Digital Twins in Networks: A Systematic Survey

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ABSTRACT

This systematic survey explores the burgeoning field of Network Digital Twins (NDTs), focusing on their role within 5G/6G network frameworks. The paper delineates the evolution, definitions, architectures, and classifications of digital twins, emphasizing their increasing integration into network operations for enhanced management and predictive analytics. A marco NDTs system is proposed for academic reference. This paper also discusses the current applications and developmental stages of NDTs across various sectors, the current state of development is discussed through a study of its purpose and how they are deployed. Challenges like security, standardization, and data management are analyzed to highlight the complexities of implementing NDTs at scale. The study forecasts future trends, including service-oriented architectures and the integration of blockchain and federated learning technologies to address security and scalability challenges. This research hopes to serve as a comprehensive resource, and standardize approaches and propel forward the practical applications of NDTs in telecommunications.

KEYWORDS

Systematic Literature Review, Digital Twins, Network Digital Twins, 5G/6G Networks, Telecommunications, Predictive Analytics, Federated Learning.

1 INTRODUCTION

In recent years, the significance of Digital Twins (DTs) has grown, showcasing the potential to transform various industries by providing detailed simulations of physical systems [47]. These simulations enhance predictive maintenance strategies, crucially reducing unexpected equipment failures and extending the life of assets [32].

The concept of the digital twin was first introduced by Michael Grieves during a Product Lifecycle Management conference in 2002 [55]. He proposed it as a virtual counterpart to the physical world, presenting an innovative approach to model systems and processes across their lifecycle [17, 18]. The aerospace sector took the lead to implement this concept in practical applications. The U.S. Air Force and NASA have invested in exploring how DT can be utilized to manage space assets and training flights [63]. In fact, ideas similar to DT had already appeared in NASA before this concept was proposed [35]. Now the technology has expanded to include manufacturing [32, 29], healthcare [25, 51], the automotive industry[20], urban planning [12], IoT systems [36], aerospace [32], and the development of 5G/6G networks. Each sector benefits from the tailored application of digital twins to optimize operations and enhance predictive analytics.

As the telecommunications industry anticipates the rollout of 5G/6G, which promises substantial improvements in speed, capacity, and latency, the significance of Network Digital Twins (NDTs) comes into sharper focus [10]. These NDTs are sophisticated virtual replicas of network setups and operational strategies, pivotal in enhancing real-time monitoring, predictive analytics, and pre-implementation simulations of network changes. The enhancement of these capabilities is crucial for meeting the demands of modern telecommunications, as shown by studies from [38] and [3]. Research on DTs in the network has just begun, and its application is still in the infancy stage[66]. At present, however, the next scenario where DTs are likely to be truly applied and fully realize their functions is the 6G network. Wireless communication can be the next scenario where DTs can be applied to fully realize their functions. As a new paradigm, 6G holds significant research and application value when combined with DTs[27].

Keyword	Arxiv	IEEE	ACM DL	ScienceDirect
Manufactur(e/ing)	79	685	1,000	1,041
5G	27	179	126	46
6G	57	200	20	19
Wireless	91	244	2,060	64
City	51	275	1,271	196
Industry	214	969	3,465	990
Urban	39	136	-	147
Product	99	438	-	579
Automotive	25	79	-	81
Energy	95	649	-	580
Healthcare	42	176	593	83

Table 1: Total Number of Papers Abstract Related to "Digital Twin" with Different Keywords By 05-2024

Building on the current foundation of existing adoption and versatility of DTs across multiple sectors, our research specifically focuses on exploring the role of NDTs within the context of 5G and 6G telecommunications technologies networks, represented by 5G/6G networks.

1.1 Main Contributions

Digital Twins have achieved relative maturity in manufacturing sectors, such as production line management. However, their application and evaluation in networks are not as widely discussed and remain somewhat underdeveloped. Table 1 shows the statistics of the number of papers with different keywords from different publishers as of 2024. As shown in Table 1, where reflects that the current research on DTs is more on Manufacturing and Industry, and there is relatively less research on 5G/6G networks. Additionally, there is a big gap in people's understanding of NDTs, the concepts involved are often more ambiguous and there are sometimes conflicts in the use of terms. Our research advances the field of Network Digital Twins (NDTs) through several integrated contributions:

Definitions and Architecture: We conduct a survey and comparison of common terminologies related to DTs, as well as different expressions of terms with similar meanings, and we present efforts towards terminology disambiguation and standardization. We also compare and summarize the characteristics and explanations of NDTs, and a more comprehensive and precis definition is finally given.

Applications and Evaluation: We explore multiple applications and potential uses of NDTs, supplemented by real-world examples. Then we selected and presented some the most representative or well-structured application cases.

Challenges and Future Research Trends: We identify and list challenges specific to different aspects of NDTs and outline future research trends that can potentially advance the field of NDTs.

Through these contributions, our study aims to provide a reference to standardize approaches and enhance the practical deployment and evaluation of Network Digital Twins (NDTs). By doing so, we seek to support the development and evolution of NDTs technologies. Additionally, we hope this article serves as a comprehensive guide, enabling researchers to quickly understand and gain an overview of the NDTs concept.

2 OVERVIEW

In this chapter, we will introduce some common or easily confused concepts and terms related to DTs and NDTs. We will also explore DTs through various classification methods. Finally, we will summarize and propose our definition of NDTs based on the current state of research.

2.1 The Concept

Different interpretations have led to various definitions and taxonomies of Digital Twins, and there is no completely unified definition [8]. Various definitions have been proposed, including "virtual representation of physical structures with communications" in [18], "a virtual part act as agents for every physical object" in [43, 15], or "a reengineering of structural life prediction and management" in [55].

There are mainly three categories for these definitions. For the first category, the definition of DT given by Michael Grieves in [18] is actually in a narrow sense. His idea overly emphasized the characteristics of digital twins as virtual informational structures, focusing on a comprehensive description of physical objects. This approach even tends toward a one-to-one correspondence, demanding an exact match from a microscopic level from the outset. A representative for the second category is [49], which discusses using machinery together with simulation techniques to enhance real-time control and optimization, but mainly concentrating on the roles of "simulation, optimization algorithms, and computing power". These two definitions place little emphasis on interaction. They mainly focus on the transition from physical to virtual, but lack the reverse relationship, which leads to insufficient integration. The last category puts more emphasis on interaction and integration, still represented by NASA [54], which emphasize "an integrated multi-physics, multi-scale, probabilistic simulation of a complex product". Different definitions emphasize distinct aspects, these three categories actually coincide with the classification of DT in the [24], namely Monitoring, Simulating, and Operational DTs. Combining these ideas, it can be considered that these all represent DTs, but they are aimed at different types of DTs.

