; and network management & control technologies connecting the interactive channel for management & control operations between virtual digital twins and real physical entities based on standard and automatic interfaces.

The implementation of the digital twin technology in the future network will enhance 6G network capabilities in multiple aspects. The powerful reality restoration capability will provide more comprehensive network states and more accurate fault locating. The flexible simulation capability will offer easier strategy simulation, safer solution pre-evaluation, and more intuitive result visualization relying on accurate, virtual, and efficient mechanism modeling. The handy management & control capability will enable simplified, automatic, and visual operations, greatly reducing labor costs.

2.2. Twin Industry

There are some relatively mature application cases of the digital twin and 5G in the manufacturing industry, for example, workshop status information display and analysis management, M&E product design optimization, machine tool fault prediction & health management, etc. [14]. The digital twin technology is still in the bud, and it will take two or three decades to achieve the digital twin fusion and interaction across platforms in various fields. It is expected that the digital twin fusion may become active in the 6G era 10 years later [15].

The twin industry in the 6G era will not be limited to the concept of "intelligent plant", but develop a new form of twin industry specific for the future society. Strategically, based on real-time dynamic analysis of market data, the industrial solutions for production, storage, and sales will be developed and updated to maximize the industrial benefits, while achieving highly industrial integration, and effectively coordinating and optimizing all business activities of the whole industry. From the aspect of technologies, based on data and models, technologies such as AI, big data, 6G, cloud computing, and edge computing will be applied to forming a smart manufacturing mode coordinated with labors, machines, and materials [16].

2.3. Twin Agriculture

The digital twin technology may simulate and deduce the agricultural production process so that some adverse factors can be eliminated in advance, further improving agricultural productivity and utilization efficiency. Moreover, by integrating blockchain technology, the digital twin can include information about enterprises, certification bodies, sales enterprises, and logistics and storage enterprises into a unified and shared chain to ensure that sources are identifiable, products are trackable, and persons in charge are held accountable. Meanwhile, the digital twin can closely follow the urban consumption demands and the supply of agricultural products, largely energizing the agricultural product flow and promoting the construction of smart agriculture ecology. Big data, IoT, cloud computing, and some other technologies will support larger-scale UAVs, robots, environment detectors, and other intelligent devices, realizing the full connection between things and between human beings and things, and making great differences in crop farming, forestry, husbandry, and fishery [16].

2.4. Twin City

The digital twin city concept was incubated in 2017 and 2018, its technical architecture was conceived in 2019, and the digital twin city was officially launched in 2020. As national strategies are issued, and local planning put in place, enterprises solutions are formulated, academic researches are arranged proactively, market spurted, industrial ecology is built, application scenarios are gradually improved, and the global consensus is reached. In short, the digital twin city is the only way and the future's choice for the construction and development of new smart cities.

Specifically, the digital twin city consists of three horizontal layers: new infrastructures, intelligent operation center, and intelligent application systems, and two vertical layers: city safety line and standard specifications. The digital twin city has nine core capabilities: IoT perception control, all-element digital expression, visualization presentation, data fusion supply, spatial analysis computing, simulation & deduction, virtual-real fusion & interaction, self-learning & self-optimization, and crowd innovation expansion.

However, as the digital twin city is implemented in place, a number of problems are revealed, such as insufficient depth of typical application scenarios, repeated construction of city information model (CIM) platforms, difficulty in coordinating time-space data standards, constraints of critical technologies, etc. The CIM-based coordination, interconnection of data specifications and standards, development of typical application scenarios and market demands, and ecological cooperation mechanisms, all are decisive to the development of the digital twin city in the next stage [17].

2.5. Twin Body

The digital twin-based body area network (BAN) technology will be one of the important features of the next generation mobile networks (NGMN), and the medical twin on this basis will be the main direction of future medical businesses. Unlike the digital twin in industrial manufacturing, the digital twin integrating personal wireless communications is people-oriented and focuses on the services for human beings. The digital twin will combine with the BAN to diversify the NGMN features and make it one of the infrastructures for critical technologies of other communications.

In the 6G era, the BAN consisting of wireless sensors intensively deployed in and outside human bodies will collect, analyze, and model human body information in real time for the digital twin of human beings, i.e., personalized "human digital twin". The "human digital twin" will facilitate efficient research on virus mechanisms and organs and help doctors to make accurate surgical predictions. Imaging when doctors are performing an operation, the "human digital twin" will simulate the condition changes of the patient after being operated on at different positions, so as to assist doctors doing best in the operation. Even after the patient is discharged, the hospital can still provide the patent with follow-up health management based on the change in the "human digital twin" of the patient. The "human digital twin" will also play a significant role in medical research. For example, the extremely complicated human brain makes it more difficult to track and study brain activities. Researchers' focuses and difficulties are always the way the brain thinks and the function of motion perception. The application of the digital twin in brain researches can ease the experimental simulation and help experimenters to discover the secrets in the brain. Similarly, the attack of viruses and bacteria can be simulated by some control over the "human digital twin" to provide a reference for the study of viral mechanisms.

The four key technical links of the "human digital twin" are data collection, transmission convergence distribution, collaborative computing & digital twin, and large network communication interaction. Data collection is to collect the physical information of human beings with different sizes of sensors, cameras, and other internal and external data collectors. Data convergence is to transfer the collected data to the data center through molecular communication or traditional electromagnetic communication. The computing is to compute and analyze the converged data with the technologies such as collaborative computing, digital twin, and holographic presentation. The communication and interaction with large networks are to transmit data to large networks for storage or further screening & analysis. For the digital twin and real-time interaction of all human information, higher requirements are imposed for indicators such as network bandwidth, latency, reliability, and security.

3. *Key Technologies of Digital Twin*

3.1. Technical Framework of Digital Twin

The current technical frameworks of the digital twin mainly include the following:

1) In the Digital Twin Whitepaper [8], the digital twin technology architecture is divided into the physical layer, data layer, model layer, and function layer. The physical layer consists of physical entities. The data layer involves data collection, data processing, and data transmission. The model layer includes mechanism models and data-driven models. The function layer covers description, diagnosis, predictions, decision making, etc.
2) In the White Paper of Digital Twin Application [1], the digital twin ecosystem consists of the basic support layer, data interaction layer, model building and simulation analysis layer, common application layer, and industrial application layer. The basic support layer contains specific devices, including industrial equipment, urban construction equipment, transportation means, medical devices, etc. The data interaction layer involves data collection, data transmission, data processing, etc. The model building and simulation analysis include data modeling, data simulation, and control. The common application layer covers four aspects: description, diagnosis, prediction, and decision-making. The industrial application layer includes a variety of applications including intelligent manufacturing and smart city.
3) In the publication Digital Twin Computing [10], digital twin computing combines various digital twins freely to implement a new world in an unprecedented, large-scale, and high-precision way, making new interactions true in cyberspace, including more complicated interactions between humans, and surpassing the

entities in reality. The twin computing technology architecture consists of real space, information/physical interaction layer, digital twin layer, digital world presentation layer, and application layer. The real space contains physical entities. The information/physical interaction layer collects data and gives feedback on the control information. The digital twin layer generates and maintains digital twins. The digital world presentation layer produces the digital twin derivatives to build a virtual world. The application layer uses the digital world presentation layer to deploy and execute applications.

To sum up, the digital twin architecture is summarized as shown in Table 2. Although the definitions for each layer are different in [1] and [7], the contents expressed are substantially consistent. The architecture in [10] is for different purposes and emphasizes more on the importance of the interaction layer and presentation layer, that is, the digital twin can produce virtual social functions through replication, fusion, exchange, etc.

Table 2 Comparison of Existing Digital Twin Architectures

Source	Institution	Contain Physical Layer	Contain Data Layer	Contain Model Layer	Contain Function Layer	Contain Application Layer	Contain Presentation Layer	Contain Interaction Layer
Digital Twin Whitepaper	China Center for Information Industry Development	√	√	√	√			
White Paper of Digital Twin Application	China Electronics Standardization Institute, Rootcloud Technology Co. Ltd.	√	√	√	√	√		
Digital Twin Computing	DTC Innovation Forum	√		√		√	√	√

From the above, it can be seen that the digital twin is a complex technical ecosystem consisting of at least three layers of abstract architectures: physical entity layer, digital twin layer, and application layer.

3.2. Main Supporting Technologies for Digital Twin

From the bottom to the top of the hierarchical digital twin architecture, the main supporting technologies are the IoT, 5G/6G, big data, modeling, simulation analysis, cloud computing, edge computing, AI, API, VR/AR, etc. Specifically, at the data layer, data collection needs IoT, data transmission requires 5G/6G, and data processing uses big data. At the model building and simulation analysis layer, modeling and simulation analysis technologies are required. At the function layer (common application layer), implementing the functions, such as description, diagnosis, prediction, and decision making, needs AI, cloud computing, edge computing, and some other technologies. At the function and industrial application layer, some visualization technologies such as API and VR/AR are needed. Besides, special attention needs to be paid to security issues in the application of the digital twin, and blockchain technology is one of the methods to solve such security issues.

Main supporting technologies for the digital twin are related to application scenarios. The digital twin application in different scenarios generally requires the following technical supports.

1. Data collection, transmission, and storage

Data is the basic element of the digital twin. It comes from target locations, physical entities, control, or service digital systems. Data collection, transmission, and storage are cornerstones of the digital twin. Twin data integrates physical perception data of all elements, all businesses or all processes, and massive data generated by models. It is characterized by multiple sources, multiple types, and multiple structures.

The physical network technology implements data perception and acquisition from the control or service systems of different hardware devices. After parsing the data format, it cleans and sorts out massive raw data, and initially screens out reasonable and reliable data output to subsequent digital twin systems. With unified or custom interfaces, it enables large-capacity, high-reliability, high-rate, and stable data transmission in 5G and 6G networks. For example, the twin city requires a larger number of connections, i.e., 107/km^2, making the uplink regional traffic density up to Tbps/km^2 level. The medical twin needs shorter latency and higher reliability, i.e., 0.1-1ms and 99.99999%, as well as lower energy consumption [18].

Selecting appropriate big data storage solutions in different application scenarios improves the reliability of massive storage and the speed of data reading & writing while reducing the costs.

2. Twin modeling

The digital twin can solve such non-linear and uncertain issues that are difficult to be solved or cannot be solved by traditional models. The core element of the digital twin is to build a matching model. Based on the constantly generated real-time data, with traditional models and AI/ML, the digital twin can not only accurately analyze, train, and predict the properties and states of physical entities, but also pay more attention to dynamic changes in twin data for iterative updates of models, making the digital twin more valuable to be continuously improved.

Digital twin models are now divided into two categories: general models and special models. General models are built to mainly study the possible unified model concept, model development methods, modeling languages, and specific tools, and describe the lifecycle control, general system behaviors, and workflow of physical entities with unified methods. Special models are built to focus on the implementation of digital twin projects, and the possible use of different model development methods and tools in different niche markets, for example, the manufacturing and quality supervision in traditional manufacturing, biopharmaceutical R&D, etc. The digital twin network, for example, models functions, NEs, and networks through big data processing based on data collection, which converts issues difficult to solve at each stage of the network into the digital world for solutions, enabling network autonomy. The AI/ML-based network knowledge graphs and user knowledge graphs enable the verification and optimization of network allocation solutions based on the twin environment. They even directly translate network demands to apply the deeper intelligence and intent state insight into the network.

