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Network Digital Twin: Concepts and Reference Architecture
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Abstract

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

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

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Table of Contents

1. Introduction

The rapid expansion of network scale and the increasing demands on these networks necessitate their dynamic adaptation to customer needs, presenting significant challenges for network operators. Network operation and maintenance are becoming increasingly complex due to the advanced nature of the networks and the sophisticated services they provide. Consequently, introducing innovations in network technologies, management, and operations is becoming more challenging due to the high risk of disrupting existing services and the elevated costs of trials without reliable emulation platforms.

A Digital Twin is a real-time digital representation of a physical entity. It features virtual-reality interrelation and real-time interaction, iterative operation and process optimization, and full life-cycle, comprehensive data-driven network infrastructure. Digital Twins have gained widespread recognition in academic publications and are now being widely adopted for Industry 4.0 use cases. The reader may refer to Section 3 for more details.

A Digital Twin for networks can be created by applying Digital Twin technologies to networks, resulting in a virtual replica of real network facilities (emulation). A Network Digital Twin (NDT) is an advanced platform for network emulation, serving as a tool for scenario planning, impact analysis, and change management. Unlike conventional network simulation, it features an interactive virtual-real mapping and a data-driven approach to establish closed-loop network automation.

Integrating a Network Digital Twin into network management allows engineers to assess, model, and refine optimization strategies under real conditions but in a risk-free environment. This ensures that only the most effective changes are implemented in the real network, following thorough validation and control checks. Moreover, a Network Digital Twin captures and aggregates critical data for analyzing the root causes of network failures, anomalies, vulnerabilities, etc. It also offers a sandbox for testing hypotheses, exercising mitigation scenarios, and validating data-driven insights without affecting end-users.

Through the real-time data interaction between the real network and its twin network(s), the NDT platform will provide the data for NDT-based applications and network designers to achieve greater simplification, automation, resilience testing ("what-if" scenarios), and full life-cycle operation and infrastructure maintenance.

2. Terminology

2.1. Acronyms and Abbreviations

AI: Artificial Intelligence

IBN: Intent-Based Networking

ML: Machine Learning

NDT: Network Digital Twin

SDN: Software Defined Networking

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 (e.g., provider network or enterprise network). This is also called, digital twin for networks. See more in Section 4.

Physical Network: Network entities composed of network infrastructure (physical network elements, virtual network elements, network topology, physical connectivities among network elements, etc.) 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 a 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, machining, smart city, healthcare, etc., to help with not only object design and testing, but also management aspects [Tao2019] [Chen2023] [Wang2024] [Liu2024]. And it is playing a vital role in fulfilling various requirements of Industry 4.0 [Javaid2023].

Compared with ’digital model’ and ’digital shadow’, the key difference between ’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. Then there is a partial or full synchronization of data flows in both directions between physical and digital components, so that control data can be sent, and changes between systems’ physical and digital objectives are automatically represented. This behavior is unlike a ’digital model’ or ’digital shadow’, which are usually synchronized manually, lacking control data, and might not have integrated a full cycle of data.

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-2023] defined concepts and terminology of Digital Twin. [ISO-2021] proposed a reference framework for Digital Twin manufacturing system, 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 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 workflow of network service management. [Dai2022] gives the concept of Digital Twin and proposes a 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 been held many times, such as IEEE DTPI - Digital Twin Network sessions [DTPI2021] [DTPI2022], and IEEE NOMS - Network Digital Twin workshops [TNT2022] [TNT2023] [TNT2024]. And IEEE Network Magazine solicited a special issue on NDT, highlighted the advances in the theories, methods, implementations, and applications of the Network Digital Twin [Cui2024].

Although the application of Digital Twin technology in networking has started, the research on Digital Twins for networks technology is still in its infancy. Current applications focus on specific scenarios (such as network optimization), where a Network Digital Twin is used as a network simulation tool to solve particular problems in 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 can play an important role generally in architectures serving use cases across the whole life cycle of a "real" (typically, physical) network. Such use cases and applications span the range of network operations (e.g., network planning, construction, maintenance and optimization), and aim to improve the automation and intelligence level of the network.

