GTI Network Digital Twin Capability Grading White Paper

Network Digital Twin Capability Grading White Paper

Version:	V1.1
Deliverable Type	□ **Procedural Document** √ **Working Document**
Confidential Level	√ **Open to GTI Operator Members** √ **Open to GTI Partners** □ **Open to Public**
Program	5G ENS
Working Group	Terminal WG
Project	Project 4: Architecture and Technology
Task	Digital twin technology for smart city, factory, medical, etc.
Source members	China Mobile, AsiaInfo, ZTE.
Support members	51world, Qualcomm, CAICT.
Editor	China Mobile: Lin Sun, Di Wang, Yuan Li, Qing Wang, Xize Wang, Shuai Ma, Shanpeng Xiao, Yang Liu, Ying Deng, Jie Wang. AsiaInfo: Zhidong Ren, Jianchao Guo, Guo Chen, Shoufeng Wang. ZTE: Jingfei Wang, Keke Su, Yu Bai, Yong Zhan.
Last Edit Date	20-12-2022
Approval Date	20-12-2022

Document History

Date	Meeting #	Version #	Revision Contents
20-12-2021		V1.0	The first version of Network Digital Twin Capability Grading White Paper.

Table of Contents

Executive Summary

Digital twin is a new stage in the development of the IoT, which continues to be highly valued by all walks of life. Network digital twin provides full life cycle digital management services for various networks through the comprehensive use of advanced technologies. The development and evolution process of network digital twin presents gradual feature and is suitable for describing by grading. Based on the comprehensive analysis of the connotation, value, technical system and key technologies of network digital twin, this white paper constructs a network digital twin capability grading system. In addition, the technical requirements are given based on the characteristics of each level, and the application value of network digital twin is reflected in combination with typical scenarios and use cases. Finally, the future evolution of network digital twin technology and industry development are summarized and prospected.

Abbreviations

Abbreviation	Explanation
5G	The Fifth-Generation Mobile Communications
AI	Artificial Intelligence
CNN	Convolutional Neural Network
DPI	Deep Packet Inspection
GIS	Geographic Information System
GNN	Graph Neural Network
ICT	Information and Communications Technology
IoT	Internet of Things
O&M	Operation and Maintenance
QoE	Quality of Experience
QoS	Quality of Service
SDK	Software Development Kit
SLA	Service Level Agreement
TSN	Time Sensitive Network

1 Overview of network digital twin development

With the integration of data and models as the core, the digital twin forms a closed-loop of intelligent decision-making optimization based on data integration, analysis and prediction by building accurate digital mapping of physical objects in digital space in real time. The digital twin is a new stage in the development of the Internet of Things. The digital twin originated in the military industry and is widely used in industry and smart cities. In recent years, it has continued to expand into vertical industries such as transportation and health care, realizing application values such as mechanism description, abnormal diagnosis, risk prediction, and decision assistance.

With the vigorous development of the digital twin technology industry, the industry application has deepened. How to apply the concept of digital twin to the whole life cycle management of communication networks to improve management efficiency, reduce O&M costs, and improve service quality has become a new proposition for operators and equipment manufacturers. Since 2020, several companies such as China Mobile, ZTE, and AsiaInfo have put forward the industry proposition of network digital twin, marking the formation of a new track for network digital twin. The Digital Twin Network (DTN) White Paper released by China Mobile clearly defines the digital twin network and proposes digital twin network architecture of "three layers, three domains and two closed loops". In “Wireless Network Intelligence White Paper”, ZTE proposes to introduce digital twins in wireless network intelligence to realize the development stages from network portrait to twin simulation to intelligent closed loop, and promote the development and evolution of network intelligence. In the article “Study on digital twins in network lifecycle management”, AsiaInfo proposes that the application of digital twin technology to assist the whole life cycle management of communication networks can improve the quality of network management, reduce network risk and cost, and realize visual perception and real-time closed-loop control.

1.1 The connotation and value of network digital twin

Network digital twin refers to the application of digital twin technology in the whole or part of the network life cycle. Through highly simulated real network modeling, near-real-time data collection, and multi-dimensional information aggregation, an accurate digital mapping of the real physical network is constructed in virtual space. On this basis, high-value applications are formed by combining simulation analysis and artificial intelligence to support the digital and intelligent evolution of the network.

The network can help industries quickly transfer data, and help production management, collaboration, and service extension. As mobile networks penetrate into buildings, hospitals, supermarkets, industrial parks and other scenarios, the demand for deterministic data transmission, extensive equipment information collection, high-precision indoor positioning, high-rate data upload, and massive device connections in industry applications is becoming stronger. Therefore, more abundant and powerful network access technologies are needed to solve key problems such as difficult management of heterogeneous networks, low network O&M efficiency, and high network O&M costs.

Network digital twin can bring significant value to network lifecycle management and technological innovation. From the perspective of network lifecycle management, digital twin technology can provide differentiated services at all stages of the network lifecycle. In the network planning stage, direct planning based on service QoE can be carried out through user service simulation enhancement and environment 3D modeling enhancement to achieve signal coverage and service coverage. In the network construction stage, relying on digital twin technology, the project progress can be tracked throughout the process, and the whole process of network planning, network construction, network operation and network maintenance can be connected to ensure data accuracy and achieve accurate matching between the network and the environment. In the network O&M stage, fault reproduction and scenario backtracking in digital twin space can help quickly locate root causes and efficiently diagnose faults. In the network optimization stage, digital twin technology combined with reinforcement learning algorithms can achieve parameter optimization and further improve the network experience.

