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Network Digital Twin: Concepts and Reference Architecture
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Abstract

Digital Twin technology has been seen as a rapid adoption technology in Industry 4.0. The application of Digital Twin technology in the networking field is meant to develop various rich network applications and realize efficient and cost effective data driven network management, and accelerate network innovation.

This document presents an overview of the concepts of Digital Twin Network, provides the basic definitions and a reference architecture, lists a set of application scenarios, and discusses the benefits and key challenges of such technology.

Discussion Venues

This note is to be removed before publishing as an RFC.

Discussion of this document takes place on the Network Management Research Group mailing list (nmrg@irtf.org), which is archived at <https://mailarchive.ietf.org/arch/browse/nmrg>.

Source for this draft and an issue tracker can be found at <https://github.com/chenezyhoucheng/network-digital-twin>.

Status of This Memo

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1. Introduction

The fast growth of network scale and the increased demand placed on these networks require them to accommodate and adapt dynamically to customer needs, implying a significant challenge to network operators. Indeed, network operation and maintenance are becoming more complex due to higher complexity of the managed networks and the sophisticated services they are delivering. As such, providing innovations on network technologies, management and operation will be more and more challenging due to the high risk of interfering with existing services and the higher trial costs if no reliable emulation platforms are available.

A Digital Twin is the real-time representation of a physical entity in the digital world. It has the characteristics of virtual-reality interrelation and real-time interaction, iterative operation and process optimization, full life-cycle and comprehensive data-driven network infrastructure. Currently, digital twin has been widely acknowledged in academic publications and adopted in Industry 4.0. See more in [Section 3](#).

A digital twin for networks can be built by applying Digital Twin technologies to networks and creating a virtual image of real network facilities (called herein, emulation). Basically, the digital twin for networks is an expansion platform of network emulation and can be seen as a tool for scenario planning, impact analysis, and change management. The main difference compared to conventional network simulation is the interactive virtual-real mapping and data driven approach to build closed-loop network automation. By integrating network digital twin into the network management, it allows network maintenance engineers to assess, model, and tweak optimization strategies in a risk-free environment, ensuring that only the most effective changes might be implemented in the real network (i.e., subject to adequate validation and control checks). Digital twin for networks also play a crucial role in root cause analysis, providing a sandbox for assessing hypotheses and validating the outcomes of data-driven insights without impacting end users, when adequate isolation guards are in place. Therefore, digital twin for networks is more than an simulation platform or network simulator.

Through the real-time data interaction between the real network and its twin network(s), the network digital twin platform might help the network designers to achieve more simplification, automatic, resilient, and full life-cycle operation and maintenance. More specifically, the network digital twin can, thus, be used to develop

various rich network applications and assess specific behaviors (including network transformation) before actual implementation in the real network, tweak the network for better optimized behavior, run 'what-if' scenarios that cannot be tested and evaluated easily in the real network. In addition, service impact analysis tasks can also be facilitated.

2. Terminology

2.1. Acronyms & Abbreviations

IBN: Intent-Based Networking

AI Artificial Intelligence

CI/CD: Continuous Integration/Continuous Delivery

ML: Machine Learning

OAM: Operations, Administration, and Maintenance

PLM: Product Lifecycle Management

2.2. Definitions

This document makes use of the following terms:

Digital Twin: Digital counterpart of a physical system (twin) that captures its attributes, behavior, and interactions and is (continually) updated with the latter's performance, maintenance, and health status data throughout the physical system's life cycle.

Network digital twin: A digital representation that is used in the context of Networking and whose physical counterpart is a data network or enterprise network. This is also called, digital twin for networks. See more in [Section 4](#).

Physical network: Object, system, process, software, or environment that the digital twin is designed to replicate and represent virtually.

3. Introduction of Concepts

3.1. Background of Digital Twin

The concept of the "twin" dates to the National Aeronautics and Space Administration (NASA) Apollo program in the 1970s, where a replica of space vehicles on Earth was built to mirror the condition of the equipment during the mission [[Rosen2015](#)].

In 2003, Digital Twin was attributed to John Vickers by Michael

Grieves in his product lifecycle management (PLM) course as "virtual digital representation equivalent to physical products" [Grieves2014]. Digital twin can be defined as a virtual instance of a physical system (twin) that is continually updated with the latter's performance, maintenance, and health status data throughout the physical system's life cycle [Madni2019]. By providing a living copy of physical system, digital twins bring numerous advantages, such as accelerated business processes, enhanced productivity, and faster innovation with reduced costs. So far, digital twin has been successfully applied in the fields of intelligent manufacturing, smart city, or complex system operation and maintenance to help with not only object design and testing, but also management aspects [Tao2019].

Compared with 'digital model' and 'digital shadow', the key difference of 'digital twin' is the direction of data between the physical and virtual systems [Fuller2020]. Typically, when using a digital twin, the (twin) system is generated and then synchronized using data flows in both directions between physical and digital components, so that control data can be sent, and changes between the physical and digital objectives of systems are automatically represented. This behavior is unlike a 'digital model' or 'digital shadow', which are usually synchronized manually, lacking of control data, and might not have a full cycle of data integrated.

At present (2024), there is no unified definition of digital twin framework. The industry, scientific research institutions, and standards developing organizations are trying to define a general or domain-specific framework of digital twin. [Natis-Gartner2017] proposed that building a digital twin of a physical entity requires four key elements: model, data, monitoring, and uniqueness. [Tao2019] proposed a five-dimensional framework of digital twin {PE, VE, SS, DD, CN}, in which PE represents physical entity, VE represents virtual entity, SS represents service, DD represents twin data, and CN represents the connection between various components. [ISO-2021] issued a draft standard for digital twin manufacturing system, and proposed a reference framework including data collection domain, device control domain, digital twin domain, and user domain.

3.2. Digital Twin for Networks

Communication networks provide a solid foundation for implementing various 'digital twin' applications. At the same time, in the face of increasing business types, scale and complexity, a network itself also needs to use digital twin technology to seek enhanced and optimized solutions compared to relying solely on the real network. The motivation for network digital twin can somehow be traced back to some earlier concepts, such as "shadow MIB", inductive modeling techniques, parallel systems, etc. Since 2017, the application of digital twin technology in the field of communication networks has gradually been researched as illustrated by the (non-exhaustive) list

of examples that are listed hereafter.