2.2 The Taxonomy

We investigated some representative taxonomies, as shown in Figure 1.

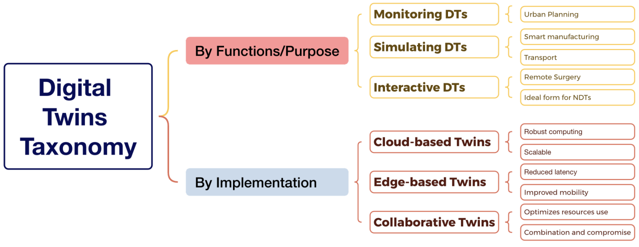

Figure 1: Some DTs Taxonomies

2.2.1 ***By Functions/Purpose.***

Through these different concepts (definitions), we identify three types of DTs and invest their usages, based on their different focused Purposes and functions.

- **Monitoring DTs**: The main purpose is to view the current and possible future status of physical objects. Currently, this method has mature applications in urban planning, which can be reflected on 3D models, like street space, utility cadastre, etc [41].
- **Simulating DTs**: This type of DTs is probably the most common and is an appropriate practice for measuring costs versus effectiveness, which puts lots effort on simulaiton aspect [4]. This type of application has a wide range of applications in smart manufacturing and transportation [44].
- **Operational DTs**: Due to its literal meaning, it is easy to be misunderstood as the opposite of Simulating DTs, that is, information and instructions from digital twins to physical twins. However, the operational also means the interactive behaviour, which is bidirectional[64]. This is the ultimate, or ideal, form of DTs because it satisfies the free flow and synchronization of data and instructions between the physical and virtual. And this is currently proven to be suitable for remote surgery [28]. It can also be the most suitable for NDTs [24]. The NDTs mentioned in this article, unless otherwise specified, are all such DTs.

In the initial definition of DTs, they are mainly used for monitoring and reflecting the status of physical entities[18, 55], which largely favors the application of digital visualization. If the narrow definition is followed, the first two may not even be applicable in some cases. However, DTs now have begun to be widely used in data utilization, prediction and simulation. In this evolution, while the immediate importance of visualization capabilities has decreased, the accuracy of simulations and predictions for data-based decisions have become critical. Through the implementation of these functions, the digital twin can effectively feedback analysis and instructions to the physical world to achieve its original design goals.

2.2.2 *By Implementation*.

DTs servitization is a trend, which should be able to meet the needs of dynamic creation in the future (will be introduced later) [58]. Under this trend, NDTs can, also, be divided into three categories based on deployment methods: Cloud-based Twins, Edge-based Twins, and Collaborative Twins [24].

Cloud-based Twins capitalize on the robust computing and storage capacities of the cloud, making them ideal for complex simulations requiring significant data processing. This deployment model has enhanced scalability and ease of integration with existing cloud services, though it may suffer from higher latency, which could compromise real-time data processing. Edge-based Twins, on the other hand, are deployed closer to data sources and physical processes they mirror, significantly enhancing their ability to operate with reduced latency and improved mobility. However, the primary challenge for Edge-based Twins lies in resource scheduling, where they may not perform as efficiently as cloud-based solutions due to limited computing capabilities.

Collaborative Twins merge the benefits of both cloud and edge deployments, optimizing resource use by distributing tasks between the cloud's powerful computing environment and the edge's proximity to operational data. However, this approach is also a compromise.

In addition to these classification methods, there are others, such as in [11], which are divided into pre-digital, digital, adaptive digital and intelligent digital twins. This article will not go into detail.

2.3 Other Terminologies

At present, the industry has not only a variety of views and research on the definition of DTs, but also some concepts about DTs are relatively complicated, and they are mixed in different articles. Readers are often easily confused about concepts between different articles. We compare these concepts in the article. This section focuses on introducing some common concepts and disambiguating some of the terms so that readers can be aware of the meaning of the current terms when reading other articles.

2.3.1 *Digital Shadow, Digital Model and Digital Twin*.

Based on the aforementioned definitions and the explanations provided by other scholars, we should be able to clearly distinguish the differences and similarities between simulating, which can be a function of DTs [19], and DTs. However, another thing that can easily confuse newcomers is the difference between Digital Shadow (DS), Digital Model (DM) and DT. In the process of creating DTs, modelling and simulation tools such as CAD are often used, which sometimes leads to a blurred distinction between models and DTs. This confusion can lead to over-hyping and misuse of DTs [62].

While it is important to distinguish these concepts, it must be acknowledged that they are often used interchangeably, and the boundaries between different terms are not always strictly defined [42].

Some scholars argue that when a virtual representation is solely used to mirror a physical object, it can be classified as a DS [14]. A digital model is a virtual representation of a physical object, system, or process. It can take various forms. As we mentioned, 3D models from computer-aided design files, or algorithms, can be deemed as DMs. However, according to the broad definition of DTs and their functional classification, it can be considered that DTs can include the other two concepts because DTs require data models and sometimes also need to reflect the form of the virtual world.

One method to distinguish them evaluates based on the following dimensions: the autonomy of data flow [26], and functionality. Figure 2 shows the difference in autonomy of data flow in those three types.

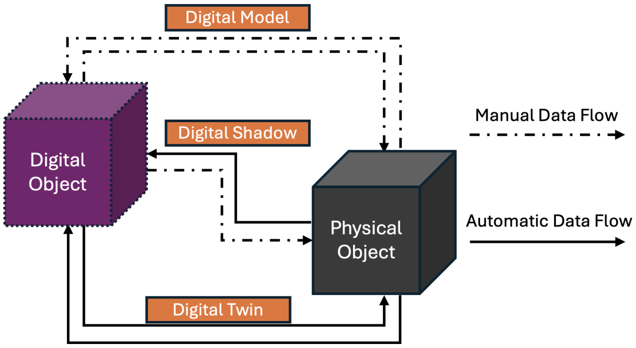

Figure 2: Data Flow in DT, DM, and DS

Without the ability to ensure the two-way flow of data and instructions, it is difficult to achieve the vision of DTs. Therefore, although it is sometimes referred to as DT in a broad sense, it is essentially downgraded to DS or DMs.

