



WHITE PAPER ON NETWORK DIGITAL TWIN

GRAND CHALLENGE #4:
EXPOSE NETWORK INFRASTRUCTURE
TO SERVICES THROUGH NETWORK
DIGITAL TWINS

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Executive Summary

The emergence of Network Digital Twins (NDTs) marks a paradigm shift in how modern networks are designed, managed, and optimized. By providing real-time, digital counterparts of network components and behaviors, NDTs enable advanced simulation, predictive analytics, and autonomous decision-making across heterogeneous domains. However, without a shared architectural vision and harmonized standardization efforts, NDTs risk remaining siloed proprietary solutions with limited scalability and interoperability. This white paper, developed within the Italian RESTART research initiative, proposes a modular and federated framework to unlock the full potential of NDTs across public and private networks, fixed and mobile domains, and even non-terrestrial infrastructures.

Key contributions include:

- A comprehensive analysis of the technological enablers required for effective NDTs deployment, ranging from data acquisition and AI-driven orchestration to edge-cloud infrastructure.
- A focused analysis of the standardization landscape, covering 3GPP, ETSI ZSM, ITU-T, and TM Forum. The white paper identifies current gaps, convergence points, and proposes concrete architectural hooks to facilitate alignment across Standard Development Organizations.
- A novel architecture featuring the concepts of *Digital Hat* and *Digital Hub*, which support the composition, federation, and dynamic lifecycle management of collaborative NDTs.
- A strategic call for harmonized and actionable standardization efforts, stressing that NDTs can only scale if supported by shared models, open interfaces, and governance frameworks. The RESTART architecture is presented not just as a technical proposal, but as a catalyst for standardization convergence.

Ultimately, this paper argues that NDTs are not just a technical evolution, but a foundational layer for the cognitive, resilient, and adaptive networks of the future. Standardization, ecosystem alignment, and a modular architectural approach are essential to ensuring their success at scale.

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Acronyms

2D Two-Dimensional.

3D Three-Dimensional.

3GPP 3rd Generation Partnership Project.

5G 5th Generation.

AAS Asset Administration Shell.

AI Artificial Intelligence.

AP Access Point.

API Application Programming Interface.

B5G Beyond 5G.

CI/CD Continuous Integration and Continuous Deployment.

CN Core Network.

DC Data Center.

DevOps Development and Operations.

DH Digital Hat.

DT Digital Twin.

DT4DI Digital Twin for Digital Infrastructure.

DTH Digital Hub.

DTN Digital Twin Network.

EMF Electromagnetic Field.

ESO European Standards Organization.

ETSI European Telecommunications Standards Institute.

EU European Union.

GIS Geographic Information Systems.

GR Group Report.

IBN Intent-Based Networking.

ICT Information and Communication Technology.

IM Image Method.

IoT Internet of Things.

IRTF Internet Research Task Force.

IT Information Technology.

ITU International Telecommunication Union.

ITU-T International Telecommunication Union - Telecommunication Standardization Sector.

LAN Local Area Networks.

LiDAR Light Detection and Ranging.

MDA Management Data Analytics.

ML Machine Learning.

MLO Multi-Link Operation.

MNO Mobile Network Operator.

MnS Management Service.

MOP Main Operator.

NDT Network Digital Twin.

NFV Network Functions Virtualization.

NPN Non-Public Network.

ODA Open Digital Architecture.

PLM Product Lifecycle Management.

PNI Public Network Integrated.

POP Participating Operator.

QoS Quality of Service.

RAN Radio Access Network.

RL Ray Launching.

RT Ray Tracing.

S-NPN Standalone Non-Public Network.

SBA Service Based Architecture.

SBR Shooting and Bouncing Rays Method.

SDN Software Defined Networking.

SDO Standards Development Organization.

SLA Service Level Agreement.

SON Self-Organizing Network.

STA Station.

TR Technical Report.

TSN Time-Sensitive Networking.

UML Unified Modeling Language.

WG Working Group.

WI Work Item.

YANG Yet Another Next Generation.

ZSM Zero-touch Network and Service Management.