4. Characteristics of Network Digital Twin

So far, there is no unified definition of the "network digital twin" characteristics within the networking industry. Referring to the characteristics of Digital Twins in other industries and the characteristics of networking itself, this document introduces five key elements (i.e., data, models, mapping, interfaces, and logic) to characterize the Network Digital Twin and its use, as shown in Figure 1. These five 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 Network Digital Twin supports all or a subset of the functions above (i.e., analyze, diagnose, emulate, and control) is use case and deployment-specific.

```
  +------------+                                          +------------+
  |            |                                          |            |
  |  Mapping   +---+                                  +---+ Interfaces |
  |            |   |                                  |   |            |
  +------------+   |                                  |   +------------+
                   |  +----------------------------+  |
                   |  |                            |  |
                   |  | Logic: Analyze, Diagnose,  |  |
                   +--+ Optimize, Control, Emulate +--+
                   |  |                            |  |
                   |  +----------------------------+  |
  +------------+   |                                  |   +------------+
  |            |   |                                  |   |            |
  |   Models   +---+                                  +---+    Data    |
  |            |                                          |            |
  +------------+                                          +------------+
```

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: Models provide a basis for emulating changes in the configuration, state or use of network elements and resources, providing information on how the real network operates and generating reasoning data that may be utilized in operational decision-making.

Various types of models including service models, data models, dataset models, transfer matrices, knowledge graphs etc.can be used to represent the real network assets and their behaviours, and composed to emulate network changes and behaviours, serving the analysis needs of various use case-based network applications.

Interfaces: Standardized interfaces ensure the interoperability of Network Digital Twin with real network operations systems. There are two major types of interfaces:

* The interface between the Network Digital Twin platform and the real network infrastructure, directly or through an associated operations (i.e. planning, control, management) system.

* The interface between Network Digital Twin platform and logic - operations applications - that consume the information provided by the NDT.

The former provides real-time data collection from 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 above four core technology elements, can provide crucial emulation-driven information to support analysis, diagnosis, and control of the real network, through its whole life cycle, with the help of optimization algorithms, management methods, and expert knowledge.

Logic: Network Digital Twin facilitates optimal resource allocation and configuration, enhancing efficiency and performance. They can enable comprehensive troubleshooting maintenance and control by diagnosing issues using the Network Digital Twin. Moreover, Network Digital Twins play a crucial role in planning and deployment, allowing for the simulation of new designs and configurations to anticipate their effects before implementation.

The Network Digital Twin environment and its elements must be controlled and driven to support required behaviors in use, e.g., to 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 usage.

> Note: Real-time interaction is not always mandatory for all NDT use cases. For example, when assessing some configuration changes or emulating some innovative techniques, the Digital Twin can behave as an isolated simulation platform without the need of real-time 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 real-time 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 real-time interaction in Network Digital Twin is a catalyst to achieving autonomous networks or self-driven network.

5. Benefits of Network Digital Twin

Network Digital Twin can help enable 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 users 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 platforms is the use of interactive virtual-real mapping to support integration of model (e.g., emulation) based analysis in real network operations environments, up to and including closed loops for network operations automation. Simulation platforms can be considered as a 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 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 detail.

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-based 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 an 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 [RFC7149][RFC7426] 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 a 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, 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 the 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 types of network elements and topologies in the network field; and the network size is characterized by the number of nodes and links in it but the network size growth pace cannot meet the service needs, especially in the deployment of end-to-end service which spans across multiple administrative domains. So, the construction of a Network Digital Twin 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 and the design and implementation of relevant models.

The requirements of the software and hardware of the Network Digital Twin system will be even more constrained. 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 Network Digital Twin 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 scale networks. 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, and the processing of model simulation and verification through a digital network twin will introduce 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, keeping Network Digital Twins in sync or auto-sync between real network and Network Digital Twin is challenging.

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 a 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 and innovative technologies such as blockchain. On the other hand, the system design can limit the data (especially raw data) requirement for building Network Digital Twin, leveraging innovative modeling technologies such as federated 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. NDT Functional Components

Based on the definition of the key Network Digital Twin elements introduced in Section 4, a Network Digital Twin architecture is depicted in Figure 2.

```
           +---------------------------------------------------------+
           |                        Instance of Network Digital Twin |
           |  +--------+   +------------------------+   +--------+   |
           |  |        |   | Service Mapping Models |   |        |   |
  input    |  |        |   |  +------------------+  |   |        |   |  output
interfaces |  | Data   +--->  |Functional Models |  +---> Network|   | interfaces
  -------> |  | Repo-  |   |  +-----+-----^------+  |   | Digital|   |------>
           |  | sitory |   |        |     |         |   | Twin   |   |
           |  |        |   |  +-----v-----+------+  |   |  Mgmt  |   |
           |  |        <---+  |  Basic Models    |  <---+        |   |
           |  |        |   |  +------------------+  |   |        |   |
           |  +--------+   +------------------------+   +--------+   |
           +---------------------------------------------------------+
```

Figure 2: Reference Architecture of Network Digital Twin

Section 4 describes functional characteristics or elements of NDT in four principal classes: data, models, interfaces, and mappings.