2.3.2 *Digital Twins and Digital Twins System*.

In a narrow sense, DTs should be defined strictly as digital components, excluding their corresponding physical objects from the definition, as shown in Figure 3. This definition focuses solely on the virtual representation, simulation, and analysis capabilities of DTs without considering the actual physical entities they mirror. Additionally, components responsible for communication between the physical and virtual realms—such as sensors, data acquisition systems, and networking infrastructure—should also be excluded from being considered part of the DTs, an example can be shown in Figure 4.

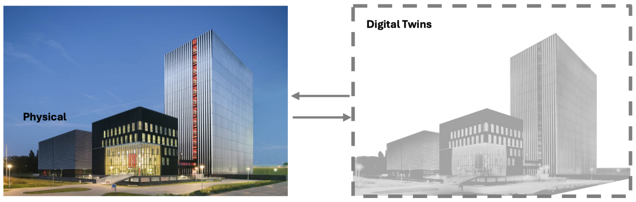

Figure 3: The Narrow Scope of "Digital Twins".[1]

In a broader sense, DTs often refer to the entire Digital Twins System (DTS), which encompasses the complete ecosystem, including digital models, physical counterparts, and the communication

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[1] Left Original Photo Source: AM4 Amsterdam Science Park exterior mid res

and data processing infrastructure that connects and supports them. To avoid being imprecise and make it more rigorous, unless otherwise specified, we will keep using the term DTs with the narrow meaning, i.e. DTs only represent the digital parts. When we discuss the term NDTs, we reflect the whole network digital twins system, where the physical objects(twins) are also involved.

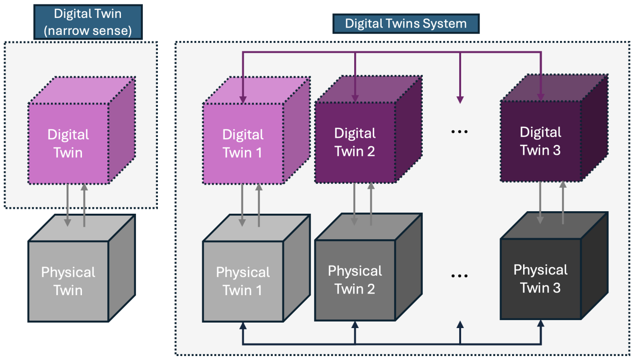

Figure 4: Comparison of DT and DTN

2.3.3 ***Network Digital Twins and Digital Twins Network.*** Network Digital Twins (NDTs) generally refer to wireless network DTs, such as 5G/6G and beyond networks. However, Digital Twins Network (DTN) is generally not always related to NDTs. This concept generally describes the joint collaboration of multiple twins, including the interaction between physical twins and virtual twins. A simple Digital Twin System or Digital Twin can be considered a virtual entity corresponding to a physical entity. After extension, they can be described as "many to many co-evolution" [63], which becomes DTN.

2.3.4 ***DT Prototype, Instance and Aggregate.*** A digital twin prototype is an initial, high-level model that is typically used during the design and testing phases of product or system development. This prototype represents a general, standardized entity model that encapsulates the essential characteristics, properties, and functionalities of a product or system[28]. At this stage, the prototype is not yet specific to any single instance or individual unit; instead, it serves as a blueprint or template from which specific instances can later be created. The digital twin prototype contains generalized information, such as design specifications, structural features, operational guidelines, and performance criteria. It allows engineers and designers to explore various design configurations, test theoretical performance, and validate design choices in a virtual environment before moving on to the production of physical objects.

A digital twin instance is a specific, digitized copy of a specific physical object or system. Each instance has its own unique data and behavior, which is usually updated in real-time through sensors and other data collection tools [40]. A digital twin instance can be created from a digital twin prototype [22]. From this perspective, DT prototype is similar to the concept of "class" in object-oriented programming languages, and instance represents a specific object instance of a class.

A digital twin aggregate refers to a collection of multiple digital twin instances, often of the same or related types of physical entities. This aggregation provides a comprehensive, macro-level view that enables system-wide analysis and optimization. By integrating data from various instances, a digital twin aggregate allows for the monitoring and assessment of overall system performance, identification of patterns and trends, and informed decision-making for system-level improvements [65, 22]. Unlike a digital twin network (DTN), which emphasizes the dynamic interaction and co-evolution of multiple DTs, including physical-to-virtual interactions, a digital twin aggregate primarily focuses on the data consolidation and holistic analysis of grouped instances without necessarily involving complex inter-twin interactions.

2.4 The Definition

We summarize the background and the different emphases of the research on DTs, and we propose our candidate definition of DTNs as follows:

A Network Digital Twin (NDT) represents a virtual twin that mirrors, simulates, and operates the life cycle and components of the physical network [38, 24]. It uses data-driven computational models to maintain real-time conditions and forecast future states [30]. The NDTs features bidirectional interfaces that not only update the virtual twin based on changes in the physical twin but also allow the virtual twin to issue commands to alter the physical network.

3 ARCHITECTURE/KEY TECHNOLOGIES

Similar to the definition of DTs, due to different understandings and emphases, as well as different needs. There is currently no, or hard to have, a unified and standard structure for NDTs system[31]. Currently, the three-layer or four-layer architecture is more common in the academic [60, 53, 59], but there is no consensus on the details and structure of each layer. In this section, we proposed a three-layer general NDTs system structure, including Physical Twins Layer, Digital Twins Layer, and Application/Service Layer, the details can be shown in Figure 6. To be noted, in our research, we deliberately chose not to adopt the term “Physical Layer” from certain sources[52] to avoid confusion. This decision is made because the term is frequently used within the context of computer network architectures, where it specifically refers to the lowest layer of the OSI model that is responsible for the transmission and reception of raw data bits over a physical medium. Instead, the Physical Twins Layer here involves all objects in the physical world that can be modeled as digital models[52].