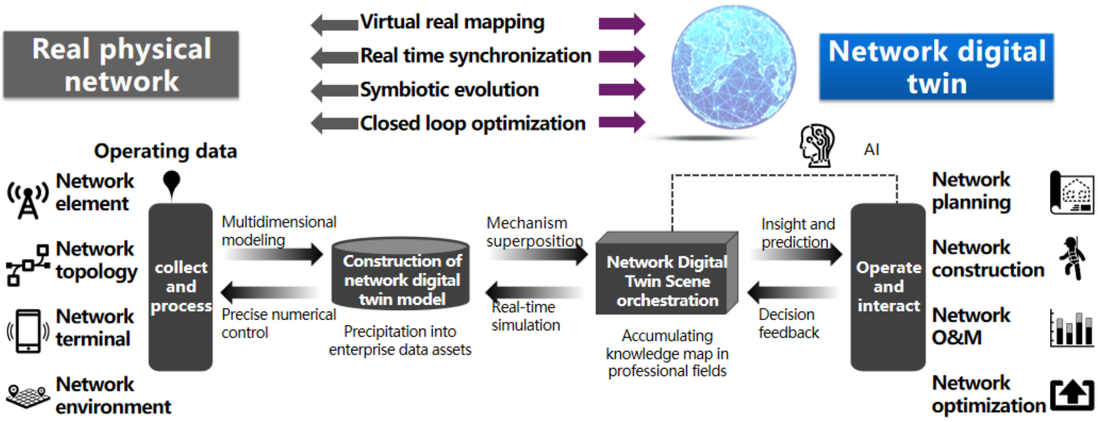

Figure 1. The principle and connotation of network digital twin

From the perspective of enabling ICT technology innovation, network digital twin can promote the verification and application of new technologies, algorithms, scenarios and data. The first is to accelerate the transformation of new technologies. First, the verification of software and hardware technologies can be realized efficiently and cost-effectively on the twin network, supporting the feasibility and value verification. At the same time, combined with visualization technology, network digital twin can support the demonstration of new technologies. Finally, the twin-based network can efficiently complete prototype development and support the transformation of new technology to products. The second is to promote the verification of new algorithms. Network digital twin can help efficiently accumulate field models, assist algorithm verification, and accelerate software version iteration. The third is to optimize the construction of new scenarios. Network parameter settings usually need to consider richer scenario model, and network digital twin can help generate new scenario models through the combination of existing models to increase the completeness of technical verification. The fourth is to promote the generation of new data. The data can be generated in digital twin space, and scene customization, data collection, automatically data cleaning and association can be carried out according to requirements.

In summary, through the comprehensive application of technologies such as perception, communication, modeling and simulation, data integration and human-computer interaction, network digital twin can provide digital management services throughout the network life cycle, and further provide customer and business centered services of visualization, automation and intelligent O&M, enabling ICT technology innovation. Network digital twin can help improve O&M efficiency, customer network experience, and ultimately forms a high-value network O&M management system.

1.2 Network digital twin architecture and key technologies

The network digital twin system consists of four parts: perception and control layer, network communication layer, digital twin layer and human-computer interaction layer, as shown in Figure 2. Through the deep integration of core technologies such as perception, control, communication, modeling and simulation, and human-computer interaction, the twin mapping of real physical networks in virtual space is realized. At the same time, a two-way closed-loop information interaction is formed, reflecting the operation status of the real physical network. As a result, network status can be further assessed, network problems can be diagnosed, and network capabilities can be optimized.

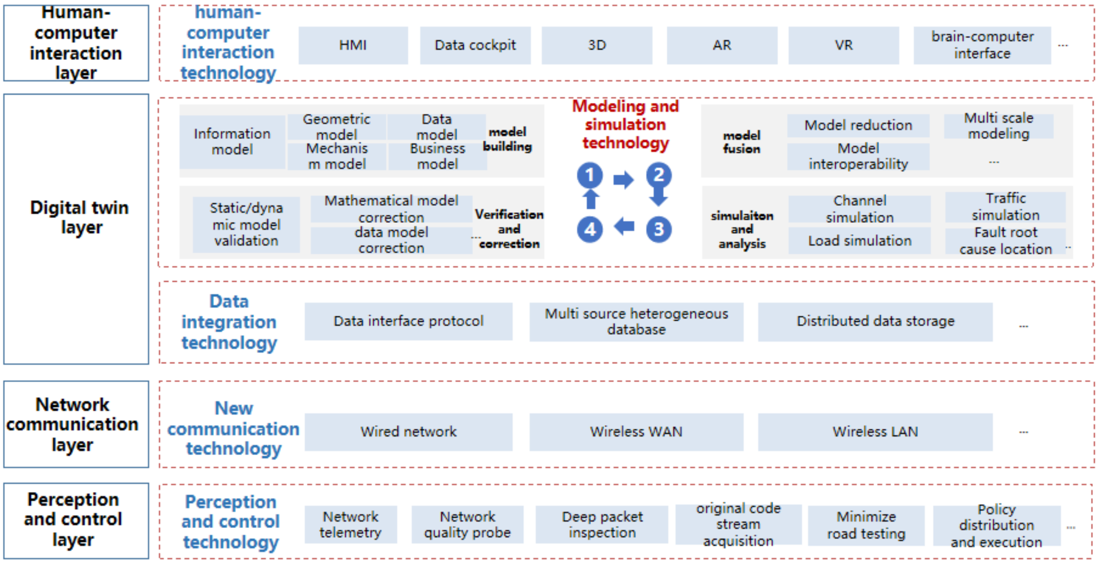

Figure 2. Network digital twin technology architecture

Network digital twin perception and control technology support the collection of various data such as terminals, network elements, network status, network topology, network environment, etc., and support the control and processing of various network objects such as terminals and network elements to ensure that the physical network and the twin network have basic interactive and control capabilities. In particular, data collection and analysis is the core of network operation and management. The traditional data collection method for network operation and maintenance is to obtain stream of data from network elements. 5G Terminal Probe, as shown in Figure 3, can provide real-time and dynamics status of device, network and service in industry proximity networks. Then, early warning for service, monitoring, network analysis and optimization can be carried out. 5G Terminal Probe effectively makes up for the lack of terminal-side information, further improves service transmission guarantee, and ensures the use perception of industry customers. In addition, Network Telemetry enables remote periodic sampling of statistical data and status data within network devices. Therefore, network device performance and failures are further monitored. Deep Packet Inspection (DPI) is used to detect and analyze traffic and packet content at key points of the network. It filters and controls the detection traffic according to the pre-defined policies, and can complete functions such as service refinement identification, service traffic flow analysis, service traffic proportion statistics, and service proportion shaping.

