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A Digital Twin Network Approach for 6G Wireless Network Autonomy White Paper

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China Mobile Research Institute (CMRI)

Contents

Preface

At present, all walks of life are using the advanced cloud platform technologies and network connection services to digitalize and automate the transformation of service to improve the service agility and the flexibility. In the field of mobile communications, although operators have been exploring, researching and deploying applications in automation of network management and service provision for many years, however, it cannot solve the problems of high network energy consumption, complex multi-standard interoperation, high operational cost and low efficiency. At the same time, as the network evolves in the direction of programmable, software-driven, service-oriented architectures, the complexity and scale of network operation and maintenance (OAM) have reached an unprecedented height. The introduction of new services and technologies also puts forward more stringent requirements for the agility of network operations, and operators urgently need a more comprehensive, intelligent, scalable and affordable network automated OAM system.

The automation of network OAM has different granularity, which can be the automation of task, function or process, or the automation of network and service life cycle management. At present, the level of 5G network OAM automation of is low, most of which rely on program-solidified expert rules and automatic scheduling flows. In some scenarios, the 5G network OAM still need to rely on manual operations. Network OAM automation based on intelligent means is still "fragmented" and "plug-in". "Fragmented" refers to a use-case driven approach to achieve a higher degree of automation and less manual intervention for certain functions, for example, base station self-starting in SON, neighborhood relationship self-optimization, PCI self-optimization, MRO, etc. "Plug-in" refers to the collection and summary of relevant data to the network management or related platform for training, and the model is sent to the corresponding network element to generate the intelligence required for OAM. This "chimney-type" automated system and R&D model can enhance the automation level of network management to a certain extent under the existing network structure, but due to the limitations of the existing network structure, the difficulty of ensuring the validity and real-time nature of data, and the difficulty of interoperability and sharing of data between different vendors, , the efficiency of network automation is low and the effect is difficult to meet expectations.

In the future, the 6G network will construct a brand-new automated network OAM system through the network digital twin, and realize the high-level "autonomy" of the whole network life cycle. The digital twin network is a network system consisting of physical network entities and their twin digital networks that can be mapped in real time. The digital twin entity of the network is the dynamic modeling or mirror copy in digital space of the real network entity. The digital domain generates perceptual and cognitive intelligence through rich historical and real-time data as well as advanced algorithmic models. It can continuously optimize and simulate the optimal state of physical networks, issue the corresponding OAM operations in advance, correct the physical network automatically, and solve the network element or network fault in advance to achieve the effect of "cure future disease". Then it can form a closed loop through the collection of corrected data to evaluate the operation and maintenance results. Through this closed-loop interaction between digital and physical domains, cognitive intelligence, and automatic OAM operations, networks can quickly recognize and adapt to complex and dynamic environments, and realize the "autonomy" of planning, building, maintaining, optimizing and curing the whole life cycle of the network.

China Mobile's "Digital Twin Network (DTN) White Paper", released in September by 2021, sets out the concept and definition of "Digital Twin Network (DTN)", and gives the reference architecture of DTN, key enabling technologies, the capability classification system and typical application scenarios [1]. On the basis of this, this paper further researches and explores the digital twin network for 6G wireless network autonomy, introduces the related basic concepts of 6G wireless network autonomy, clarifies the technical features, designs the network architecture, plans the key technology system, and illustrates the whole lifecycle autonomy of 6G wireless networks based on digital twin networks through specific case studies. Finally, the key technical problems which need to be further studied and solved are put forward.

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1. Current Situation and Vision of Network Operation and Maintenance Optimization of Operators

The 5G network has greatly improved the communication quality, but the endless new network services and the continuously expanding network scale have brought many challenges to the OAM and optimization of the 5G network, and the complexity of the network OAM has been increasing. The deployment of innovative technologies is also becoming more difficult.

In the traditional 2C scenario, there are some problems, such as high terminal power consumption, limited energy-saving effect of the current network, low proportion of 5G terminals on-off, low ratio of 5G shunting and resident, and complex optimization and maintenance of the adjacent areas of the system. In the 2B scenario, the base station equipment product library planned to industry private network is not perfect, and it cannot satisfy the changes of coverage and scenarios flexibly. At the same time, the 2B service exclusive maintenance system is not perfect, and network maintenance staff skills cannot meet the cross-layer and cross-domain maintenance capacity needs. In addition, the construction cost of the private network is high, and the 2B service application scenarios are quite different. Scenarios with large uplink and large downlink rate classes, low delay control classes, and high reliability requirements will lead to higher networking cost. The terminal problems can also affect service stability.

With the development of cloud computing and virtualization technology, the traditional network has begun to shift to software and programmable, showing the new characteristics such as cloudification of resources, on-demand design of services, orchestration of resources, etc. , which makes network management and OAM more complex. Due to the lack of an effective simulation, prediction and verification platform, it is difficult to shift from the existing scheduled maintenance to the predictive OAM. And network optimization operations have to be directly applied to the current network infrastructure, which leads to high cost and risk of network optimization. On the other hand, due to the high reliability requirement, it is difficult for the network operators to use the current network environment directly for the research of network innovation technology. The R&D cycle of new network technologies is long and the deployment is difficult.

Facing the future, the mode of network communication, the type of service carried, the objects served by the network and the type of equipment connected to the network will present a more diversified development trend, which makes the network highly dynamic and complex, and requires the network to be more flexible, scalable and responsive to requirements, becoming an autonomous network with self-optimization, self-evolution and self-growth capabilities. The self-optimization network predicts the trend of the future network state in advance, intervenes the possible performance deterioration in advance, continuously optimizes and verifies the optimal state of the physical network in the digital domain, and issues the corresponding OAM operations in advance to correct the physical network automatically. The self-evolution network analyze and make decisions on the evolution path of network architecture and functions based on artificial intelligence, including the optimization and enhancement of current network elements and the design, implementation, verification and implementation of new elements. The self-growth network identifies and forecasts different service requirements, automatically arranges and deploys various domain network functions, generates end-to-end service flows to meet the service requirements, automatically expands the capacity of the sites that are short of capacity, and performs automatic planning, hardware self-on, software self-loading operations for areas that do not covered by the network.

2. Self-Intelligence Network Signposts and Inspiration

With the development of 5G era, many new industries and scenarios will emerge, new applications will be deployed, and new network technologies will be introduced and expanded in the future. How to implement the OAM of the increasingly complex large-scale network efficiently and continuously introduce new technology rapidly and iteratively is a common problem for the industry. Facing the communication network with the largest number of customers in the world, the richest services and the largest network, China Mobile network OAM is accelerating the transformation and upgrading of digital intelligence, strivingto build a cloud-network integrated, highly automated and intelligent network system, and consolidating the foundation for digital and intelligent transformation in all walks of life[2]. China Mobile has released “China Mobile Automated Driving Network White Paper” in 2021, which defines the scenario classification standard for processes, enhances the level of network OAM autonomy in a step by step and iterative manner. The paper provides inspirations and thought for realizing 5G and even the 6G network autonomy.

2.1 Signposts

The "self-intelligence network" requires the automation and intelligentization of the "network". It combines the intelligentization and automation technologies such as AI with networks to achieve the network predictability and operational autonomy, aiming to construct the automatic and intelligent OAM ability of the whole life cycle of communication network.

The self-intelligence network hierarchical framework divides the network autonomy capability into six levels of L0 ~ L5. The self-intelligence network hierarchy from L0 to L5means different network characteristics and capabilities. At the same time, based on the guiding principle of the framework of TM Forum self-intelligence network, and combined with the actual needs of network OAM and management evaluation, the characteristics of each level of network autonomy capability are described from the angle of guiding the implementation of the IT system. The correspondence and evolutionary path [2] of network autonomy capability and its characteristics are shown in the following figure:

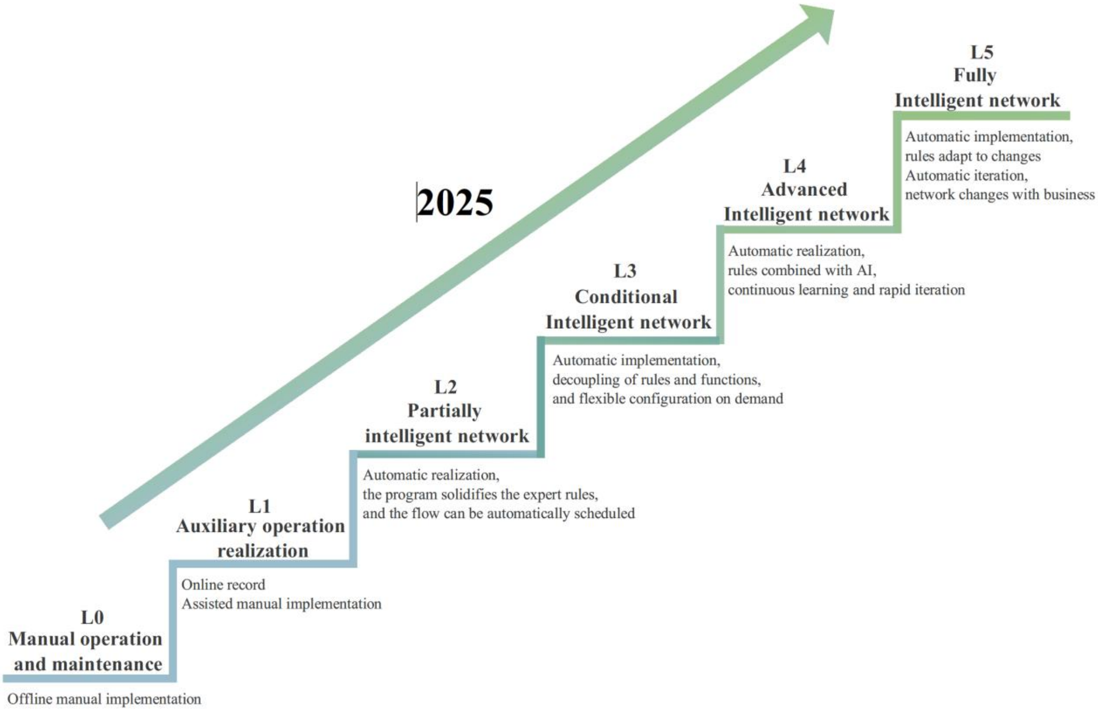

Fig. 2.1-1. Self-intelligence network classification and evolution path

In line with the concept of self-intelligence network, China Mobile plans the digitalization and intellectualization transformation of network OAM, strengthens the construction of automation and intelligentization capacity, and sets the overall goal of reaching L4 in 2025 at the level of network OAM autonomy. L4 means that the network is highly intelligent, can complete the intelligent workflow of automatic perception, analysis, decision and making execution for the target scene, and can form a complete automatic closed-loop process without human intervention. Among them, the ability of automatic perception makes the whole process of data collection, processing, association, sharing, storage and management automatic to realize high efficiency and standardization of data management. Theautomatic analysis ability is to realize the intelligent analysis and modeling of the network, to improve the generalization and generality of the model. The automatic decision-making and execution ability is to have certain credible evaluation and autonomous decision-making ability, and allow the algorithms to evaluate the quality of decisions independently and execute them automatically in the network, so as to realize the security and credibility of the algorithm. The network can provide rich platform-level, distributed computing service, support the automation of information management and control and process interaction on the interface, have a certain intentional interface capability, and automatically generate rules or policies according to user intent requirements.

The goal of 6G network is to realize L5 level self-intelligence network. L5 means that the whole process of the network is intelligent, the network has the full intention management ability, there is no need to set service rules artificially, and it can customize strategy according to the intelligence of service scenario and automatically iterately evolve, so as to truly realize that the network changes with the business. L5 level self-intelligence network aims to provide fully automatic, zero-wait, zero-touch, zero-failure innovative network services and ICT services to consumers and vertical industry customers, and build a communication network with self-service, self-repairing, self-optimization, self-healing capabilities.

2.2 Challenges

Through the practice of 5G self-intelligence network, we find that different from other simple systems, the mobile communication system has the characteristics of "high systematization, high complexity, high dynamicity and high reliability", which brings many challenges to data acquisition, algorithm development and application deployment.

In the data aspect, the current network data is closed, and it is difficult to obtain the depth data within the network element. In the current network system, whether it is the 2/3/4G network or the newly built 5G network, the distinction between the data used for network element self-optimization and network O&M management, the functional coupling relationship between the network elements and the network management equipment and the system architecture have not changed substantially. The type richness and statistical precision of the internal data of the network element are much better than the data reported to the southbound network management by the network element, which in turn is better than the data that can be obtained by the northbound network management equipment of the operator. However, due to the consideration of the privacy of the device, the consumption of the device processing resources and the transmission resources, a large amount of data within the network elements is not open to the operators, and it is only used for the algorithm R&D of interfaces within the network element and between network elements of the same manufacturer. As a result, operators cannot get a complete, real-time and precision perception of the real state of the network, and the management and control of the network can only be supported by the surface statistical data of various longer periods. At the same time, there are some problems of poor data quality in the available data, such as partial data missing, unbalanced sample set and lack of data annotation, etc. . Due to the limited data storage resources, most of the data stored in the network are half-year historical data with poor timeliness.