1 Introduction

Network Digital Twins (NDTs) are rapidly emerging as a key enabler for the intelligent, real-time management of complex network infrastructures. This white paper explores how NDTs can revolutionize network operations - through simulation, prediction, and automation - and proposes a unified framework to guide their adoption, rooted in the experience of the RESTART program. The aspects of NDT addressed in this document specifically focus on the Network Management Domain, which inherently requires interaction with the Network Control Plane to ensure coordinated and effective operations ¹.

As modern networks grow in complexity and scale, NDT emerges as a transformative solution, enabling not only real-time simulations - that is, simulations designed to deliver timely and context-aware insights that are directly usable within network management processes - but also emulations, where real control and management components interact with virtualized network environments. These capabilities allow for dynamic performance assessments, fault scenario exploration, predictive analytics and proactive decision-making under realistic conditions, without impacting the live network.

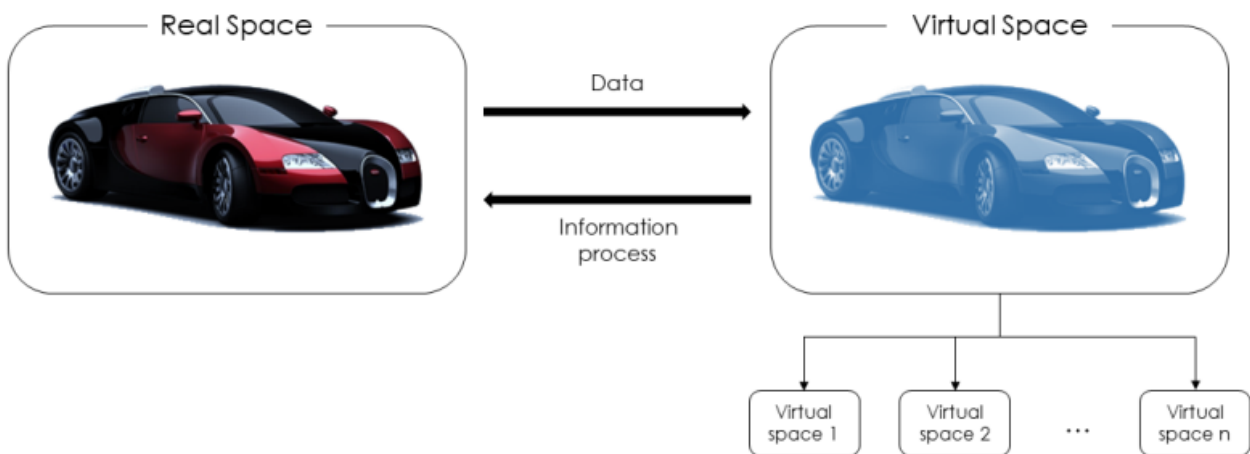


Figure 1: Adapted representation of Grieves' DT model [1], based on the version provided in [2].

The origins of the DT concept trace back to the technology accumulation period, where advancements in Two-Dimensional (2D) design and simulation tools laid the foundation for digital representation. This was followed by the concept development period (2000-2015), during which Michael Grieves formally introduced the DT model in a 2002 presentation at the University of Michigan [1]. Grieves' DT model, depicted in Figure 1, envisions a digital representation of a physical system, maintaining continuous synchronization throughout its lifecycle. This is enabled by a bidirectional flow of data, where real-time updates from the physical system refine its digital counterpart, and insights from the virtual model feed back into the real-world system for optimization and predictive decision-making. This approach allows for testing, validating, and refining changes in the virtual replica before applying them to the physical system, significantly reducing risks and improving efficiency. Moreover, by leveraging multiple virtual sub-spaces, system designers can simulate emergent behaviors under diverse conditions and perform destructive testing and scenario analysis at minimal cost. The application explosion epoch that followed turned DT into a critical tool across industries, revolutionizing how

¹Note that while both domains operate in real-time, they do so with different scopes and timing requirements, reflecting the specific operational processes they are intended to support.

organizations monitor, optimize, and manage their assets. Table 1 summarizes the key phases of DT evolution.

As a result of its evolution, a DT system can now be fundamentally defined as a framework comprising three key components: a physical, digital, or “phygital” target system (e.g., a network, a node, a software, a service, etc.); its virtual, software-based counterpart (i.e., the actual “digital twin”) and an adaptive communication link that ensures continuous synchronization between them [2].