Within academia, [Dong2019] established the digital twin of 5G mobile edge computing (MEC) network, used the twin offline to train the resource allocation optimization and normalized energy-saving algorithm based on reinforcement learning, and then updated the scheme to MEC network. [Dai2020] established a digital twin edge network for mobile edge computing system, in which a twin edge server is used to evaluate the state of entity server, and the twin mobile edge computing system provides data for training offloading strategy. [Nguyen2021] discusses how to deploy a digital twin for complex 5G networks. [Hong2021] presents a digital twin platform towards automatic and intelligent management for data center networks, and then proposes a simplified the workflows of network service management. [Dai2022] gives the concept of digital twin and proposes an digital twin-enabled vehicular edge computing (VEC) network, where digital twin can enable adaptive network management via the two-closed loops between physical VEC networks and digital twins. In addition, international workshops dedicated to digital twin in networking field have already appeared, such as IEEE DTPI 2021&2022-Digital Twin Network Online Session [DTPI2021], [DTPI2022], and IEEE NOMS 2022 - TNT workshop [TNT2022].

Although the application of digital twin technology in networking has started, the research of digital twin for networks technology is still in its infancy. Current applications focus on specific scenarios (such as network optimization), where network digital twin is just used as a network simulation tool to solve the problem of network operation and maintenance. Combined with the characteristics of digital twin technology and its application in other industries, this document believes that network digital twin can be regarded as an indispensable part of the overall network system and provides a general architecture involving the whole life cycle of real network in the future, serving the application of network innovative technologies such as network planning, construction, maintenance and optimization, improving the automation and intelligence level of the network.

4. Characteristics of Network Digital Twin

So far, there is no standard definition for characteristic of "network digital twin" within the networking industry. This document introduces four key elements (i.e., data, models, mapping, and interfaces) to characterize the network digital twin. These four elements can be integrated into a network management system to analyze, diagnose, emulate, and control the real network. To that aim, a real-time and interactive mapping is required between the real network and its virtual twin network. Whether a Digital Twin supports all or a subset of the functions above (i.e., analyze, diagnose, emulate, and control) is deployment specific.

Referring to the characteristics of digital twin in other industries and the characteristics of the networking itself, the digital twin network should involve at least four key elements: data, mapping, models and interfaces as shown in Figure 1.

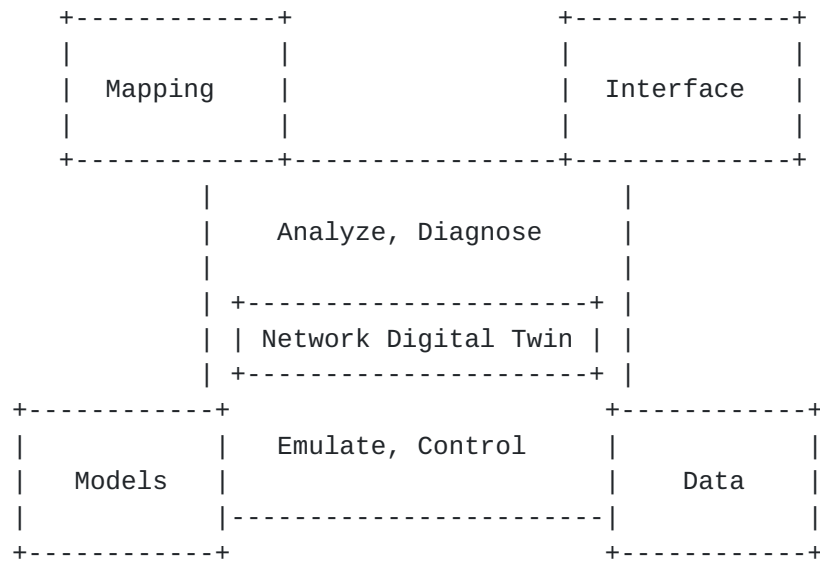


Figure 1: Key Elements of Network Digital Twin

Data: A network digital twin should maintain historical data and/or real time data (configuration data, operational state data, topology data, trace data, metric data, process data, etc.) about its real-world twin (i.e. real network) that are required by the models to represent and understand the states and behaviors of the real-world twin.

The data is characterized as the single source of "truth" and populated in the data repository, which provides timely and accurate data service support for building various models.

Models: Techniques that involve collecting data from one or more sources in the real-world twin and developing a comprehensive representation of the data (e.g., system, entity, or process) using specific models. These models are used as emulation and diagnosis basis to provide dynamics and elements on how the live real network operates and generates reasoning data utilized for decision-making.

Various models such as service models, data models, dataset models, or knowledge graph can be used to represent the real network assets and, then, instantiated to serve various network applications.

Interfaces: Standardized interfaces ensure the interoperability of network digital twin. There are two major types of interfaces:

- * The interface between the network digital twin platform and the real network infrastructure.

- * The interface between network digital twin platform and applications.

: The former provides real-time data collection and control on the real network. The latter helps in delivering application requests to the network digital twin platform and exposing the various platform capabilities to applications.

Mapping: Used to identify the digital twin and the underlying entities and establish a real-time interactive relation between the real network and the twin network or between two twin networks. The mapping can be:

- * One to one (pairing, vertical): Synchronize between a real network and its virtual twin network with continuous flows.

- * One to many (coupling, horizontal): Synchronize among virtual twin networks with occasional data exchange.

Such mappings provide a good visibility of actual status, making the digital twin suitable to analyze and understand what is going on in the real network. It also allows using the digital twin to optimize the performance and maintenance of the real network.

The network digital twin constructed based on the four core technology elements can analyze, diagnose, emulate, and control the real network in its whole life cycle with the help of optimization algorithms, management methods, and expert knowledge. One of the objectives of such control is to master the network digital twin environment and its elements to derive the required system behavior, e.g., provide:

- * repeatability: that is the capacity to replicate network conditions on-demand.

- * reproducibility: i.e., the ability to replay successions of events, possibly under controlled variations.

and "the mirroring pace and scope" should be controlled for a given twin instance.