3.1 Communication Methods

In order to better understand the subsequent description, it is necessary to explain the three communication methods first.

There are mainly three types of communication methods, namely: Physical-to-physical Communication, Virtual-to-virtual Communication, and Bidirectional Communication between the physical and digital worlds. A schematic diagram can be seen in Figure 5.

3.1.1 ***Physical-to-physical Communication.*** In NDTs, Physical-to-physical (P2P) communication is fundamental to the operations of the Physical Twins Layer in the NDT architecture. This type of

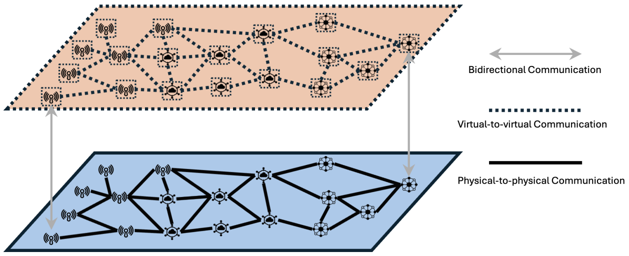

Figure 5: Communication Methods

communication involves direct interaction between physical devices such as sensors, IoT devices, and 5G/6G base stations. The primary goal is to ensure seamless and efficient transmission of raw data and control commands across various components of the physical network. Techniques are employed to achieve high-speed, reliable connections essential for real-time data processing and decision-making [63]. This communication also incorporates advanced encryption and security protocols to maintain data integrity and prevent unauthorized access, thus safeguarding the foundational communication within the network. To be noted, DNTs do not need to focus more on how they work or communicate, or in other words, the physical principle. However, the network hardware within this system must be capable of receiving and executing instructions, as a consequence, the communication can be changed.

3.1.2 ***Virtual-to-virtual Communication.*** In the Virtual Twins Layer, virtual-to-virtual (V2V) communication plays a critical role by facilitating interactions between digital representations of physical entities. This involves the exchange of data and commands between virtual models and simulations that mirror real-world network components and behaviors. This communication should utilizes data-driven models and algorithms to ensure that the virtual entities interact in a manner that accurately reflects their physical counterparts. Communication in this realm should also be optimized for speed and efficiency, for example, leveraging data compression and caching techniques to handle large volumes of information rapidly.

3.1.3 ***Bidirectional Communication.*** Bidirectional communication ensures a continuous and dynamic exchange of information between the Physical and Virtual Twins layers as well as between the system and the Application/Service Layer. This type of communication allows for the upward flow of data, for example, the states and discrete events, from physical devices to virtual models and the downward transmission of insights or decisions from the virtual back to the physical devices. For instance, data on network performance collected from physical devices is processed and analyzed virtually; the insights generated can then be used to adjust physical operations in real-time.

3.2 Physical Twins Layer

The Physical Twins Layer is the fundamental building block of the NDTs system architecture. It's primarily responsible for gathering and initially processing data from the physical environment. This layer includes a wide variety of physical components such as sensors, actuators, and devices that can detect, measure, and affect the environment. Among these can be state-of-the-art 6G base stations and a wide range of user equipment, including smartphones, tablets, wearables, and a comprehensive array of IoT devices.

The main goal of the Physical Twins Layer is to collect and process data as accurately and quickly as possible using advanced, high-speed, low-latency communication technologies. Moreover, this layer should not only meet the demands of wireless networks, such as the extreme data rates, enhanced spectral efficiency and coverage, wide bandwidths, enhanced energy efficiency, ultra-low latency, and extremely high reliability envisioned in 6G[48]. Additionally, it should also play a crucial role in maintaining the security and robustness of data transmission. As the first layer to handle real-world data, it uses advanced encryption and performs data integrity checks to safeguard against unauthorized access and data breaches, ensuring a secure digital twin environment to consolidate the next processing procedures.

3.3 Digital Twins Layer

The Digital Twins Layer includes digital counterparts of physical objects but is not limited to these representations.

We propose that this layer should minimally include three core components (or functionalities): Communication Components, Data Storage Components, and Computing and Modeling Components.

3.3.1 ***Communication Components.*** This component is vital in the NDTs system architecture, especially the Digital Twins Layer, acting as the essential link between the physical and virtual objects. It manages the transmission and transformation of data, ensuring a fluid and uninterrupted flow. This component converts raw data into structured formats that the Virtual Twins Layer can readily use, optimizing compatibility and usability across the system. It also integrates advanced data processing functions such as mapping to align real-world elements with their digital counterparts, and preliminary data analysis techniques like cleansing to remove inaccuracies and aggregation to combine data points for more complex analysis. In a boarder sense, the V2V communication functions should also be implemented and counted in this component.

3.3.2 ***Data Storage Components.*** The Data Storage Components are for effective data management, encompassing temporary storage for quick data processing, metadata storage for efficient organization and retrieval, and robust data security measures. These measures include data encryption to protect data privacy, access control to ensure that only authorized users can interact with the data, and security auditing to monitor and verify compliance with security protocols. Together, these components should also under a comprehensive system that safeguards data integrity while facilitating smooth and secure data operations.

3.3.3 ***Computing and Modeling Components.*** The Computing and Modeling Component should be capable of abstracting and aggregating computing and modeling units of various complexities and granularities to meet specific requirements. This includes capabilities for modeling, simulation, and prediction, as well as conducting 'what-if' analyses. Additionally, it should incorporate