Complex virtual entities built through the fusion of different models require calibrations to realize and constantly update the accurate mapping between twin models and physical entities.

3. Simulation, AI/ML

AI/ML has developed rapidly over the past several years. The use of AI/ML for simulation, training, prediction, and decision-making of twin data and twin models is superior to the direct application to physical entities. By setting different conditions, AI/ML even can test the parameters that cannot be set in reality, to avoid possible errors. AI automatically executes data preparation, analysis, and fusion for in-depth knowledge mining, to explain and predict the causes, processes, and results of real events/incidents. This will generate various types of services, and greatly improve the data value and response capabilities & accuracy of different services. AI/ML can give full play to the role of the digital twin. In order to improve the availability of the digital twin, upon the quick and effective analysis of massive data, strategies or parameters optimized by AI/ML training and inference are fed back to twin physical entities in real time.

4. Interaction and security

Based on twin data, technologies such as 3D GIS, AR, VR, and even XR can be used to reproduce the real world in the digital world, for digital virtual consistency in aspects of geometric dimensions, physical structures, and motion characteristics, visualization, as well as information mapping and feedback of physical entities and digital models.

The trust mechanism established through the blockchain can ensure the security of service transactions to a certain extent. The blockchain makes twin data tamper-proof, trackable, and traceable while preventing errors and deviations due to data tampering, and improving the security of the digital twin.

4. Digital Twin Solution for 6G

4.1. Digital Twin Network for 6G

4.1.1. Lifecycle Twin Network

When looking forward to the 6G service, we believe that it will extend to all-scenario on-demand services in all industries. The future differentiated demands in different vertical industries will show exponential growth, but the network bearer resources can only develop linearly, indicating a huge gap between demand and supply. At the same time, the 6G will further integrate a wider range of cloud, edge, network, terminal, and fog resources. These resources now are fragmented and discrete, in lack of cross-domain management, control, and coordination, plus the poor perception of lifecycle states of end-to-end resources, making it difficult to build the network bearer capacities featured by all-domain perception and quick coordination. The wireless access network is characterized by a tremendous number of base station cells, a large number of device models, wide distribution of station sites, complex networking, and high energy consumption. It is the highest part of the CAPEX in mobile communication networks and the highest one in the OPEX. Currently, all links of the networks from planning, construction, operation, to optimization, require massive manpower as well. With the iterative development, the mobile communication networks become more and more complex, the business scenarios get more and more diversified, designs for user experience go more and more profound, and the network O&M and optimization complexity shows exponential growth, to the extent that cannot be handled by human beings.

The 6G network shall fulfill the demands that services are offered as expected, networks changed as needed, and resources shared as desired, realizing a good vision of "0" O&M, visualization, self-optimization, self-orchestration, and self-evolution in all scenarios in all domains.

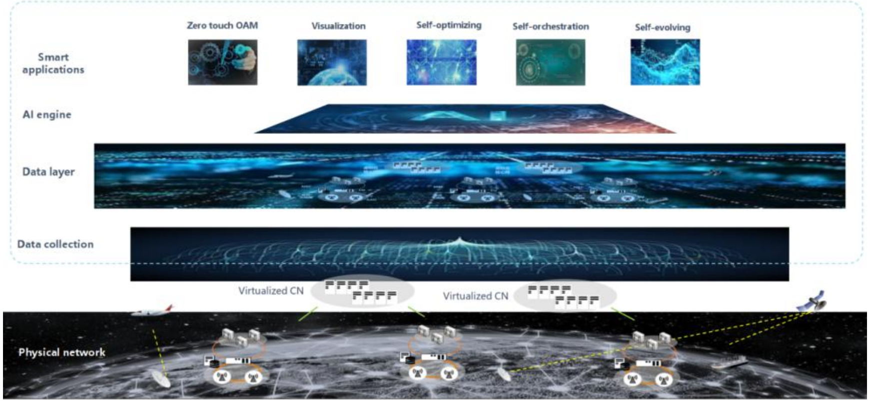

Figure 2 6G Network Autonomy Based on Digital Twin Network

The above visions challenge the architecture and capabilities of the 6G network itself. On the data plane, to implement the real-time perception of network statuses, the system can obtain relevant data in near real time. Through unified data models and standard interfaces, supplemented by self-correction and self-generation capabilities, the system guarantees data quality. On the intelligent plane, the network enables accurate modeling and simulation verification, quick iterative optimization and decision-making, and centralized or distributed intelligent generation modes as required.

The digital twin network is an important technical means and path to achieve the 6G network visions and address challenges in networks and capabilities.

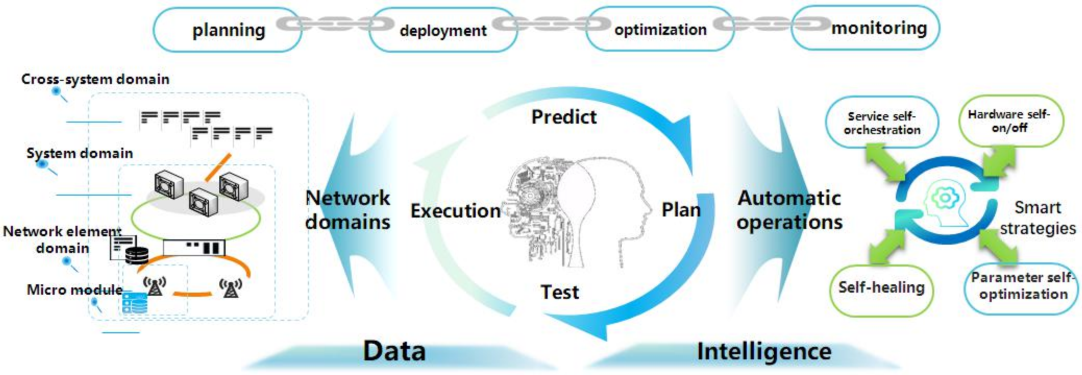

Figure 3 Lifecycle Digital Twin Network

Digital twin network technologies include functional modeling, NE modeling, network modeling, network simulation, parameter & performance models, automation testing, data collection, big data processing, data analysis, AI/ML, failure prediction, and topology and router optimization. They convert issues difficult to solve at each stage of the network into the digital world for solutions, enabling network autonomy through monitoring, prediction, optimization, and simulation.

The 6G network based on digital twin and AI technologies is an autonomous network with self-optimization, self-evolution, and self-growth capabilities. The self-optimizing network predicts the trend of future network statuses in advance for early intervention of possible performance gradation. It continuously identifies the optimal status and verifies the simulation of physical networks in the digital domain, while issuing proper O&M operations in advance to automatically calibrate the physical networks. The AI-based self-evolving network analyzes and makes decisions on evolution paths of network functions, including optimization & enhancement of exiting network functions, and design, implementation, verification, and execution of new functions. The self-growing network identifies and predicts the demands of different services. Upon automatic orchestration and deployment of network functions in different domains, it generates end-to-end service flows that meet the service requirements. The network automatically expands the stations with insufficient capacities while planning the areas not covered by the network, starting hardware, and loading software automatically.

As a new concept applied to the network field, the digital twin technology requires more consensus in the industry. This may take a long time in the industry and other sectors. At the same time, the digital twin technology relies on massive data collection, which will increase the device costs, and the data collection also needs breakthrough innovations.

The 5G network automation and intelligence is a kind of automatic analysis for specific scenarios aiming to assist in manual decision-making. It is problem-oriented and independently implemented for specific domains. The autonomous approach is based on vendors' private implementation. Its typical application scenario is the patch-based SON standard. It solves simple problems with complex methods. Different automation modes between different systems make it difficult to interconnect, so human intervention is required. The 6G network autonomy requires systems to automatically process all scenarios and achieve cross-domain autonomy. It is necessary to lead the entire ecosystem to implement unified principles for network autonomy in their development, deployment, and operation:

- Mobile networks are complex systems but members follow unified simple rules
- Closed-loop control based on perception, analysis, decision-making, and execution
- Mobile network resource abstraction and schema abstraction
- Function decoupling, managed by their respective orchestration systems by category
- The control ring forms a hierarchical architecture for autonomy of the entire network from bottom to top
- Reusable software components, uniform interfaces, for flexible inserting/splicing
- Native supporting digital twin network
- Native support online simulation test
- Design concept from manual management to machine management
- Native supporting self-evolution

- Native AI

The 6G network autonomy, on the basis of traditional 5G NFVI and NFVMANO, forms the AI/ML layer, simulation test layer, twin network layer, and closed-loop control layer, for hierarchical orchestration management, and supporting the building of a cross-domain hierarchical structure for network autonomy on this basis.

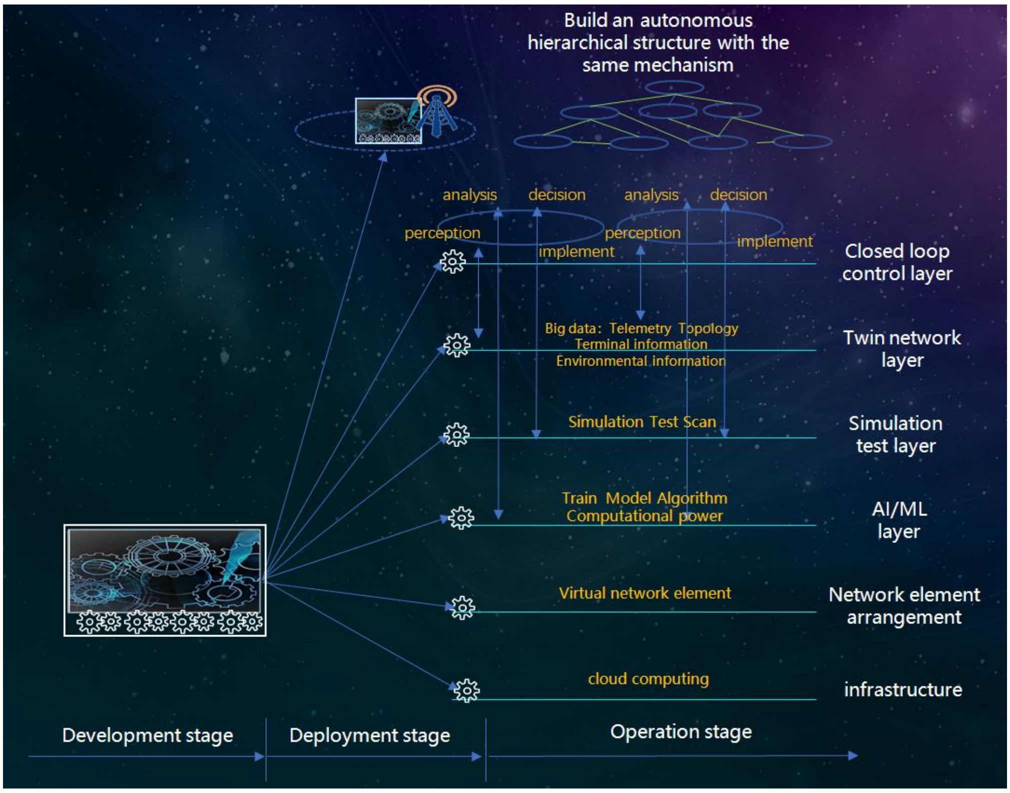

Figure 4 Autonomous Architecture of Twin Network

The network autonomous architecture based on the digital twin contains the following potential key technologies:

1. Efficient and intelligent network measurement technology: Telemetry is a remote high-speed data collection technology from physical devices to virtual devices and now it has been widely applied in cloud computing, microservices, and some other fields. Devices actively transmit information about traffic statistics, CPU, or memory data periodically to collectors at push mode. Compared with the traditional pull mode (in which, the interaction is established through requests and replies), the new push mode enables more real-time and higher-speed data collection.