Note: Realtime interaction is not always mandatory for all twins. For example, when assessing some configuration changes or emulating some innovative techniques, the digital twins can behave as an isolated simulation platform without the need of realtime telemetry data. It might be useful to have interactive mapping capability so that the validated changes can be evaluated under real network conditions whenever required by the testers. Whether realtime interaction between virtual and real network is mandatory

is a configurable parameter. Adequate validation guards have to be enforced at both twin and physical network. Enabling realtime interaction in network digital twin is a catalyst to achieve autonomous networks or self-driven network.

5. Benefits of Network Digital Twin

Network digital twin can help enabling closed-loop network management across the entire lifecycle, from deployment and emulation, to visualized assessment, physical deployment, and continuous verification. By doing so, network operators and end-users to some extent, as allowed by specific application interfaces, can maintain a global, systemic, and consistent view of the network. Also, network operators and/or enterprise user can safely exercise the enforcement of network planning policies, deployment procedures, etc., without jeopardizing the daily operation of the real network.

The main difference between network digital twin and simulation platform is the use of interactive virtual-real mapping to build closed-loop network automation. Simulation platforms are the predecessor of the network digital twin, one example of such a simulation platform is network simulator [NS-3], which can be seen as a variant of network digital twin but with low fidelity and lacking for interactive interfaces to the real network. Compared with those classical approaches, key benefits of network digital twin can be summarized as follows:

- (a) Using real-time data to establish high fidelity twins, the effectiveness of network simulation is higher; then the simulation cost will be relatively low.
- (b) The impact and risk on running networks is low when automatically applying configuration/policy changes after the full analysis and required verifications (e.g., service impact analysis) within the twin network.
- (c) The faults of the real network can be automatically captured by analyzing real-time data, then the correction strategy can be distributed to the real network elements after conducting adequate analysis within the twins to complete the closed-loop automatic fault repair.

The following subsections further elaborate such benefits in details.

5.1. Optimized Network Total Cost of Operation

Large scale networks are complex to operate. Since there is no effective platform for simulation, network optimization designs have to be tested on the real network at the cost of jeopardizing its daily operation and possibly degrading the quality of the services supported by the network. Such assessment greatly increases network

operator's Operational Expenditure (OPEX) budgets too.

With a network digital twin platform, network operators can safely emulate candidate optimization solutions before deploying them on the real network. In addition, operator's OPEX on the real network deployment will be greatly decreased accordingly at the cost of the complexity of the assessment and the resources involved.

5.2. Optimized Decision Making

Traditional network operation and management mainly focus on deploying and managing running services, but hardly support predictive maintenance techniques.

Network digital twin can combine data acquisition, big data processing, and AI modeling to assess the status of the network, but also to predict future trends, and better organize predictive maintenance. The ability to reproduce network behaviors under various conditions facilitates the corresponding assessment of the various evolution options as often as required.

5.3. Safer Assessment of Innovative Network Capabilities

Testing a new feature in an operational network is not only complex, but also extremely risky. Service impact analysis is required to be adequately achieved prior to effective activation of a new feature.

Network digital twin can greatly help assessing innovative network capabilities without jeopardizing the daily operation of the real network. In addition, it helps researchers to explore network innovation (e.g., new network protocols, network AI/ML applications) efficiently, and network operators to deploy new technologies quickly with lower risks. Take AI/ ML application as example, it is a conflict between the continuous high reliability requirement (i.e., 99.999%) and the slow learning speed or phase-in learning steps of AI/ML algorithms. With network digital twin, AI/ML can complete the learning and training with the sufficient data before deploying the model in the real network. This would encourage more network AI innovations in future networks.

5.4. Privacy and Regulatory Compliance

The requirements on data confidentiality and privacy on network providers increase the complexity of network management, as decisions made by computation logics such as an SDN controller may rely upon the packet payloads. As a result, the improvement of data-driven management requires complementary techniques that can provide a strict control based upon security mechanisms to guarantee data privacy protection and regulatory compliance. This may range from flow identification (using the archetypal five-tuple of addresses, ports and protocol) to techniques requiring some degree of payload

inspection, all of them considered suitable to be associated to an individual person, and hence requiring strong protection and/or data anonymization mechanisms.

With strong modeling capability provided by the network digital twin, very limited real data (if at all) will be needed to achieve similar or even higher level of data-driven intelligent analysis. This way, a lower demand of sensitive data will permit to satisfy privacy requirements and simplify the use of privacy-preserving techniques for data-driven operation.

5.5. Customized Network Operation Training

Network architectures can be complex, and their operation requires expert personnel. Network digital twin offers an opportunity to train staff for customized networks and specific user needs. Two salient examples are the application of new network architectures and protocols or the use of "cyber-ranges" to train security experts in threat detection and mitigation.

6. Challenges to Build Network Digital Twin

According to [Hu2021], the main challenges in building and maintaining digital twins can be summarized as the following five aspects:

- * Data acquisition and processing
- * High-fidelity modeling
- * Real-time, two-way communication between the virtual and the real twins
- * Unified development platform and tools
- * Environmental coupling technologies

Compared with other industrial fields, digital twin in networking field has its unique characteristics. On one hand, network elements and system have higher level of digitalization, which implies that data acquisition and virtual-real communication are relatively easy to achieve. On the other hand, there are various different type of network elements and typologies in the network field; and the network size is characterized by the numbers of nodes and links in it but the network size growth pace can not meet the service needs, especially in the deployment of end to end service which spans across multiple administrative domains. So, the construction of a digital twin network system needs to consider the following major challenges:

Large scale challenge: A digital twin of large-scale networks will significantly increase the complexity of data acquisition and storage, the design and implementation of relevant models. The

requirements of software and hardware of the network digital twin system will be even more constraining. Therefore, efficient and low cost tools in various fields should be required. Take data as an example, massive network data can help achieve more accurate models. However, the cost of virtual-real communication and data storage becomes extremely expensive, especially in the multi-domain data-driven network management case, therefore efficient tools on data collection and data compression methods must be used.

Interoperability: Due to the inconsistency of technical implementations and the heterogeneity of vendor adopted technologies, it is difficult to establish a unified digital twin network system with a common technology in a network domain. Therefore, it is needed firstly to propose a unified architecture of network digital twin, in which all components and functionalities are clear to all stakeholders; then define standardized and unified interfaces to connect all network twins via ensuring necessary compatibility.