This section describes the important functional components of NDTs - reflecting these functional elements - in greater detail. It also briefly describes how an NDT consisting of these components may be used in operations systems to deliver the various functional NDT use cases.

The core functional components of an NDT may be posited as follows: a Data Repository component, a Service Mapping Models component, and an NDT Management component. These key components might be placed within one single network administrative domain and provide service to the operations applications (e.g., SDN controllers, network emulation applications) within that domain or in other network administrative domains. They may be also placed in each network administrative domain and coordinate among each other to provide services to operations applications. One or multiple NDT instances may be maintained and operated in service of a given real network.

The Data Repository component is responsible for collecting and storing network data. It collects and updates the real-time operational and instrumentation data of the various network elements through the appropriate real network-facing input interfaces (e.g., data collection interface and intent interface), as well as from other operations system components. It also provides data services (e.g., fast retrieval, concurrent conflict handling, batch service) through appropriate output interfaces (e.g., query interface) to a Service Mapping Models component.

Service Mapping Models complete data modeling, and provide data or other functional model instances supporting various network applications. Models include two major types, basic and functional models:

o Basic models refer to network element models and network topology models used to reflect the basic configuration, environment information, operational state, link topology, etc. of the network and its elements.

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

The Network Digital Twin Management component manages the NDT operation and its subcomponents to useful effect, serving applications that require and make use of the information generated by the NDT. It manages the session-based operation of the NDT, managing the life-cycle of these operations under the direction of associated applications; it monitors the performance and resource consumption of the NDT (including individual models) and controls various operational aspects of the NDT, including topology management, configuration management, performance management, and security management.

The "real network" the physical counterpart of an NDT - 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, or an industrial Internet of Things (IoT), etc. The real network can span across a single network administrative domain or multiple network administrative domains. It can include both physical entities and some virtual entities (e.g., vSwitches), which together carry traffic and provide actual network services. All or a subset of network elements in the real network deliver network data, directly or through other systems, to the NDT, through appropriate input interfaces. Network elements may receive control inputs, through specific output interfaces, from operations systems in which NDTs play a role. The input and output interfaces might vary as a function of the specific NDT use case. The number of input interfaces or output interfaces is also determined by specific NDT use cases. This document focuses on the IETF-related real network such as IP bearer network and data center network.

8. A Sample NDT-Based Use Case Realization

Considerable industry work and research has focused on automation-supporting network systems. For example, [ETSI-GS-ZSM-002] describes a framework architecture for network automation. It uses so-called management services as a fundamental conceptual unit of currency, and describes the enablement of automation use cases through composition and extensions of such management services. For example, a closed-loop might be represented as a composition of appropriate data, analytics, intelligence/decision, and orchestration/control services.

The role and utility of NDT may be represented architecturally by following similar principles, e.g., [ETSI-GS-ZSM-015] or [RFC8969]. As described in Section 7, an NDT instantiation encompasses models, data, mapping, and interfaces. These components then work in composition with other logic, functions or services to deliver an overall functional architecture matching specific NDT use cases.

For example: an NDT instance may be used as a core element of an intent-drive network controller. In such a case, an "outer" closed-loop (or, intent-assurance closed-loop) would detect gaps between target service objectives set by intents and actual observed service characteristics, propose candidate mitigation solutions to soften the observed deviation, and drive the enforcement of the mitigation in the network. Finding such mitigations would rely, e.g., on an "inner loops" that include an NDT: for example, prospective solutions would be proposed, their impacts on services evaluated by the NDT acting as a "sandbox" in virtual space, and the process might be iterated until a satisfactory solution is found. At that point, the selected mitigation is passed to the outer loop for actuation.

Many automation use cases may be thought of as following a similar pattern: a solution corresponding to some kind of optimization criteria is found through iteration in virtual space using an NDT instance; the solution is then placed at the disposal of other, active components of the operations system. However, all use cases involving NDTs can be represented as some composition of the core data/modeling functions, and appropriate other functions/services.

