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Digital Twin Network: 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 realize efficient and intelligent management and accelerate network innovation. This document presents an overview of the concepts of Digital Twin Network (DTN), provides the definition and reference architecture, application scenarios, and then describes the benefits and key challenges of such technology.

Status of This Memo

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1. Introduction

With the advent of technologies such as 5G, Industrial Internet of Things, Edge Computing, and Artificial Intelligence, the ICT (Information and Communications Technology) and other vertical industries such as smart cities or smart manufacturers are transformed dramatically through replacing what is used to be manual processes with digital processes.

With the fast growing of the network scale and the increased demand placed on the network, accommodating and adapting dynamically to customer needs becomes a big challenge to network operators. Indeed, network operation and maintenance are becoming more complex due to higher complexity of the managed networks. As such, providing innovations on network will be more and more difficult due to the high risk of interfering with existing services and higher trial cost if no reliable emulation platforms are available.

Digital Twin is the real-time representation of physical entities in the digital world. It has the characteristics of virtual-reality interrelation and real-time interaction, iterative operation and process optimization, as well as full life-cycle, and full business data-driven. So far, it has been successfully applied in the fields of intelligent manufacturing, smart city, or complex system operation and maintenance [Tao2019] to help with not only object design and testing, but also operation and maintenance.

A digital twin network platform can be built by applying Digital Twin technology to networks and creating a virtual image of physical network facilities (emulation). Through the real-time data interaction between the physical network and its twin network, the digital twin network platform might help the network designers to achieve more simplification, automatic, resilient, and full life-cycle operation and maintenance. Having an emulation platform that allows to reliably represent the state of a network is more reliable than a simulation platform. The emulated platform can thus be used to assess specific behaviors before actual implementation in the physical network, tweak the network for better optimized behavior, run 'what-if' scenarios that can't be tested and evaluated easily in the physical network. Service impact analysis tasks will also be facilitated.

2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP

14 [RFC2119][RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Definitions and Acronyms

PLM: Product Lifecycle Management

IBN: Intent-Based Networking

AI: Artificial Intelligence

ML: Machine Learning

OAM: Operations, Administration, and Maintenance

CI/CD: Continuous Integration / Continuous Delivery

4. Definition of Digital Twin Network

The concept of a virtual equivalent to a physical product or the digital twin was first introduced in the Product Lifecycle Management (PLM) course in 2003 by Scholar Michael Grieves [Grieves2014]. It has been widely acknowledged in both industry and academic publications. However, there is no standard definition of "digital twin network" within the networking industry or SDOs. This document defines digital twin network as a virtual representation of the physical network. Such virtual representation of the network is meant to be used to analyze, diagnose, emulate, and then control the physical network based on data, model and interface. To that aim, a real-time and interactive mapping is required between the physical network and its virtual twin network.

As shown in Figure 1, the digital twin network involve four key technology elements: data, mapping, models, and interfaces

```
              +-------------+                +--------------+
              |             |                |              |
              |  Mapping    |                |  Interface   |
              |             |                |              |
              +-------------+----------------+--------------+
                       |                           |
                       |    Analyze, Diagnose      |
                       |                           |
                       | +----------------------+  |
                       | | NETWORK DIGITAL TWIN |  |
                       | +----------------------+  |
           +------------+                        +------------+
           |            |   Emulate, Control     |            |
           |   Models   |                        |    Data    |
           |            |------------------------|            |
           +------------+                        +------------+
```

Figure 1: Key Elements of Digital Twin Network

Data: A digital twin network 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., physical 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 the "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, process) using specific models. It is used as emulation and diagnosis basis to provides dynamics and elements on how live physical network operates and develop 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 physical network assets and then instantiated to serve various network applications.

Interfaces: Standardized interfaces can ensure the compatibility of digital twin network. There are two major types of interface: (1) the interface between the digital twin network platform and the physical network infrastructure and (2) the interface between digital twin network platform and applications. The former provides real time data collection and control on the physical network; the latter helps deliver application requirements to

digital twin network platform and exposure the various abilities to applications.

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

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

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

Such mapping provides a good visibility of actual status which makes it more convenient to analyze and understand what is going on in the physical network. It also allows using the digital twin to optimize the performance and maintenance of the physical network.

The digital twin network constructed based on the four core technology elements can analyze, diagnose, emulate, and control the physical network in the 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 digital twin network environment and its elements to derive the required system behavior, e.g., provide:

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

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

5. Benefits of Digital Twin Network

Digital twin network can help enable closed-loop network management across the entire lifecycle, from deployment and emulation, to visualized assessment, physical deployment, and continuous verification. In doing so, network operators (and end-users to some extent) can get a global, systemic, and consistent view of the network. Also, network operators can safely exercise the enforcement of network planning policies, deployment procedures, etc., without jeopardizing the daily operation of the physical network.