Data modeling difficulties: Based on large-scale network data, data modeling should not only focus on ensuring the accuracy of model functions, but also has to consider the flexibility and scalability to compose and extend as required to support large scale and multi-purpose applications. Balancing these requirements further increases the complexity of building efficient and hierarchical functional data models. As an optional solution, straightforwardly clone the real network using virtualized resources is feasible to build the twin network when the network scale is relatively small. However, it will be of unaffordable resource cost for larger scales network. In this case, network modeling using mathematical abstraction or leveraging the AI algorithms will be more suitable solutions.

Real-time requirements: Network services normally have real-time requirements, the processing of model simulation and verification through a network digital twin will introduce the service latency. Meanwhile, the real-time requirements will further impose performance requirements on the system software and hardware. However, given the nature of distributed systems and propagation delays, it is challenge to keep network digital twins in sync or auto-sync between real network and network digital twin.

Changes to the digital object automatically drive changes in the real object can be even challenging. To address these requirements, the function and process of the data model need to be based on automated processing mechanism under various network application scenarios. On the one hand, it is needed to design a simplified process to reduce the time cost for tasks in network twin as much as possible; on the other hand, it is recommended to define the real-time requirements of different applications, and

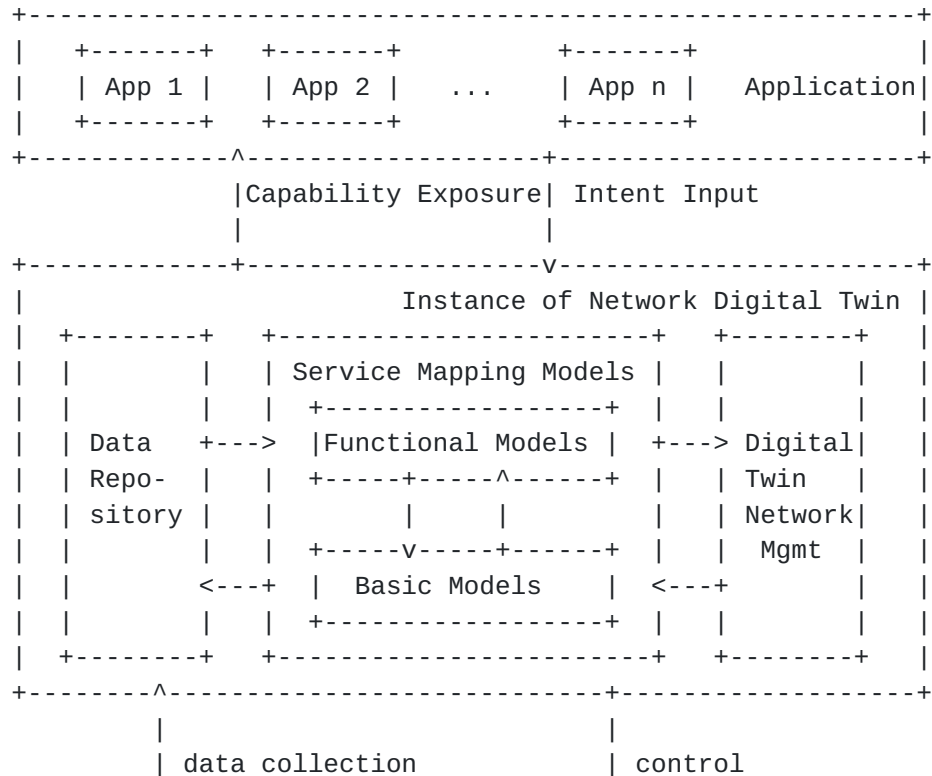
then match the corresponding computing resources and suitable solutions as needed to complete the task processing in the twin.

Security risks: A network digital twin has to synchronize all or subset of the data related to involved real networks in real time, which inevitably augments the attack surface, with a higher risk of information leakage, in particular. On one hand, it is mandatory to design more secure data mechanism leveraging legacy data protection methods, as well as innovative technologies such as block chain. On the other hand, the system design can limit the data (especially raw data) requirement on building digital twin network, leveraging innovative modeling technologies such as federal learning.

To address the above listed challenges, it is important to agree on a unified architecture of network digital twin, which defines the main functional components and interfaces ([Section 7](#)). Then, relying upon such an architecture, it is required to continue researching on the key enabling technologies including data acquisition, data storage, data modeling, interface standardization, and security assurance.

7. A Reference Architecture of Network Digital Twin

Based on the definition of the key network digital twin technology elements introduced in [Section 4](#), a network digital twin architecture is depicted in Figure 2. This network digital twin architecture is broken down into three layers: Application Layer, Digital Twin Layer, and Real Network Layer.



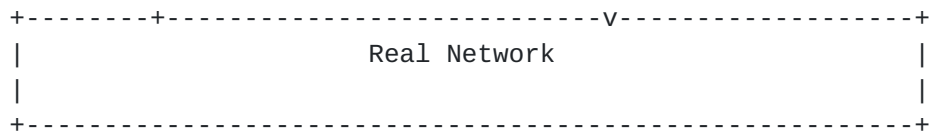


Figure 2: Reference Architecture of Network Digital Twin

Real Network: All or subset of network elements in the real network exchange network data and control messages with a network digital twin instance, through twin-real control interfaces. The real network can be a mobile access network, a transport network, a mobile core, a backbone, etc. The real network can also be a data center network, a campus enterprise network, an industrial Internet of Things, etc.

The real network can span across a single network administrative domain or multiple network administrative domains. And, the real network can include both physical entities and some virtual entities (e.g. vSwitches, NFVs, etc.), which together carry traffic and provide actual network services.

This document focuses on the IETF related real network such as IP bearer network and data center network.

Digital Twin Layer: This layer includes three key subsystems: Data Repository subsystem, Service Mapping Models subsystem, and Network Digital Twin Management subsystem. These key subsystems can be placed in one single network administrative domain and provide the service to the application (e.g., SDN controller) in other network administrative domain, or lied in every network administrative domain and coordinate between each other to provide services to the application in the upper layer.

One or multiple network digital twin instances can be built and maintained:

- * Data Repository subsystem is responsible for collecting and storing various network data for building various models by collecting and updating the real-time operational data of various network elements through the twin southbound interface, and providing data services (e.g., fast retrieval, concurrent conflict handling, batch service) and unified interfaces to Service Mapping Models subsystem.
- * Service Mapping Models complete data modeling, provide data model instances for various network applications, and maximizes the agility and programmability of network services. The data models include two major types: basic and functional models.
 - Basic models refer to the network element model(s) and network topology model(s) of the network digital twin based

on the basic configuration, environment information, operational state, link topology and other information of the network element(s), to complete the real-time accurate characterization of the real network.