In the aspect of algorithm, due to the high dynamic of the network environment, the distribution of the original data of network characteristics also shows a high dynamic. It’s often not true in real networks that the precondition used by academia for algorithmic innovation, "independent and distributed data". Modeling based on "non-independent same distribution" and "non-independent different distribution" data is a common problem to be solved in the industry, which needs to be abstracted into scientific problems and make full use of network knowledge. On the other hand, due to the "high reliability guarantee" of the mobile communication system, the algorithm and the network autonomous decision made by it must be "safe" and "credible" to interface with the current network operations system. At present, only after the algorithm is put on line or the decision is executed, the network performance can be judged by the network performance statistical indices, which has the risk of network performance deterioration. In order to guarantee the "credibility" of the algorithm, it is necessary to break through the interpretability of the algorithm. Although there has been some research and breakthrough in the academic world, there is no systematic and automatic solution to solve the "black box" of the nonlinear model represented by the deep neural network. The selection of simple models with better structural interpretability may result in performance loss. Finally, there are a lot of repetitive development and optimization in the algorithms for different network autonomous scenarios. The centrally deployed AI open platform can reduce the R&D cost of algorithms to a certain extent, but it still cannot solve the "chimney" model of R&D. The algorithm cannot be reused and migrated efficiently among nodes, regions and autonomous environments.

In the aspect of application deployment, the network autonomous scenario of mobile communication network is multitudinous and complex, most applications need to concatenate many production links, and the correlation analysis between the links mainly depends on the human operator. In the field of network OAM alone, 11 types of scenarios, 37 core competencies and more than 1300 sub-processes are sorted out, and the analysis work is time-consuming and labor-consuming. At the same time, the R&D mode of many AI applications is still the high-cost and low-efficiency "chimney" mode. The algorithm is deployed on the server connected to the network management equipment or network element equipment, which displays "plug-in" mode. The generation, deployment, evaluation and iterative optimization of intelligence in network autonomous scenario rely heavily on manual work, which affects the improvement of network autonomous level.

2.3 Inspirations

Towards the goal of achieving level L4 self-intelligence networks by 2025 and full level L5 self-intelligence networks in the future, the network needs to achieve a deep openness of data in terms of perceptual automation, and realize the automation of the whole process of data acquisition, data Processing, data association, data sharing, data storage and data management. In the aspect of analysis and decision automation, the network needs to support the trusted and interpretable framework of the algorithm, and needs to support autonomous decision-making without human intervention. In the aspect of application execution, the network must be able to realize the self-generation of autonomous scenarios and autonomous targets, and support the intelligentization of the whole process of the targets and scenarios. In the aspect of network architecture, it should have complete autonomous closed loop, platform-level and distributed computing power. The network needs to support the management information and process interaction needed to perform automation on the interface, and has the ability of purposive interface. There are four key technology needs to be highlighted:

1. Deep data openness

As mentioned above, a large amount of data within the network element is not currently open to the operators, which leads to the operators’ inability to achieve a comprehensive, real-time and sophisticated perception of the true state of the network. Operators' control of the network can only stay within the scope supported by various long-term statistical data at the surface level, and cannot achieve a high level of autonomy, which has become the primary problem to be solved for 6G network autonomy.

Considering the privacy protection of the equipment supplier, it is not a feasible solution to directly expose all the data inside the equipment. So what data will be further opened? How is it open to operators? It should not only protect the internal privacy inside the device, but also represent the state of the network element to meet the needs of the network autonomous scenario. In this regard, in addition to the new standardized data types, we also need to think about more cost-effective acceptable technical solutions.

2. Data value increases

At present, although a large amount of data can be obtained by means of soft and hard mining, road surveying, MDT, MR, and network management data extraction, there are problems such as poor data quality, low value density, low acquisition efficiency and poor timeliness, which not only waste a lot of network storage and transmission resources, but also cannot support the generation of network intelligence. How to make the data exactly match the requirements of the network autonomous scenario in every phase of the whole life cycle, such as collection, processing, storage, knowledge transformation and application, so as to avoid the waste of resources and increase the value density of data. It is the key problem to be solved in the process of 6G network autonomy.

In order to achieve the above goal, 6G network needs to enhance the ability of data analysis and value mining, to accurately perceive massive heterogeneous data, to actively push and collect dynamic data on demand, and to avoid data redundancy. We can use the AI technology to mine data value, and improve the response speed of data service by cloud-edge-end distributed storage and strategy optimization of different value data. Through model training and knowledge reasoning, scenario dynamic adaptation is carried out to realize the intelligent orchestration invocation of the data services and the intelligent adjustment of the configuration parameters.

3. Autonomous requirements generation

At present, the method of discovering problems artificially and solving them by AI is always limited by the limitation of artificial cognition, and the intelligentization ability and potential of network cannot be maximized. At the same time, relying on manual stovepipe problem-solving methods often produces conflicting results between different network operations optimization use cases, for example, the improvement of the coverage performance of a cell results in the increase of the disturbance and the decrease of the service experience index, which leads to the reciprocating and inefficient optimization work. 6G-oriented, more abundant network scenarios will have different requirements for network architecture, functions and services, and the configuration-based approach will not be able to meet and adapt them to the maximum. Facing the unknown new industry and new demand in the future, it is even more unrealistic to manually discover and summarize the need for network autonomy. All of the above show that 6G network needs the technical means of auto-sensing and auto-excavating network autonomous demand, auto-generating and auto-dispatching network autonomous use cases, so as to avoid the conflict between use cases, and ensure the best effect of overlay implementation, minimize human involvement.

4. Low cost trial and optimizing

In order to avoid negative impact on network performance and user's service experience, the OAM optimization decisions in current networks are usually evaluated and validated by experts or tested for a long time before implementation. The introduction of a new feature, for example, typically requires lab performance testing, field performance testing, and on-line FOA testing before upgrading current network equipment for up to a year. On the other hand, the effect of decision after implementation can only be known through statistical or road test related network performance indicators, and the iterative optimization cycle is long, the cost is high. To achieve the goal of complete self-intelligence for 6G networks, the network needs to have the ability of automatic evaluation, high-efficiency closed-loop, agile iteration, so it needs low-cost trial and error and high-efficiency optimization technology.

3. 6G Network Autonomy Based on Network Digital Twin

After years of development, the digital twin technology is becoming more and more perfect, and it is becoming the new grasp of national digital transformation, the new direction of multinational enterprise business layout and the new focus of global information technology development. The digital twin technology provides a new idea and solution for the research of the 6G network. By constructing the digital twin network, 6G can realize the autonomous network with self-optimization, self-evolution and self-growth capabilities, to meet the aforementioned key technical requirements. The 6G wireless network autonomous system based on the digital twin network needs to introduce new concepts, design new network architectures and construct corresponding key technology systems.

3.1 Basic Concepts

"Digital twin" is defined by professor Grieves. It consists of three parts: physical objects, virtual objects, and the flow of information between physical objects and virtual objects. Subsequently, the term "Digital Twin" was formally introduced in a NASA technical report and defined as "a system or aircraft simulation process that integrates multiple physical quantities, scales, and probabilities". In recent years, with the continuous development of the digital twin technology, its application in aerospace, intelligent manufacturing, smart city and other fields has been relatively mature. Digital twin is becoming a new focus of national digital transformation, a new direction of business layout of multinational enterprises, and a new focus of global information technology development [5].

Although the definition and connotation of the digital twin technology have not been agreed between academic and industrial circles, there is a preliminary consensus on its typical characteristics. The first characteristic is bi-directional precise mapping, which means that the digital twin technology can realize the full presentation, accurate expression and dynamic monitoring of physical objects in twin contents. The second characteristic is real-time, which requires a full real-time connection between physical objects and twin contents. The twin contents are the representation of the physical objects which changes with the time axis, and the mapping of the real-time states of the physical objects. The third characteristic is extensibility. The digital twin technology has the capabilities to integrate, add and replace digital models and can be extended for multi-scale, multi-physical quantity, multi-level model content. The forth characteristic is whole life cycle. The digital twin technology can run through the entire product life cycle, including design, development, manufacturing, service, maintenance and even scrap recycling.

3.1.1 Digital Twin Network

The digital twin technology provides a new idea and solution for realizing 6G network autonomy, which is constructing the digital twin network by digital twin of network itself. Digital Twin Network is a real-time interactive mapping network system which is composed of physical network entities and their twin digital networks. The twin digital network elements of the physical network elements can be constructed by means of data acquisition and simulation, and then the digital twin contents of the network elements and the digital twin content of the network are formed in the digital domain. In this system, various network management and applications can use the digital twin contents of the network to analyze, diagnose, simulate and control the physical network efficiently based on data and models.

As the digital mirror image of the physical network facilities, the digital twin content of the network has the same network elements, topology and data as the physical network, which can realize the fine "replication" of the whole process of the network and equipment. It provides a digital verification environment close to the real network for optimizing operation and policy adjustment of network OAM. Therefore, compared with the traditional simulation platform, the AI model and the pre-verification result of the network-based digital twin content have higher reliability. On the other hand, the digital twin network also records and manages the behavior of the digital twin content of the network, supports its tracing and playback, and thus can complete the pre-verification without affecting the network operation, greatly reduces the cost of trial and error. In addition, the digital twin network has the capability to build and expand itself, and can be combined with AI technology to explore new service requirements that have not yet been deployed to the current network and verify their effectiveness in the digital twin network, thus realize the network self-evolution.

China Mobile's "Digital Twin Network (DTN) White Paper" [1] puts forward the overall structure of "three layers, three domains and double closed loops". On this basis, this paper proposes that resource objects in digital twin networks will have "three contents" and "five states" for 6G wireless network autonomy, and the digital twin network can be continuously optimized through the "double closed loops". The complete logical architecture design is shown in the following figure:

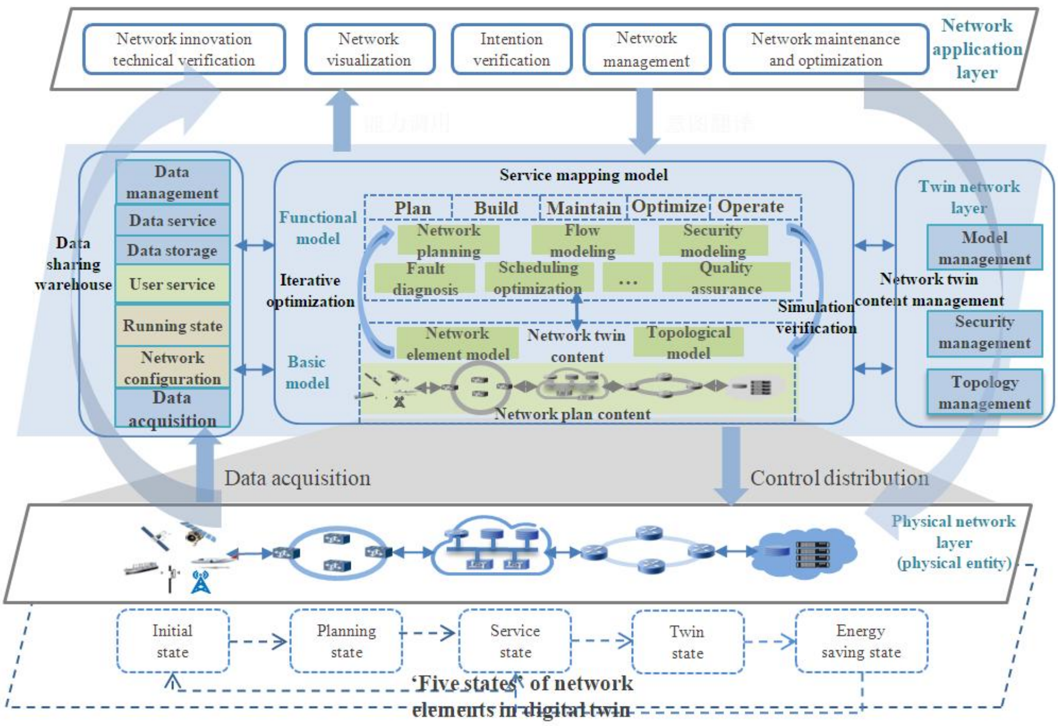

Fig. 3.1.1-1. "three layers, three domains and double closed loops" architecture for Digital Twin Networks

Note: The network twin content refers to the digital twin content of the network, and network plan content refers to the digital plan content of the network

3.1.2 Three Contents

6G wireless network autonomy objects can theoretically be a variety of granular network resources, such as functions, services, base stations, chips, boards, spectrum, power, and so on, which depend on the specific network autonomy scenario. These resource objects will have three contents in the digital twin network: the physical entity, the digital twin content and the digital plan content.

The physical entity is the physical object itself. For hardware, it is the form of hardware itself, such as base station boards, antennas, chips, etc. For software, it is the carrier of software, such as mirror files, various forms of software code, etc.

The digital twin content is the digital object twinned by physical objects. For example, twinning the network element generates the digital twin content of the network element, and twinning the network generates the digital twin content of the network. By collecting multi-dimensional measurement data on physical entities, and modeling physical processes of physical entities, we construct images of physical entities in the digital domain. In the digital twin network, the digital twin content is synchronized with the physical entity state. Considering the complexity and cost, the digital twin content does not need to reproduce the physical entity 100% in an all-round way, but selects the state attributes and processes to be tracked for modeling according to the requirements of the network autonomous scenario.

The digital plan content is a digital model which is generated by the network after planning the expected state of the physical object at some time in the future. It represents the optimization of physical objects for the future. The network adjusts the physical entity according to the data in the digital plan content, which makes it approach the goal of network autonomy. The digital plan content may include adjustable configuration parameters of physical entities, loadable software functions, optimized connection relationships, and so on.