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      +--------------------------------------------------------------+
      |                                                              |
      |                 Service Demand Generators                    |
      |                                                              |
      +-----------+-------------------------------------------^------+
                  |                                           |
              Service Intents                         Intents Report
                  |                                           |
                  V                                           |
      +-------------------------------------------------------+------+
      |                                                              |
      |  +-------------+                                             |
      |  |             |                      Network Controller     |
      |  |   Intent    |                                             |
      |  | Translation |                                             |
      |  |             |                                             |
      |  +---+---------+                                             |
      |      |                                                       |
      |      |                                      Outer Loop       |
      |      |      +----------------------------------------------+ |
```

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      |      |      |                                              | |
      |      |      |   +---------------------------------------+  | |
      |      |      |   |               Inner Loop              |  | |
      |      |      |   | +------------------------------------||  | |
      |      |      |   | |   +----------------------------+   ||  | |
      |      |      |   | |   |           NDT              |   ||  | |
      |      V      V   | |   |+------+ +-------+  +------+|   ||  | |
      |+------------+-+ | +-> || Data | | Models|  | NDT  |+---+|  | |
      ||              | |     ||      | |       |  | Mgmt ||    |  | |
      || Service Data | |     |+------+ +-------+  +------+|    |  | |
      ||   vs. Intents| |     |                            |    |  | |
      ||              | |     +----------------------------+    |  | |
      |+--------------+ +---------------------------------------+  | |
      |                            |        +----------------+     | |
      |                            |        |                |     | |
      |                            |        |  Orchestration |     | |
      |                            +----->  |     Control    +-----+ |
      |                                     +----------------+       |
      |                                                              |
      +-----------^-------------------------------------+------------+
                  |                                     |
                  |Data Collection               Control|
                  |                                     |
      +-----------+-------------------------------------V------------+
      |                                                              |
      |                   Physical Netework                          |
      |                                                              |
      +--------------------------------------------------------------+
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Figure 3: Example of Detailed NDT Architecure

9. 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.

9.1. 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 data collection method shall meet the requirements of the Network Digital Twin application. When 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 types 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.ietf-opsawg-collected-data-manifest].

Data repository works to effectively store large-scale and heterogeneous network data and 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.

9.2. 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. The operation status can be monitored and displayed, and the network configuration change and optimization strategy can be pre-verified. For example, [I-D.ietf-nmop-simap-concept] provides a foundation for multi-layered topologies.

For small scale network, network simulating tools (e.g., [NS-3] and [Mininet]) and emulating tools (e.g., [EVE-NG] and [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. Mathematical abstraction methods can be used for large-scale networks to build basic network models efficiently. Knowledge graph, network calculus, and formal verification can be candidate methods. Some relevant research has emerged in recent years, such as [Hong2021], [G2-SIGCOMM], and [DNA-2022]. Moving forward, improving the extensibility and accuracy of the models represents a significant 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 (e.g., [I-D.giraltyellamraju-alto-bsg-requirements]). 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 the capacity of a wireless link, among others). Because these perturbations are 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) without using 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 algorithms will play a great role in building complex network functional models. As a research hotspot in recent years, many successful cases have been demonstrated, such as [RouteNet], [MimicNet], etc. In the future, in addition to improving the generalization ability and interpretability of AI models, there is also a 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.

9.3. 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 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 express queries across diverse data sources, whether the data is stored natively as RDF or viewed as RDF via middleware.

9.4. 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 Network Digital Twin 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 so as to avoid either hardware or software vendor lock and achieve interoperability. Besides the interfaces listed above, some new interfaces or protocols can be created to better serve Network Digital Twin system.

9.5. Twinning Management

Twinning 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 the network business into the constructed model by constructing 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 Network Digital Twin 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 Network Digital Twin 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 a green (energy efficient) network.

10. 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 policies and validating real-time situations.