- Functional models refer to various data models used for network analysis, emulation, diagnosis, prediction, assurance, etc. The functional models can be constructed and expanded by multiple dimensions: by network type, there can be models serving for a single or multiple network domains; by function type, it can be divided into state monitoring, traffic analysis, security exercise, fault diagnosis, quality assurance and other models; by network lifecycle management, it can be divided into planning, construction, maintenance, optimization and operation. Functional models can also be divided into general models and special-purpose models. Specifically, multiple dimensions can be combined to create a data model for more specific application scenarios. New applications might need new functional models that do not exist yet. If a new model is needed, 'Service Mapping Models' subsystem will be triggered to help creating new models based on data retrieved from 'Data Repository'.

- * Network Digital Twin Management fulfils the management function of network digital twin, records the life-cycle transactions of the twin entity, monitors the performance and resource consumption of the twin entity or even of individual models, visualizes and controls various elements of the network digital twin, including topology management, model management and security management.

Notes: 'Data collection' and 'change control' are regarded as network-facing interfaces between virtual and real network. From implementation perspective, they may form a sub-layer or subsystem to provide common data collection and change control functions, enabled by a specific infrastructure supporting bi-directional flows and facilitating data aggregation, action translation, pre-processing, and ontologies. It might not be possible or necessary to 'synchronize' all twin state or flows from twin entity to physical entity or network management system. Bi-directional interaction means that: data, state, or flows are reported or collected from the physical network or the network management system to a twin instance, and configure changes or 'necessary' data sent from a twin instance to physical.

Application Layer: Various applications (e.g., Operations, Administration, and Maintenance (OAM)) can effectively run over a network digital twin platform to implement either conventional or innovative network operations, with low cost and less service impact on real networks. Network applications make requests that need to be addressed by the network digital twin. Such requests are exchanged

through a northbound interface, so they are applied by service emulation at the appropriate twin instance(s).

8. Enabling Technologies to Build Network Digital Twin

This section briefly describes several key enabling technologies to build digital twin work system, based on the challenges and the reference architecture described in above sections. Actually, each enabling technology is worth of deep researching respectively and separately.

8.1. Data Collection and Data Services

Data collection technology is the foundation of building data repository for network digital twin. Target driven mode should be adopted for data collection from heterogeneous data sources. The type, frequency and method of data collection shall meet the application of network digital twin. Whenever building network models for a specific network application, the required data can be efficiently obtained from the data repository.

Diverse existing tools and methods (e.g., SNMP, NETCONF [[RFC6241](#)], IPFIX [[RFC7011](#)], and telemetry [[RFC9232](#)]) can be used to collect different type of network data. YANG data models and associated mechanisms defined in [[RFC8639](#)][[RFC8641](#)] enable subscriber-specific subscriptions to a publisher's event streams. Such mechanisms can be used by subscriber applications to request for a continuous and customized stream of updates from a YANG datastore. Moreover, some innovative methods (e.g., sketch-based measurement) can be used to acquire more complex network data, such as network performance data. Furthermore, data transformation and aggregation capabilities can be used to improve the applicability on network modelling. Toward building data repository for a digital twin system, data collection tools and methods should be as lightweight as possible, so as to reduce the volume of required network equipment resources, and meaningful so it can be useful. Several solutions related to data collection are work-in-progress in IETF/IRTF, e.g., adaptive subscription [[I-D.ietf-netconf-adaptive-subscription](#)], efficient data collection [[I-D.zcz-nmrg-digitaltwin-data-collection](#)], and contextual information [[I-D.claise-opsawg-collected-data-manifest](#)].

Data repository works to effectively store large-scale and heterogeneous network data, as well provide data and services to build various network models. So, it is also necessary to study technologies regarding data services including fast search, batch-data handling, conflict avoidance, data access interfaces, etc.

8.2. Network Modeling

The basic network element models and topology models help generate virtual twin of the network according to the network element

configuration, operation data, network topology relationship, link state and other network information. Then the operation status can be monitored and displayed, and the network configuration change and optimization strategy can be pre-verified.

For small scale network, network simulating tools (e.g., [[NS-3](#)], [[Mininet](#)], etc.) and emulating tools (e.g., [[EVE-NG](#)], [[GNS-3](#)]) can be used to build basic network models. By using the packet processing capability of virtual network element, such tools can quickly verify the functions of the control plane and data plane. However, this modeling method also has many limitations, including high resource consumption, poor performance analysis ability, and poor scalability. For large scale network, mathematical abstraction methods can be used to build basic network models efficiently. Knowledge graph, network calculus, and formal verification can be candidate methods. Some relevant researches have emerged in recent years, such as [[Hong2021](#)], [[G2-SIGCOMM](#)], and [[DNA-2022](#)]. Going forward, how to improve the extensibility and accuracy of the models is still a big challenge.

As an example, the theory of bottleneck structures introduced in [[G2-SIGCOMM](#)], [[G2-SIGMETRICS](#)] can be used to construct a mathematical model of the network (see also [[I-D.giraltyellamraju-alto-bsg-requirements](#)] for more info). A bottleneck structure is a computational graph that efficiently captures the topology, the routing and flow properties of the network. The graph embeds the latent relationships that exist between bottlenecks and the application flows in a distributed system, providing an efficient mathematical framework to compute the ripple effects of perturbations (e.g., a flow arriving or departing from the system, or the dynamic change in capacity of a wireless link, among others). Because these perturbations can be seen as mathematical derivatives of the communication system, bottleneck structures can be used to compute optimized network configurations, providing a natural engineering sandbox for building network models. One of the key advantages of bottleneck structures is that they can be used to compute (symbolically or numerically) key performance indicators of the network (e.g., expected flow throughput, projected flow completion time, etc.) without the need to use computationally intensive simulators. This capability can be especially useful when building a digital twin or a large-scale network, potentially saving orders or magnitude in computational resources in comparison to simulation or emulation-based approaches.