The physical entity and the digital twin content of the object are commonly mentioned in the digital twin technology, while the digital plan content is a new concept based on the characteristics of network autonomy. The digital plan content represents the decision-making content and results of the digital domain in the network autonomous scenarios, which is the aim of keeping the digital twin content in synchronization with the physical object, and reflects the level of decision-making intelligence of the digital twin network. It is an important link in the network autonomous closed loop. Currently, the construction of digital twin systems in various industries is mainly concerned with the real-time and accuracy of synchronization between physical objects and their digital twin contents in the upward direction, while in the downward direction, the delay, accuracy and performance jitter of the digital plan content implemented into the physical object also directly affect the effect of network autonomy. The relation of "three contents" is that the digital twin content is the mapping of the physical entity state. According to the digital twin content and related data, the network generates the digital plan content, and optimizes the physical entity according to the digital plan content. The following diagram shows the relationship between the three contents:

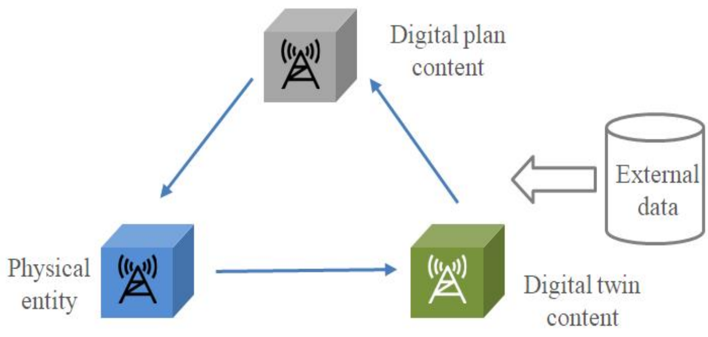

Fig. 3.1.2-1. The relationship of "three contents" in the digital twin network

3.1.3 Five states

Different from the separate plan, construction, maintenance and optimization stages in the current network, 6G network will realize high-level autonomy in the whole life cycle through digital twin, that is, all states of network equipment from delivery to withdrawal are managed in the digital twin network. In order to distinguish the different relationships and technical requirements between devices at different stages of the life cycle and the twin digital network, and in order to be compatible with current network devices that do not support digital twin, this white paper proposes five states of the design scheme: the initial state, planning state, service state, twin state and energy-saving state.

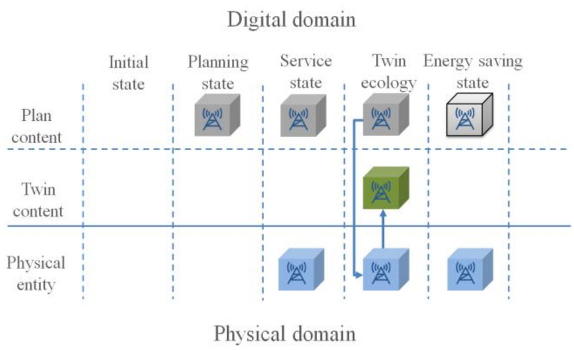

Fig. 3.1.3-1. The relationship between the "three contents" and the "five-states"

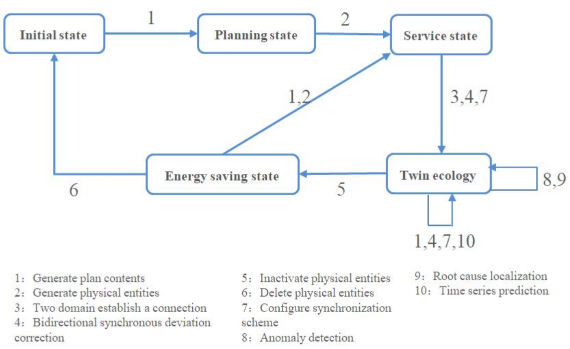

Figure 3.1.3-2. The transformation between the five states

The initial state is the state in which the resource object has not entered the network or has been removed from the network. The object does not exist in the digital domain or physical domain of the digital twin network. At this point, the object may exist in the product library as an inventory resource for network operations, or it may be removed from the network as a backup resource to make up for lost time. If the object has ever run on the network, its corresponding historical run data is preserved.

The planning state means that the object only exists in the plan of digital twin network, that is, the digital twin network has planned the digital plan content of the object, but the physical object has not entered the network or is disconnected from the network due to the fault. The digital plan content may include deployment location, specification parameter value, parameter value, physical property value, connection relation and so on. Physical objects are initially configured according to a digital plan content after network initiation.

The service state is the state that an object enters after it has started the network and is initially configured according to the digital plan content. With the initial configuration data obtained, the object can run normally on the network and provide services. In this state, if the digital twin network needs to plan the object continuously, the object will enter the "twin state", otherwise (if the computing resource is limited, or the object is a static object) will stay in the "service state", the plan content is no longer continuously updated, and objects run in the network based on the most recent plan configuration data.

The twin state. The object has a digital twin and a digital plan in the digital twin network. The physical object is kept in sync with the digital twin content, and is continuously optimized and adjusted according to the latest digital plan content. In this state, the digital twin content and digital plan content are connected with physical objects for continuous optimization.

Energy-saving state. The object exists in the network, but its digital plan content is empty and there is no digital twin content. When certain resource objects are not needed in the planning scheme of the digital twin network, they can be turned off to save energy. For hardware modules, shutting down an object is equivalent to a power-off operation, and for software entities, shutting down an object is equivalent to de-instantiating. When the object reappears in the planning scheme in the future, it will enter the "planning state".

From this, it can be seen that the planning state is a transitional state, and the objects temporarily in the planning state will be transferred to the service state, or the twin state or the energy-saving state after being connected to the network, and the equipment on the network will mainly switch between these three states. For devices that do not support digital twin, they will switch between the service state and the energy-saving state. For devices that support digital twin, when they are in the twin state, the technical requirements for the interaction between physical objects and twin digital objects are the most. The correspondence between "three contents" and "five states" is shown in Table 3.1.3-1.

Table 3.1.3-1. The relationship between three contents and five states

Three contents \ Five states	Initial state	Planning state	Service state	Twin state	Energy-saving state
Digital plan content	No	Yes	Yes, static	Yes, dynamic	No
Digital twin content	No	No	No	Yes, dynamic	No
Physical entity	No	No	Yes	Yes	Yes

Note: For the digital plan content and the digital twin content, the mark "No" means no current digital plan contents or digital twin contents, but there may be historical digital plan contents or digital twin contents.

3.1.4 Double closed loops

In order to achieve the 6G high-level network autonomy, the network should have complete autonomous closed loops in architecture, as well as platform-level and distributed computing power in order to realize hierarchical and muti-domain multi-level closed loop autonomy. The autonomous closed loop mentioned in standardization and industry organizations generally includes four links: observation, analysis, decision-making and implementation. In the digital twin network, the digital twin content synchronizes the physical network state to realize "observation", the digital plan content corresponds to the "decision" result, and the physical entity is the "execution" object. For the "analysis" part, because the digital twin network has the digital network environment with high fidelity, it can verify the decision-making effect and provide the possibility for closed-loop optimization of decision-making in the digital domain, and makes the "analysis" itself a closed-loop process. Therefore, the autonomous closed loop of digital twin networks is "double closed loops".

The inner closed loop is the process of simulation verification and iterative optimization for the generation of the digital plan content. Digital twin networks contain all kinds of functions or components needed for network life cycle autonomy, such as all kinds of plan, simulation tools, intelligent models needed for iterative optimization, etc.. The ultimate goal is to make the next time plan of the network based on the digital twin content in advance, that is, to generate the digital plan content of the network. The problem solved by the inner closed loop is how to generate the theoretically better digital plan content in the digital domain for the next time network state.

The outer closed loop means that after the digital plan content is sent to the physical network, the new state of the physical network is synchronized to the digital twin body, and the digital twin network evaluates the effect of network autonomy in the digital domain. According to the gap between the inner closed-loop and the goal, the function and parameter of the inner closed-loop are analyzed and optimized, so that the inner closed-loop can generate more effective digital plan content, thus approaching the goal of network autonomy. Due to various technical factors, the realization of the goal of network autonomy cannot be achieved by only one planning process. The problem solved by the outer closed loop is the inevitable deviation between the twin digital network and the physical network caused by technical factors. For example, due to the errors introduced by data acquisition and transmission technology, the digital twin content of the network are not consistent with the real state of the network. Due to the insufficient type of collected data and the suboptimal prediction algorithm, the prediction of the network state at the next moment is inaccurate. Due to the insufficient accuracy of the simulation technology, the implementation effect of the planned configuration or new features is not verified, etc.

3.2 Technical Features

Section 2.3 summarizes the key technology requirements for high-level autonomy of 6G networks based on the 5G self-intelligence network practice, which includes deep data openness, data value density increase, autonomous demand self-generation, and low-cost trial and error optimization. To meet these technical requirements, this white paper presents four technical characteristics of digital twin networks:

1. The models in digital twin networks can be divided into data class models, simulation class models and intelligent class models. Both standardized and non-standard models coexist.

The model in the digital twin network can be used in every link of double closed loops. The model of the digital twin content and the digital plan content is the frame structure of them. The model of digital twin content is combined with real-time data to generate digital twin contents. The digital twin network plans the related contents according to the model of the digital plan content, and generates the digital plan content. A data class model is a set of data attributes that are dependent on data collection and represent the network history and current state, and is mainly used to track the dynamic changes of network states. In order to support the deep openness of data, we need to develop more comprehensive data class model standard according to the specific requirements of network autonomous scenarios. Considering the difference of vendor implementation, non-standard data class models can be used in combination with standard data class models if they can bring performance gain. On the other hand, the digital twin content generated only by the data class models cannot carry out the trial-and-error and optimization of new features or decision-making actions effectively. The simulation class model that can simulate the physical process and function of the network is also needed, and the intelligent class model of the input-output mapping relationship should be established. The three can be selected or combined according to the demand. For the simulation class models, the digital twin content of the real physical process or function of the network can be generated by extracting the latest value of the configuration data from the data class models. For the intelligent class models, based on the training samples extracted from the data class models, the mapping relation among the network elements can also be used as the function digital twin. The three models need to provide a standardized interface to achieve model interconnection and replacement. The implementation of the models can be diverse.

2. Self-generation and self-analysis of network autonomy requirements can realize the data twin content and the digital plan content which are customized and dynamically generated.

In order to support the full self-intelligence network, the digital twin network can analyze and predict the network state continuously based on the digital twin content of the network, automatically discover the network governance requirements and scenarios, and generate network autonomous use cases. The digital twin network can be automatically resolved into the corresponding network autonomous use cases for the upper-level intention input by the operator. The digital twin network can quickly locate the root cause and implement the cure plan for the fault and alarm. All these depend on the accurate description of network states and data relationship by the digital twin content of the network. In order to guarantee the performance and reduce the cost of data acquisition and transmission, the digital twin content and the digital plan content of the network should be on-demand customized and dynamically generated. Among them, on-demand customization refers to the selection of model classes (data class models, simulation class models, intelligent class models) of digital twin contents and digital plan contents according to the requirements of network autonomous scenarios and use cases, the construction of the model of digital twin content and digital plan contents, the parameters configuration of digital twin contents and digital plan contents, and the maximization of data volume and frequency of virtual real synchronization.. Dynamic generation means that the models and contents of network digital twin contents and digital plan contents can be dynamically increased or decreased according to the changes of the network, and dynamically adjusted according to the frequency of virtual and real synchronization., The contents can be the data attributes contained in the data class model, the structure of the intelligent model, etc. All of these require digital twin networks with native intelligence to accurately identify high-value data and models in different autonomous scenarios and network environments.

3. Digital Twin content and digital plan content model based on parallel delivery and real-time data acquisition can automatically build and expand of digital twin contents and digital plan contents of networks.

In order to support the whole life cycle autonomy of the network, the management of digital twin contents and digital plan contents of the network should be synchronized with the physical network automatically without human participation. The equipment supplier develops the digital models (digital twin content and digital plan content models) of the product simultaneously at the design and development stage. The model is used to adjust and optimize the product offline until the product meets the delivery standard. The equipment supplier delivers a digital model of the product to the operator along with the physical entity of the product. When the product is deployed in the network, the digital twin network will automatically acquire the digital model of the product, expand the digital twin content of the existing network according to the topological connection relation, then generate its digital twin content through data collection, and generate the digital plan content though digital domain optimization. In the parallel delivery digital model, the standardized model part can be obtained by the digital twin network, while the non-standardized model part may still be hidden inside the product. Therefore, it is necessary to establish the mapping relationship between the non-standard model and the standard model.

4. Design the simulation scenarios automatically. Orchestrate the simulation workflow on demand. Optimize the simulation performance.

In order to make the network have the ability of automatic pre-evaluation of effects, efficient closed-loop and agile iteration, the digital twin network should be able to design simulation scenarios automatically, orchestrate simulation workflows automatically and evaluate and optimize simulation performance. Simulation scenarios refers to the network and service scenarios, user distribution, effect impact objects, network performance indicators and so on, which need to be verified under specific network autonomy scenarios and use cases.. Due to the cost of simulation and verification, digital twin networks need to resolve the network scenarios, verification indicators and simulation performance requirement of simulation pre-verification according to the target of autonomous scenarios, and construct the required simulation scenarios, orchestrate the workflow of each scenario, manage the resources required for simulation validation, evaluate and optimize simulation performance (E. G. simulation accuracy, simulation time) on demand.

Figure 3.2-1 illustrates the digital twin network, the digital twin content of the network, the digital plan content of the network, the double closed loops, the relationship among the models, and the corresponding positions of the four technical features. The number in the circle represents the technical feature number.