IBN can be envisaged in a Network Digital Twin context to show how Network Digital Twin improves the efficiency of deploying network innovation. Several rounds of adjustment and validation can be emulated on the Digital Twin platform instead of directly impacting real network during the testing phase. Therefore, the Network Digital Twin can be an important enabler platform for implementing IBN systems and fostering their deployment.

11. Sample Application Scenarios

Network Digital Twin can be applied to solve different problems in network management and operation.

11.1. Human Training

The usual approach to network Operations, Administration, and Maintenance (OAM) with procedures applied by humans is open to errors in all these procedures, which impact 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 multiple 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.

11.2. Machine Learning Training

Machine learning requires data and its context to be available in order to be applied. 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, retrain or adjust to the production environment context. This demands a specific adaptation 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.

11.3. DevOps-Oriented Certification

The potential application of Continuous Integration/Continuous Delivery (CI/CD) models network management operations increases the risk associated to the deployment of non-validated updates, which 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.

11.4. 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 the identification of vulnerabilities, bugs and zero-day attacks before production delivery.

11.5. Network Inventory Management

With the development of enterprise digitization, the number of enterprise IoT devices, virtualized Cloud software inventory components (e.g., virtual firewall), and network hardware inventory (e.g., switches or routers) also increases. YANG data models of various network inventories are being specified in [IETF-IVY] working group. 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 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 assessments will be further simplified. Such an approach will ease the implementation of a unified control strategy for all inventory component types connected to an enterprise network. It also makes actors on assets more accountable for breaching their compliance promises. Special care should be considered to protect the inventory data since it may 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.

12. Research Perspectives: A Summary

This document presents an overview of the Network Digital Twin concepts and reference architecture. From the perspective of system architecture and functional implementation, building a complete Network Digital Twin still faces challenges in data accuracy, modeling complexity, and real-time synchronization. Future research must continue to address the standardization of interfaces and data models to ensure that NDTs can effectively aggregate heterogeneous network data and support cross-domain interoperability.

Moreover, compared to the early stages of NDT research, the field is now rapidly evolving alongside advancements in AI, particularly Large Language Models (LLMs) and AI Agents. Future research should prioritize the synergy between NDT and these technologies, investigating how NDT can function as a high-fidelity "sandbox" to verify the actions of autonomous agents and mitigate the risks of model hallucinations. The integration of Agentic AI and NDT will be a key driver toward higher levels of autonomy in network management.

13. Security Considerations

This document describes concepts and definitions of NDT. As this document presents system architecture, the following security considerations are abstract and generic, i.e., they provide mainly principles, guidelines or requirements. However, the implementation and deployment of NDT will need to carefully investigate the following security considerations, which may be categorized into different aspects:

* Data Management

Synchronization: Synchronizing the data between the real and twin networks may increase the risk of sensitive data and information leakage.

Data Access: Strict control and security mechanisms must be provided and enabled to prevent data leaks. Also, appropriate access rights must be provisioned to prevent unauthorized entities to access sensitive data (e.g., logging data used for legal data retention).

* Data Security and Privacy Protection.

Confidentiality: Ensuring that sensitive data used in the Digital Twin is protected from unauthorized access. This includes encrypting data both at rest and in transit.

Integrity: Ensuring that the data used in and produced by the digital twin is accurate and unaltered. This can be achieved through cryptographic hash functions and other integrity verification methods.

Access Control: Implementing strict access control measures ensures that only authorized users can access, modify, or interact with the digital twin. This includes using multi-factor authentication (MFA) and role-based access control (RBAC).

* System Security

Authentication and Authorization: Ensuring robust authentication and authorization mechanisms to prevent unauthorized access to the digital twin environment.

Vulnerability Management: Regularly auditing, updating, and patching the digital twin software and underlying infrastructure to mitigate vulnerabilities.

Monitoring and Logging: Implementing comprehensive logging and monitoring to detect and respond to security incidents in real-time.

* Network Security

Segmentation: Isolating the NDT environment from the main operational network to limit the potential impact of a security breach.

Encryption: Encrypting network communications to prevent interception and eavesdropping.

Access Control List: Deploying , e.g., firewalls and IDS/IPS with appropriate policies to protect the NDT from external and internal threats.

* Operational Security

System Access: Data verification, model validation, and mapping operations between the real and digital counterpart networks by authenticated and authorized users only.

Secure Development Practices: Ensuring the NDT software is developed following secure coding practices to minimize vulnerabilities.

Incident Response: Having a well-defined incident response plan (e.g., playbooks) to address and mitigate any security incidents quickly.

Regular Audits and Assessments: Conduct security audits and risk assessments to identify and address potential security gaps.

* Resilience and Reliability

Redundancy: Implementing redundancy and failover mechanisms ensures the Digital Twin remains operational during and after a security/failure incident.

Backup and Recovery: Regularly back up NDT data and have a robust recovery plan to restore operations in case of data loss or corruption.

14. IANA Considerations

This document has no requests to IANA.

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