2. Unified data modeling for different network applications: Data modeling is to abstractly organize various types of data in the real world. The data modeling of wireless networks relies on multiple different data modeling technologies. Wireless

access devices and network topology can obtain effective solutions in the digital twin space only when a unified data model is established for them.

3. Network visualization technology: The big data-based visualization applies advanced visual effects to the presentation of wireless access networks and deeply integrates with high-performance manipulations. This helps decision-makers to discover rules behind data and improves their decision-making efficiency and capabilities.

4. Closed-loop network automation management and orchestration technology: Smart orchestration is a new type of network "brain" to implement the unified control and allocation of network functions and resources. Its core technology is the closed-loop control of network functions.

5. High-performance AIOps technology, especially in prediction, cause analysis, exception detection, and intent translation: The AIOps is essentially a series of O&M functions implemented by applying the native AI, focusing on the O&M data analysis, including monitoring, log analysis, security, etc. The AIOps platform enables O&M automation, O&M improvement, and continuous insight into business performance. Operations that may take several hours in the past now can be completed in a few seconds with higher accuracy on the AIOps platform.

Network automation technologies applicable to service-based and virtualized networks: including service registration, service discovery, lifecycle management, and some other technologies, as well as the automation framework under cloud-based native services/microservices, such as Service Mesh, FaaS/BaaS, Serverless, etc.

4.1.2. Knowledge-driven Twin Network Control

To build a 6G all-scenario all-domain network intelligent control architecture, technical breakthroughs must be made in the following three key technologies from the analysis and research of the current industry:

(1) **Service custom:** The 6G network independently explores the implicit relationship model of all-domain resource behaviors, such as services, users, computing, storage, connections, and data, while effectively and autonomously discovering and automatically implementing the user, data, and network custom service issues.

(2) **Smart self-networking:** The 6G network autonomously infers and generates programmable deployment paradigms for on-demand services and efficient resource sharing in all scenarios.

(3) **Network self-control:** The self-planning, self-configuration, self-assessment, self-healing, self-evolution, and some other service issues for control and allocation of the 6G network can be implemented in on-demand, agile, and closed-loop ways in complex scenarios where human beings and machines, virtuality and reality, and twins coexist.

The 6G all-scenario services are based on the wireless network autonomous control engine driven by all-domain knowledge graphs. In this control system, the business QoE evaluation system is established based on user perception models (human vital sign model, as well as human visual, auditory, tactile sense, gestation, and emotion models) specific for different application scenarios. Business characteristics are extracted and classified, including interaction characteristics, popularity, latency, throughput, and packet loss rate requirements of users' businesses, terminal mobility, object location, 3D model characteristics of objects, user behavior mode, etc. The network knowledge graphs are generated based on machine learning, including slicing knowledge graphs, energy consumption knowledge graphs, automatic data labeling knowledge graphs, communication semantic knowledge graphs, wireless environment knowledge graphs, etc. The ML-based user behavior mode and exception prediction help to form user knowledge graphs, providing users with the perception QoE module, orchestrating network behavior predictions, offering network deployment policy generation module, and implementing the verification and optimization of network deployment schemes based on the twin environment. By reproducing the above knowledge graphs, a twin environment of the native network is built to support the quick iteration, development, and testing of network deployment schemes, for the purpose of all-domain, intelligent, and real-time network control.

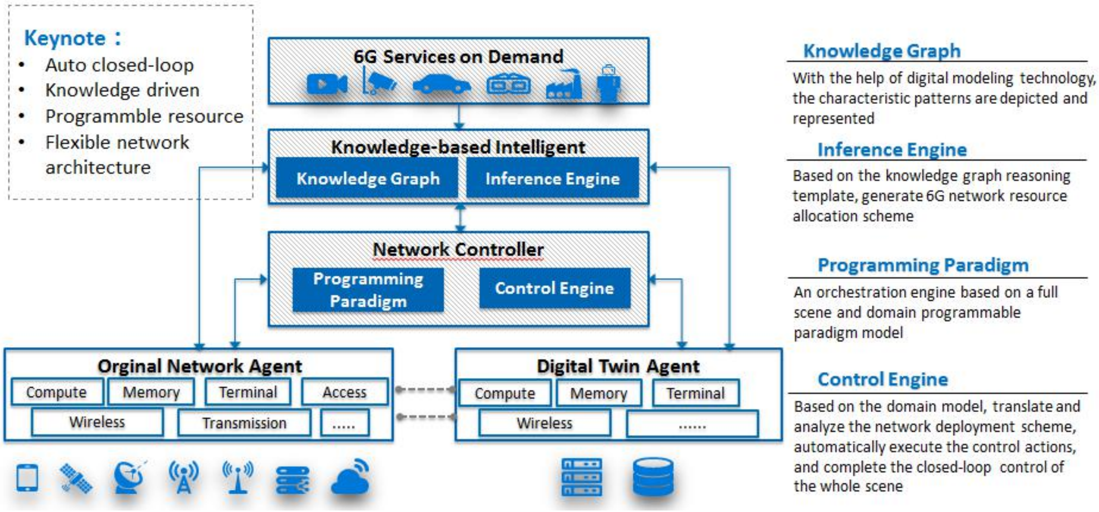

Figure 5 Autonomous Control Architecture and Technologies of 6G Network Based on Digital Twin

1. On-demand service control system of the 6G network based on the digital twin

The 6G control system mainly aims to implement the all-scenario, hierarchical model, lifecycle, programmable, and intelligent network control. Multi-layer models for control include end-to-end network, single-domain network (radio access network, transmission network, and core network), and various wireless devices. The lifecycle of the control covers the planning, construction, maintenance, and optimization of 6G wireless networks. The reprogrammable feature is the object programming management of all wireless domains and is the basis for automation and intelligentization. Intelligentization is to implement intelligent control with the knowledge intelligent agent (knowledge graph and reasoning engine) and network control agent (reprogrammable paradigm and control engine) by following the closed-loop concept of monitoring, analysis, reasoning, and execution.

The core of the control engine is model-driven control automation. The control model provides the control configuration through the reprogrammable paradigm. The control engine automatically executes control actions of each layer based on reprogrammable paradigm configurations. In addition, the objects managed by the model and engine are expandable.

The reprogrammable paradigm refers to the digital modeling for constructing the all-domain network management model, including the end-to-end model and domain model (wireless network, core network, and transmission network). The digitalized modeling information, exchanged between the network intelligent agent and the network control agent, must be recognized and executed by both of them. The reprogrammable paradigm modeling includes the information model and data model. The information model represents the data behavior logic of the model, and the data model represents the specific language for the information model.

The control engine is responsible for parsing the data model of the reprogrammable paradigm, translating the control actions in the wireless domain for the model, and automatically executing the wireless control actions for each layer, including being driven by the knowledge intelligent agent and coordinating with the corresponding network management. In addition, the network management is layered, including the all-domain management, wireless network management, transmission network management, and core network management.

The wireless closed-loop control covers end-to-end network control in a closed-loop manner. Because the all-network devices are distributed, the loop closing process can be classified into device-level intelligent loop closing, single-domain intelligent loop closing, and all-domain intelligent loop closing based on the real-time and autonomy of intelligent data. The device-level intelligence is embedded and integrated into a single device. From the perspective of the control system, the single-domain-level and all-domain-level control should be focused on.

The knowledge intelligent agent and network slicing control agent are introduced to all domains for all-network intelligent loop closing. Through all-domain knowledge intelligent agents, actions including modeling, analysis, training, and reasoning need to be implemented for all-network data. Then, the knowledge intelligent agent provides the execution solution to the network control agent, and the network control agent comprehensively makes decisions and implements execution.

In each subdomain, the single-domain knowledge intelligent agent and single-domain network control agent are introduced for single-domain intelligent loop closing for the wireless network, transmission network, and core network. The knowledge intelligent agent implements analysis and reasoning for the single-domain data, predicts the trend for the service and resource KPIs, analyzes the root cause, and offers the candidate reprogrammable paradigm for single-domain network control agents to decide and execute, implementing single-domain intelligent loop closing.

2. 6G Network Knowledge Graph

It requires the complete characteristics of all objects and elements to construct the knowledge graph of the space-air-ground integrated wireless network for 6G user sensing. The wireless knowledge graph can be described in a hierarchical structure. The knowledge includes sub-graphs which are wireless environment knowledge, wireless NE knowledge, and user knowledge. The sub-graph can be further decomposed into characteristic subsets containing relevant characteristics.

In the knowledge-graph-driven 6G autonomous control structure, based on the requirements of the NE intelligentization use case, it is considered to create profiles for base stations and UEs, to describe the attributes, statuses, and behavioral characteristics of UEs and each service object in the base station. The profile is created based on objectification modeling.

In the base station, each service object has its own attribute, status, and behavioral characteristics, which are changing constantly with time. To describe all information of an object at a time point, the service at this time point needs to be sliced. The slice should contain values of all attributes, status, and behavioral characteristics of the service object.

The NE knowledge graph is the general name for all service object profiles, including the attributes, status, and behavioral characteristics under different perspectives. The relationship between service objects cannot be completely and accurately presented through a sole perspective, and thus the model is constructed based on different perspectives in service relationships.

The UE profile describes the attributes, statuses, and behavioral characteristics of terminals. Since the UE profile involves multiple protocol layers and multiple types of services, the profile for one UE needs to be disassembled due to the difference in the changing frequency of its attributes, status, and behavioral characteristics.