Within the networking context, a DT applied to a network or a portion thereof is referred to as an NDT. As such, a NDT embodies a complex paradigm capturing the full intricacy of a network, including its elements, functions, and behaviors [3]. Building on the foundational principles of the DT concept, NDT naturally extends these attributes, adapting them to the dynamic and multifaceted nature of network systems. An NDT provides a holistic and continuously evolving representation of an operational network or its segments, offering deep insights into performance and optimization. Through continuous interaction and closed-loop synchronization with its physical counterpart, the NDT remains perpetually updated via scalable real-time data acquisition and Big Data storage. By integrating data fusion techniques, Artificial Intelligence (AI)-driven analytics, and adaptive modeling, the NDT dynamically evolves, ensuring that network modifications, whether operational adjustments, emerging anomalies, or environmental changes, are immediately reflected in its digital representation. Furthermore, AI-powered predictive and prescriptive capabilities allow the NDT to detect hidden patterns, simulate responses, and activate self-healing mechanisms. This predictive maintenance capability enables network operators to refine strategies in a controlled, risk-free environment, enhancing resilience, efficiency, and cost-effectiveness while meeting the stringent demands of modern telecommunications infrastructures. Furthermore, DTs can drive technological advancements by identifying potential critical issues in existing technologies, and they could have a positive impact on the environment by enabling more efficient resource utilization. Moreover, in the context of cybersecurity, NDT offers a proactive and risk-free testbed that reveals latent vulnerabilities, validates countermeasures, and refines incident response strategies before they are applied to the live network [4]. Two other key concepts relevant to network-oriented DTs are:

- **Nested NDT:** first discussed in 3GPP Technical Specification Group SA5 [5], this concept models a hierarchy of interconnected and orchestrated NDTs. More recently, the idea has been generalized to all types of NDTs in 3GPP TS 28.561.
- **Digital Twin Network (DTN):** introduced in ITU-T Recommendation Y.3090, a DTN is a collection of interacting DTs that together provide a coordinated, end-to-end representation of a complex physical network.

Within the NDT landscape, the ITU-T and 3GPP communities approach the concept from complementary angles. ITU’s DTN model stresses the orchestration of many interacting DTs, whereas 3GPP’s Nested NDT framework focuses on collaboration among network-centric twins during simulation and emulation phases.

This white paper synthesises these two viewpoints and provides a new perspective: explain where the approaches diverge, identify their common ground, and propose a single, standardized framework that encompasses innovation matured within the RESTART program, which is pursuing various initiatives to advance this technology. Some projects are focused on establishing robust architectural foundations for the NDT, while others adopt application-driven approaches aimed at realizing specific use cases. The outcomes of these studies inform the analysis presented in this white paper, which is structured as follows.

In Chapter 2, we identify and discuss the potential enablers required to unlock the full capabilities of the NDT paradigm. These include comprehensive data availability, from nationwide geographic data

to business-specific local data, and efficient data exchange mechanisms, along with cloud infrastructure, edge computing, Software Defined Networking (SDN), Development and Operations (DevOps) practices, advanced software development, management and orchestration strategies, and the pervasive influence of AI/Machine Learning (ML) as well as network softwarization solutions, synchronization or localization. Chapter 3 provides an in-depth analysis of current standardization efforts in the field of NDT, highlighting the diverse approaches adopted by different standardization bodies and revealing a critical challenge: the absence of a unified, standardized architecture capable of supporting a broad range of interoperable, cross-domain scenarios. To address this gap, Chapter 4 proposes a structured NDT architecture that begins with its core components and progressively identifies the missing elements that must be integrated, with particular emphasis on establishing essential interfaces to achieve a truly interoperable and scalable ecosystem. Finally, Chapter 5 delves into how the NDT enables new implementation possibilities and use cases, including the concept of Nested NDT, initially introduced in the 3rd Generation Partnership Project (3GPP) TR 28.915 and refined in the TS 28.561, where a more generalized approach was adopted by extending the idea of collaborative NDT to all types of NDT. This notion has garnered interest within the RESTART research initiative on NDT, particularly with a view to contributing to future standardization efforts. However, these applications remain subject to the constraints imposed by the current standardization framework.