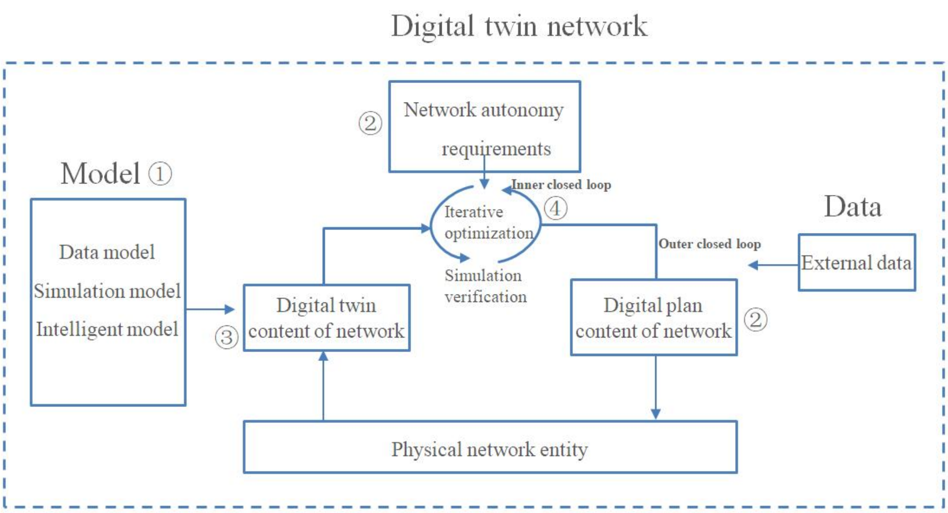

Fig. 3.2-1. The relationship between the basic concepts of the digital twin network

3.3 Network Architecture

Compared with 5G, 6G has the new digital twin network of the native intelligence plane, the data plane and virtual-real interaction, and realizes a high level of autonomy in the whole life cycle of 6G network through the interaction and fusion of native intelligence and the digital twin network.

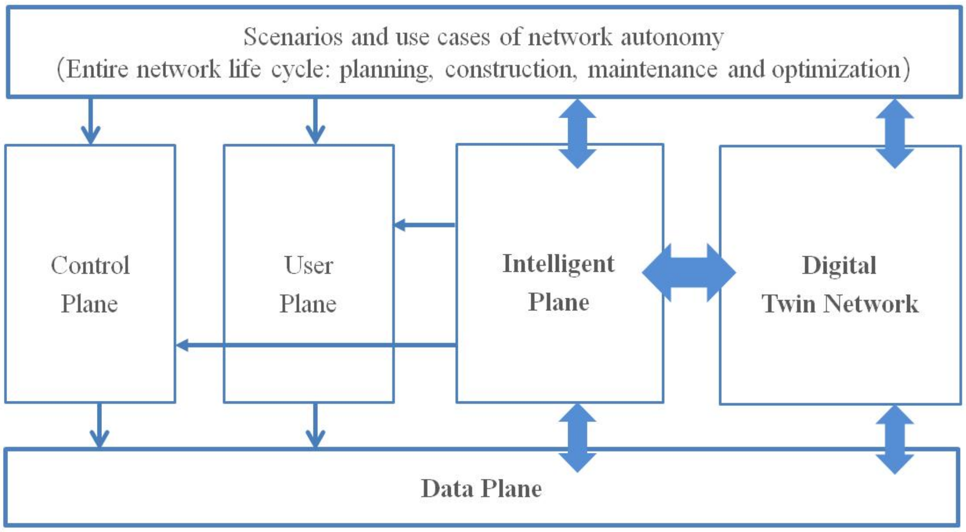

Fig. 3.3-1. The schematic diagram of the 6G digital twin network, the intelligence plane and the data plane

3.3.1 End to End Architecture

The 6G digital twin network will present a hierarchical cross-domain architecture that combines centralized and distributed architectures. The digital twin content, the digital plan content and the basic functions of digital twin in local domain are used to support the network autonomy in the local domain. The end-to-end digital twin platform stores the end-to-end network-level digital twin contents, digital plan contents and basic functions of digital twin built based on the digital twin contents of each domain to support the end-to-end network-level autonomy requirements. The multi-layer, cross-domain, closed-loop autonomy architecture facilitates the generation of digital twin contents and digital plan contents on demand nearby, eases the pressure on the data acquisition and transmission, protects the equipment internal data privacy, and timely supports network autonomous requirements within the scope of different scale, and takes into account the real-time nature of network element twins and the end-to-end integrity of cross-domain twins. The architecture can support optimization of various applications and services based on digital twin contents at the edge of the network, as well as end-to-end global service optimization. At the same time, it is also easy to integrate with other architectures (such as the 6G native AI network architecture [6]). As can be seen from Figure 3.3.1-1, the digital twin content, the digital plan content and basic functions of the digital twin content constitute an end-to-end digital network system.

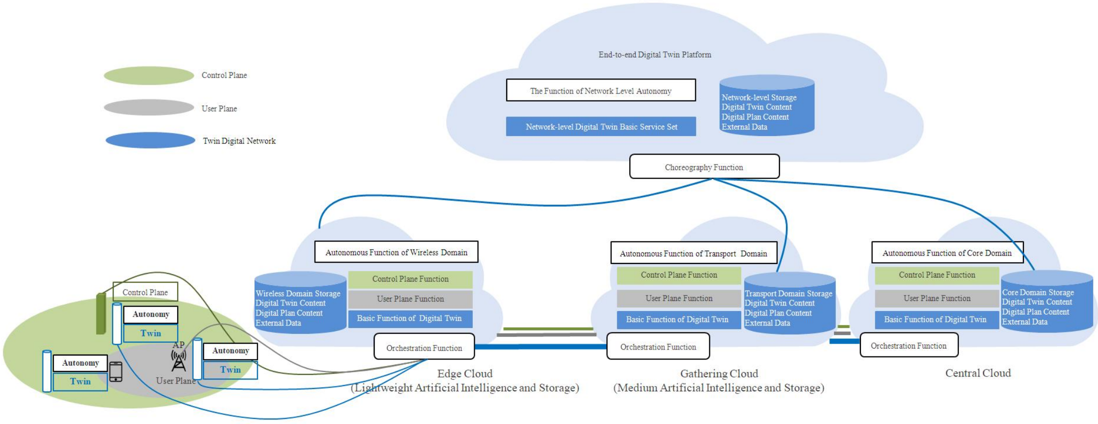

Fig. 3.3.1-1. The end-to-end architecture diagram of the twin digital network

In order to support the main technical characteristics of the digital twin network, the design of basic functions of digital twin and its influence on network architectures are analyzed as follows:

1. Generate and analyze network autonomy requirements: the network itself discovers the requirements for plan, construction, maintenance and optimization by analyzing the upper-layer intention and network status. For non-real-time network autonomous use cases, this function can be implemented on the management side. Control plane support is needed for autonomous use cases with high real-time requirements.
2. Construct, arrange and adjust digital twin content and digital plan content models: select model types, construct model structures, orchestrate and combine models according to the requirements of autonomous scenarios. For more static autonomous scenarios, model construction can be implemented on the management side. For highly dynamic autonomous scenarios, the model may need to be adjusted quickly according to the changes of network states, so the support of the control plane is needed. To reduce resource overhead, high-value data and models in different autonomous scenarios and network states need to be identified and adjusted online.
3. Generate and update network digital twin content: combining real-time data acquisition and model generation and updating network digital twin contents. Because digital twin contents need to track the state changes of the real network, it has high requirements for real-time and accuracy of data acquisition and synchronization in autonomous scenarios with strong dynamics, and needs the support of control plane. To reduce resource overhead, it is necessary to identify high-value data in different autonomous scenarios and network states and adjust data collection and synchronization policies online.
4. Generate and implement the digital plan content of the network: based on the goal of network autonomy and the digital twin content of the network, through iterative

optimization algorithms and effect verification, generate the digital plan content with better regional performance and implement it into the physical network. For autonomous use cases implemented on the management side, the real-time requirements of this function are not strong. The cases can be achieved by trying multiple optimization algorithms and carrying out sufficient modeling and simulation. For autonomous use cases implemented on the control plane, they need the support of high real-time technology.

To sum up, the digital twin network will flexibly choose appropriate architecture, construct, orchestrate and adjust various models, and generate, update and implement digital twin content and digital plan content according to the performance requirements of network autonomous scenarios. In this process, the digital twin network will strongly depend on the high performance data and intelligence capability. The current chimney-type data collection means and plug-in intelligent provision methods can no longer support them. Systematic, native data and intelligent capability systems in 6G networks are required, that is, the addition of "data planes" and "smart planes" is necessary.

3.3.2 Data Plane

Considering the data challenge in network self-intelligence practice and the demand of digital twin networks for high-performance data services, 6G will add "data plane" to the network architecture [7]. Data elements in the data plane will cover the internal and external data of the network, including service data, user data, network data, perception data, external data, resource layer data, etc. Basic data services include data acquisition, data preprocessing, data storage, data access, data sharing and coordination, etc. Basic data service has the following technical characteristics: support of reliable authentication, authorization, access, efficient data storage and management, dynamic data acquisition on demand, data pre-processing and aggregation, ability to open to foreign trade and injection, etc. Figure 3.3.2-1 shows the logical functional architecture of the 6G network data plane.

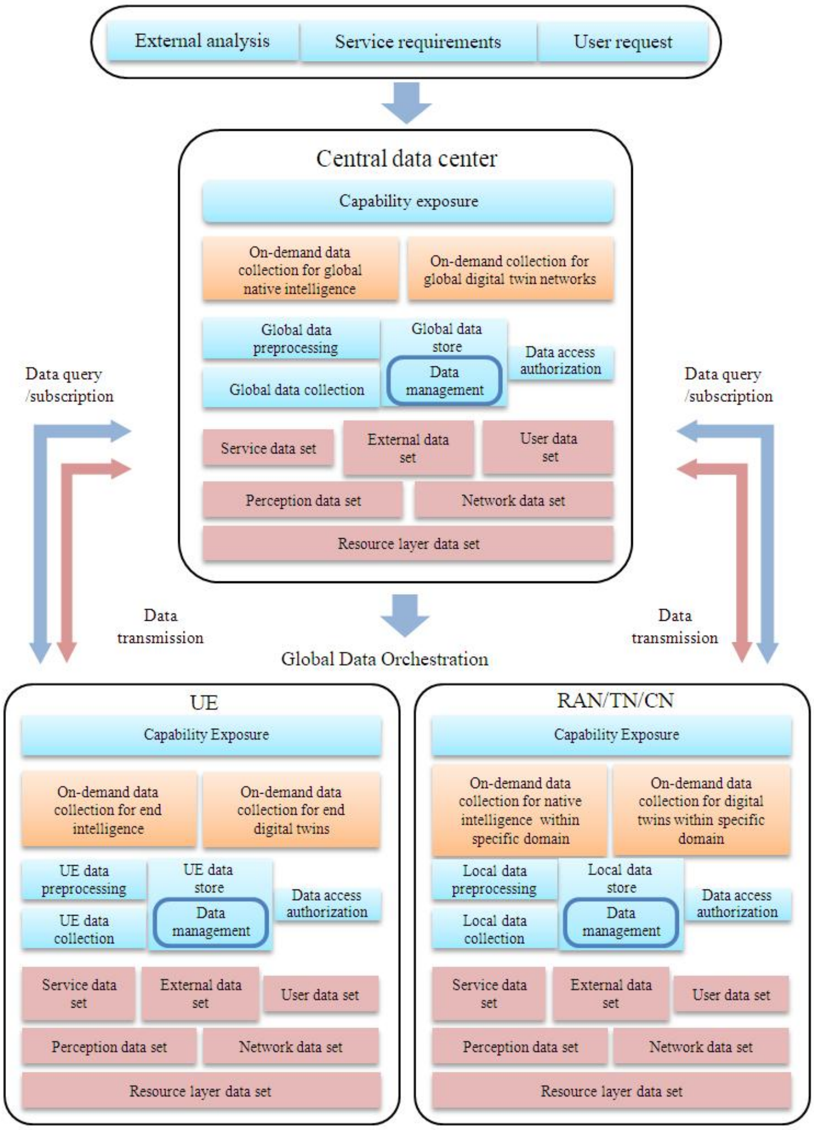

Fig. 3.3.2-1. The schematic diagram of 6G new data plane functional architecture

The 6G digital twin network invokes data plane infrastructure services to generate, store, access, and transport its digital twin contents, digital plan contents, and various models. In order to realize the digital twin content and the digital plan content of on-demand and dynamically generated network, the data plane needs to be combined with the new intelligence plane of 6G network [7]. The close combination of AI and data services will promote the evolution of data service capabilities in data collection, processing, storage, knowledge transformation, application and other aspects to form self-growth data services. Through the combination of AI and data services, AI provides network awareness and intelligent strategies/algorithms for data collection, processing and flow, and provides knowledge association for data applications. The self-growth data service has the following characteristics: accurate perception of massive heterogeneous data, active push and dynamic on-demand collection, avoiding data redundancy and improving data analysis and value mining capabilities. Data value mining is carried out by AI means, and the response speed of data services is improved by cloud-edge-end distributed storage and strategy optimization for data of different values. Through model training and knowledge inference, scenario dynamic adaptation is carried out, and intelligent orchestration and adjustment of configuration parameters of data services are realized.

Data service capability can be improved from data collection, data middle processing and data application to realize self-growth of data service [8]. The digital twin content and the digital plan content of the network can be used as a kind of data application.

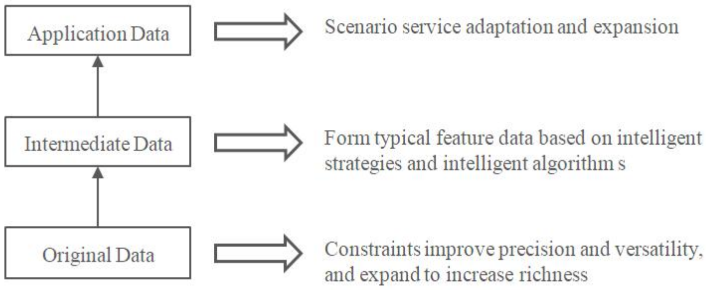

Fig. 3.3.2-2. Data service self-growth

3.3.3 Intelligent Plane

At the design stage, 6G considers deep integration with AI. Different from the AI function superposition and plug-in in 5G, 6G native AI controls and orchestrates computing power, data and models end-to-end, and supports deep integration of technologies in connection, computing, data, AI and other technologies of different fields at the architecture level. It supports on-demand orchestration of AI capabilities to wireless, transport, host, core, and cloud to provide the basic capabilities required for intelligence for high-level network autonomy and diversified service requirements. [6] proposed the intelligent plane architecture of 6G native AI.