The functional model aims to realize the dynamic evolution of network performance evaluation and intelligent decision-making. Data driven AI/ML algorithm will play a great role in building complex network functional models. As a research hotspot in recent years, many successfully cases have been demonstrated, such as [[RouteNet](#)], [[MimicNet](#)], etc. In the future, in addition to improving the generalization ability and interpretability of AI models, we also need to focus on how to improve the real-time and interactivity of

model reasoning based on data and control in network digital twin layer.

8.3. Network Visualization

It is the internal requirement of the network digital twin system to use network visibility technology to visually present the data and model in the network twin with high fidelity and intuitively reflect the interactive mapping between the real network entity and the network twin. Network Visibility technology can help users understand the internal structure of the network, and also help mine valuable information hidden in the network.

Network Visibility can use algorithms such as hierarchical layout, heuristic layout or force oriented layout (or a combination of several algorithms) for topology layout. The related topology data can be acquired using solutions provided in [[RFC8345](#)], [[RFC8346](#)], [[RFC8944](#)], etc. Meanwhile, network digital twin system can select different interaction methods or combinations of interaction methods to realize the visual dynamic interaction mapping of virtual and real networks. The data query technology, such as SPARQL, can be used to express queries across diverse data sources, whether the data is stored natively as RDF or viewed as RDF via middleware.

8.4. Interfaces

Based on the reference architecture, there are three types of interfaces on building a network digital twin system:

- (d) Network-facing interfaces are twin interfaces between the real network and its twin entity. They are responsible for information exchange between real network and network digital twin. The candidate interfaces can be SNMP, NETCONF, etc.
- (e) Application-facing interfaces are Application-facing interfaces between the network digital twin and applications. They are responsible for information exchange between network digital twin and network applications. The lightweight and extensible [[RESTful](#)] interface can be the candidate northbound interface.
- (f) Internal interfaces are within network digital twin layer. They are responsible for information exchange between the three subsystems: Data Repository, Service Mapping Models, and Digital Twin Network Management. These interfaces should be of high-speed, high-efficiency and high-concurrency. The candidate interfaces or protocols can be XMPP [[RFC7622](#)] or HTTP/3.0 [[RFC9114](#)].

All these interfaces are recommended to be open and standardized interfaces so as to avoid either hardware or software vendor lock, and achieve interoperability. Besides the interfaces list above,

some new interfaces or protocols can be created to better serve digital twin network system.

8.5. Twinning Management

Twining management is the key to the efficient deployment and potential value of network digital twin systems in production networks. Twinning management technology inputs all information and data from each step of network business into the constructed model through the construction of digital threads for optimization, prediction, and guidance. Then, the implementation results are analyzed to see if they meet expectations, and any actions are fed back to form a closed loop. Twinning management involves various network components (e.g., controller, orchestrator) and domains (security, for example) from end to end, including, but not limited to, the following main technologies:

- * **Orchestration of twins:** Manage and organize multiple twin model instances, including the creation, deletion, storage, version control, and deployment of model instances, and arrange required modeling resources as needed to maximize resource utilization efficiency.
- * **Collaboration Management:** Coordinate multiple participants, such as network administrators, data scientists, security teams, etc., to ensure the accuracy and real-time performance of the twins. Involve collaborative tools, workflow design, data sharing, and permission control to promote cooperation and information sharing among all parties.
- * **Conflict Detection and Resolution:** Identify and address conflicts including user intents, access control policies, or multiple applications interacting within the digital twin network system. Conflict detection and resolution techniques may use various mechanisms, such as rule-based policies, role-based access control, or dynamic conflict resolution algorithms (e.g. [[Pradeep2022](#)] and [[Zheng2022](#)]).
- * **Energy-Efficient Twinning:** Focus on energy efficiency in digital twin network system. It includes monitoring and optimizing the energy consumption of both network equipment and digital twin system operation, reducing the energy expenditure of network operation, and achieving the goal of green network.

9. Interaction with Intent-Based Networking (IBN)

Intent-based, means that users can input their abstract 'intent' to the network, instead of detailed policies or configurations on the network devices. [[RFC9315](#)] clarifies the concept of "Intent" and provides an overview of IBN functionalities. The key characteristic of an IBN system is that user intent can be assured automatically via

continuously adjusting the policies and validating the real-time situation.

IBN can be envisaged in a network digital twin context to show how network digital twin improves the efficiency of deploying network innovation. To lower the impact on real networks, several rounds of adjustment and validation can be emulated on the network digital twin platform instead of directly on real network. Therefore, the digital twin network can be an important enabler platform to implement IBN systems and fooster their deployment.

10. Sample Application Scenarios

Network digital twin can be applied to solve different problems in network management and operation.

10.1. Human Training

The usual approach to network OAM with procedures applied by humans is open to errors in all these procedures, with impact in network availability and resilience. Response procedures and actions for most relevant operational requests and incidents are commonly defined to reduce errors to a minimum. The progressive automation of these procedures, such as predictive control or closed-loop management, reduce the faults and response time, but still there is the need of a human-in-the-loop for multiples actions. These processes are not intuitive and require training to learn how to respond.

The use of network digital twin for this purpose in different network management activities will improve the operators performance. One common example is cybersecurity incident handling, where "cyber-range" exercises are executed periodically to train security practitioners. Network digital twin will offer realistic environments, fitted to the real production networks.

10.2. Machine Learning Training

Machine Learning requires data and their context to be available in order to apply it. A common approach in the network management environment has been to simulate or import data in a specific environment (the ML developer lab), where they are used to train the selected model, while later, when the model is deployed in production, re-train or adjust to the production environment context. This demands a specific adaption period.

Network digital twin simplifies the complete ML lifecycle development by providing a realistic environment, including network topologies, to generate the data required in a well-aligned context. Dataset generated belongs to the network digital twin and not to the production network, allowing information access by third parties, without impacting data privacy.

10.3. DevOps-Oriented Certification

The potential application of CI/CD models network management operations increases the risk associated to deployment of non-validated updates, what conflicts with the goal of the certification requirements applied by network service providers. A solution for addressing these certification requirements is to verify the specific impacts of updates on service assurance and Service Level Agreements (SLAs) using a network digital twin environment replicating the network particularities, as a previous step to production release.

Network digital twin control functional block supports such dynamic mechanisms required by DevOps procedures.