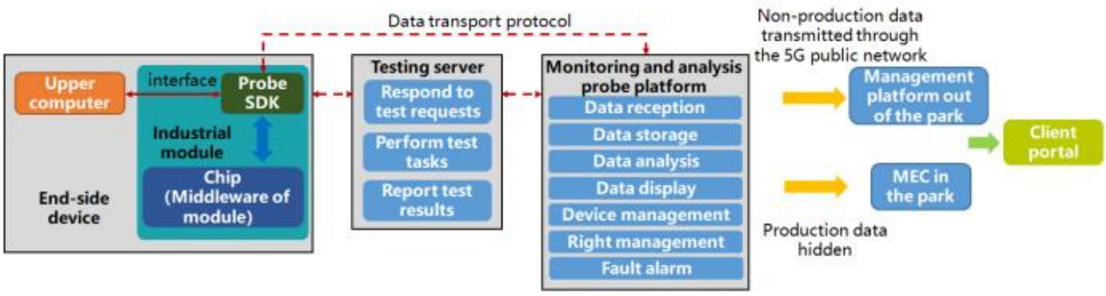

Figure 3. Architecture diagram of 5G end-side service quality probe system

Network digital twin data integration technology supports to realize the interconnection of southbound, northbound, horizontal and internal data of the system. Network digital twin builds a multi-source heterogeneous database to store, manage, and maintain structured data such as network resources, alarms, performance, logs, and work orders, as well as unstructured data such as voice and images. For example, the MQTT protocol has the characteristics of simplicity, low bandwidth usage, and QoS for data transmission. It supports the transmission of any type of digital twin data, which can meet the needs of low power consumption and low network bandwidth, and provide communication guarantee for a large number of low-power, unreliable working network environment IoT devices. MongoDB is a database based on distributed file storage, which has the characteristics of high performance, easy deployment, easy to use, and convenient data storage. It supports the storage of complex data types and provides a scalable, high-performance data storage solution for network digital twin applications.

Network digital twin modeling technology maps physical entities such as people (network operation and maintenance personnel), machines (network element equipment), networks (various heterogeneous networks), methods (network knowledge such as operation and maintenance manuals and operation instructions), and environment (field environment) into virtual space, and builds them into geometric models, information models, and mechanism models. At the same time, the atomic model is arranged and combined according to the network topology relationship and business requirements to meet the visual, manageable and controllable requirements of network intelligence, and realize network personalized service upgrade. The geometric model represents the interaction relationship with the entities in the physical space in the form of two-dimensional or three-dimensional graphics in the virtual space, so as to realize the visualization of network equipment, network topology, network faults and other information. The information model implements the normalized semantic description of the properties, capabilities, interfaces, and data flows of physical entities. Through the information model, data perceived from the physical space can be transmitted to the virtual space in a standardized way for visualization and intelligent analysis. The mechanism model can truly reflect the objective laws of physical space, and on this basis, the entities of physical space can be managed and controlled. The mechanism model includes three types: 1) The operation mechanism of the network device or system accurately expressed through mathematical formulas; 2) Rule sets or knowledge graphs formed based on the experience summarized by domain experts in the process of work; 3) AI mechanism model trained by machine learning algorithm based on big data.

Network digital twin simulation and intelligent technology can provide simulation services for network digital twins based on the algorithms such as fault diagnosis and intelligent operation and maintenance algorithms, and the data such as network infrastructure operation parameters, business data, historical faults, alarm logs. Through simulation, network digital twin can provide full technical verification and capability guarantee for real physical networks and related services in an efficient and forward-looking manner in a virtual environment, reducing the risk of trial and error of new technologies and functions. Taking industry proximity network O&M as an example, through the comprehensive analysis of network O&M objects and typical faults, intelligent O&M algorithms are used to train industry proximity network intelligent O&M models, as shown in Figure 4. Through network digital twin simulation, intelligent applications such as fault delimitation, fault scene identification and root cause localization, and fault prediction are realized. Taking intent-driven network as another example, there are three major challenges: 1) Mobile communication networks have high requirements for reliability and performance, and cannot tolerate the system to try and explore new strategies; 2) There is currently no mature technology that can accurately predict the achievement of intentions; 3) There is currently no mature technology for intent conflict management. In order to overcome the above difficulties, network digital twin combining with intelligent technology can explore the optimal strategy to achieve the intent. At the same time, the intention achievement and intention conflict situation are monitored and summarized in the twin network and the intention achievement and intention conflict detection results are fed back to the intent processing module to realize the intention conflict management.