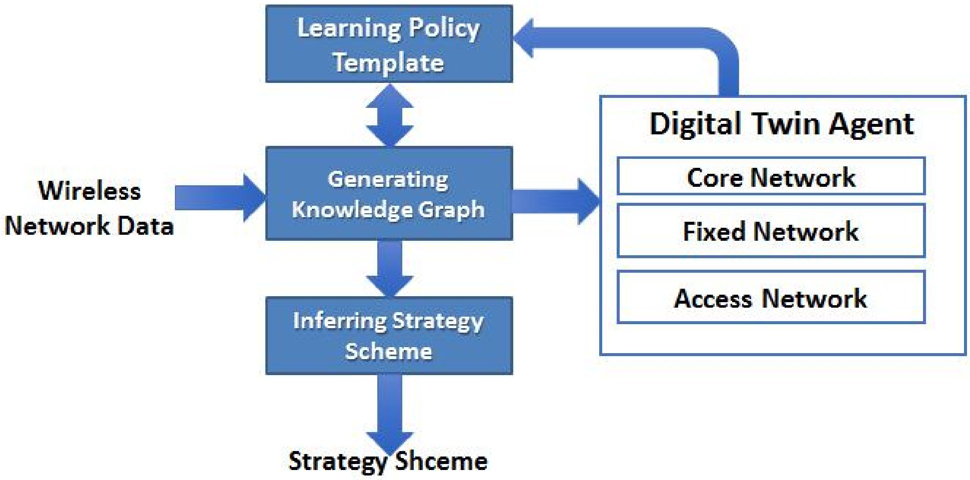

Figure 6 Strategy Learning and Reasoning System Driven by the Wireless Knowledge Graph

Figure 6 shows that the preceding generated wireless network knowledge graph can provide knowledge graph model data for training the twin network. The twin network performance knowledge obtained through training can be used to generate the network allocating policy template through machine learning approaches (such as deep learning). Through the wireless network knowledge graph, the network changes are identified or predicted, and the policy template applicable to the network changes is derived. The generated network allocating solution is sent to the wireless network control engine for decision making and execution.

The twin network needs to offer the following network performance knowledge in order to assess the user requirement satisfaction and experiences

1) Network KPI: The latency, throughput, connection success rate, coverage, packet loss rate, handover success rate, delay jitter, and so on for each network unit;

2) Knowledge related to user sensing: QoS/QoE-related parameters, user's five senses, emotional model parameters, and so on;

3) User/object status knowledge: Human vital sign model parameters, 3D object model parameters, and so on.

Various algorithms of the original network need to be copied in order to verify the network allocating solution. The algorithms include the following: algorithms and strategies on each protocol layer of the core network, transmission network, and access network, the routing and handover algorithm strategies of the space-air-ground integrated networks, federated self-learning cross-domain alliance control algorithm strategies, resource-spectrum-driven wireless network autonomous control algorithm strategies, intelligent edge buffer technology, smart avoidance control algorithm for deterministic communication faults, and so on.

3. Knowledge-driven digital twin network control

The decision making based on the knowledge-driven digital twin network has the following advantages:

- **Virtual modeling based on knowledge and scenario information**: The ontology base is used to unify the multi-source heterogeneous data; The ontology-based modeling can better map the actual physical world to the virtual model; The requirement input and reasoning provided by the knowledge graph are applied in addition to the ontology-based model, to generate more accurate virtual model corresponding to the real physical network.
- **Smart strategy template generation**: The experience and knowledge visualized based on the knowledge graph can be used in network maintenance measures such as fault diagnosis for the initially established virtual model, to import the knowledge graph for decision making and obtain the decision making results; The decision making process is a cyclic process. That is, the formed decision is applied in the virtual model for repeated execution, to obtain the network maintenance measures decisions, and the strategy template is repeatedly updated based on the strategy performance. The updated strategy template is saved in the knowledge graph. The template, which is called again when the same scenario and service occur on the network, no longer needs to be generated repeatedly.
- **Precise on-demand management of network resources:** In network

resource management, knowledge can be used for template selection as well as a supplement for background or user preference used for network decision making, to improve the machine learning algorithm performance and implement the accurate on-demand allocation of resources.

To implement personalized resource allocation, proper estimation of services must be performed for each user, so that the service resources can be accurately reserved for each user. This requires not only the collection of the current status of users but also the utilization of user history behavior knowledge to accurately predict users' intent and allocate network resources.

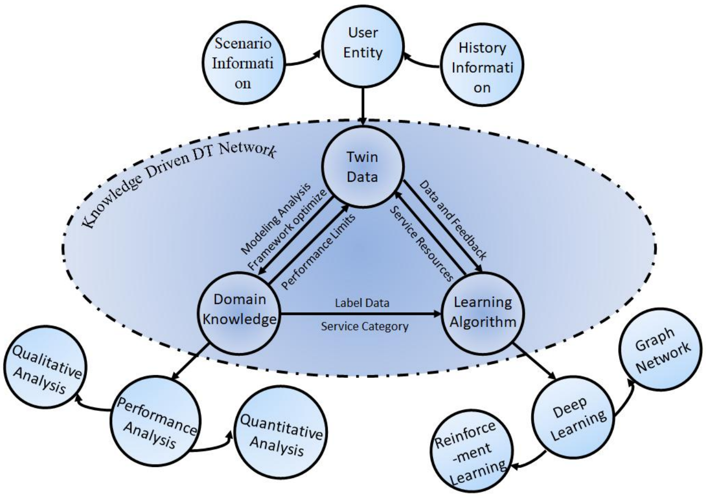

Figure 7 Knowledge-Driven DT Service Classification Framework

To achieve this goal, knowledge-driven 6G technology represented by the knowledge graph can offer user behavior reasoning and explore inter-user associations. As shown in Figure 7, a single user can be regarded as a node in the multi-dimensional knowledge graph to analyze the association between different users in different requirement dimensions. Alternatively, the user twin can be regarded as a knowledge graph to explore the association between the user's own attributes to implement the attribute-based knowledge reasoning.

The knowledge-driven digital twin resource management also has the following distinct characteristics:

- **Knowledge attribute associations**: The knowledge graph can be used to reason out new attributes of the current user based on the attribute or information of its associated node. In the reasoning process, the knowledge graphs map each twin to a node in the knowledge graph. In this case, if each twin is a knowledge graph, the twin is a data resource that can implement communication. When a user needs a certain type of data in a certain knowledge graph, the real network can transmit the data sub-graph of related information in the graph to the requesting party. This enables the user to obtain the association between information while the user obtains information.

Highly efficient on-demand resource allocation: Collecting user behavioral information under different statuses based on the digital twin technology helps create the user preference and knowledge graph. Then different QoS requirements can be obtained through analysis, to implement on-demand resource allocation based on user preference. Sensors are used to collect the environmental characteristics, and the environmental characteristics and user preferences are used to analyze the impact of different environments on user requirements, to accurately obtain the user requirements in different environments. In addition, knowledge, as effective information obtained through analysis and summarization, can serve as a supplementary input for machine learning algorithms, improving algorithm performance such as efficiency and accuracy.

4.1.3. Intent-Driven Twin Network Management

Various new services and applications emerge, with the rapid development of big data, cloud computing, Internet of Things and other technologies. Therefore, the network operation and maintenance become more complex. In addition, it is increasingly essential to guarantee 6G’s requirements for embedded security. In this scenario, it becomes an important research of network to ensure highly reliable operation of network services and create low-cost self-healing of network failures. DT networks are composed by both the real physical network and virtual twin network, and they are mapped to each other. The virtual twin network has the same characteristics, information and attributes as the real physical network. On the one hand, the DT network enables real-time modeling of the communication network and helps uniformly manage the operating model and data of physical network elements. In this way, the DT network can promote dynamic operation and maintenance and smart decision-making for the network. On the other hand, the DT network can provide real-time digital display interfaces to the network administrator, in order to implement end-to-end network monitoring and network policy verification.

Intent-driven network (IDN) is a new network management form, aiming at network autonomy. IDN combines artificial intelligence, machine learning, and network orchestration technology, so as to apply the deeper intelligence and intent status insight into the network. To be specific, IDN is designed to reduce the complications in creating, managing, and implementing network strategies, and reduce the manual operations related to traditional configuration management. This is consistent with the vision that the 6G network intelligently discovers users' requirements and provides on-demand services to users. In IDN, the network administrators declare the expected results or goals to describe the intent. And the network software determines how to implement the goal through artificial intelligence and machine learning. Therefore, IDN can automatically execute policy and provide real-time visualization of the network operations to verify the intent. In addition, predicting the potential deviation to the intent and formulating the correction policy can ensure the effective execution of the intent and realize the autonomous monitoring and correction of the network.

From the perspective of network communication, IDN initially realizes the digitalization of user intent. Intent-driven DT network can directly translate the network requirements, collect the network status in real time, and dynamically optimize the network policy. The benefits to 6G networks are as follows.

- **Reduced manual participation**: Intent-driven DT network automatically converts intent to configurations, and network administrators no longer need to manually configure the network. The network translates the intent and verifies its validity, and then the options are reported to the network administrator to change the configuration.

- **Quick troubleshooting**: Intent-driven DT network continuously monitors the network status and instantly discover network running problems. Machine learning can be used to verify the feasible solutions in the twin network, and determine the optimal solution, and send the solution to the physical NE for execution.
- **Improved network security**: Generally, Intent-driven DT network proactively detects threats during the monitoring, especially for encrypted communications. Once a security vulnerability is detected, the network can instantly identify the vulnerability and take control measures. In other words, IDN can save massive time for planning, tests, verification, and manual configuration.
- **Optimized strategy analysis**: Intent-driven DT network continuously collects the network operation and maintenance data. It then analyzes the data using multiple methods to provide valuable information related to network performance, security threats, and so on. After fully understanding the network operation status, the network administrator can make better decisions to generate the optimal network configurations.

1. Intent-driven twin network architecture

The DT network is an effective way to implement lifecycle management of intent. It integrates the twin network and IDN, dynamically generates optimal solutions that can be executed, and produces good results based on the real-time network status.

Figure 8 shows the intent-driven twin network management and control, including three layers:

- **Physical network layer**: The physical network layer includes various infrastructures of the 6G network. Technologies such as in-band network telemetry can be used to collect the physical network element operation status. Moreover, the network data and network control information can be interacted with the digital twin entities through the southbound interface of the twin network.

- **Twin network layer**: The twin network layer is the sign of the DT network, including three key subsystems of the database, service mapping model, and digital twin management. The database collects and stores various types of network data, including network operating status and history configuration data of the physical network layer. Meanwhile, the data service, unified interface and data support are provided to service mapping model and digital twin management. The service mapping model executes key operations such as scheduling optimization, fault diagnosis, traffic analysis, topology model, and simulation verifications, and then the network strategy is verified in the twin network and executed on the physical network layer. The digital twin management completes the intent translation, configuration verification, automatic troubleshooting, and intent assurance. The users' intent is translated to effective and feasible network strategy, and automatically completes troubleshooting.
- **Network application layer**: The network application layer provides open interfaces to users, and users can directly manage the network. Users can enter the intent in natural languages through text, audio, or graphical interfaces, without mastering the professional knowledge and expertise of network management.