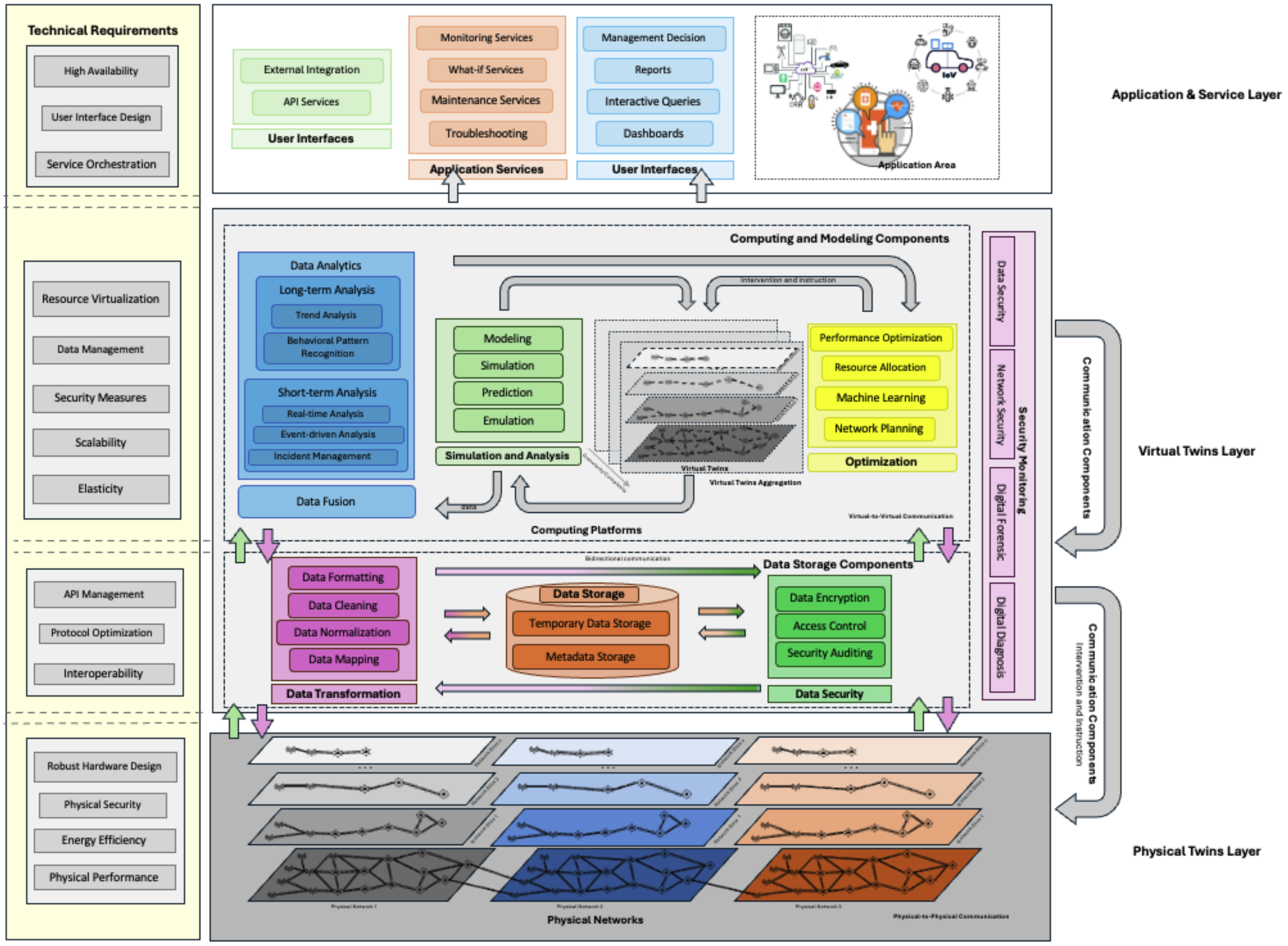

Figure 6: NDTs System Architecture

a comprehensive fault detection system capable of swiftly identifying and diagnosing operational issues, alongside robust system optimization tools that fine-tune performance across diverse network scenarios. Moreover, its predictive maintenance algorithms proactively suggest repairs and upgrades, significantly reducing downtime and extending the lifespan of network components.

These advanced functionalities often rely on deep analytics and machine learning algorithms, which provide substantial support to the upper Application/Service Layer. These algorithms continuously learn from ongoing operations and simulations, thereby enhancing their accuracy and efficacy.

3.4 Application & Service Layer

The Application & Service Layer is the uppermost tier of the NDTs system architecture, where it directly orchestrates services and delivers enhanced experiences for end-users. This layer incorporates a vast array of applications spanning augmented and virtual reality, autonomous vehicles, smart city technologies, and telemedicine, all designed to seamlessly integrate with daily human activities and infrastructural operations. Moreover, the Applications & Service Layer should be characterized by its Service-oriented Architecture (SOA) which enables it to offer modularized and reusable services. This modularity allows for services to be independently deployed, managed, and scaled, meeting specific user demands without affecting the overall system. Furthermore, it supports isolated operations where individual services can function in a standalone mode, enhancing fault tolerance and reducing dependencies. This isolation is essential for ensuring that any disruptions in one service do not cascade to others, thereby maintaining the robustness and continuity of user services. Besides, each service should be both resilient and precisely tailored to meet evolving user needs and environmental contexts.

4 NDTS APPLICATIONS

There are not many real applications at present, and most of them are still in the conceptual stage and academic simulation research stage. There are few real NDTs reported and combined with hardware. In order to better combine the above proposed NDTs ideas and structure for discussion, we selected and summarized several well-implemented NDTs applications. By investigating and analysing those existed implementations, we hope to introduce and propose the most likely important future development trends and emerge challenges of NDTs.

4.1 Ericsson

Ericsson's exploration of digital twins in network management addresses challenges in optimizing and automating 5G networks [61]. By implementing Network Digital Twins, they provide a safe virtual environment for testing and optimizing network parameters like radiated power without affecting real-world operations. This approach not only complies with strict regulatory standards but also enhances network performance through machine learning techniques, leading to more efficient power usage and improved user experiences without compromising service quality. This methodology exemplifies a strategic use of digital twins to enhance network reliability and efficiency while adhering to regulatory constraints.

The reason we analyze this case is that it is an NDTs case that meets the basic design ideas and purposes. Although it is not complex enough, it basically has the structure and functions of NDTs and also uses AI techniques as a tool. It's worth mentioning that the focus of this application case is the use of reinforcement learning. Despite thousands of rounds of training, the cost is minimal because the training environment does not affect the real world. Besides, they used Nvidia's Omniverse platform for interaction and visualization [23]. Currently, there are many platforms, but there is no unified standard, and no one platform is better than the others in all aspects. However, each platform has different focuses and advantages. Here, the Omniverse they used has been proven to be adaptable and recommended for NDTs development in many cases.