10.4. Network Fuzzing

Network management dependency on programmability increases systems complexity. The behavior of new protocol stacks, API parameters, and interactions among complex software components are examples that imply higher risk to errors or vulnerabilities in software and configuration.

Network digital twin allows to apply fuzzing testing techniques on a twin network environment, with interactions and conditions similar to the production network, permitting to identify and solve vulnerabilities, bugs and zero-days attacks before production delivery.

10.5. Network Inventory Management

With the development of enterprise digitization, the number of enterprise Internet of Objects (IoT) devices, virtualized Cloud software inventory component (e.g., virtual firewall), and network hardware inventory (e.g., switches or routers) also increases. The endpoints connected to an enterprise network lack coherent modelling and lifecycle management because different services are modelled, collected, processed, and stored separately. The same category of network devices (including network endpoints) may be repeatedly discovered, processed, and stored. Therefore, the inventory is difficult to manage when they are tracked in different places without formal synchronization procedures.

Network digital twin management can be used as a means to ensure consistent representation and reporting of inventory component types. In doing so, the enforcement of security policies and assessment will be further simplified. Such an approach will ease implementing a unified control strategy for all inventory components types connected to an enterprise network. It also make actors on assets more accountable for breaching their compliance promises. Special care should be considered to protect the inventory data since it may be gather privacy-sensitive information.

The network inventory management for twins or various inventory components can be used, for example, to exercise the implication of End of Life (EoL), dependency, and hardware dependency "what-if" scenarios.

11. Research Perspectives: A Summary

Research on network digital twin has just started. This document presents an overview of the network digital twin concepts and reference architecture. Looking forward, further elaboration on network digital twin scenarios, requirements, architecture, and key enabling technologies should be investigated by the industry, so as to accelerate the implementation and deployment of digital twin network.

12. Security Considerations

This document describes concepts and definitions of digital twin network. As such, the following security considerations remain high level, i.e., in the form of principles, guidelines or requirements.

Security considerations of the network digital twin include:

- * Secure the digital twin system itself.
- * Data privacy protection.

Securing the network digital twin system aims at making the digital twin system operationally secure by implementing security mechanisms and applying security best practices. In the context of digital twin network, such mechanisms and practices may consist in data verification and model validation, mapping operations between real network and digital counterpart network by authenticated and authorized users only.

Synchronizing the data between the real network and the twin network may increase the risk of sensitive data and information leakage. Strict control and security mechanisms must be provided and enabled to prevent data leaks.

13. IANA Considerations

This document has no requests to IANA.

14. Open issues

Refer to: <https://github.com/cheneyzhoucheng/network-digital-twin/issues> (<https://github.com/cheneyzhoucheng/network-digital-twin/issues>).

15. Informative References

- [Dai2020] IEEE Transactions on Industrial Informatics, "Deep Reinforcement Learning for Stochastic Computation Offloading in Digital Twin Networks", August 2020.
- [Dai2022] Journal of Communications and Information Networks, "Adaptive Digital Twin for Vehicular Edge Computing and Networks", March 2022.
- [DNA-2022] NSDI 22, "Differential Network Analysis, USENIX Symposium on Networked Systems Design and Implementation", 2023.
- [Dong2019] IEEE Transactions on Wireless Communications, "Deep Learning for Hybrid 5G Services in Mobile Edge Computing Systems: Learn from a Digital Twin", July 2019.
- [DTPI2021] "IEEE International Conference on Digital Twins and Parallel Intelligence - Digital Twin Network Session", July 2021, <<https://www.dtpi.org/video/10>>.
- [DTPI2022] "IEEE International Conference on Digital Twins and Parallel Intelligence - Digital Twin Network Session", October 2022, <<https://c.trvqd.com/#/television?id=1584825225713631235&preview=2>>.
- [EVE-NG] "Emulated Virtual Environment Next Generation", n.d., <<https://www.eve-ng.net/>>.
- [Fuller2020]
IEEE Access, "Digital Twin: Enabling Technologies, Challenges and Open Research", 2020.
- [G2-SIGCOMM]
ACM SIGCOMM, "Designing data center networks using bottleneck structures", August 2021.
- [G2-SIGMETRICS]
ACM SIGMETRICS, "On the Bottleneck Structure of Congestion-Controlled Networks", December 2019.
- [GNS-3] "Graphical Network Simulator-3, GNS3", n.d., <<https://www.gns3.com/>>.
- [Grieves2014]
"Digital twin: Manufacturing excellence through virtual factory replication", 2003, <<https://www.3ds.com/fileadmin/PRODUCTS-SERVICES/DELMIA/PDF/Whitepaper/DELMIA-APRISO-Digital-Twin-Whitepaper.pdf>>.
- [Hong2021] ACM SIGCOMM 2021 Workshop on Network-Application Integration (NAI' 21), "NetGraph: An Intelligent Operated

Digital Twin Platform for Data Center Networks", 2021.

[Hu2021] Journal of Intelligent Manufacturing and Special Equipment, "Digital twin: a state-of-the-art review of its enabling technologies, applications and challenges", 2021.

[I-D.claise-opsawg-collected-data-manifest]
Claise, B., Quilbeuf, J., Lopez, D., Martinez-Casanueva, I. D., and T. Graf, "A Data Manifest for Contextualized Telemetry Data", Work in Progress, Internet-Draft, [draft-claise-opsawg-collected-data-manifest-06](https://datatracker.ietf.org/doc/html/draft-claise-opsawg-collected-data-manifest-06), 10 March 2023, <<https://datatracker.ietf.org/doc/html/draft-claise-opsawg-collected-data-manifest-06>>.

[I-D.giraltyellamraju-alto-bsg-requirements]
Ros-Giralt, J., Yellamraju, S., Wu, Q., Contreras, L. M., Yang, Y. R., and K. Gao, "Supporting Bottleneck Structure Graphs in ALT0: Use Cases and Requirements", Work in Progress, Internet-Draft, [draft-giraltyellamraju-alto-bsg-requirements-03](https://datatracker.ietf.org/doc/html/draft-giraltyellamraju-alto-bsg-requirements-03), 23 September 2022, <<https://datatracker.ietf.org/doc/html/draft-giraltyellamraju-alto-bsg-requirements-03>>.