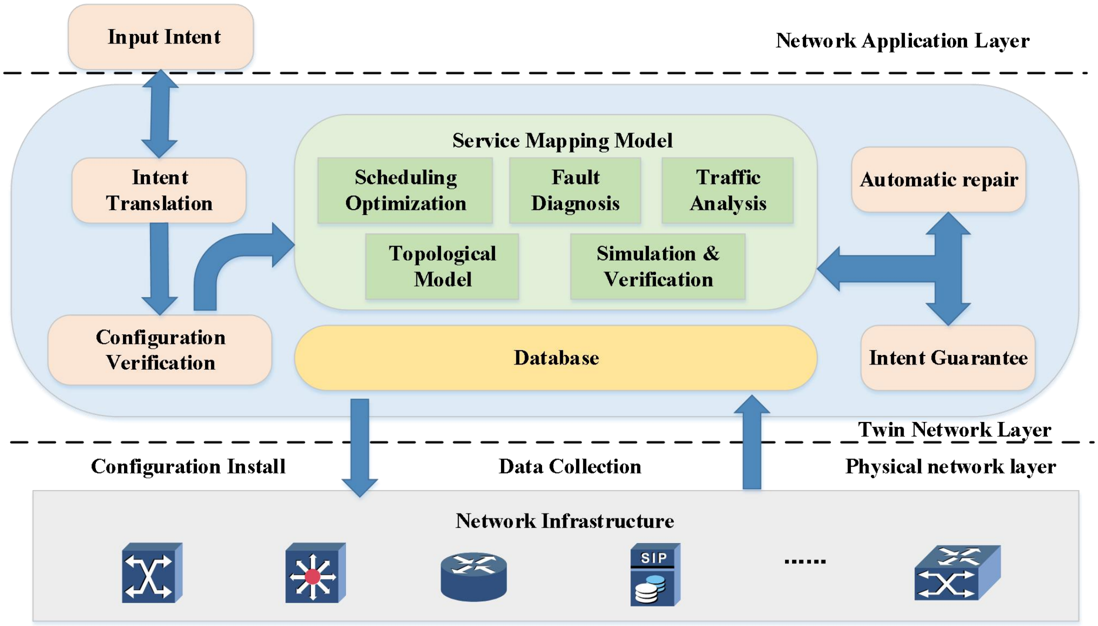

Figure 8 Intent-Driven DT Network Architecture

From a technological standpoint, the physical network forms massive network configurations after user intent is translated. If the configurations are sent directly to the physical network, they may affect other services, resulting in unanticipated consequences. The DT network service mapping mode validates and simulates configuration delivery in advance, allowing for the detection of configuration anomalies. Numerous service mapping models may implement configuration verification, intent assurance, and automatic troubleshooting in intent-driven twin network control systems to verify user intent from the network application layer in real-time. Additionally, the intent assurance and automated troubleshooting capabilities based on the service mapping model convey the physical network's working status to the twin network layer's database via data collection. The service mapping model continually checks users. Suppose it determines that the network is deviating from the service intent. In that case, the DT network can utilize intelligent technologies such as AI to do root cause analysis and produce a troubleshooting approach. The DT network's service mapping model validates the troubleshooting strategy in advance to guarantee its accuracy and then delivers the strategy to the physical network via an automated configuration module.

2. Key procedure of intent-driven twin network

The DT network in the communication domain can accurately show the network operating status in real time. The real-time interaction between the twin network and the physical network can predictably maintain and optimize network strategy. Figure 9 demonstrates the major steps required in intent-driven twin network control loop.

From a physical 6G network to a virtual 6G network, the procedure traverses network intent, configuration data, real-time status, data aggregation, and performance design to establish a virtual entity relationship in the DT network. The virtual 6G network can validate and optimize the strategy in advance to ensure efficient network deployment and minimize the impact on the real network, thereby boosting the capability for intelligent network simplification.

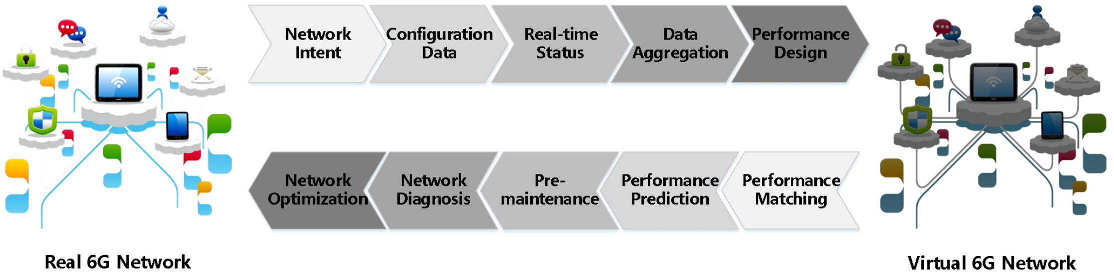

Figure 9 Key Procedure of the Intent-Driven Twin Network

The intent-driven twin network may be used to ensure the end-to-end performance of a network. The DT network technology is capable of simulating the network operation state and the implementation impact of network strategies to enhance network lifecycle management performance and assure the correctness of end-to-end closed-loop management. Assume the system identifies a decline in the end-to-end service performance. In this situation, the DT network may do intelligent analysis using real-time data monitoring and historical operation and maintenance data to precisely detect the network issue and give a matching network recovery solution to the physical network following the twin network's verification.

4.1.4. Terminals data-related supporting technologies

Data collection is essential for constructing 6G digital twin networks. As one of the main ways of data collection, the terminals first sense and collect data and then extract, process, and transmit data to meet the needs of the digital twin networks. The data-related supporting technologies of the terminals to 6G digital twin networks can be listed as follows:

1) Comprehensive and effective data acquisition.

Comprehensive coverage of the acquired data is required to meet the needs of the digital twin network. With the development of information technology, the data can be obtained through a variety of terminals, including mobile phones, wearable devices, vehicles, IoT sensors, and so on. More and more data can be collected and stored in real time. At the same time, it is necessary to deal with the tradeoff between comprehensiveness and effectiveness of the data. Irrespective of the validity of the data, it may result in a large amount of data obtained by the terminals, such as irrelevant data, abnormal data, and redundant data. Targeted data acquisition would increase the effectiveness of the data, thereby conducive to reducing the burden on the terminal.

2) Data mining and processing.

Even if the data volume can be reduced owing to targeted data acquisition, the data acquired by the terminal is still massive for transmission. It is necessary to conduct data mining, knowledge extraction and generalization. Partial data can be processed within the terminals.

3) Iteration and optimization of data.

Based on the acquired new data along with other stored data，it can meet true time optimization of data. Various kinds of data require different iteration periods. To fully realize an immersive remote experience, the acquired data require real-time performance. Iterative optimization for different data may drop the outdated data and invalid ones. It can also update twin model parameters, and improve 6G services adaptability to the practical wireless environment. The updated data and previous data can rectify each other，in case some data is missing or changes dramatically. Thus，it can ensure the accuracy, consistency and comprehensiveness of the data. Besides, it can reduce the burden of data storage and processing on the terminals.

4) Exchange and integration of data.

In a 6G wireless network, multiple types of terminals with different statuses are distributed at various locations. The data from multiple terminals can be exchanged and integrated. Mutual complementation and enhancement would be performed to build an overall model based on valid data acquired. Besides, through data fusion, data from different sources can be used for one specific terminal in user-centric networks.

4.2. Other Applications of the Digital Twin

4.2.1. Smart Transportation

The digital twin can provide new technological support and development direction for the intelligent transportation system (ITS). The physical objects in the ITS are mirrored, and the digital twin can implement full data sensing, real-time information sharing, and accurate collaborative decision making, to promote the original ITS into a revolutionary transformation and upgrade toward a scientific, accurate, and ecological integrated traffic management system.

As shown in Figure 10, the DT-enabled ITS has the following seven typical application scenarios.

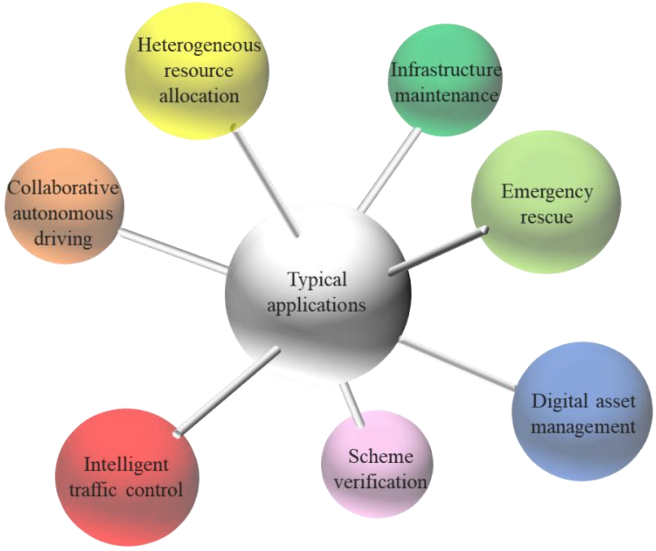

Figure 10 Typical applications of DT-enabled ITS

1. Intelligent traffic control

In the ITS, there are significant problems of the high cost of interaction between vehicles and the MEC, long latency for decision making on the cloud server, and poor execution of scheduling commands by vehicles. In the DT-enabled ITS, a twin of the physical traffic is created in the virtual world to create a high-definition mirror of the ITS. Through road network layout, infrastructures, twin data of the vehicular users, the cloud server can implement simulation optimization, properly arrange public vehicle scale, and implement traffic guidance based on the vehicles' preferences. On the edge layer, rapid interaction between the vehicular user's digital twin and the MEC can avoid frequent information transmission between the vehicle entity and the MEC. In the meantime, the driving path of higher efficiency is planned in advance based on the user's personalized driving requirements. This improves transportation efficiency and provides vehicular users with high-quality driving experiences.

2. Collaborative unmanned driving technology

Collaborative driving for autonomous vehicles (AVs) can significantly increase the capacity for the intelligence bottleneck of individual AVs. However, AVs with different sensing, calculation, and communication capabilities need to frequently share information and decisions to determine the collaboration group scale and work distribution of different AVs. In the DT-enabled ITS, the resource status of AVs and the users' requirements and preferences are synchronized to the digital twin connected with the MEC. Therefore, the digital twins of AVs in the virtual world compose an all-new virtual interaction network in the MEC, where the DTs can implement information communication and formulate strategies for the AVs. This saves the calculation and transmission resources and implements the smart group collaborative driving of the AVs.

3. Heterogeneous resource allocation

In the future, the ITS application scenarios are broadened, the performance indicators are diversified, and the service needs are more detailed. However, there are insufficient considerations of the device difference and service personality for the current resource allocation solution, which cannot provide high-quality services for vehicles in different application scenarios. In the DT-enabled ITS, the resource status of the physical entity is synchronized to its digital twin in real time, and the cloud server can flexibly implement integration and scheduling for the digital twin, to conduct transportation resource management in small granularity. On the basis of real-time monitoring and configuration of the resource status, the cloud server and MEC can customize the knowledge-based resource slice through big data analysis and artificial intelligence, to satisfy the personalized resource need of diversified services, significantly improving the service experience quality for users.