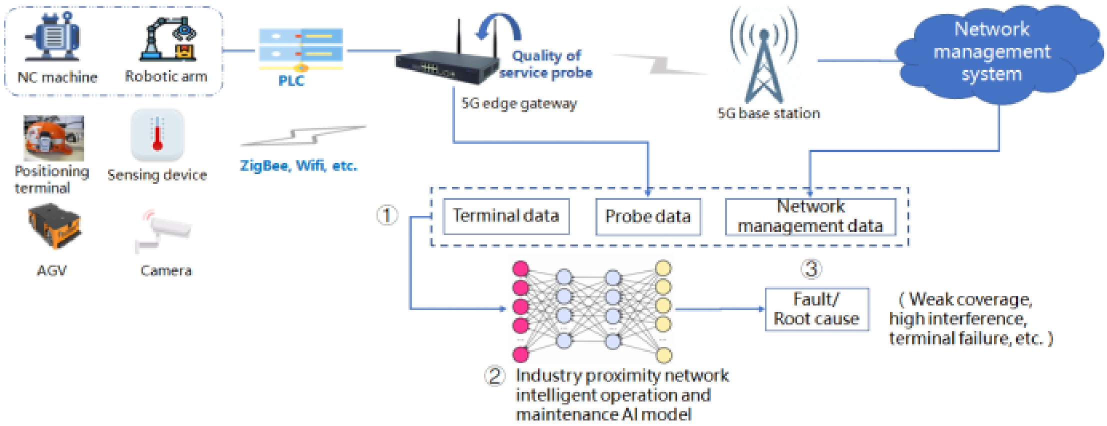

Figure 4. Intelligent O&M framework for industry proximity networks

Network digital twin human-computer interaction technology can provide network visualization management capabilities, including infrastructure visualization, network parameter configuration visualization, data flow visualization, SLA visualization, etc. In addition, it can also support the realization of human-computer collaborative interaction through natural language, machine language and body language. Visualization involves technologies such as GIS, 3D visualization (unity3D, WebGL/canvas) and so on. Among them, GIS is a specific and very important spatial information system. It is a technical system for collecting, storing, managing, operating, analyzing, displaying and describing relevant geographical distribution data of the entire or part of the earth's surface (including the atmosphere) space with the support of computer hardware and software systems. In 3D visualization, Unity is a real-time 3D interactive content creation and operations platform, providing a complete set of software solutions. Unity can be used to create, operate, and monetize any real-time interactive 2D and 3D content. WebGL (Web Graphics Library) is a 3D drawing protocol, which allows JavaScript and OpenGL ES 2.0 to be combined. By adding a JavaScript binding for OpenGL ES 2.0, WebGL provides hardware 3D accelerated rendering for HTML5 Canvas.

2 Network digital twin capability grading and technical requirements

2.1 Network digital twin capability grading

Digital twin is complex system engineering, with the characteristics of cross-industry and cross-domain. Its development and evolution process presents phased characteristics, which is suitable for description by a grading system. Through the network digital twin capability grading, on the one hand, it can help enterprises fully evaluate the current stage of network digital twin, so as to identify the shortcomings, and formulate targeted network digital twin optimization plans according to the shortcomings. On the other hand, it can help enterprises clarify the capability requirements and technical characteristics of network digital twins at all levels, facilitate the formulation of network technology capability evolution routes that meet their own development requirements, and achieve long-term development.

Based on the dismantling and scenario analysis of network digital twin technology, combined with the research results of digital twin grading at home and abroad, the network digital twin can be divided into six levels: Level 0 to Level 5 (as shown in Figure 5). Form a network digital twin grading system that is "visible, manageable, controllable, self-healing, self-governing and self-developing". Each level presents go forward one by one relationship, the higher level covers the requirements of the lower level, and has the technical ability to meet the requirements of the lower level.

Level 0 (visible): It supports digital modeling of the attributes, service characteristics and external environment of the network element to form a "network portrait". It supports accurate mapping of key elements such as network operation data into the digital twin space, as well as all-round real-time monitoring and display of the network and surrounding environment.

Level 1 (manageable): It supports to integrate network mechanisms, business processes, expert rules and core algorithms into digital twin system. Therefore, the acquired network data can be analyzed and simulated in the twin space. It supports to simulate the characteristics of real network element devices to the greatest extent and support the life cycle management of the entire network.

Level 2 (controllable): It supports to form a closed-loop process from network state awareness, to simulation analysis, to decision generation, and finally to decision execution. It supports to deliver the decision instructions from the twin space directly to the physical network and correctly executed.

Level 3 (self-healing): It supports to implement the functions such as network anomaly detection alarms, fault root cause location and repair strategy generation, based on multi-source data and AI capabilities such as classical machine learning. It also supports self-diagnosis and self-healing of network faults.

Level 4 (self-governing): It supports to predict, rehearse, and automatically generate optimization decisions for possible events in network, based on multi-source data and AI capabilities such as deep learning, reinforcement learning, and optimization theory. It also supports functions such as predictive maintenance of equipment, predictive network governance, and network autonomous optimization, forming network intelligent closed-loop autonomy capabilities.

Level 5 (self-developing): It supports to build a twin network that maps 1:1 to the physical network. By integrating AI capabilities and intent-driven technologies, in network planning, construction, operation, maintenance and optimization, it enables a completely unmanned intervention autonomous driving network.

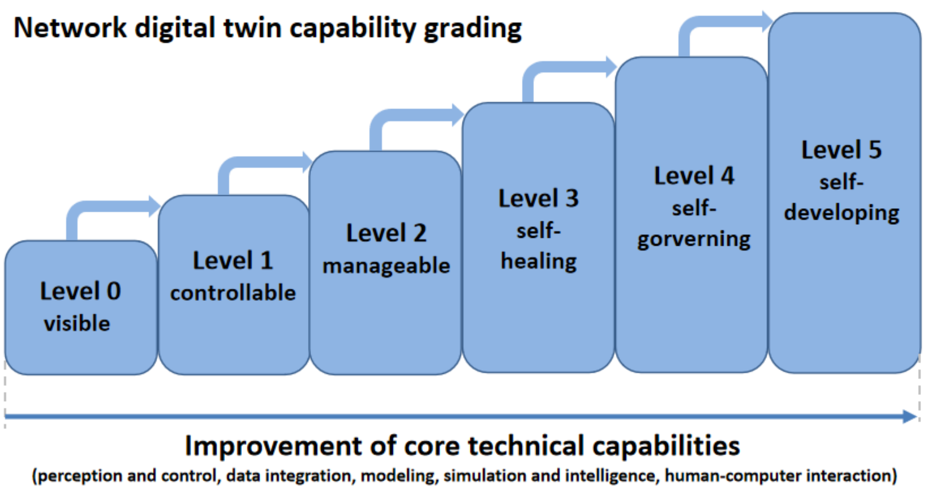

Figure 5. Network digital twin capability grading

2.2 Technical requirements for different levels

Each level of network digital twin has different technical characteristics and requirements. In terms of perception, it focuses on the breadth, depth, timeliness and reverse control ability of perception data acquisition. The breadth is divided according to the degree and number of perceived physical entities and virtual network elements in the entire network. The depth progresses step by step according to whether it can collect spatial resources, protocols, interfaces, routes, signaling, processes, performance, alarms, logs, status, and 24-hour full service data. Timeliness involves perception dimension, strategy and frequency. In terms of reverse control, the transition from no reverse control capability to all instructions can be automatically executed in the physical network element ontology to realize the evolution from manual intervention to intelligent decision-making.