[I-D.ietf-netconf-adaptive-subscription]
Wu, Q., Song, W., Liu, P., Ma, Q., Wang, W., and Z. Niu, "Adaptive Subscription to YANG Notification", Work in Progress, Internet-Draft, [draft-ietf-netconf-adaptive-subscription-04](https://datatracker.ietf.org/doc/html/draft-ietf-netconf-adaptive-subscription-04), 12 December 2023, <<https://datatracker.ietf.org/doc/html/draft-ietf-netconf-adaptive-subscription-04>>.

[I-D.zcz-nmrg-digitaltwin-data-collection]
Zhou, C., Chen, D., Martinez-Julia, P., and Q. Ma, "Data Collection Requirements and Technologies for Digital Twin Network", Work in Progress, Internet-Draft, [draft-zcz-nmrg-digitaltwin-data-collection-03](https://datatracker.ietf.org/doc/html/draft-zcz-nmrg-digitaltwin-data-collection-03), 9 July 2023, <<https://datatracker.ietf.org/doc/html/draft-zcz-nmrg-digitaltwin-data-collection-03>>.

[ISO-2021] ISO, "Digital Twin manufacturing framework - Part 2: Reference architecture: ISO/CD 23247-2", 2021, <<https://www.iso.org/standard/78743.html>>.

[Madni2019]
"Leveraging digital twin technology in model-based systems engineering", January 2019.

[MimicNet] ACM SIGCOMM 2021 Conference (SIGCOMM '21), "MimicNet: Fast Performance Estimates for Data Center Networks with Machine Learning", 2021.

- [Mininet] "Mninet: An Instant Virtual Network on your Laptop", n.d., <<http://mininet.org/>>.
- [Natis-Gartner2017] "Innovation insight for digital twins - driving better IoT-fueled decisions", 2017, <<https://www.gartner.com/en/documents/3645341>>.
- [Nguyen2021] IEEE Communications Magazine, "Digital Twin for 5G and Beyond", February 2021.
- [NS-3] "Network Simulator, NS-3", n.d., <<https://www.nsnam.org/>>.
- [Pradeep2022] "Conflict Detection and Resolution in IoT Systems: A Survey. IoT 2022", February 2022.
- [RESTFul] O'Reilly Media, Inc, "RESTful Web APIs", 2013.
- [RFC6241] Enns, R., Ed., Bjorklund, M., Ed., Schoenwaelder, J., Ed., and A. Bierman, Ed., "Network Configuration Protocol (NETCONF)", [RFC 6241](#), DOI 10.17487/RFC6241, June 2011, <<https://www.rfc-editor.org/rfc/rfc6241>>.
- [RFC7011] Claise, B., Ed., Trammell, B., Ed., and P. Aitken, "Specification of the IP Flow Information Export (IPFIX) Protocol for the Exchange of Flow Information", STD 77, [RFC 7011](#), DOI 10.17487/RFC7011, September 2013, <<https://www.rfc-editor.org/rfc/rfc7011>>.
- [RFC7622] Saint-Andre, P., "Extensible Messaging and Presence Protocol (XMPP): Address Format", [RFC 7622](#), DOI 10.17487/RFC7622, September 2015, <<https://www.rfc-editor.org/rfc/rfc7622>>.
- [RFC8345] Clemm, A., Medved, J., Varga, R., Bahadur, N., Ananthakrishnan, H., and X. Liu, "A YANG Data Model for Network Topologies", [RFC 8345](#), DOI 10.17487/RFC8345, March 2018, <<https://www.rfc-editor.org/rfc/rfc8345>>.
- [RFC8346] Clemm, A., Medved, J., Varga, R., Liu, X., Ananthakrishnan, H., and N. Bahadur, "A YANG Data Model for Layer 3 Topologies", [RFC 8346](#), DOI 10.17487/RFC8346, March 2018, <<https://www.rfc-editor.org/rfc/rfc8346>>.
- [RFC8639] Voit, E., Clemm, A., Gonzalez Prieto, A., Nilsen-Nygaard, E., and A. Tripathy, "Subscription to YANG Notifications", [RFC 8639](#), DOI 10.17487/RFC8639, September 2019, <<https://www.rfc-editor.org/rfc/rfc8639>>.
- [RFC8641] Clemm, A. and E. Voit, "Subscription to YANG Notifications

- for Datastore Updates", [RFC 8641](#), DOI 10.17487/RFC8641, September 2019, <<https://www.rfc-editor.org/rfc/rfc8641>>.
- [RFC8944] Dong, J., Wei, X., Wu, Q., Boucadair, M., and A. Liu, "A YANG Data Model for Layer 2 Network Topologies", [RFC 8944](#), DOI 10.17487/RFC8944, November 2020, <<https://www.rfc-editor.org/rfc/rfc8944>>.
- [RFC9114] Bishop, M., Ed., "HTTP/3", [RFC 9114](#), DOI 10.17487/RFC9114, June 2022, <<https://www.rfc-editor.org/rfc/rfc9114>>.
- [RFC9232] Song, H., Qin, F., Martinez-Julia, P., Ciavaglia, L., and A. Wang, "Network Telemetry Framework", [RFC 9232](#), DOI 10.17487/RFC9232, May 2022, <<https://www.rfc-editor.org/rfc/rfc9232>>.
- [RFC9315] Clemm, A., Ciavaglia, L., Granville, L. Z., and J. Tantsura, "Intent-Based Networking - Concepts and Definitions", [RFC 9315](#), DOI 10.17487/RFC9315, October 2022, <<https://www.rfc-editor.org/rfc/rfc9315>>.
- [Rosen2015] IFAC-Papersonline, "About the importance of autonomy and DTs for the future of manufacturing", 2015.
- [RouteNet] IEEE Journal on Selected Areas in Communication (JSAC), "RouteNet:Leveraging Graph Neural Networks for network modeling and optimization in SDN", October 2020.
- [Tao2019] IEEE Transactions on Industrial Informatics, "Digital Twin in Industry: State-of-the-Art", April 2019.
- [TNT2022] "IEEE International workshop on Technologies for Network Twins", 2022, <<https://noms2022.ieee-noms.org/ws4-1st-international-workshop-technologies-network-twins-tnt-2022>>.
- [Zheng2022] "Intent Based Networking management with conflict detection and policy resolution in an enterprise network, Computer Networks, Volume 219", December 2022.

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