The benefits of digital twin network can be classified into: low cost of network optimization, optimized and safer decision-making, safer testing of innovative network capabilities (including "what if"

scenarios), privacy and regulatory compliance, and customize network operation training. The following subsections further elaborate on such benefits.

5.1. Lower the Cost of Network Optimization

Large scale networks are complex to operate. Since there is no effective platform for simulation, network optimization designs have to be tested on the physical 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 digital twin network platform, network operators can safely emulate candidate optimization solutions before deploying them in the physical network. In addition, the operator's OPEX on the real physical 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.

Digital twin network 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, it is also extremely risky.

As mentioned above, digital twin network can greatly help assessing innovative network capabilities without jeopardizing the daily operation of the physical network. In addition, it also 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%) of network and the slow learning speed or phase-in learning steps of AI/ML algorithms. With digital twin network platform, AI/ML can complete

the learning and training with the sufficient data before deploying the model in the real network. This will greatly 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 payloads content. 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. Some examples of these techniques include payload inspection, including decryption with user explicit consents, or data anonymization mechanisms.

Given digital twin network operation assumes the mapping between real traffic or services and the traffic used by the digital twin network for assessment purposes in particular, the need for privacy is of the utmost importance. The lack of personal data permits to lower the privacy requirements and simplifies the use of privacy-preserving techniques.

5.5. Customize Network Operation Training

Network architectures can be complex, and their operation requires expert personnel. Digital twin network 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 the threat detection and mitigation.

6. Reference Architecture of Digital Twin Network

Based on the definition of the key digital twin network technology elements introduced in Section 4, a digital twin network architecture is depicted in Figure 2. The digital twin network architecture is broken down into three layers: Application Layer, Network Digital Twin Layer and Physical Network Layer.

```
+---------------------------------------------------------+
|   +-------+   +-------+          +-------+              |
|   | App 1 |   | App 2 |   ...    | App n |   Application|
|   +-------+   +-------+          +-------+              |
+-------------^-------------------+-----------------------+
              |Capability Exposure|intent input
              |                   |
+---------------------------------v-----------------------+
|                                     Network Digital Twin|
|  +--------+   +------------------------+   +--------+   |
|  |        |   | Service Mapping Models |   |        |   |
|  |        |   |  +------------------+  |   |        |   |
|  | Data   +--->  |Functional Models |  +---> Digital|   |
|  | Repo-  |   |  +-----+-----^------+  |   | Twin   |   |
|  | sitory |   |        |     |         |   | Entity |   |
|  |        |   |  +-----v-----+------+  |   |  Mgmt  |   |
|  |        <---+  |  Basic Models    |  <---+        |   |
|  |        |   |  +------------------+  |   |        |   |
|  +--------+   +------------------------+   +--------+   |
+--------^------------------------------------------------+
         |                            |
         | data collection            | control
+-------------------------------------v-------------------+
|                   Physical Network                      |
|                                                         |
+---------------------------------------------------------+
```

Figure 2: Reference Architecture of Digital Twin Network

1. The lowest layer is the Physical Network. (All) network elements in the physical network exchange massive network data and control with network digital twin entity, through twin southbound interfaces. As the physical object of the network twin, the physical network can be a mobile access network, a transport network, a mobile core, a backbone, etc. The network can also be a data center network, a campus enterprise network, an industrial Internet of Things, etc. The network can span across a single network domain or multiple network domains.

2. The Intermediate layer is the Network Digital Twin. This layer includes three key subsystems: Data Repository subsystem, Service Mapping Models subsystem, and Digital Twin Entity Management subsystem.

   * 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, batch service) and unified interfaces to Service Mapping Models subsystem.

* Service Mapping Models complete data modeling, provides 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 and network topology model of the network digital twin based on the basic configuration, environment information, operational state, link topology and other information of the network element, to complete the real-time accurate characterization of the physical network.

  + Functional models refer to various data models such as network analysis, simulation, 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. it can also be divided into general model and special-purpose model. Specifically, multiple dimensions can be combined to create a data model for more specific application scenarios.

* Digital Twin Entity Management completes the management function of digital twin network, records the life-cycle of the entity, visualizes and controls various elements of the network digital twin, including topology management, model management and security management.

3. Top layer is Application Layer. Various applications (e.g., OAM, IBN) can effectively run over a digital twin network platform to implement either conventional or innovative network operations, with low cost and less service impact on real networks. Network applications raise requirements that need to be addressed by the digital twin network. Such requirements are exchanged through a northbound interface; then the service is emulated by various twin service instances. Once checked, the changes can be safely deployed in the physical network.