4.2 HEAVY.AI

The 6G NDTs system proposed by Lin et al. adopts a layered architecture approach, including the physical network layer, the twin layer, and the network application layer. The physical network layer contains the physical facilities and operating environment of the 6G network. The twin layer is the core of the NDTs, consisting of the data domain, the model domain, and the management domain. This layer is a dynamic, accurate, and up-to-date digital mapping of the physical network. The network application layer uses the data and insights generated by the twin layer to improve network operations and management [30].

HEAVY.AI has developed an NDTs application called HeavyRF, which integrates the SQL backend of Omniverse and HeavyDB, using the latter for real-time processing of radar and other terrain data and RF propagation simulation. HeavyRF is able to run real-time RF simulations on extremely high-resolution terrain data, which is particularly important for 5G and 6G network planning, as these networks need to be simulated in environments with higher transmitter density and more obstruction attenuation. By orchestrating simulations with SQL, HeavyRF can also perform real-time data extraction, loading, and transformation operations on input data, and perform rich operations on simulation outputs, such as associating terrain locations and simulated signal strengths with building polygons to calculate the minimum, maximum, and average signal power received by each building [30]. Through this experiment, they show how DTNs can revolutionize network management through predictive analytics, real-time simulations, and AI-driven optimizations. And, the effectiveness and usefulness of the Omniverse platform are proven.

This example can be considered relatively valuable for reference. Firstly, this architecture is well adopted and aligns with our proposed three-layer NDTs system architecture concept. Additionally, its modular design and the scope of its applications are within reasonable limits, adhering to the fundamental principles of NDTs systems and appropriately designing functions and modules within different layers.

5 OPEN CHALLENGES

When exploring the application of Digital Twins (DTs) technology in 5G/6G networks, we are faced with a series of open challenges. These challenges range from communication, standardization, security to computing costs and data acquisition. Digital twin technology provides unprecedented possibilities for the management and optimization of network systems by creating virtual copies of physical entities. However, the implementation of this technology is not without obstacles. we conducted a comprehensive investigation and identified several critical challenges that currently stand as the most formidable and pressing issues needing resolution in the field. This section will introduce these challenges in detail and explore how they affect the application of digital twins in future communication networks.

5.1 Uniform Standards and Generalizations

The standardization progress of DTs is significantly behind that of applications. Most of the current standards are related to production. In 2018, the International Organization for Standardization (ISO) initiated the creation of the ISO 23247 series of standards, which provide a framework for manufacturing-focused digital twin systems [52]. However, the development of standards for NDTs has not yet emerged. The platforms used are varied, but none are specifically designed for NDTs. This lack of a comprehensive platform results in inconsistencies in standards during the design phase, as well as challenges in migration and scalability.

One of the primary purposes of NDTs is to create virtual replicas for network simulation and what-if testing, which can significantly reduce costs. This also suggests that NDTs can quickly adapt and generalize from small and simple network instances to complex and specific network structures [2]. The structural differences between various physical networks make migration a major issue, resulting in elevated production and design costs. Graph network structures offer a promising solution, and some studies are currently being conducted on this topic [13]. Combining this with DL, especially deep reinforcement learning, has the potential to be used in an environment where the network topology changes dramatically [50, 37].

5.2 Security

There are many aspects to security issues. Security risks during communication are one of them. As mentioned above, communication is mainly divided into three types: P2P, V2V and bidirectional communication.

Data involved in P2P and bidirectional communication must be gathered, transmitted, and stored using established communication protocols. These common techniques are known to have several security vulnerabilities [39]. V2V can also introduce security issues because it allows different processes to exchange data, potentially exposing sensitive information. Key issues include unauthorized access, data tampering, and privilege escalation. Ensuring secure IPC requires measures like encryption, authentication, and strict access controls to prevent these vulnerabilities.

Currently, there is some academic research and effort on the application of DTs in broader fields and their associated security risks with cases [1, 21, 56]. It is inappropriate to provide detailed descriptions and reintroduce every security risk since this is an abroad topic. However, we reorganize and summarize key points based on the NDTs architecture we proposed in Figure 7.

5.3 Communications

A major feature of DTs is that communication is bidirectional. The situation and challenges also vary between different communication methods. In NDTs, the physical-to-physical communications within networks follow the physical principle.

5.3.1 *Real-time synchronization.*

Low latency is a must in many scenarios, such as Ultra-Reliable Low Latency Communications (uRLLC). In P2P and bidirectional communication, this challenge is even more obvious because large and frequent data transfers across physical media become difficult. Because of the need to cross the physical medium, large and frequent data transfers become difficult. 6G may reduce latency to less than 5G's 1 ms [57], maybe be less than 10 μs [35], and the new generation of network technology is expected to solve this problem [63]. However, the speed of physical signal transmission may still not be comparable to the data transfer under the same medium.

5.3.2 *Fault Tolerance.*

In NDTs system, entities need to be updated and synchronized in real-time. Therefore, any errors in the synchronization process may be magnified and lead to the collapse of the entire system. Specifically, when the DT issues an instruction to an entity, if the status of the two entities is no longer consistent, the specific instruction may not be able to be executed or result in serious problems [63]. In addition, disconnection is also common. Short-term disconnection will not have a significant impact on the system (that is, the frequency of synchronization can be reduced to a safe level). However, long-term component disconnection may result in the loss of historical records and deterioration of data quality.

Simply using RL agents does not seem to be a direct solution, thus, other automatic error correction mechanisms are needed.

5.4 Continuous updates and Computing Cost

Continuous updates and computing costs in NDT systems encompass a range of activities such as updating states, predicting future states, issuing control instructions, and receiving and processing feedback. Maintaining a fine-grained simulation with continuous updates imposes significant performance overheads. The frequent updates, while potentially improving accuracy, also lead to substantial and often unnecessary consumption of computing resources.

In NDTs systems, different physical and virtual objects have varying levels of impact on the overall system performance. It is important to avoid the excessive allocation of resources to components that yield minimal returns. Hence, the rational allocation of computing resources, supported by sophisticated algorithms, becomes imperative to optimize system performance effectively [16].