In terms of data integration, it focuses on the southbound, northbound and horizontal interface capabilities, structured, semi-structured and unstructured data access and processing capabilities, as well as the data interoperability capabilities between systems. For example, southbound interfaces are graded based on whether they include data acquisition interfaces and control delivery interfaces between discrete network digital twins and physical network elements. Northbound interfaces are graded based on whether they include intent translation interfaces and capability call interfaces between the network application layer and the network digital twin, and whether they meet the requirements of the network application calling the data and model provided by the digital twin system through the interface to realize the functions of monitoring, diagnosis, prediction and simulation in various network scenarios. Horizontal interfaces are graded according to whether they support the capability call between network digital twins, whether they can dynamically drive other network digital twins based on data and models, whether they can support the call to AI model services, third-party simulation interfaces, and other capabilities, and whether they can support the correction feedback of the built-in functional model based on real-time data.

In terms of modeling, it is necessary to establish the basic properties, state attributes, relationships, rules and other representation of each digital twin object. Among them, the basic properties are used to describe the entity object including the basic parameters, types, characteristics, etc. The state attributes describe the form of the entity object when it is transformed at a critical point in the whole life cycle management, such as operation status and business status. Relationships are used to express the association between objects, such as logical topology, combined association and others. Rules are used to define the operation rules of digital twins, such as alarm rules and performance alert rules. The difference between the levels lies in the modeling method, from manual modeling to the innovation of automated modeling based on artificial intelligence algorithm training and deduction, the modeling accuracy has increased from coarse granularity to very high precision, and at the same time, the requirements are gradually improved.

In terms of simulation and intelligence, the system is graded according to whether it has simulation capabilities, scene orchestration capabilities, and whether it combines artificial intelligence algorithms to improve the simulation effect of the system. For example, network digital twin can be divided into different levels according to the parallel operation capability of scene orchestration, whether it supports real-time simulation and whether it has data aggregation capability.

In terms of human-computer interaction, the network digital twin is graded according to whether it supports functions such as data charting, HMI, 3D visualization, data cockpit, AR/VR, brain-computer interface, etc.

2.2.1 Level 0 (visible)

In terms of perception and control, perception mainly involves the environmental data of the physical network and the static data related to network elements, such as physical appearance, device model, etc. A small amount of critical dynamic data running on the network is typically updated every few hours. There is no instruction delivery interface in control section.

In terms of data integration, network digital twin provides static data acquisition interfaces related to physical and virtual network elements in southbound. It provides network digital twin application capability interfaces in northbound such as data presentation and visual expression. It supports structured and unstructured data storage of related network resource instances of network digital twin.

In terms of modeling, network digital twin of Level 0 provides a three-dimensional visual model of network equipment and network element data. The model mainly contains the basic information, such as shape, length, width, height, size, position, etc. The geometric modeling accuracy is coarse-grained.

In terms of simulation and intelligence, there is no need to have relevant capabilities.

In terms of human-computer interaction, it supports 3D visualization for one-way visual transmission.

2.2.2 Level 1 (manageable)

In terms of perception and control, perception mainly involves the environmental data of physical network and static data related to network elements, reflecting the current situation of physical networking. The key dynamic data of network operation is usually updated every 30 minutes or an hour. There is no instruction delivery interface in control section.

In terms of data integration, network digital twin provides static and dynamic data acquisition interfaces related to physical and virtual network elements in southbound. It provides the capability call interface required for network digital twin applications in northbound, which can realize resource status information presentation and unified resource scheduling. It supports structured and unstructured data storage of related network resource instances of network digital twin and business operation data.

In terms of modeling, on the basis of Level 0, the YANG data model is established by combining NetFlow, sFlow and other original code stream acquisition technologies and the open config protocol. The geometric modeling accuracy is general accuracy, and the appearance is modeled with an approximate shape, with a certain texture effect.

In terms of simulation and intelligence, Network digital twin can use DPI and SDK to analyze network packets and network performance data. It also supports to simulate network elements and network links combined with traffic simulation technology. In specific scenarios and low timeliness conditions, it has 10^2-level digital thread parallel operation capability, coded scene construction and orchestration capability, limited simulation capability and data aggregation capability for specific scenarios.

In terms of human-computer interaction, based on the capabilities of Level 0, human-computer interaction is carried out in combination with the data cockpit.

2.2.3 Level 2 (controllable)

In terms of perception and control, perception mainly involves the physical network data such as basic configuration, environmental information, operation status, link topology, alarm events, performance, reflecting the network operation comprehensively. The relevant operating situation data is usually updated at a frequency of 15 minutes or faster. Control part sets the scope and principle of the instruction in advance, and the issuance and execution of the instruction requires human decision-making intervention.

In terms of data integration, network digital twin provides data acquisition interfaces and control command issuance interfaces between discrete network digital twins and physical network elements in southbound. It provides capability call interfaces between network applications and network digital twins in northbound to support the applications to call various data and models provided by the digital twin system, and realize the functions of monitoring, diagnosis and prediction of the entity status. It supports structured, semi-structured and unstructured data storage of related network resource instances and various business data.

In terms of modeling, the network topology model and business model are established through protocol simulation and artificial intelligence algorithms based on Level 1. The geometric modeling accuracy is high precision with accurate contours and detailed independent expression of components and the local structure can be appropriately simplified.

In terms of simulation and intelligence, channel simulation, traffic simulation, load simulation and protocol simulation are realized on the basis of Level 1, and single-domain simulation is realized. At the same time, network digital twin supports to set the operation rule and the digital twin system issues instructions through Open config when the operation rule is triggered. In large-scale scenarios and medium-timeliness conditions, it has 10^3-level digital thread parallel operation capability, component-based scene construction and simple scene orchestration capability, real-time simulation and large-scene data aggregation capability.