7. Challenges to build Digital Twin Network

As mentioned in the above section, digital twin networks can bring many benefits to network management as well as facilitate the introduction of innovative network capabilities. However, building an effective and efficient digital twin network system remains a challenge. The following is a list of the major challenges:

- Large scale challenge: The digital twin of large-scale networks will significantly increase the complexity of data acquisition and storage, the design and implementation of models. And the requirements of software and hardware of the system will be even more constraining.

- Interoperability: It is difficult to establish a unified digital twin platform with a unified data model in the whole network domain due to the inconsistency of technical implementations and the heterogeneity of vendor technologies.

- Data modeling difficulties: Based on large-scale network data, data modeling should not only focus on ensuring the accuracy of model functions, but also need to consider the flexibility and scalability of the model. Balancing these requirements further increase the complexity of building efficient and hierarchical functional data models.

- Real-time requirement: For services with real-time requirements, the processing of model simulation and verification through a digital twin network will increase the service delay, so the function and process of the data model need to be based on automated processing mechanism under various network application scenarios; at the same time, the real-time requirements will further increase performance requirements on the system software and hardware.

- Security risks: the digital twin network synchronizes all the data of physical networks in real time, which inevitably augments the attack surface, with a higher risk of information leakage, in particular.

To address these challenges, the digital twin network needs continuous optimization and breakthrough on key enabling technologies including data acquisition, data storage, data modeling, network visualization, interface standardization, and security assurance, so as to meet the requirements of compatibility, reliability, real-time and security.

8. Interaction with IBN

Implementing Intent-Based Networking (IBN) is an innovative technology for life-cycle network management. Future network will be possibly Intent-based, which means that users can input their abstract 'intent' to the network, instead of detailed policies or configurations on the network devices. [I-D.irtf-nmrg-ibn-concepts-definitions] clarifies the concept of "Intent" and provides an overview of IBN functionalities. The key characteristic of an IBN system is that user's intent can be assured automatically via continuously adjusting the policies and validating the real-time situation.

IBN can envisaged in a digital twin network context to show how digital twin network 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 digital twin network platform instead of directly on physical network. Therefore, digital twin network can be an important enabler platform to implement IBN system and speed up the deployment of IBN in customer's network.

9. Application Scenarios

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

9.1. 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, 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 digital twin network 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. Digital twin network will offer realistic environments, fitted to the real production networks.

9.2. ML 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.

Digital twin network 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 digital twin network and not to the production network, allowing information access by third parties, without impacting data privacy.

9.3. 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 SLAs using a digital twin network environment replicating the network particularities, as a previous step to production release.

Digital twin network control functional block supports such dynamic mechanisms required by DevOps procedures.

9.4. 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.

Digital twin network 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. Summary

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

11. Security Considerations

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

Security considerations of the digital twin network include:

- Secure the digital twin system itself.

- Data privacy protection.

Securing the digital twin network 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 physical network and digital counterpart network by authenticated and authorized users only.

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

12. Acknowledgements

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13. IANA Considerations

This document has no requests to IANA.

14. Open issues

o Investigate related digital twin network work and identify the differences and commonality, e.g., How is this concept and architecture different from digital twin for industry application? How can existing network management models be re-used?

15. References

15.1. Normative References

[RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <https://www.rfc-editor.org/info/rfc2119>.

[RFC8174] Leiba, B., "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words", BCP 14, RFC 8174, DOI 10.17487/RFC8174, May 2017, <https://www.rfc-editor.org/info/rfc8174>.

15.2. Informative References

[Grieves2014]
Grieves, M., "Digital twin: Manufacturing excellence through virtual factory replication", 2003.

[I-D.irtf-nmrg-ibn-concepts-definitions]
Clemm, A., Ciavaglia, L., Granville, L. Z., and J. Tantsura, "Intent-Based Networking - Concepts and Definitions", draft-irtf-nmrg-ibn-concepts-definitions-03 (work in progress), February 2021.

[Tao2019] Tao, F., Zhang, H., Liu, A., and A. Nee, "Digital Twin in Industry: State-of-the-Art. IEEE Transactions on Industrial Informatics, vol. 15, no. 4.", April 2019.

Appendix A. Change Logs

v03 - v04

o Change the I-D title from "Concepts of Digital Twin Network" to "Digital Twin Network: Concepts and Reference Architecture".

o Update data definition and models definitions to clarify their difference.

o Remove the orchestration element and consolidated into control functionality building block in the digital twin network.

- o Clarify the mapping relation (one to one, and one to many) in the mapping definition.

- o Add explanation text for continuous verification.

v02 - v03

- o Split interaction with IBN part as a separate section.

- o Fill security section;

- o Clarify the motivation in the introduction section;

- o Use new boilerplate for requirements language section;

- o Key elements definition update.

- o Other editorial changes.

- o Add open issues section.

- o Add section on application scenarios.

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