6G network autonomy is one of the driving forces of the native AI. The demand for intelligence in digital twin networks will be obtained through the intelligent surface of 6G. The requirements includes network autonomous demand generation and resolution, iterative optimization to generate digital plan content, the generation and update of digital twin network intelligent models, the on-demand dynamic adjustment of digital twin content, digital plan content, their models, etc. These requirements will become AI use cases in the intelligent plane [8], which will be satisfied by calling various AI services of the network (including AI training, AI verification, AI reasoning and AI data). In this process, the performance requirements of network autonomy will be resolved or mapped into the quality requirements of each AI service (QoAIS), which will be satisfied through the QoAIS evaluation and guarantee mechanism of the intelligent plane. Figure 3.3.3-2 shows the functional design of the intelligent plane.

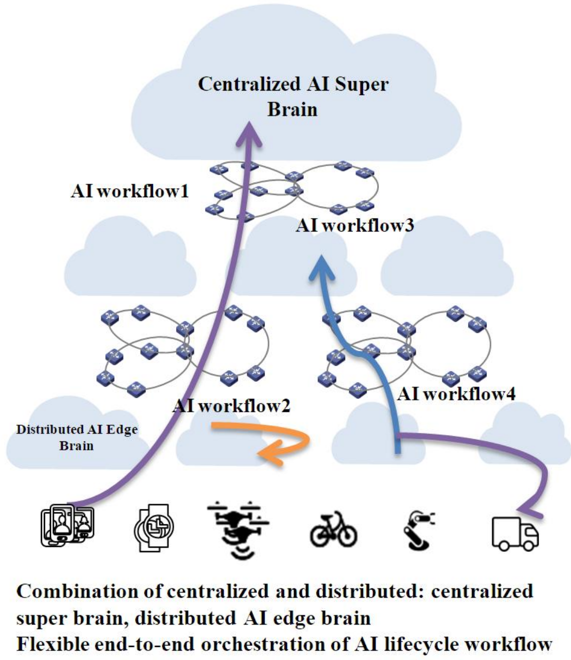

Fig. 3.3.3-1. AI lifecycle workflow orchestration

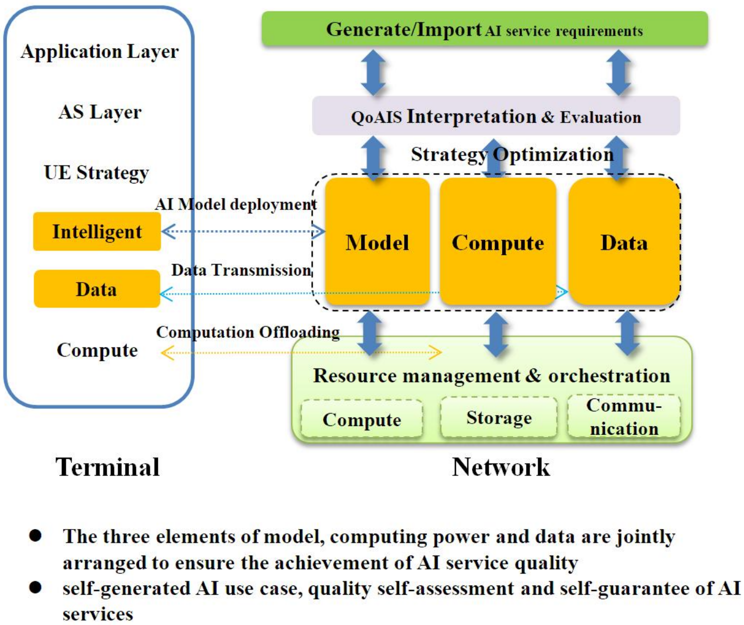

Fig. 3.3.3-2. The schematic diagram of function design of the 6G intelligent plane

3.4 Key Technologies

Based on the technical requirements of 6G network high level autonomy mentioned in 2.3, this section briefly introduces the technologies that may meet the above requirements. Facing the deep openness of data, it is necessary to carry out the research on data collection, analysis and extension. In order to improve the value density of data, the knowledge graph can be used to analyze data in a deeper level. The self-generation of autonomous requirements and low cost trial-and-error optimization can be realized by pre-validation of model performance based on reinforcement learning and simulation microservitization. In addition, in order to ensure the stability of the digital twin network, the correction technology of the digital twin network will also be introduced in this section.

3.4.1 Data Acquisition and Analysis Techniques

The construction of digital twin network is inseparable from data collection. The data collected from terminals, base stations, the core network and the network management in wireless communication network is multi-source heterogeneous data. After standardized pre-processing operations such as cleaning, classification, association and construction, heterogeneous data is highly aggregated to form a basic data warehouse. The basic data warehouse can maintain different data sources, on this basis, the data can be further analyzed, such as correlation analysis, clustering, native factor extraction and knowledge graph construction, etc., to establish a topic library oriented to specific topics/services. Based on the correlation analysis of native factors in communication network, data warehouse can provide various characteristic data sets for various intelligent network optimization application scenarios. The logical architecture of the data acquisition and analysis technology is shown in the figure.

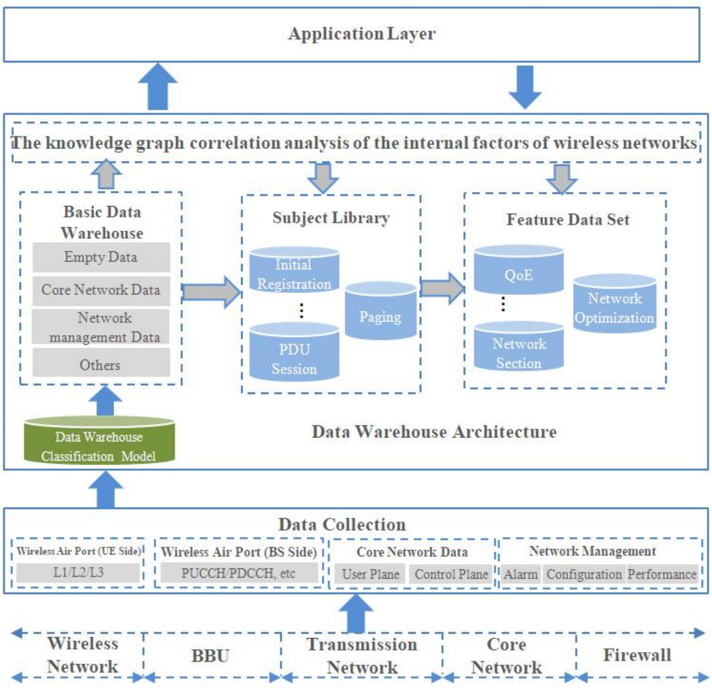

Fig. 3.4.1-1. The logical architecture of data acquisition and analysis technology in wireless communication network

The data collection technology covers multiple processes of data collection. In the current network, DPI (Deep Packet Inspection) collection technology is mainly used to complete collection, timestamp, de duplication and other functions. The obtained signaling data is parsed into bit-level data by signaling decoding technologies, and the service data is reconstructed and reshaped by DPI and DFI (Deep/Dynamic Flow Inspection). It is translated and identified for different protocols and applications. These data can be used to associate backfill and generate interface data through user information and other analysis techniques. In 6G network, more data needs to be collected to meet diversified requirements, such as, the data collection supported by new interfaces such as MANO, SDN-C, and Vswitch under SDN networking.

Data preprocessing refers to data processing, time partitioning, structured processing of unstructured data, ETL warehousing and other operations on the collected original data of wireless communication network, including associated backfilling of data, data cleaning, data conversion, data encryption and data loading.

After data acquisition, pre-processing and statistical index extraction, the basic data warehouse is obtained [9]. The basic data warehouse is the preparation area of the basic subject database. It usually tries to retain the most original and complete characteristics and attributes of data, classifies network data according to the data model, and performs full or incremental update processing on source data [10].

Data processing technology including the construction of the knowledge graph of data, the association rules analysis of data, the clustering and native factor extraction processing of data, the complete and consistent analysis of network data at the levels of subject-oriented, characterizing the various data involved in each classification and the relationship between the data, and the construction of the feature data set, for example, quality of experence (QoE) feature data set, wireless network optimization feature data set, etc.

Data warehouse also has on-demand customization function [11], which can further process data and extract characteristic data according to various communication scenarios and research needs of communication personnel based on the analysis results of the association rule analysis module in the subject library, such as quantitative representation of nodes and correlation degree between two nodes. In addition, feature data can be evaluated according to feature extraction efficiency, feature sensitivity, fit degree and other indicators to further filter the data, screen out features corresponding to specific KPIs and meet the requirements, and build customized feature data sets.

3.4.2 Data Enhancement Techniques

The digital twin network uses real wireless network status data to train the virtual scenario, and can carry on the data augmented on the real data, can be used to simulate the virtual scene of a more comprehensive, is able to provide more variety of training data, then preliminaries verification network key performance indicators or models, and can achieve better performance, more robust decision-making configuration or models.

Take large-scale MIMO weight optimization as an example. On the one hand, the weight combination space of large-scale MIMO is huge, and the number of parameters increases exponentially with the increase of base stations, which is limited by time cost and money cost. It is difficult for the real wireless network to collect all the beam pattern data samples under the combination of user distribution (such as user position information, user DOA information) and antenna weights (such as beam azimuth, dip angle, horizontal beam width, vertical beam width, etc.). On the other hand, frequent adjustment of large-scale MIMO weights may adversely affect the performance of wireless networks. Data augmentation technology can be used to combine the physical model of wireless communication with real wireless network data to augment the data of the beam pattern, and generate more virtual beam pattern scenes under user distribution, channel environment and antenna weights, which can be used to guide the intelligent weight optimization algorithm design of antennas. Based on this, the mass MIMO antenna weight configuration scheme is pre-verified and iterated to improve the timeliness and robustness of mass MIMO weight optimization.

Conditional Generative Adversarial Networks (CGAN) are one of the key technologies to achieve beam pattern expansion [12]. Generative Adversarial Networks (GAN) are often applied to computer vision and text generation by adding additional conditional information to exert some control over the generated data. Due to the generation adversarial structure of CGAN themselves, and the randomness and controllability of the input noise, CGAN have a certain application prospect in the field of communication, which is mainly reflected in two aspects: one is the virtual-real adversarial learning, which adapts dynamically to the network environment through the self-adaptive adjustment of CGAN's own structure. The second is for data augmentation, through the input noise and controllable conditions to achieve the purpose of augmenting the data set. The beam pattern expansion module based on CGAN uses the user position distribution and antenna weights as conditions to generate a module to expand the beam pattern, and at the same time, the discriminant module outputs the discriminant results of the augmented sample and the real sample. The effective and controllable data augmentation is realized through the virtual-real antagonistic learning of the generated module and discriminant module.

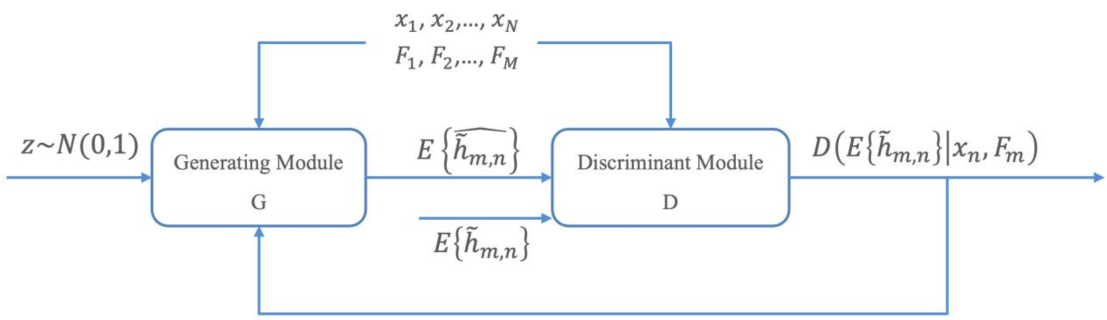

Fig. 3.4.2-1 The beam pattern extension module based on CGAN

3.4.3 Pre Verification of Data and Knowledge Collaboration Driven

At present, intelligent algorithm driven by data and knowledge synergistically is one of the research hotspots. In the field of machine learning, especially data-driven methods such as deep learning and reinforcement learning, by combining traditional theoretical knowledge with data-driven algorithms, the limitations of traditional theoretical models and data-driven algorithms can be effectively solved, such as the complex ity of traditional theoretical models and the demand for data quantities of data-driven algorithms. Therefore, in the digital twin technology, the combination of the two can be considered to reduce the data requirements of the algorithm [13]. Meanwhile, communication theory models can also be used to guide the design of reinforcement learning algorithms based on deep neural network to reduce computational complexity and improve algorithm performance. Intelligent algorithms co-driven by data and knowledge can be used in the pre-validation module of digital twin networks. As shown in Figure 3.4.3-1, in the KPI pre-verification module of large-scale MIMO antenna weight tuning, user position distribution, antenna weight scheme and corresponding beam pattern can be taken as input, and reinforcement learning based on the deep neural network can be used to estimate the parameters required in the KPI model established based on traditional theoretical knowledge (for example, unknown parameters such as signal intensity, interference intensity and noise estimated by deep neural network), and further KPI pre-validation results are obtained according to KPI models (such as Shannon channel capacity formula, etc.), and the pre-validation performance is improved through data and knowledge co-drive.