The dynamic nature of environmental changes, such as alterations in the locations of objects within the Internet of Things (IoT) network systems, introduces additional complexity to computation prioritization. These changes necessitate adaptive strategies to prioritize calculations based on the current system state and environmental context. The interplay of multiple factors can precipitate significant alterations in the system's environment, thereby demanding high efficiency and speed in computational processes.

To address these challenges, more efficient, and computing resource-saving Deep Reinforcement Learning (DRL) algorithms can be a breakthrough. For instance, [45] used the Proximal Policy Optimization (PPO) algorithm, which simplifies the complex computations involved in Trust Region Policy Optimization (TRPO), making it a viable approach for handling the computational demands of NDTs with higher computational efficiency.

5.5 Random Access

NDTs, especially for 6G, have special requirements and application scenarios. One of the prospective scenarios of 6G is Massive Machine Type Communications (mMTC). The difference between this and DTs on the other areas is that the communication here is based on network protocols. Therefore, it is not easy to manage a large number of devices, such as IoT devices.

For example, grant-based random access protocols. When a device wants to connect to the network, it needs to send a preamble to the base station (or network). The network has a set of unique preambles (signals) that devices can use. These preambles are designed to be orthogonal, meaning they are distinct and do not interfere with each other. This is important because if two devices use the same preamble at the same time, their signals can clash, causing confusion for the network. Each device randomly selects one preamble from the pool when it wants to connect. This selection process is random to distribute the network load and avoid constant collisions [35]. The limited number of preambles and collisions are challenges for 6G, because when IoT devices increase dramatically, higher device management capabilities are also required [7]. At the same time, 6G NDTs systems will also have synchronization issues. For DTs and their physical counterparts (PTs) to stay synchronized, the PTs need to periodically connect to the network using these preambles. Collisions and delays disrupt this process, leading to desynchronization between the DTs and PTs.

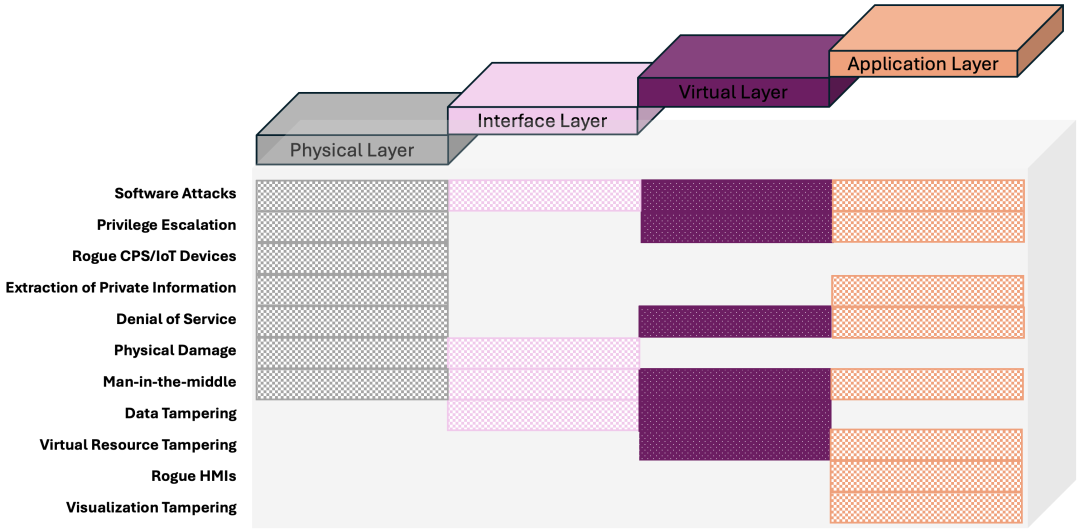

Figure 7: The Most Likely Risks in Each Layer

5.6 Data Acquisition and Ownership

In the realm of NDTs systems, data acquisition is pivotal due to the intricate nature of synchronizing physical entities with their digital counterparts. This involves capturing vast amounts of real-time data from a multitude of sensors and devices, necessitating advanced data fusion algorithms and big data analytics. The real-time data acquisition process is essential for maintaining an up-to-date and accurate digital representation of the physical network, which allows for effective monitoring, control, and optimization. One of the primary challenges in data acquisition for 5G/6G DTs is ensuring the timeliness and accuracy of the data collected. As 5G/6G networks are expected to support a wide range of applications with varying requirements, from ultra-reliable low-latency communications (URLLC) to massive machine-type communications (mMTC), the DTs must handle heterogeneous data sources and types efficiently. This is further complicated by the sheer scale and coverage of 5G/6G networks, which necessitate robust data collection mechanisms capable of processing and integrating data from diverse environments and devices.

The issue of data ownership in NDTs is equally critical. Ownership pertains to the rights and responsibilities associated with the data generated and used by the digital twin. In a 5G/6G context, data ownership is complex due to the involvement of multiple stakeholders, including network operators, service providers, and end-users. Each of these entities generates and relies on data for various purposes, from network management and optimization to personalized user services [46]. Besides, to mitigate transmission delays, NDTs systems can strategically cache and pre-fetch related data on the designated device or edge node [59]. By deploying data closer to the point of use, it brings more serious issue in managing the data and protect privacy because of more data ownership and temporary storage.

Until now, it is still difficult to mitigate the acquisition, ownership or both. The two are also often prone to conflict with each other.

5.7 Granularity

In some other DTs fields outside of the network, high-fidelity modelling is relatively more important because the physical form needs to be reflected in the digital world as much as possible [66]. However, increased model fidelity comes at the cost of increased computational load. Detailed models require processing large volumes of data and performing complex simulations, which can strain computational resources and affect the responsiveness and scalability of the DTs.

Although NDTs do not need to focus too much on high fidelity in some cases, they also have a similar problem, which is granularity. Granularity represents a critical and challenging aspect that fundamentally influences the effectiveness and applicability of the twin. Granularity, which refers to the level of detail at which a digital twin simulates and represents its physical counterpart, must be carefully calibrated to balance between computational feasibility and the fidelity of the simulation.