4. Infrastructure maintenance

The ITS, with incomplete sensing ability, low accuracy, and insufficient intelligence, can hardly implement highly accurate and all-around comprehensive monitoring and predictive maintenance for vehicles and infrastructures. In the DT-enabled ITS, the sensors deployed in the vehicles and on the road and infrastructures can implement status monitoring and regular update to the twins on the cloud. The cloud server comprehensively considers the infrastructure status and environmental factors based on the information provided by the digital twins to formulate optimal decisions. In addition, the digital twin will save the history status information and create the all-element lifecycle digital profile and the predictive management and maintenance system for the vehicles, roads, and infrastructures. This improves driving safety as well as reduces the maintenance overhead for vehicles, roads, and infrastructures.

5. Road emergency rescue

Faced with the explosive growth of the traffic and driving needs of different users, the ITS can hardly manage the execution of scheduling commands by normal vehicles when planning the optimal path for emergency vehicles as the green passage. In the DT-enabled ITS, the cloud server can assign different rewards for different traffic flow statuses and comprehensively consider the driving time, rewards, personalized driving needs of the digital twins of vehicles to plan the optimal driving path, enabling users with different driving needs to comply with the scheduling commands. On this basis, the cloud server and MEC can quickly adjust the traffic lights and the emergency incidents corresponding to the road rewards, to significantly shorten the time for the emergency vehicle to pass and reduce the loss of the emergency incident and the impact on normal vehicles.

6. Digital asset management

Digital assets of great utilization value will be generated after the collection, integration, analysis, and deep learning are implemented on traffic data. In the DT-enabled ITS, the twins can replace the physical entities to complete the classification, screening, storage, authorization, and transaction, and create the all-element lifecycle digital profile. In this way, a new model for commercializing the ITS data assets can be created for the digital account of the twin. In addition, the additional benefits also encourage physical entities in the ITS to proactively participate in the data sensing and maintenance. This is beneficial for the deployment of various applications and services in the ITS, promoting the construction of the ecological industrial chain for the ITS industry.

7. Test solution verification

The traditional ITS has high cost and redundant cycles, making it difficult to test the algorithms, solutions, and architectures on large scales. In the physical world, massive intelligent sensors dynamically map the sensed data into the twins in the twin world in real time, creating a virtual world test platform for the deduction and test of new algorithms, new solutions, and new architectures. The twin of the data requester can negotiate and make decisions with the digital twins of the data owners in the virtual world, to develop the transaction plans for data. In the meantime, tests of new algorithms, new solutions, and new architectures can be implemented repeatedly on the digital twins in the virtual world for prompt corrections. In the end, new algorithms, new solutions, and new architectures can be deployed on the applications of the physical entities while the test cost and cycle are both reduced.

DT-enabled Intelligent Traffic Control

Traffic jams will increase the time for driving, energy consumption, environmental pollution, and accident rate, and will directly hamper urban development. In the existing intelligent traffic control system, the information can be shared among different physical entities through the vehicular networks to make the traffic smart. Specifically, as shown in Figure 11, IoTs devices such as cameras, magnetic sensors, and millimeter-wave radars are deployed along the road to sense traffic data in real time. The BS transmits collected traffic data to the cloud server. The cloud server comprehensively analyzes the historical data and the data collected by the IoT devices to predict the traffic status and determine the traffic scheduling decisions that are sent to the vehicle users through the BS. During the traffic flow control, if a vehicle user needs to plan the optimal path, the user can send a path planning request to the connected BS. After the BS forwards the user's request to the cloud server, the cloud server conducts analysis based on the driving needs and traffic flow and determines the optimal driving path accordingly for the vehicle user, to improve the driving experience for the vehicle user.

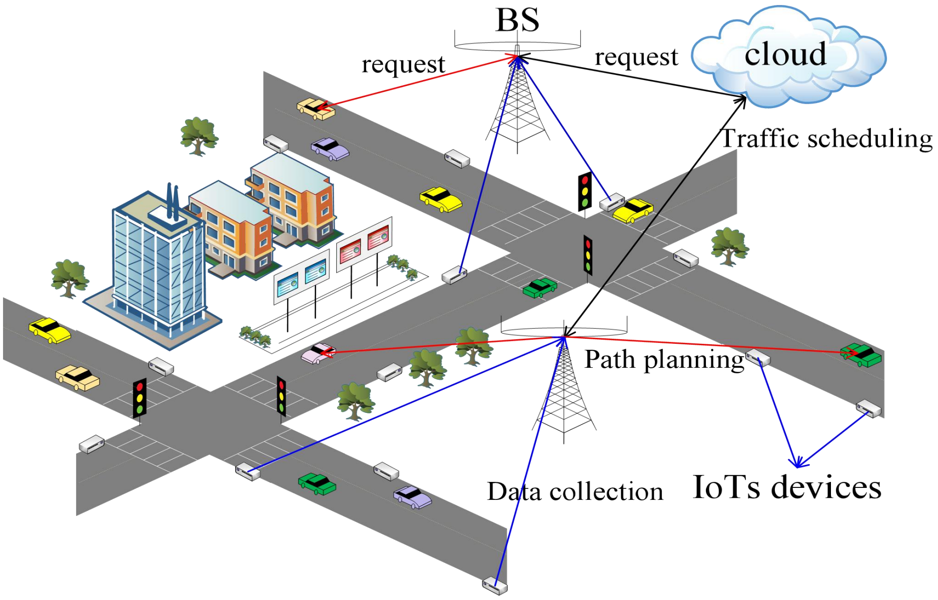

Figure 11 Intelligent Traffic Architecture

Though the traffic system and vehicle users, in theory, can benefit from the current scheduling architecture, there are a series of new challenges in the application of the system.

- **High cost**: In the ITS, the test cost is high for new algorithms, new solutions, and new architectures of traffic flow scheduling and control, and consequently frequent massive tests in the real world are impossible.
- **Long latency**: The number of networked vehicles drastically increases, causing a long latency to determine and distribute the scheduling decisions for planning paths for massive users. Thus, the traffic operation system can hardly reach the expected efficiency.
- **Poor execution**: The existing ITS is a path recommendation system, and can hardly ensure that all vehicle users will follow the control scheduling commands sent from the cloud. As a result, the vehicle traffic cannot be effectively managed.
- **Poor experience**: When the cloud server is planning traffic flow solutions, the primary reference indicators are usually the shortest distance or shortest driving time, and the server does not consider personal needs. Therefore, it cannot provide high-quality driving experiences for vehicle users.

To deal with the preceding challenges, it is urgent to create ecological, digitalized, intelligent, and controllable ITS, improving the comprehensive command, rapid response, and scheduling and control capability for road traffic management and effectively supporting green, intelligent, and immersive traffic.

The new paradigm of the DT-enabled intelligent traffic flow control combining the digital twin technology and the current traffic flow control architecture is the optimal idea to deal with the preceding challenges. Specifically: 1) The digital twin can implement real-time traffic data collection, accurate update of traffic entity status, and synchronized display of traffic operation. Thus, it provides a test platform for the deduction and tests of new algorithms, new solutions, and new architectures; 2) The interaction between the digital twins of vehicles in the virtual world and the cloud server can help plan driving paths for vehicle users in advance, effectively reducing the path planning latency; 3) In the DT-enabled traffic control system, road segments can be used as a resource to motivate users. The cloud server can give different rewards to different segments based on the vehicle density. In addition, the driving status of individual vehicles will be synchronized to the twins in real time, and therefore the cloud server can get to know the scheduling command execution by vehicles and adjust the scheduling decisions promptly; 4) The digital twins can reflect the personalized driving preferences of the vehicles, and provide the optimal path based on the personalized needs of the driving time and driving reward during the control and scheduling, to improve the service experience of vehicle users.

1. Virtual-real mapping of the traffic control system

The virtual traffic DT platform is primarily composed of the digital twin of the traffic environment, digital twins of the vehicles, and cloud server. The digital twin of the environment is divided into different areas based on the base station coverage, and a digital twin is deployed to represent the real traffic environment in each area. With highly precise maps as basic data, the digital twin can adopt different types of real-environment data and 3D rebuild technology, to reconstruct the traffic scenarios in the physical world with high precision. In addition, IoT devices deployed along the road, such as cameras, laser radars, and geomagnetic sensors, and multiple types of sensors installed on the vehicles can collect traffic data in different road segments and dynamically sense the traffic environment, and the data is efficiently transmitted on demand through the heterogeneous networks, to realize the data interconnection between the digital twin world and the real physical world. The digital twins of vehicles store the driving needs and preferences of vehicles. When the driving needs or preferences need to be updated for the vehicle, the on-board unit (OBU) for communication can be used to update the information via the BS to the digital twin on the cloud. Based on the current traffic environment and the driving needs and preferences of individual digital twins, the cloud server develops the optimal traffic control solution, dynamic multiplexing solution of road resources, and important vehicle path planning solutions.

2. DT-enabled traffic scheduling solution

Different from the traditional traffic scheduling idea of using the shortest distance or shortest driving time as primary indicators, the DT-enabled intelligent traffic scheduling further considers the personalized needs of vehicle users and uses the road as resources and the price as the motivation method to guide vehicle users to comply with the control solution. Firstly, from the perspective of the traffic flow condition, the IoTs devices deployed along the road and sensors on vehicles in the real traffic will collect the original traffic flow data in real time. The collected data will be preliminary processed by the MEC, and the result will be uploaded to the cloud server. The cloud server can specify proper rewards based on the traffic flow of each road segment to motivate vehicle users to choose different road segments for driving. For example, the cloud server can specify negative rewards in congested road segments to charge fees from vehicle users. Similarly, the cloud server can specify positive rewards in road segments with few vehicles. Secondly, from the perspective of vehicle users, different vehicle users have different driving habits and different preferences regarding driving time and driving reward. Therefore, time and reward can be used as basic elements to establish the personalized model for individual vehicle users. For example, vehicle users who are sensitive to driving rewards are more willing to choose longer road segments and spend more time to get more rewards. Accordingly, vehicle users' needs and preferences are accurately mapped by the digital twins deployed on the cloud, thus promoting the cloud server to configure optimal rewards for different segments by comprehensively considering the current traffic status and users' driving needs and preferences. The digital twin architecture can implement closed-loop management in collecting the traffic environment and users' needs and preferences in real time, specifying road segment rewards, scheduling traffic flows, selecting paths for vehicle users, and updating the traffic status.