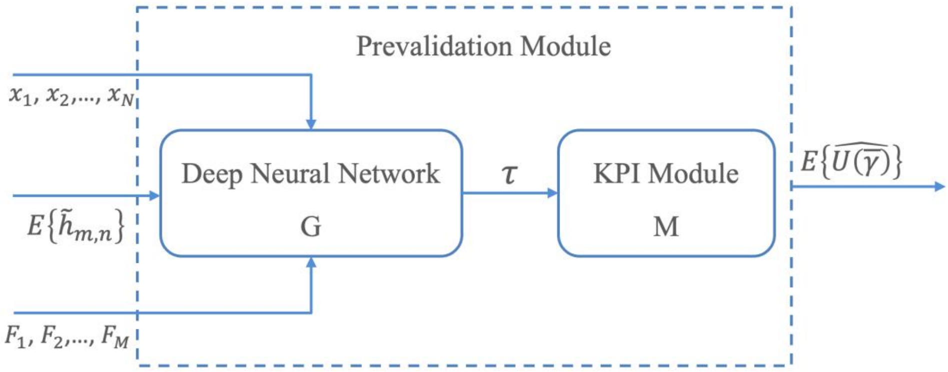

Fig. 3.4.3-1.The KPI pre-validation module

3.4.4 Knowledge Graphs and Graph Neural Networks

Digital twin network terminal nodes are characterized by densitization, dynamics, regularization of business requirements, etc. In order to effectively clarify the internal factor correlation between these changes, The development of intelligence theories such as data mining, knowledge graphs and machine learning has made it possible to collect, analyze, cluster, and analyze the correlation relationships of internal factors in massive data, which can effectively clarify the correlation relationships between these changes, so as to improve the effectiveness, versatility, and intuitiveness of digital twin networks [14,15].

For example, knowledge graphs can be used to get the correlation of native factors of wireless communication network protocol. First to build knowledge graphs, the first step need to define the mapping of the type of entity and attribute, the second step requires the definition of the relationship between different entities, the third step defines entities and relationships to write for the form of a triple (The triple is a general representation of knowledge map consisting of the two entities with the semantic connection relationships and the relationships between entities). Finally, the required knowledge graph is formed according to the obtained triples. In association rules based on the wireless communication network protocol based native factors of knowledge graphs (through the acquisition of the data fields with the internal algorithm to calculate the correlation), by defining node sparse representation of vector and find out the similarity between the node cosine similarity so as to realize the update of knowledge graph figure structure, the combination of knowledge graphs new topological structure associated with the node analysis. This method completes the calculation of the correlation degree of each node and the representation and learning of the feature vector, which provides a technical support for the deep inference and mining of the correlation between nodes. The implementation process of this method is shown in Figure 3.4.4-1.

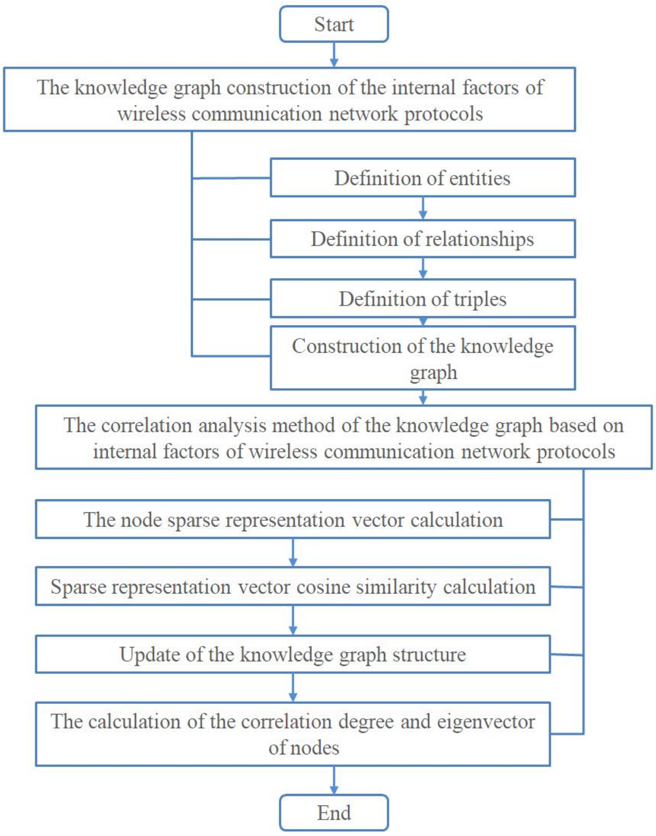

Fig. 3.4.4-1. The construction of knowledge Atlas and the flow of association analysis method

Further, if we make full use of wireless network big data and artificial intelligence to build wireless network meta-model (a pre-training model with multi-scene migration ability) and meta-algorithm (an algorithm that can guarantee performance in multi-scene and multi-task environment by applying the meta-model to different scenarios), it can also form digital twin networks with strong generalization ability that can be migrated to a variety of environments.

However, with the introduction of knowledge graphs, the deep learning method used by the digital twin network faces challenges. Traditional deep learning methods have achieved great success in feature extraction based on Euclidean spatial data. However, the data in knowledge graphs is generated from non-Euclidean spatial data, and the performance of traditional deep learning methods in processing non-Euclidean spatial data is still unsatisfactory. This is because the data nodes and topology in the knowledge graph are not regular and different data nodes are not independent. By introducing the graph neural network [16], the model can take into account the scale, heterogeneity and deep topological information of input data, which shows convincing and reliable performance in mining deep effective topological information of knowledge atlas, extracting key complex features of data and realizing rapid processing of massive data.

3.4.5 Simulation Serviceability

The current simulation platform has specialized simulation functions, and it is difficult for different models to interact with each other. Typical simulation characteristics such as simulation modeling, resource scheduling and system management are not supported enough, so it is difficult to serve as an efficient pre-verification environment for digital twin networks [17]. For the 6G-oriented digital twin network, it is necessary to increase the research on the service of simulation platforms, and form a complete set of service simulation support platforms for cross-domain collaboration.

The 6G-oriented digital twin network simulation should have the following capabilities: (1) On-demand service organization: During the operation of the platform, it can refer to the specific requirements and provide corresponding simulation support, without human interaction, so as to realize the self-configuration function of SON autonomous network. (2) Universal network access: Design a lightweight communication mechanism, such as Restful API, to allow cross-end access of all kinds of networks and devices. (3) Resource pool construction: Standardized methods and processes are used to integrate various resources into a resource pool to serve multiple users. Different physical and virtual resources can be dynamically allocated and reallocated according to user requirements. (4) Service linkage: different simulation components can be linked according to needs and combined to form standardized interfaces and more diverse standards of services. (5) Improved reusability: Through the micro-service mechanism, well-defined service interfaces are utilized to provide more precise services in smaller modules, thus facilitating interface reuse.

Current research on micro-service simulation architecture [18] indicates that the modeling and simulation architecture based on micro-service can provide a series of flexible and pluggable micro-service simulation technology components, and each micro-service component realizes a small and highly reusable function, which can be assembled and linked flexibly on demand for different scenarios. Simulation tools and simulation scheduling platforms are deployed in the cloud. Users can submit and manage simulation tasks through the cloud application platform, and quickly obtain flexible, reliable and secure simulation services. The architecture can be divided into five layers, with the application portal layer as the input design, the application service layer as the business provision, the data exchange layer as the resource schedule, the resource layer as the model encapsulation, and the physical network layer as the basic support, forming a functional closed loop of micro-service simulation [19]. Using container virtualization technology and distributed system architectures as the infrastructure base, "cloud migration" of the existing simulation platform is realized based on the principle of DevOps. Through the linkage of simulation components of microservices, the communication between three contents and the transformation between the five states of the resource objects in the digital twin network are realized.

3.4.6 Correction techniques for pre-verification results

In the long-term operation of the digital twin network, there may be errors in data acquisition and transmission, big difference between predicted data and real data, difference between twin environment and real environment, etc. These will make the difference between the decision-making and the expected decision-making of the digital twin network, and even have a negative impact on the real network. These differences may arise from each link of the digital twin network, such as data acquisition, state prediction, decision-making generation, pre-verification of decision-making effect, etc. The differences in these modules can be corrected separately. For example, the training data of the state prediction module is updated online to correct the deviation of the prediction model, or to correct the deviation of the module which directly affects the final decision of the twin network layer, that is, the decision effect pre-verification module.

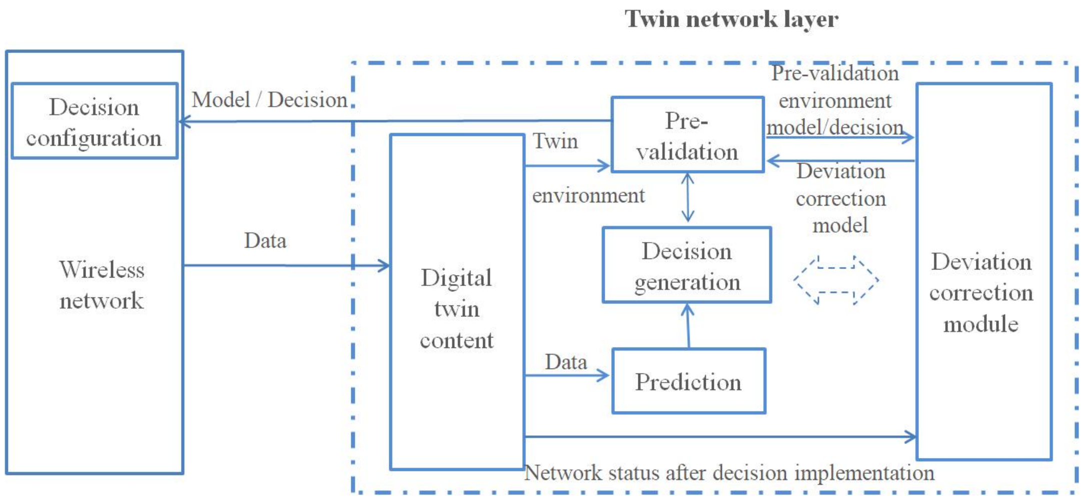

Fig 3.4.6-1. The decision pre-verification result rectification process

In the large-scale antenna beam weight optimization scenario, the correction module can be designed to correct or optimize the pre-verification result of the decision-making effect. When the weight of the antenna beam in the decision is assigned to the physical network, the network state will be updated and synchronized to the digital twin content, that is, the network state after the decision is implemented, which is reported by the digital twin content to the correction module in the twin network layer. At the same time, the correction module collects the information of pre-verification environment (including base station parameters, building parameters, user location, etc.) and the decision of weight configuration d. Then according to these data, the correction model of RSRP pre-verification performance r is generated to correct the r, so that it is more in line with the real effect of the wireless network after the weight configuration decision is implemented. The twin network layer can evaluate multiple candidate weight allocation decisions based on the performance of pre-verification, and can further determine the cause of pre-verification performance bias, such as data acquisition and transmission error, state prediction error, network digital twin simulation error. The specific calculation method [13] is as follows:

Denote d_{t+1} as expert weight allocation decision for storing history of the deviation correction module, $\hat{r}_{d_{t+1}}$ as RSRP performance of the expert decision, u_{t+1} as reinforcement learning algorithm weight allocation decision, $\hat{r}_{u_{t+1}}$ as RSRP performance of the algorithm, $\hat{s}_{t+1}$ as prediction of the next user distribution state, $\overline{s}_{t+1}$ as state of the real user distribution at the next moment of the acquisition, $best(d_{t+1},u_{t+1})$ as the optimal weight configuration, and r_{t+1} as the real RSRP of this weight decision. For example, through a neural network algorithm, a model that obtains corrected pre-validation results is trained with historical state-decision-pre-validation result pair and state-decision-network performance pair. With the input of states, decision and prediction performance, we can get the pre-verification performance after correcting deviation:

Pre-verification performance of expert decision making:

$$\hat{r}_{d_{t+1}}^{DT} = f(\hat{s}_{t+1}, d_{t+1}, \hat{r}_{d_{t+1}}, \overline{s}_{t+1})$$

Pre-verification performance of the reinforcement learning algorithm decision making:

$$\hat{r}_{u_{t+1}}^{DT} = f(\hat{s}_{t+1}, u_{t+1}, \hat{r}_{u_{t+1}}, \overline{s}_{t+1})$$

3.5 Whole life cycle autonomy of network

Network life cycle generally includes plan, construction, maintenance and optimization stages. The current network autonomy level is low, and the network life cycle of each stage is separated from each other. More work needs to be done manually offline. Resource and time cost are high, and OPEX is high as well. 6G will take over the whole life cycle of the network through the digital twin network. Based on the "three contents", "five states" and "double closed loops", the technical proposals in each stage is optimized and verified on-line , forming a high level of closed-loop autonomy and greatly reducing human consumption. In the digital twin network, the life cycle of the network will go through three stages: "continuous planning", "virtual-real docking" and "fault self-healing".