In terms of human-computer interaction, the management and control capability of the mobile terminal is realized on the basis of Level 1.

2.2.4 Level 3 (self-healing)

In terms of perception and control, perception mainly realizes end-to-end data perception such as physical entities, logical network elements, spatial resources, protocols, interfaces, routes, signaling, processes, performance, alarms, logs and status, and realizes holographic mirroring of network operation. Part of the perception data is updated at the frequency of seconds. In the control part, instructions that comply with equipment standards and specifications can be issued, and the execution of instructions requires human decision-making intervention.

In terms of data integration, based on Level 2, network digital twin provides an intent translation interface between network applications and network digital twins to realize functions such as monitoring, diagnostics, and prediction of entity status in Northbound. It supports structured, semi-structured and unstructured data storage of relevant network resource instances and various business data (including historical data and real-time data).

In terms of modeling, based on Level 2, combined with data weaving capabilities, network digital twin supports to weave data from different domains (such as cities, networks, network elements, devices) , and to establish validation rule models. The geometric modeling accuracy is high precision with accurate contours and detailed independent expression of components.

In terms of simulation and intelligence, AI algorithms are combined to realize root cause positioning and optimal scheme and strategy based on Level 2. Combined with classical machine learning, optimization theory and other technologies, network digital twin supports to realize the basic AI capability management network. In quasi-urban scenarios and high timeliness conditions, it has 10^4-level digital thread parallel operation capability, exploratory scene construction and complex scene orchestration capability, real-time simulation and large-scene and cross-domain data aggregation capability.

In terms of human-computer interaction, the requirements are the same as in Level 2.

2.2.5 Level 4 (self-governing)

In terms of perception and control, perception mainly realizes all business data collection. A small number of data is updated at the frequency of milliseconds with network telemetry technology. In the control part, some instructions can be automatically executed in the physical network element ontology after they are issued, and some instructions need to be executed with human decision-making intervention.

In terms of data integration, based on Level 3, network digital twin provides capability call to AI models and simulation interfaces in Northbound, to realize functions such as monitoring, diagnosis, prediction and simulation in complex network scenarios.

In terms of modeling, based on Level 3, network digital twin combines with intelligent algorithms to establish AI training models. The geometric modeling accuracy is extremely high-precision, with accurate contours and detailed independent expression of components and with composition structure relationships and disassembly sequences, to achieve 1: 1 accurate restoration of physical entities.

In terms of simulation and intelligence, on the basis of Level 3, the simulation capabilities are connected in series through cross-domain data weaving capabilities to build all regional network simulation capabilities. Deep learning, reinforcement learning and AI data training are further used to realize network independent optimization, and the optimal scheme calculated by CNN and other algorithms is supported to compare with the expert model to optimize the algorithm model. Network optimization is enabled by predicting points of failure in the digital twin environment. In city-level scenarios and quasi-real-time conditions, network digital twin has 10^5-level digital thread parallel operation capability, automatic scene construction and scene simulation orchestration capability, real-time simulation and data aggregation capability at any spatial scale.

In terms of human-computer interaction, AR/VR capabilities are integrated on the basis of Level 3.

2.2.6 Level 5 (self-developing)

In terms of perception and control, perception mainly realizes all business data collection, and supports multi-dimensional, multi-strategy and multi-frequency on-demand collection on the basis of Level 4. Most data is updated at the frequency of milliseconds with network telemetry technology. All the control instructions can be automatically executed in physical network element.

In terms of data integration, the requirements are the same as in Level 4.

In terms of modeling, the requirements are the same as in Level 4.

In terms of simulation and intelligence, based on Level 4, network digital twin uses AI technology to introduce intent recognition. It can classify and extract the operation data and configuration data of network planning, construction, operation, maintenance and optimization in the whole life cycle, and finally form an autonomous driving network, to realize the identification, verification and simulation of the intention strategy and fully automatically guide the control layer to issue instructions. In super city-level scenarios and real-time conditions, network digital twin has 10^6-level digital thread parallel operation capability, intelligent scene construction and real-time scene simulation orchestration capability, real-time simulation and data aggregation capability at any spatial scale.

In terms of human-computer interaction, the brain-computer interface capability is integrated on the basis of Level 4, and some of the structured thinking frameworks of the human brain can be obtained through the brain-computer interface for intention analysis and disassembly.

3 Typical scenarios and use cases of network digital twin

3.1 5G private network visualization

Based on multi-scale modeling technology and three-dimensional visualization technology, network digital twin can realize the mapping of network entities in physical space to digital twins in virtual space, support dynamic interactions, associative interactions and immersive simulations between digital twins and physical network devices. The digital large screen can efficiently display the network digital twin information (as shown in Figure 6). On the one hand, customized network design and networking solutions in virtual scenarios can be quickly displayed through digital large screen, highly restoring the real network and showing network capabilities to industry customers. Therefore, digital large screen plays an important role in wireless network management. On the other hand, as the basis of network digital twin visualization, network topology visualization can present network nodes and links as points and lines on the digital large screen, so as to clearly and intuitively reflect the network operation status and assist users in evaluating and analyzing the network. Through real-time network data collection, circulation and display, topology perspective and traffic holography are realized, and the physical network is changed from a "black box" to a "white box".

The network digital twin of 5G private network visualization is generally at Level 0, and some capabilities such as data perception and modeling can reach Level 1 or above. The digital large screen demonstrates the obvious value of network digital twin in visualization and decision-making. Through visualization, it helps users and network administrators understand the internal structure of the network more intuitively and understand the network operation status, so as to explore the useful value information in the network, improve the efficiency of network production and operation, and help users manage and make decisions about their production operations.