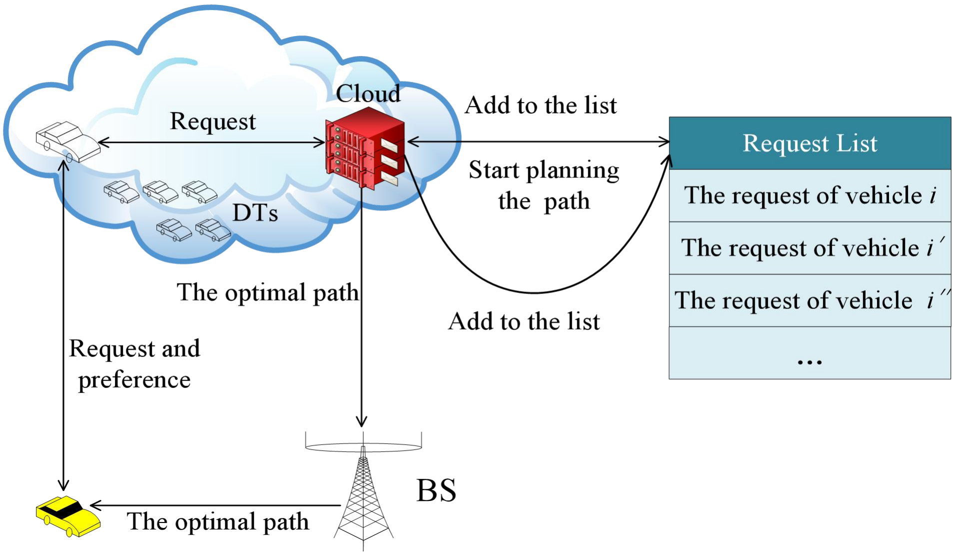

Figure 12 DT-enabled Intelligent Traffic Control

In the closed-loop scheduling process, the digital twin maps the needs and preferences of the vehicles. As shown in Figure 12, if there are travel needs for a vehicle, its digital twin sends a driving path planning request to the cloud server, and the cloud server adds the request into the service list based on its start time. Then, based on the scheduling time interval provided by the digital twin, the cloud server comprehensively considers the traffic flow status and reward, as well as the vehicle's start point, destination, needs, and preferences and uses optimization algorithms such as heuristic algorithms, game theory, and artificial intelligence to plan the proper driving path for each vehicle user. If the vehicle does not reach the destination after a round of path planning, the cloud server will add the service request of the digital twin into the service list again and wait for the next scheduling. After a round of path planning for vehicle users in the virtual world, the cloud server will send the scheduling command and path recommendations to the vehicle user via the BS, to implement the DT-enabled traffic flow control.

4.2.2. IoT

The vision of 6G is "three dimensions and generalization, and intelligent connection for the world". With the rapid development of information technology, 6G will enable a series of intelligent IoT applications that requires ultra-low latency and ultra-high reliability, such as the future intelligent transportation system and smart city [19].

Communication and computing are both indispensable to promote the Internet of Everything. In the IoT scenario, as shown in 13, MEC and communication are hot topics in recent years [20]. It features decentralization, low-latency computing, data security and privacy, and joint optimization for computing and communication. However, it is also faced with the challenges of general computing, task planning and distribution, distributed storage and collaborative computing, and public use and security of edge nodes.

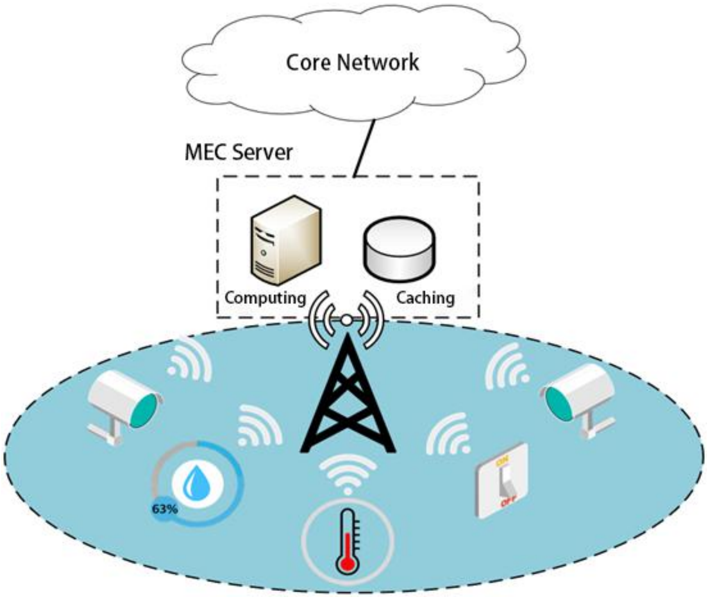

Figure 13 MEC and Communication under IoT Scenarios

For the Internet of Everything, how to conveniently manage and control massive nodes is also a hot topic in addition to the construction of models. The common control method following the "node-gateway-cloud platform-control-end" pattern cannot be used for intelligent operations, and its scalability and network robustness do not meet the requirements of new services. However, introducing digital twins will effectively resolve the control problem.

One of the major functions of the DT-driven Internet of Everything control system model is to simulate, monitor, diagnose, predict, and control the formation process and behavior of physical or simulated nodes in actual environments.

Simulation: Before the deployment of heterogeneous physical network nodes, the communication and computing processes are simulated in a virtual simulation environment (for example, NS3 or other network simulation platforms) to learn node status in the actual operating environment as much as possible. Behavioral policies, the probability of service success, parameter setting, and issues not considered/expected in the design stage will provide the foundation for subsequent service planning, service parameter determination, and decision making in abnormal situations. Node operation in different service environments can be simulated by changing the parameter setting in the virtual environment. The influence of different service parameters on the probability of service success can be simulated by changing task parameters.

Monitoring and diagnosis: In the node service process, service data will be reflected in the digital twins of the nodes in real time. The digital twin system of the nodes enables dynamic, visual real-time monitoring of the actual node service process and allows fault diagnosis and positioning on actual nodes based on the real-time monitoring data and historical data obtained.

Prediction: The building of a node digital twin mode makes it possible to perform integrated simulations and validation of the testing process of node function and service performance in digital space to predict potential service, functional, and performance defects of the nodes. For those defects, the corresponding parameters can be modified in the digital twins of the nodes. On that basis, simulation of the service, functional, and performance testing process of the nodes is repeated until the problems are solved.

Control: In the node service process, the process data of real-time service is analyzed to control the status and behavioral policies of the physical nodes, including service policies, parameter changes, etc.

Figure 14 shows the architecture of the DT-driven Internet of Everything control system, in which the IoT sub-net is the physical entity layer, the twin convergence network is the digital twin layer, and the management and control center on top of them is the application layer. This networking architecture has four characteristics:

First, edge intelligence is used and digital twin technology is introduced into the architecture. The twin network is at the center of the system architecture, enabling quick response, intelligent computing, and delivery driven by computing tasks.

Second, there is a large-scale hierarchical structure. Data information is transmitted from the IoT subnet to the twin network and then to the backhaul network. Finally, the data is organized by the management and control center. The clear hierarchical structure greatly boosts functional stability and scalability.

Third, heterogeneous intensive networking. Multiple communication systems and heterogeneous networks are supported. For intensive data, time-sharing scheduling is enabled so that the number of nodes and communication constraints are no longer bottlenecks for networks.

Fourth, efficient, automatic networking. The architecture employs the automatic configuration technology for dynamic restructuring and reconstruction, enhancing network robustness.

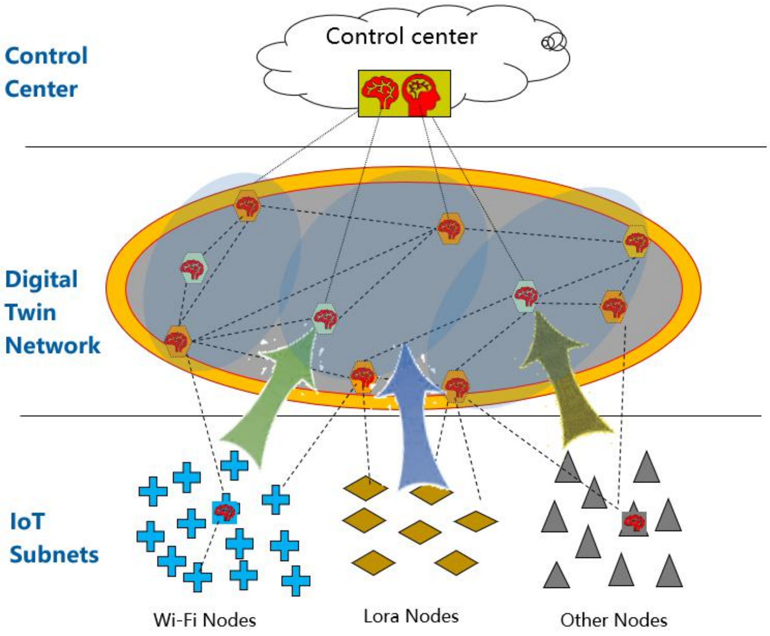

Figure 14 Architecture of the DT-Driven Internet of Everything Control System

Meanwhile, the twin convergence layer at the core of the new architecture is expected to deliver five functions:

First, support for flexible access. The twin convergence layer has multiple communication systems, supports heterogeneous networks and intelligence operations, and is capable of automatic configuration of network access and strong access scalability.

Second, destruction-resistant restructuring and reconstruction. In the event of network outages due to signal quality or other uncertainties, the twin convergence layer allows cut-vertex detection to automatically locate the outage point and perform dynamic network restructuring and mobile node scheduling to maintain network system stability.

Third, intelligent judgment. For multi-source data, comprehensive judgment is performed so that algorithm is used to determine whether to report data situations and take countermeasures.

Fourth, an application layer gateway to facilitate intelligent service data processing and node collaboration.

Fifth, intelligent command execution. Commands on the control layer can be executed with a single click and intelligent analysis of ambiguous commands can be conducted for intelligent command delivery and scheduling.

Taking the architecture in Figure 14 as an example, after the introduction of digital twin technology, large-scale twin convergence of physical and simulation nodes is realized in the architecture of the Internet of Everything control system. The architecture is also capable of self-networking, self-configuration, and self-access and supports multi-hop connections and various wireless communication networks, such as WiFi, ZigBee, LoRa, etc.

During actual application, the twin convergence network layer first simulates the services used by the IoT node to be deployed. For example, a twin layer similar to NS3 software is used to build twins for ZigBee nodes and the services to be run by the nodes (e.g., temperature and humidity measurement and analysis) are deployed to simulate the communication and computing processes between the actual nodes and the twin convergence nodes (ZigBee protocol communication or network mapping). Parameters in multiple dimensions are set to replicate the status of the actual node operating environment. Data produced by the twins is uploaded to the management and control center via the backhaul network and then analyzed and maintained by administrators to find and correct issues emerging in the simulation process and those expected.

After that, the physical nodes are deployed and correspond to the digital twins in the twin convergence network. With data information about the physical nodes uploaded via the backhaul network visible on the management and control center, administrators can monitor nodes in a dynamic, visual, and real-time manner. They can also diagnose and locate faults on the real-time monitoring data and historical data obtained.

With the above modeling, the twin layer will become the key to truly simulating and predicting the actual operation. Therefore, the integrated simulations and validation of the testing process of node function and service performance are continued to predict potential node service defects. For those defects, the corresponding parameters can be modified in the digital twins. On that basis, simulation of the service, functional, and performance testing process of the nodes is repeated until the problems are solved. As a result, the main purpose of employing the digital twin technology is achieved.

In addition, while the digital twin application described above focuses more on "reading" node data, the adoption of digital twin technology, in fact, will be a huge help in "writing" in node control and management. For target nodes of active control, control commands can be delivered to physical nodes via the twin layer for remote management and control. For example, a physical node can run various services. At some point of time when it needs to handover the service type, the control terminal can deliver a control command to the twin layer for simulations. If the indicators conform to the original setting, the twin layer will synchronize the services to the physical node so that the node can run those services. The twin layer will also collect data from the physical node for further analysis and improvement.