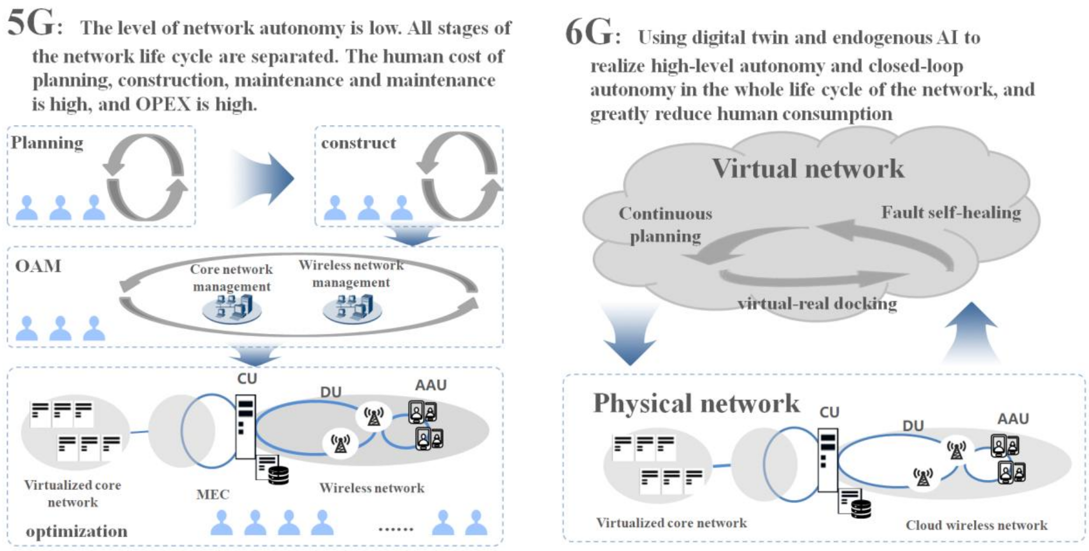

Fig 3.5-1. The comparison between 5G network OAM management and 6G digital twin network autonomy

3.5.1 Continuous planning

In the digital twin network, the digital domain is constantly synchronizing the current state of the network, predicting the future state of the network, and planning the parameters (digital plan content) of the network in advance for the next moment. Therefore, the traditional network planning and optimization work will be realized by the "generating digital plan content" in the digital twin network, which is divided into "generating long-term digital plan content" and "generating short-term digital plan content" according to the time scale. For example, when the coverage, capacity and service requirements change, based on wireless resources and equipment capabilities, the design of network or site solutions (including regional network planning, blind site planning, heating site planning, site expansion) belongs to the generating digital plan content. In order to make the network performance indicators meet the predetermined requirements (such as coverage, capacity, mobility, access, user experience, load, PCI, ANR, energy saving and other indicators), the optimization of parameter configuration and software upgrade performed belong to the generating short-term digital plan content. The following diagram illustrates a common process framework for the digital plan content generated by digital twin networks:

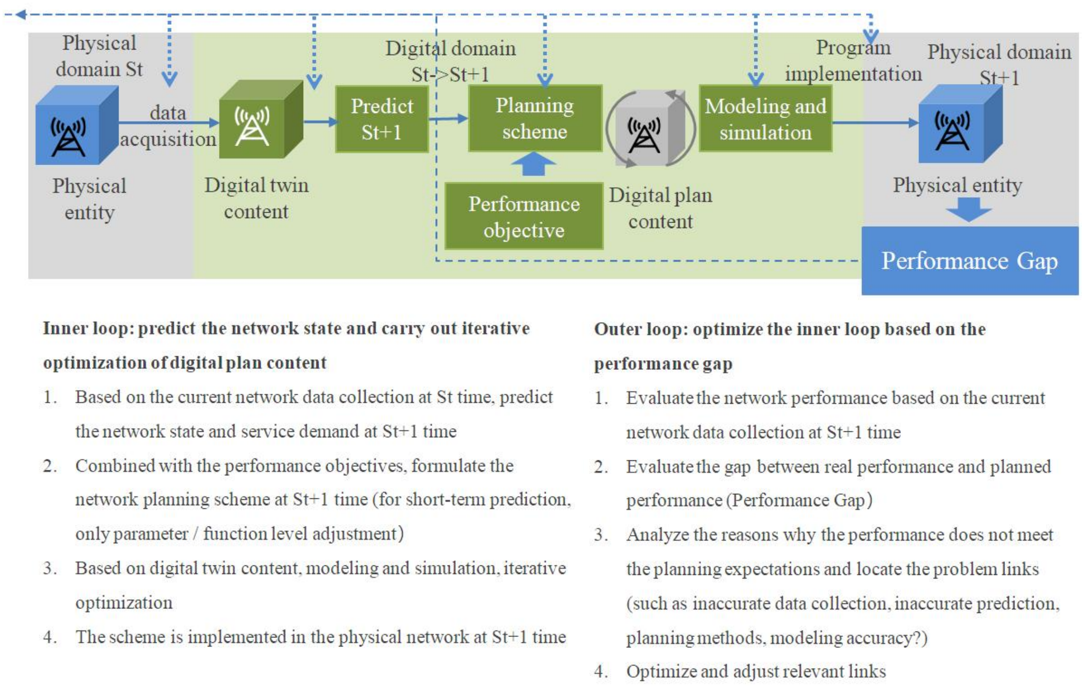

Fig 3.5.1-1. The process for the digital plan content generated by digital twin networks.

3.5.2 Virtual and real connection

The network construction stage mainly depends on the manpower, and the network automation ability mainly manifests in the equipment self-start aspect. Take the base station equipment as an example, the base station self-start makes the base station or the hardware module enter the normal working state on the planning site. Except for manual installation and power-up, all other processes are automated, including self-activation (software, configurations, licenses), self-check, self-authentication, self-configuration, and so on. The existing network already supports the self- check, self-authentication, self-activation processes. In the 6G digital twin network, the physical entity and the digital domain docking should be completed in this process, the self-configuration of basic software and wireless parameters should be completed by connecting the pre-generated "digital plan content", and a two-way synchronous connection should be established to construct the digital plan content and digital twin content, complete the transformation from "planning state" to "service state" or "twin state". The following diagram illustrates process of virtual-real docking in a 6G digital twin network:

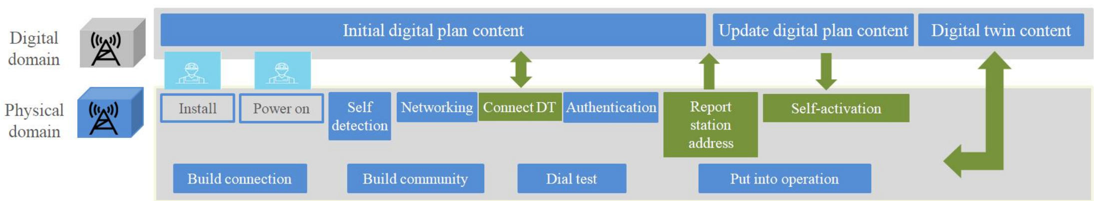

Fig 3.5.2-1. The virtual-real connection process in the 6G digital twin network

3.5.3 Combination of prevention and cure

Through the continuous planning of the digital twin network, the risk of some network performance deterioration can be avoided, and some potential faults can be cured ahead of time. However, some of the types of faults caused by external emergencies, such as cell retreatment, link failure, equipment power failure, etc., cannot be avoided and can only be repaired after the fact. Therefore, in the self-healing aspect, the digital twin network requires both active prevention and passive remediation. On the other hand, due to the low probability of network failure, it is very difficult to obtain fault samples in current networks, and the effectiveness of self-healing schemes is difficult to verify. Digital twin networks have the capability to generate virtual network scenarios and pre-verify the effects, which can help to solve the traditional problems of few failure samples and difficult to verify the effectiveness of solutions.

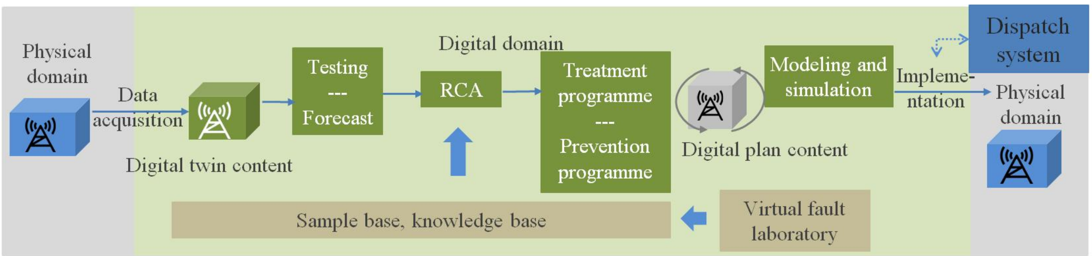

Fig 3.5.3-1. The fault self-healing process of the 6G digital twin network

In addition to continuously optimization of the network digital plan content in the fault scenarios to achieve self-healing goals through "double closed loops", the digital twin network will also build a knowledge base for fault identification and self-healing through the "virtual fault laboratory". Real fault knowledge is generated by collecting the digital twin content and the digital plan content under the real fault scenarios. Implement cures, collect samples, and generate virtual fault knowledge by artificially creating faults on twin digital networks. At the same time, the expert experience of OAM personnel needs to be combined to provide sufficient information for fault detection, prediction, root cause location, prevention and treatment.

3.6 Case description

This section will illustrate the concepts, characteristics, architectures and technologies of the digital twin network in real-world application scenarios though three network optimization examples, as well as the potential performance advantages of these cases based on digital twin network.

3.6.1 Optimization of beam weight for large-scale antennas

In order to meet the challenges of more flexible beam configuration, more accurate user requirements and more complex optimization scenarios, 5G wireless networks need to intelligently optimize the beam weights of large-scale antennas and generate custom beams for scenarios according to geographical features and user distribution. At present, there are many kinds of heuristic optimization methods, such as genetic algorithms, particle swarm algorithms, moth algorithms and so on, but the existing simulation techniques can only evaluate part of the performance of these technical solutions, such as RSRP at the downlink receiver. It is impossible to simulate and evaluate more indicators, so it is impossible to fully pre-verify the performance of the technical solution and accurately evaluate the effect of the beam configuration scheme applied in the current network. The resulting decisions may affect network performance.

The intelligent antenna weight optimization technology based on network digital twin combines the physical model of wireless communication with the real wireless network data to build the digital twin content of the network, and integrates the expert experience as the guarantee of the weight decision. The performance of the decision is pre-verified to further ensure the performance of the decision, based on which the weight assignment scheme of the large-scale MIMO antennas is iteratively optimized. The principle of intelligent antenna weight optimization technology based on network digital twin is shown in the figure.

According to the current network state and corresponding network optimization requirements, the technology collects real wireless network data including network environment information, channel state information and user state information , etc. on demand, and combines data models, simulation models and intelligent models to build the twin network layer including the user state prediction model, the decision-making generation model, the decision-making selection model and other mainly modules. Among them, wireless mobile networks, including base stations and terminals, constitute the physical entity of digital twin networks. The twin data of mobile networks in the digital domain, including user location information, the control beam RSRP received by the user, and base station parameters (such as base station location, system bandwidth, carrier frequency band, base station transmit power, antenna parameters, air interface channel model) , etc. , constitute the attributes in the digital twin model of the network. The beam weights of the area to be optimized by the network are combined as the attributes in the digital plan content model.

The inner loop of the digital twin network can predict the state of the network at the next moment (user position information) , and then make the beam weight decision. The combination of expert knowledge (mapping between user location distribution and beam weights) and artificial intelligence (reinforcement learning) is used to generate the weight assignment decision. The expert knowledge guarantees the lower limit of the beam weight decision applied to the physical network, and the digital twin network chooses one with better coverage of the beam weights generated by expert knowledge and reinforcement learning as the effect verification object. Then, the digital twin network can pre-verify the coverage of the network in the pre-verification environment, and iteratively optimize the weight decision to generate the final digital plan content. The digital twin network sends the antenna weight assignment instruction to the real wireless network to optimize the network coverage performance. The outer loop of digital twin network can estimate the distance from the coverage target and analyze the cause of the error according to the coverage performance of real network feedback, train the correction model and correct the coverage performance of the digital twin network pre-verification, and optimize the reinforcement learning decision generation algorithm and the expert experience base.

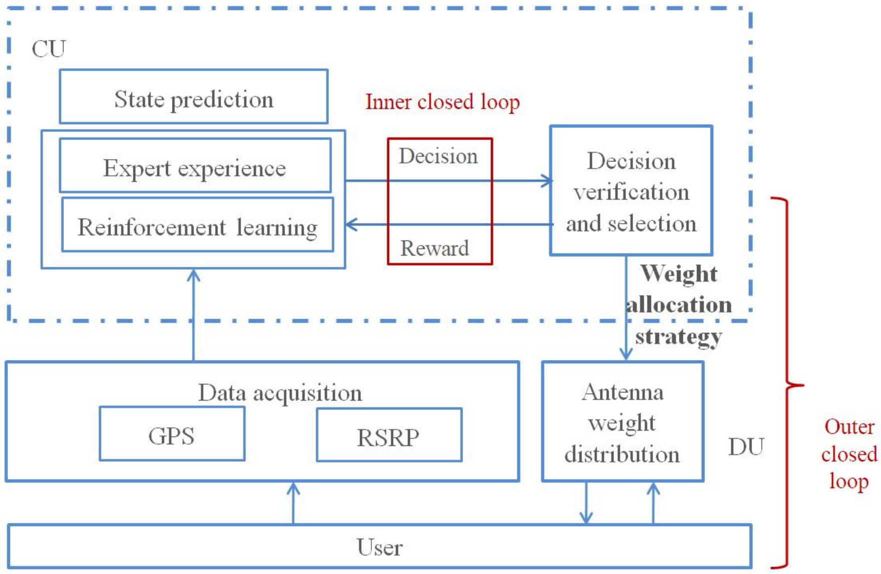

Fig 3.6.1-1. The schematic diagram of intelligent antenna weight optimization of based on network digital twin

For the future of 6G wireless networks, higher frequency applications (such as millimeter wave, terahertz radiation, etc.) will lead to smaller coverage and more intensive deployment of wireless sites. The need for large-scale antenna beam weight optimization for inter-cell cooperation will become more prominent. Meanwhile, the beam weight optimization of ultra-large scale antennas without cellular structure, as well as the joint optimization of intelligent reflector and the beam weight of base station antenna may become the typical scenarios of the 6G wireless network autonomy. For these scenarios, the technology solution based on the digital twin of the network can be used to obtain reliable and better performance antenna weights, reducing the cost and complexity of network optimization.