Figure 6. Visualized digital large screen

3.2 5G private network planning and construction

In the current network planning and construction process, there are many problems and difficulties. First, the current network planning tool can only support level-based network planning based on RSRP/SINR, and cannot meet the clear requirements of industry customers for network QoS. Second, network planning can only be used for static scenarios currently. For industry application scenarios that may change dynamically, static network planning is difficult to match. Third, in industrial application scenarios, it usually takes several months for network optimization and even network reconstruction after network construction based on the existing solution, greatly increasing network construction costs.

Taking the port container yard scenario as an example (as shown in Figure 7), the environment features are as follows. First, the stacking height of port goods can reach over 20 meters, and wireless signals cannot penetrate through metal container boxes. Second, during the port operation process, as the goods need to be transferred, the container stacking height, quay bridge location and container location often change, resulting in the continuous change of wireless signal coverage area and signal interference level. Third, roads are narrow, long, and densely distributed. The road between yards can be at most 500 meters, and the distance between two adjacent roads is about 60 meters. Therefore, the existing method cannot meet the demands, and the 3D network modeling of network digital twin can be used to implement accurate 5G network planning, ensuring the design of 5G deployment solutions and the wireless signal coverage in the corresponding port area.

Figure 7. The port container yard scenario

Based on the laser point cloud and tilt photography measurement data of physical environment, a deep learning algorithm model is constructed by using computer graphics and deep learning algorithms. By using the deep learning algorithm model, the on-site environment is identified, geometry reconstruction is extracted, and the three-dimensional physical environment model is obtained. By using the ray tracing model and the network channel model, and superimposing variables such as container trucks, quayside bridges and containers, the dynamic environment of the port can be simulated.

The network digital twin of 5G private network planning and construction is generally at Level 1, and some capabilities such as data perception, modeling, simulation and analysis can reach Level 2 or Level 3. The planning and construction of a digital twin-based 5G network presents the explicit value of the network digital twin in terms of ultimate visualization, simulation verification, and decision-making assistance. Using network digital twin, when changing the location and antenna form of the base station arbitrarily, the effects of different coverage schemes can be quickly verified. By traversing various typical scenarios, the best network planning scheme can be ultimately outputted. At the same time, based on network digital twin, reasonable base station location, accurate network planning and better guarantee of service SLA can be achieved, which will greatly reduce the workload of subsequent network optimization.

3.3 5G private network lightweight operation and maintenance

The scene of various industries is complex, and there are common phenomena of network heterogeneity and customization. Enterprise users have higher requirements for complex network system operation and maintenance, which is difficult for traditional operators' network management and agent maintenance and maintenance teams. Figure 8 shows the overall architecture diagram of 5G converged industrial proximity network technologies. It can bridge heterogeneous proximity networks, such as passive communication, short-range communication, Bluetooth, TSN, etc, perform data distribution, process the field operation data uploaded by 5G, and realize the management of heterogeneous proximity networks. Based on digital twin network services, the industry proximity network digital twin platform defines complete industrial network and process with self-optimization capabilities, including interactions between wireless connections, factory networks, and 5G networks. It also provides information modeling, identity resolution, and model-driven intelligent network operation and maintenance for industry proximity network, to make the network visible, manageable and controllable, greatly reducing O&M costs and improving service efficiency.

The industry proximity network digital twin platform has following core capabilities. 1) Real-time monitoring: To build a network health evaluation system from four dimensions of device status, network coverage, network performance and service quality, realizing real-time perception and monitoring of equipment and networks. 2) Anomaly detection: To extract key indicators from the data of 5G Terminal Probe, relying on the rule base and machine learning algorithms, continuously count and aggregate analysis indicators, and build a dynamic threshold baseline to detect anomalies in advance and correlate alarms. 3) Failure analysis, Based on 5G Terminal Probe, gateway logs and small server data, root cause analysis is performed for common faults such as unreachable, terminal disconnection and service jitter.

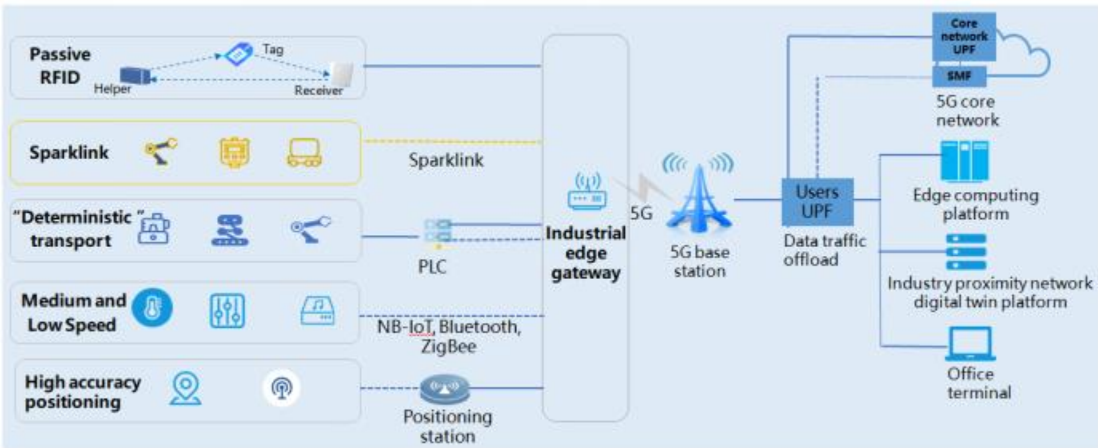

Figure 8. Overall architecture of 5G converged industrial proximity network

The network digital twin of 5G private network lightweight O&M is generally at Level 1, and some capabilities such as data perception, data integration, simulation and analysis can reach Level 2 or above. The lightweight O&M of 5G private networks based on digital twin technology demonstrates the obvious value of network digital twin in business simulation analysis and network lifecycle management. According to the requirements for real-time monitoring of 5G private network SLA operation, based on 5G Terminal Probe, data analysis and AI capabilities, the lightweight O&M technical solution of 5G private networks is formed. The solution can realize visualization of control and service data flow, and realize network fault discovery and self-healing maintenance through network fault diagnosis and root cause analysis.