The above content describes the example architecture of the DT-driven Internet of Everything control system. In fact, the combination of digital twin technology and the Internet of Everything will enable a large number of applications. For example, it will be easier for mobile operators to authenticate and manage devices accessing their mobile networks, exercise prioritized control on devices influencing mobile network stability or occupying too many resources, and ease the resource usage threshold on specially approved devices with high requirements. The introduction of digital twin will bring convenience to both users and managers. As a result, users can conveniently and perfectly deploy services, whereas managers can quickly authenticate node users and perform coordination and planning.

4.2.3. UE Twin

The past few years have seen tremendous changes in the network and communication industry. The growth of mobile users has become almost saturated, only playing a minor role in driving operator performance. However, with people growing increasingly reliant on the mobile Internet, a wide range of mobile services have appeared and numerous emerging applications, such as 360° panoramic videos, virtual reality (VR), augmented reality (AR), are being commercialized at speed. The demand for data computing quantity posed by those services continues to increase. A growing number of applications in vertical industries also require lots of computing and processing workloads. Internet-powered real-time computing with high transmission reliability is necessary for autonomous driving, industrial control, and other applications. In this sense, future mobile services will put more emphasis on the needs of users and services, offering a brand new user experience. Mobile interactive gaming with huge data volume, 3D, AR/VR, hologram images, and other new mobile service applications have been incorporated into the technical requirements on future mobile communication systems.

The network requirements of new services will become more differentiated, diverse, and highly dynamic, which means that the network in the future will be a highly dynamic complex network compatible with various types of user requirements. This network will be a completely heterogeneous, large-scale network able to support the huge connectivity necessary for connecting everything in the Internet of Things and the ubiquitous wireless big data applications.

However, the UEs carrying those emerging services are not large-scale computers and therefore are not capable of processing a large volume of data. At the same time, the traditional communication network alone cannot meet the bandwidth and latency requirements posed by the large data volume. Against this backdrop, the introduction of computing, including popular research topics in recent years, such as edge computing, service cache, and network operator, can address these problems better. Digital twins can ease the pressure on UEs due to emerging services. If applied in such scenarios, it will substantially improve the situation faced by future mobile services.

Taking the example of C-RAN architecture[19], this section discusses the application values of digital twins in addressing the above problems.

As noted, the technical framework of digital twin is an architecture containing three layers of abstraction: physical entity layer, digital twin layer, and application layer. Mobile phones and other UEs are on the physical entity layer. The application layer will be faced with insufficient computing power on the entity layer when deploying actual applications. This problem can be better addressed if the architecture is driven by a digital twin. As shown in Figure 15, after the introduction of digital twin, a digital twin layer will be put above UEs—a twin that may be deployed on the mobile edge cloud. That is, each UE accessing the network will have a twin on the edge cloud. Data on physical UEs and their twins will affect each other. That means a faulty physical UE can be corrected by correcting the twin data on the edge cloud and that validation in the twin can be done by correcting data on the physical device. For services with higher requirements on bandwidth and latency, a twin can substantially ease the computing pressure on the physical device. It relies on the powerful computing power of the edge cloud to complete required computing tasks and transmit them to the operator. This prevents the downlink bandwidth pressure due to data flowing to the UE and the higher latency due to insufficient UE computing power.

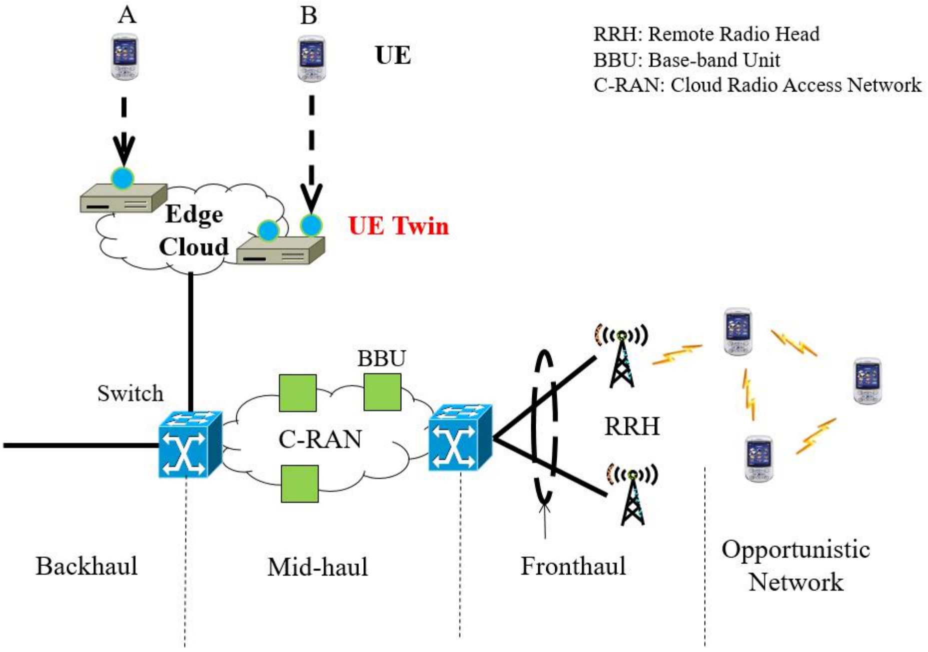

Figure 15 C-RAN-Based UE Digital Twin

Take a smart UE for commercial application for example. The mobile edge cloud in an operator network can generate a twin for the UE to synchronize the computing requests with a large data volume in real time. When the user accesses VR or another computing service with a large data volume, the twin will receive the data from the UE. With the powerful computing power of the server that hosts the twin, data is computed at speed and then returned to the UE to ensure service reliability and low latency of big data computing. In such a system framework, UEs do not need to possess strong computing power or influence the mobile, portable user experience like bulky computers. Instead, they satisfy the ever-changing service requirements by handing complicated computing over to UE twins and focusing on network communication.

In addition, applying UE twin technology enabled by digital twin in the future network architecture will not occupy excessive operator resources. A mobile edge cloud often has the twins of multiple mobile UEs using limited computing resources at the same time. However, once a UE is offline, the cloud recovers the information about the UE and stores it by encapsulation so that the twin will no longer occupy system resources. When the UE registers to access the network again, the cloud restores the information recovered previously. When multiple UEs are simultaneously online, computing requests with large data volumes are uploaded in a time-sharing manner to satisfy the needs of all UEs as far as possible. If multiple UEs are online and initiating computing requests with large volumes of data simultaneously, the algorithm should be further optimized. Using a proper communication and computing resource allocation algorithm on the cloud can address the allocation problem of network communication, computing, and caching resources, improving the service experience for users.

UE twin is an implementation form of edge computing and possesses some advantages of digital twin technology.

In edge computing technology, conventional task offloading is generally implemented by a cloud carrying and computing certain tasks on UEs. However, for new services emerging in an endless stream, no convenient way can be adopted to ensure and validate the implementation result on UEs, leading to poor service experience for users, despite the capability of the cloud to carry large-scale computing. Based on digital twin technology, UE twin technology builds the twins of physical UEs on the mobile edge cloud. It emphasizes that the system, software, and other information on the twins are the same as those on the UEs (realized through virtualization and software-defined technologies) so that all types of data can be fully synchronized between the two sides. UEs can upload various types of data information (without specifying any service) and model policies trained for certain services can be validated and optimized on the twins and then delivered to UEs (without being requested by the UEs), ensuring service implementation results on the UEs.

In addition, UE twins based on digital twin technology reach a balance between real-time capability and separability. Real-time capability means that a twin interacts with the physical UE in real time for real-time exchange of services and data. Separability means that a twin can even operate independently without the physical UE. During the time separation, less communication bandwidth and other resources are consumed. It is also ensured that, within a period after separation, the consistency of key indicators between the twin and the physical UE satisfies the degree of precision required for services (which is realized by deep learning and other AI approaches). Later, the twin can interact with the physical UE to compare and synchronize data. The advantage of the latter is what conventional task offloading does not have. UE twins will provide technical support for emergency scenarios where service quality should be ensured despite the short supply of communication resources.

Compared with traditional edge computing, UE twins can offer customized computing services without scheduling by complex algorithms, substantially reducing the latency of computing service provision. As noted, UE twins can simulate and predict the transmission environment and requirements of actual users with its built-in

AI, thereby optimizing and tuning the policies accordingly.

While UE twin exploration will be meaningful, few studies have been conducted on the actual application of UE virtualization, in contrast to the extensive research on future network virtualization applications.

In addition, for the edge cloud, the digital twin can also be converged with other technologies to bring more applications and benefits. For example, it can be combined with federated learning and blockchain technologies. Regarding bandwidth, latency, and other constraints, digital twin technology can be introduced for modeling optimization and algorithms to reduce the edge connection latency in the next-generation operator networks. This will further optimize the positive influence of the introduction of twins on network architecture. Digital twin technology combined with deep reinforcement learning can be introduced to serve as a bridge between the entity layer and the application layer to seek algorithms to reduce the average offloading latency, the offloading failure rate, and the service migration rate in edge meshes. In this way, the digital twin will help find the optimal solution for task communication and computing and even act as a digital double to improve security by preventing attacks on the actual network.

5. Development Prospect of Digital Twin

As the 6G, AI/ML, and security technology advances and become mature, digital twin, as a technology relying on sensing and control, will help build more sophisticated and effective digital models, form a digital twin society by connecting information silos, create a community with shared life for mankind[18], and enable sustainable development.

With the potential to be applied in a wide range of scenarios, the digital twin will greatly empower 6G and various sectors, such as industry, agriculture, and city, bringing unlimited possibilities and convenience to industrial manufacturing, agricultural production, urban governance, social services, and people's life. Digital twin technology will continue to evolve to meet the new objectives and requirements in building a community with shared life for mankind.

There may be new technical breakthroughs and potential standardization demand if digital twin is applied in the 6G network for purposes from providing technical support, such as twin network modeling, data acquisition, and intelligent computing, to overcoming the adverse influences (higher cost and greater energy consumption) of large-scale data collection and transmission.

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Abbreviations

AIOps	Algorithmic IT Operations
AV	Autonomous Vehicle
BaaS	Backend as a Service
CAPEX	Capital Expenditure
CIM	Computer Integrated Manufacturing
DT	Digital Twin
FaaS	Function as a Service
IDN	Intent-driven Network
ITS	Intelligent Transportation System
KPI	Key Performance Indicator
NE	Network Element
NFVI	Network Functions Virtualization
NFV-MANO	Network Functions Virtualization Management and Orchestration

MEC	Mobile Edge Computing
O&M	Operation and Maintenance
OPEX	Operating Expense
QoE	Quality of Experience
QoS	Quality of Service
SON	Self-Organizing Network
NGMN	Next Generation Mobile Networks
VR	Virtual reality
AR	Augmented Reality