The importance of granularity in NDTs stems from its direct impact on the twin's ability to provide actionable insights and precise control over network operations [60]. A higher granularity level allows for a more detailed and accurate representation of the network, enabling finer detection of issues, more precise predictions, and more effective optimizations. However, modelling at a very detailed level requires significant computational resources and extensive data, which can limit the model's scalability and responsiveness. Conversely, a lower granularity level simplifies the model, reducing the computational load and data requirements. While this enhances the model's scalability and operational efficiency, it may compromise the accuracy and usefulness of the insights generated.

6 THE FUTURE TRENDS

6.1 Service-oriented and Isolated NDTs

The evolution towards 6G necessitates a paradigm shift in how NDTs technologies are implemented within the IoE. SOA are important in this transformation, which offers a dynamic and flexible framework that can adapt to the diverse and rapidly changing needs of digital twin applications. In a service-oriented design, each component of a digital twin is developed as an independent service, allowing for greater scalability and easier maintenance [24]. This modularity not only enhances the development process but also simplifies updating and scaling individual services without disrupting the entire system. Moreover, SOAs facilitate the integration of heterogeneous systems and devices, which is essential for the IoE environments anticipated in 6G networks. By enabling discrete services to communicate and function interdependently, service-oriented digital twins can meet specific performance requirements while maintaining high levels of operational efficiency.

Resource isolation is another needed feature that must be integrated into future NDTs designs to ensure robustness and reliability. In a shared network environment, where numerous digital twins operate concurrently, dedicated resource allocation can lead to substantial inefficiencies. Conversely, effective resource isolation strategies such as virtualization or containerization allow multiple twin-based services to coexist on the same physical infrastructure without interference, thus optimizing resource utilization. This approach ensures that each digital twin service receives the necessary computational and communication resources to function optimally , and secures each service from potential disruptions or security threats posed by other tenants. The combination of service-oriented design and stringent resource isolation protocols is thus essential for sustaining high-performance, secure, and scalable digital twin operations in the forthcoming 6G networks and is a trend in the development of NDTs.

6.2 Blockchain-based NDTs System

As mentioned above, NDTs systems face security and privacy challenges, which is one of the problems that the academic community is trying to solve. Some scholars believe that blockchain is a viable solution because it provides decentralization, enhanced security and transparency [35], and in addition, interaction records should be traceable and transparently monitored [34].

However, the adoption of blockchain in NDTs system is not without its hurdles. One of the primary concerns is scalability; traditional blockchain networks often struggle to handle high transaction volumes efficiently, which can be particularly problematic in IoT environments where numerous devices frequently interact. This scalability issue is compounded by the significant energy demands associated with blockchain operations, which pose a substantial challenge for IoT devices that typically have limited computing and power resources. The regulatory environment for blockchain also varies greatly across different countries, which creates a complex and often confusing framework for its global implementation. Legal uncertainties and the absence of standardized regulations can deter companies from integrating blockchain into DTs solutions, as they may be wary of adopting a technology that might not align with future regulatory changes. The positive point is that there are a lot of studies on this in academia. The academic community remains optimistic about the potential of blockchain to revolutionize NDTs system security. Ongoing research is focused on developing more scalable and energy-efficient blockchain solutions that can be integrated into IoT networks without overwhelming device capabilities. it may be possible to find a generalized blockchain-based NDTs systems in the future.

6.3 Federated Learning

Compared with Blockchain, federated learning may have better application value and lower cost. It also has better and more flexible advantages in data ownership. Using dispersed federated learning, such as collaborative federated learning based on local aggregation at end-devices, ensures privacy on the one hand, and makes it more difficult for the aggregation server to infer local information from the local aggregated learning model on the other hand [6, 33]. Reinforcement learning has demonstrated its role in network optimization, and reinforcement learning combined with federated learning will be more widely used and more powerful in NDTs systems [9]. The integration of these two methodologies enables more effective handling of the decentralized nature of modern networks, especially in edge computing environments. Reinforcement learning excels at making sequential decisions and adapting to dynamic environments through interactions. When combined with federated learning, which facilitates learning across multiple decentralized nodes without requiring the sharing of data, the system can optimize network management tasks in real time while maintaining data privacy. Federated learning allows multiple edge devices to collaboratively learn a shared prediction model while keeping all the training data on the device, decentralizing the computation and protecting user privacy in the DTs [5].

This combination of dynamic adjustment and privacy reserved scheme can be more important in the future NDTs research.

7 DISCUSSION

In this systematic survey, we explored the evolving field of Network Digital Twins (NDTs) with a focus on their integration within 5G/6G network frameworks. We presented a detailed analysis of the evolution, definitions, architectures, and classifications of digital twins. Currently, different reviews and surveys have different focuses, and there are many complex and mixed concepts which can cause confusion and misunderstandings easily. Therefore, our work aims to address these issues to some extent and enable researchers to quickly understand and get started with the concepts of DTs, especially NDTs.

Despite the comprehensive nature of this survey, several limitations need to be acknowledged. Firstly, the rapidly evolving nature of digital twin technology means that some of the latest developments may not have been fully captured. Additionally, our reliance on published literature may have excluded some proprietary advancements made by private companies. The scope of our survey, while extensive, may not cover all possible applications of NDTs, particularly in niche or emerging areas. Lastly, the diversity in terminologies and classifications of digital twins presented a challenge in synthesizing a unified framework. Currently, industry-specific research on NDTs is relatively limited, and we still lack some relevant information, such as the cost of deploying NDTs, their practical implementation status, and overall progress. These areas are critical and could significantly impact the future development of NDTs. Moreover, the level of support from development teams or open-source communities for the expansion of such NDTs, such as simulators/emulators, is also a concern. Tool-related issues may not be fully addressed through academic literature or online resources alone. Therefore, we hope to conduct in-depth hands-on research in the future, personally testing industry tools, and attempting to provide some recommendations and guidance.

8 CONCLUSION

Our study provided a comprehensive survey of the current state and future possibilities of Network Digital Twins within the evolving telecommunications landscape. By systematically analyzing the roles, components, challenges, and future prospects of NDTs, it became evident that these systems play a important role in enhancing network performance and reliability in the future and may provide more breakthrough applications. Our research outlined the necessity for ongoing development in areas such as security protocols, integration techniques, and standardization to fully realize the benefits of NDTs. Future research should focus on overcoming these challenges and exploring innovative ways to integrate NDTs more seamlessly across various network scenarios.

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