3.4 5G private network optimization

In 5G networks, the demand for network optimization of 5G private networks is dynamic, while the network routing configured by existing network management platform is relatively fixed. The network optimization scheme based on digital twin technology calculates the optimal path in real time and distributes the calculation results to the physical network with adaptive dynamic network requirements. Therefore, it can effectively increase the network capacity of 5G private network. As shown in Figure 9, the core methods of 5G network optimization based on digital twin include: 1) The expert experience models is used to output routing and forwarding paths. 2) The performance data of the network (such as delay, packet loss and jitter) are transformed into vector form and the optimal path of the comprehensive dimension is calculated by matrix operation and GNN algorithm. 3) Through the CNN algorithm, the optimal path calculated above and the results calculated by the expert experience model are compared and modified, and the optimal routing algorithm model is continuously constructed. 4) The routing configuration is delivered to the twin network. Combined with preset conditions and rules, network digital twin verifies whether it meets the requirements of the real-time network through simulation analysis. 5) The results verified in the network digital twin are sent to the physical network to help O&M personnel continuously optimize the network. At the same time, the verification results are fed back to the expert experience model as input conditions, and relevant parameters and feature values are continuously optimized. The network digital twin combining artificial intelligence algorithm can optimize 5G network routing. As increasing of running time, the feedback time of the optimal path will be shorter and the results will be more accurate, which will ultimately meet the goal of 5G private network dynamic routing strategy.

The network digital twin of 5G private network optimization is generally close to Level 2, and some capabilities such as data perception, simulation and analysis can reach Level 3 or above. 5G network optimization based on digital twin technology shows the obvious value of network digital twin in integrating expert experience and intelligent algorithms to perform service simulation and strengthen network life cycle management. In order to meet the requirements of 5G private network dynamic routing, expert experience models and artificial intelligence algorithm models are built in the digital twin space, then the performance data (historical data, quasi-real-time data and real-time data) of the network are input into different models, and the calculation results are compared to form the optimal scheme, so that the network routing will be further optimized and the cost of the scheme will be reduced.

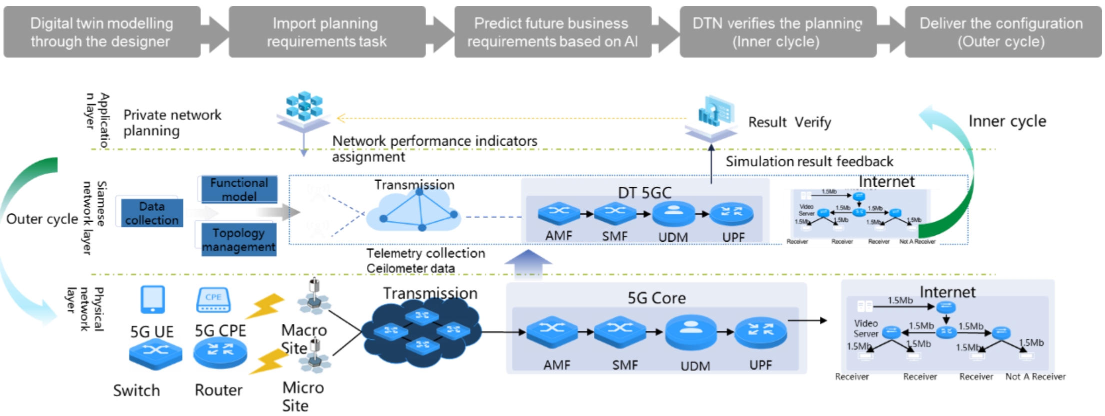

Figure 9. 5G network optimization based on digital twin

4 Conclusion and prospect

With the development and popularization of digital twin technology, the application of related technologies in the field of communication networks has gradually been widely concerned and in-depth studied by the industry. Through the comprehensive use of perception control, data integration, modeling, simulation and visualization technologies, the network digital twin builds an accurate mapping of the physical network in virtual space, helping the whole life cycle management of the network, and continuously reducing costs and increasing efficiency.

Based on the existing network digital twin scenarios and requirements at home and abroad, according to the scenario value, technology maturity and implementation cost, the network digital twin is divided into six levels in this white paper, which is visible, manageable, controllable, self-healing, self-governing and self-developing. In addition, the corresponding technical requirements are given for different capability levels, and the typical scenarios and use cases of network digital twin are analyzed. It can help relevant practitioners evaluate network capabilities and relevant values of each level. Through comparative analysis, it can be seen that the current application of network digital twin is mostly concentrated at Level 0, Level 1 and Level 2. Level 0 focuses on full visibility of the network and environment to facilitate operational decision-making. The capabilities of Level 1 and Level 2 overlap with existing network management systems, and the corresponding technical maturity is high and the implementation cost is low, which can be used as an important means to improve network service quality and reduce O&M costs. Level 3 application scenarios can bring high application value. However, it has technical difficulties and high implementation costs. The application scenarios of Level 4 and Level 5 are difficult to implement on the basis of existing network technologies, and key breakthroughs are expected to be achieved in the 6G era.

As a hot spot, network digital twin continues to attract extensive attention from academia and industry. In terms of academic research, the research of network digital twins mainly focuses on modeling and intelligence, to solve the problems caused by lack of training samples or environmental data of AI algorithm and real-time dynamic changes of the network in scenarios such as computing resource allocation, network slice management, fault detection and maintenance. In terms of industrial promotion, most manufacturers mainly realize the best visualization of large screens, network intelligent operation and maintenance, remote environmental exploration and other network digital twin scenario applications based on visualization and simulation technologies. Most of the applications are still in the concept demonstration or pre-research stage, and the projects with actual deployment are still a minority. There are two main directions for the development of network digital twin in the future: 1) Combine digital twin technology to solve current network problems, carry out new product research and development, and upgrade current network capability. 2) Focus on intelligent perception, passive Internet of Things, 5G evolution, 6G, proximity networks, brain-computer interfaces and other technology directions, lay out technical capabilities in advance, build a high-level network digital twin system, and deeply empower applications.