3.6.2 Intelligent deep RAN slices

The intelligent RAN slice based on network digital twin aims at mining slice configuration experience, capturing short-term environmental change characteristics and achieving efficient and reliable slice resource management. The traditional wireless access network (RAN) slicing scheme mainly adopts the slicing configuration method based on the optimization model, which is constrained by the specific service quality and the total resource quantity, and aims at maximizing the network performance or the operator revenue. The optimal slice resource allocation scheme is solved by classical iterative algorithms. However, the slice resource management method based on the optimization model relies too much on the prior traffic model and the computational complexity increases significantly with the increase of network size [19, 20].

In order to realize environment-self-adaptive, low-complexity and high-performance intelligent RAN slice, mining slice configuration experience and capturing short-term environmental change characteristics to achieve high-efficiency and high-reliability slice resource management, it is necessary to explore the digital twin framework of real-data-driven network slicing system, study the intelligent RAN slicing system based on the network digital twin and the twin enhancement technology of near real-time interaction with real environment. So that the slicing scheme can adjust actively and adaptively to adapt to the environment quickly under the circumstance that the distribution of user traffic is difficult to predict and the network scale keeps growing.

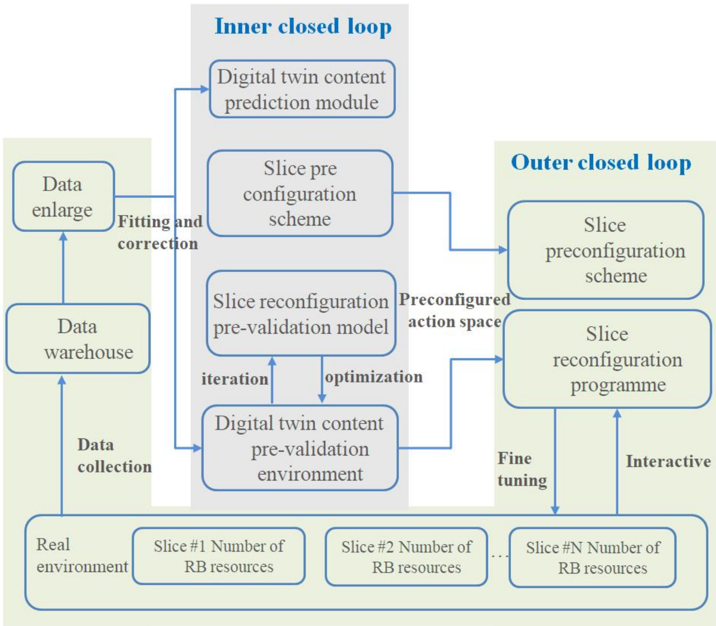

Fig 3.6.2-1. The sketch map of intelligent RAN slice based on network digital twin

Figure 3.6.2-1 is a schematic of the intelligent RAN slice based on network digital twin. The data warehouse is composed of the data collected in the real environment and preprocessed. It provides training samples to the digital twin prediction module and the pre-verification module, at the same time, the training data is augmented by GAN, which is used to match and correct digital twin contents. The digital twin prediction module updates the slice pre-configuration scheme with the predicted future network state output. The pre-verification module interacts with the slice reconfiguration module in the digital twin content and iteratively optimizes the performance of the reconfiguration module of digital twin contents until convergence. Then, the slice reconfiguration module interactively fine-tunes with the real world to quickly adapt to the real world. In the slice reconfiguration algorithm, the slice pre-configuration space is used as the input of dynamic slice reconfiguration module. Then the greedy strategy is used to select the slice configuration action, and the network environment feeds back the statistical information of the slice satisfying rate, spectrum efficiency and packet loss rate in the slice window, to calculate the network reward and further update the utility and number of slices configuration actions.

The architecture includes the physical entity, digital twin contents, digital plan contents, the inner closed loop and the outer closed loop. The physical entity includes peripheral equipments consisting of base stations, user devices and other peripherals, software and hardware systems, and so on. Digital Twin contents are the twins of wireless networks in digital domain, including the digitalization of user-side features and base station-side features. The digital plan contents are the combination of slice resource blocks in the region to be optimized. In the two closed loops, the inner loop is composed of the digital twin prediction module, the slice pre-configuration module, reconfiguration module and the pre-verification module. They form a closed loop for iterative tuning until that the prediction module, the slice pre-configuration module, and the reconfiguration module converge. The outer loop is composed of the pre-configuration module, re-configuration module and data warehouse which actually act on the actual system. In the outer closed loop, the digital twin contents are corrected according to the real data collected by the data warehouse and the slicing effect of the network feedback. The correction includes error analysis of the pre-verification module and the prediction module, network fitting and generalization error analysis, and fine-tuning based on real samples.

For the future 6G wireless network, Cloud RAN is the general trend. From the point of view of the service capability, 6G wireless network will be reconfigured into more fine-grained service RAN. The protocol stack will turn microservice into the function module, and will break through the traditional protocol design idea. The calling relation between the function and the function is no longer restricted by the upper and lower layer protocol relation. The function module can be flexibly called and dynamically combined into the required RAN stack according to the service performance requirements. Therefore, the RAN slice of 6G wireless network includes not only the slice of physical resources, but also the slice of the protocol stack function to realize the deep RAN slice. In this wireless autonomous scenario, the slice configuration optimization scheme can be extended based on the use case scheme, using the network digital twin to generate and optimize in advance.

3.6.3 Federated scheduling of multi-dimensional resources

The amount of data brought about by emerging technologies, applications and scenarios continues to grow, and there is a more urgent need for computing power and networks in all walks of life. Increasing the overall scale of computing power has become a focus of common concern in the industry. Building computing power networks has also become a national strategy. The 6G computing power network puts forward higher requirements for efficient allocation and scheduling of wireless communication resources such as time-frequency resources, space resources, future computing resources, cache resources and so on. Moreover, the large-scale computing power network has a large resource cost. Following the principle of sustainable development, it is necessary to take energy-saving measures for computing power network. Improving resource scheduling accuracy and reducing overhead such as redundancy is one of the important ways to save energy, which can be achieved through the digital twin of the network.

By analyzing and reasonably predicting service traffic, user distribution, channel state information and other data, energy-saving strategies are generated independently by the network on the premise of ensuring sufficient communication resources to guarantee the performance of the network in all aspects. The strategy can perform channel shutdown, symbol shutdown, carrier shutdown, base station switch and other operations on the base station, and complete the scheduling of communication resources such as time slot, frequency, and space. It can reduce the energy consumption of the base station with lower load and effectively improve the energy utilization rate.

Digital Twin Network divides resource objects into three forms: the physical entity, digital twin contents and digital plan contents. In this scenario, the physical entity consists of the6G wireless network including macrobase stations, microbase stations, edge computing nodes and users. Digital twin contents realize the twin of 6G wireless networks in the digital domain through the system-level simulation platform. The base station parameters (base station location coordinates, coverage cell radius, carrier frequency, load power, antenna parameters, etc.), user location information and service distribution state are modeled. Digital plan contents are network resource allocation schemes and switch operation schemes for each micro base station, which can integrate multi-dimensional resources (communication, frequency and cache), as well as the precise allocation of user location and user service. The optimal energy-saving state of the network can be achieved by making decision through iterative computation.

After the data acquisition and model building, the digital twin network generates the digital plan content through the agent module (reinforcement learning) based on the predicted state of the network at the next moment (including user location information, service types, etc.) to meet the minimum performance requirement of communication network service. The simulation verification and iterative optimization before the release of the configuration change are completed through the inner closed loop. Minimum performance requirements ensure that the basic functionality of the network is not affected by provisioning and base station switching operations.

The prediction of network state is not absolutely accurate, although it needs to be verified repeatedly before making a decision. After the decision is made, it is necessary to correct the predicted network performance of the digital twin network according to the feedback of the real physical network. By analyzing the difference between the predicted location and the actual location, the difference of the service requirement and other parameters, the reason of the deviation of the performance prediction is further determined. And then the network execution strategy is adjusted according to the specific situation. The external loop is formed between the physical network layer and the twin network layer.

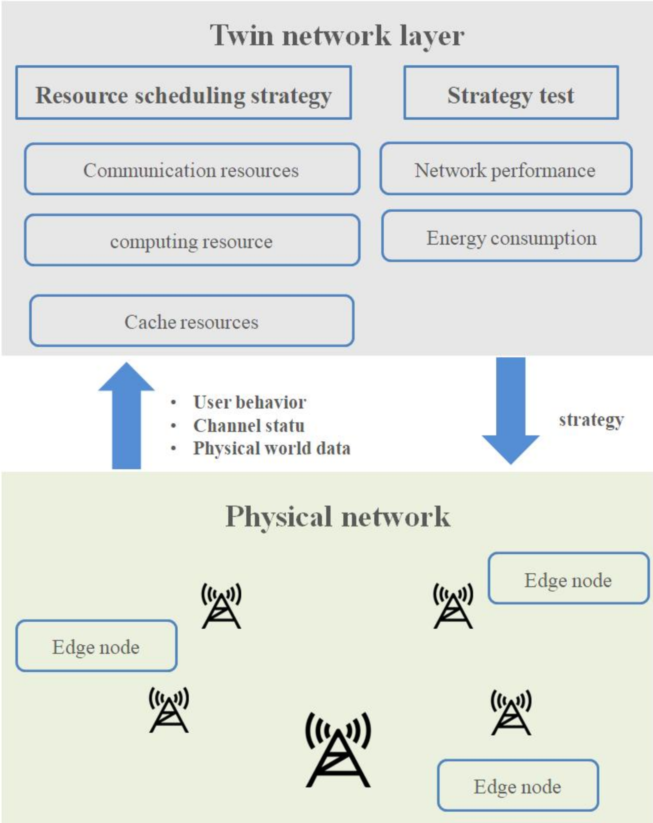

Fig 3.6.3-1. The multi-dimensional resource joint scheduling architecture based on the network digital twin

4. Summary and Outlook

Based on the "Digital Twin Network (DTN) White Paper", this paper further explores the digital twin network for 6G wireless network autonomy. This paper introduces the basic concepts of the digital twin network, three contents, five states and double closed loops, puts forward four technical features, and designs an end-to-end network architecture. This paper discusses the relationship between the digital twin network and the new data plane and intelligence plane of 6G, and plans the key technology system. Through three specific cases, this paper expounds the 6G wireless network life cycle autonomy based on the digital twin network.

At present, there is no consensus on the concept and connotation of the digital twin network, and a unified definition and architecture of the digital twin network still need to be achieved. As a complex system based on large-scale communication network, the digital twin network has many technical problems to be solved in data, models and architectures. In the aspect of data, the protection of data privacy, the compatibility of different vendors'data, and how to design the digital twin content and the plan content models for different network autonomy scenarios and guarantee the data quality are the problems that need to be considered. In terms of models, further research is needed on how to interconnect different types of models and how to use multiple models to correct the accuracy of digital twin contents. In the aspect of architectures, how to achieve the on-demand customization and dynamically generated digital twin content and the plan content, how to construct the digital twin content of the global/network according to the digital twin content of the local/network element, and how to realize the self-resolution of the pre-verification intent and the self-organization of the processes to meet the performance requirements of different network autonomy scenarios (such as real-time, accuracy, etc.) need to be explored by the industry.

In addition to the above three aspects, we think there are the following key technical issues to be further explored for the digital twin network for 6G wireless network autonomy:

1. How to construct the universal intelligent digital twin contents of the whole network and form the twin network with high generalization capability and strong migration capability. Although the digital twin contents of the network have been applied in some current networks, these twin contents are often built based on a large amount of expert knowledge and the background of specific fields, have poor versatility, and often only fit specific physical or logical region in the network environment. In the future, we still need to pay attention to how to make full use of wireless network big data, knowledge graphs and artificial intelligence to build wireless network meta-models and meta-algorithms, forming a network digital twin content with strong generalization ability and migration to a variety of wireless network environments.
2. How to realize the controllability of virtual network scenario generation and improve the reliability of the digital twin network augmented data and pre-verification results? The virtual network scenario is designed to simulate the real network performance. Its performance evaluation system and control mechanism need to be established. In addition, digital twin networks also need to be able to generate augmented data and pre-verification results under specific conditions, so as to achieve custom scenario simulation driven by specific intents.
3. How to improve the use efficiency of real wireless network data and reduce the cost of digital twin network modeling? Considering the data acquisition cost of real wireless networks, digital twin networks should reduce the number of training samples as far as possible, but small samples will make digital twin networks unable to match the real scenarios. Therefore, it is necessary to balance the relationship between validity and complexity. In addition, how to use simulation data to aid digital twin network modeling is also an important research direction.

Abbreviations

Abbreviations	Full English Names
SON	Self-Organizing Networks
PCI	Physical Cell Identifier
MRO	Mobility Robustness Optimization
DTN	Digital Twin Network
ICT	Information and Communication Technology
AI	Artificial Intelligence
MDT	Minitization of Drive Test
MR	Measurement Report
FOA	First Office Application
IoT	Internet of Things
KPI	Key Performance Indicator
QoAIS	Quality of AI Service
DPI	Deep Packet Inspection
DFI	Deep/Dynamic Flow Inspection
ETL	Extract Transform Loading
QoE	Quality of Experience
MIMO	Multiple Input Multiple Output
DoA	Delay of Arrival
CGAN	Conditional Generative Adversarial Networks
GAN	Generative Adversarial Networks
ANR	Automatic Neighbor Relationship
RAN	Radio Access Network
RSRP	Reference Signal Receiving Power

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Digital Twin

Ubiquitous Intelligence