The overarching message of this white paper is unequivocal: to discuss a broad and extensible NDT paradigm that enables unrestricted and scalable scenarios, active engagement with standardization bodies is essential. By unifying fragmented perspectives and aligning them with concrete architectural blueprints, this paper charts a strategic path forward for NDTs, ensuring they become foundational components of tomorrow's networks.

Table 1: Evolution stages of DT technology based on findings in [6].

Stage	Time Period	Key Developments
Technology Accumulation	Late 20th Century	• Development of 2D drawing tools. • Emergence of simulation technologies as precursors to DTs.
Concept Development	2000–2015	• 2002: The University of Michigan established a PLM Center. Michael Grieves published <i>Conceptual Ideal for PLM</i>, introducing a “virtual digital expression equivalent to physical products” [7]. • 2010: NASA introduced DT representations in its space technology roadmap [8]. • 2011: AFRL disclosed the “Airframe Digital Twin” project [9].
Application Explosion	2010s–Present	• DT solutions have penetrated a wide array of industries. • Large manufacturers have proposed product landing solutions based on DTs. • Dassault launched its 3DEXPERIENCE strategy and platform. • ANSYS introduced <i>TwinBuilder</i>. • DTs solutions were extended to energy, smart cities, transportation, agriculture, healthcare, smart homes, and other industries. • Gartner recognized DTs as a top strategic technology trend in 2017, 2018, and 2019. • The volume of academic publications on DTs has grown exponentially.

2 Key Enablers

Unlocking the full potential of NDT requires a multi-layered technological stack. In this chapter, we walk through the essential enablers—starting from data availability, through infrastructure and software platforms, up to orchestration and AI. Together, they form the backbone of a responsive and scalable NDT ecosystem. Some of these are foundational, i.e., indispensable for the very existence of NDTs, while others enhance their efficiency, scalability, and overall effectiveness, facilitating seamless integration and operation. A fundamental requirement is the availability of reliable, real-time data [10]. The ability to gather detailed and precise information from physical systems is essential for creating an accurate digital representation. Additionally, a robust infrastructure is required to store and process this data, alongside a software-based technological platform capable of managing data analysis and ensuring connectivity between various system components [11]. The creation of NDT represents a significant opportunity for both traditional and software-based networks. However, software-based networks offer distinct advantages over traditional ones, primarily due to their ability to leverage network Application Programming Interfaces (APIs) and open interfaces, which enhance adaptability and efficiency. The adoption of software-based networks enables more flexible network management, quicker responses to market demands, and reduced operational costs, making it a strategic choice for maintaining a competitive edge in an ever-evolving sector [12]. Through APIs, information from diverse sources and systems can be integrated, enabling the creation of accurate and dynamic digital models of network infrastructures. In this context, the use of standardized data models, services, and interfaces is crucial to ensuring seamless communication and interoperability - even between NDTs belonging to different networks and domains. This open and interconnected architecture fully unlocks the potential of NDT, facilitating data sharing across networks, applications, and businesses. Another key aspect is process management. NDTs enable the definition, monitoring, and optimization of network management workflows, maximizing the benefits derived from NDT adoption [13].

Finally, AI plays a key role in the development and optimization of NDTs, becoming a pervasive and transversal component across multiple domains. By leveraging AI algorithms and predictive analytics, AI enables real-time analysis of vast amounts of data, enhancing the ability to anticipate future scenarios and optimize operations [14]. In this context, AI is not merely a supporting tool but serves as a core driver of strategic decision-making and innovation in NDTs, making it an underlying component of nearly all key enablers [15]. The most significant NDT enablers are summarized in Figure 2 and will be described in the following.

2.1 Data Availability

The successful creation and deployment of NDTs depend on the availability of data, which can be broadly classified into two main categories:

- *Geographic Nationwide Data*: these data encompass large-scale territorial and network-related information relevant to multiple stakeholders. To foster transparency and facilitate cross-sector collaboration, this data should be made publicly accessible, enabling the seamless sharing of resources and insights.
- *Business-Specific Local Data*: these data are related to proprietary and often confidential datasets that originate from a company's facilities, operations, and production processes. These datasets are essential for informed strategic decision-making, process optimization, service enhancement, and overall operational efficiency.

Together, these data sources form a comprehensive ecosystem that empowers stakeholders to develop and refine NDTs, enabling both strategic foresight and real-time operational intelligence.

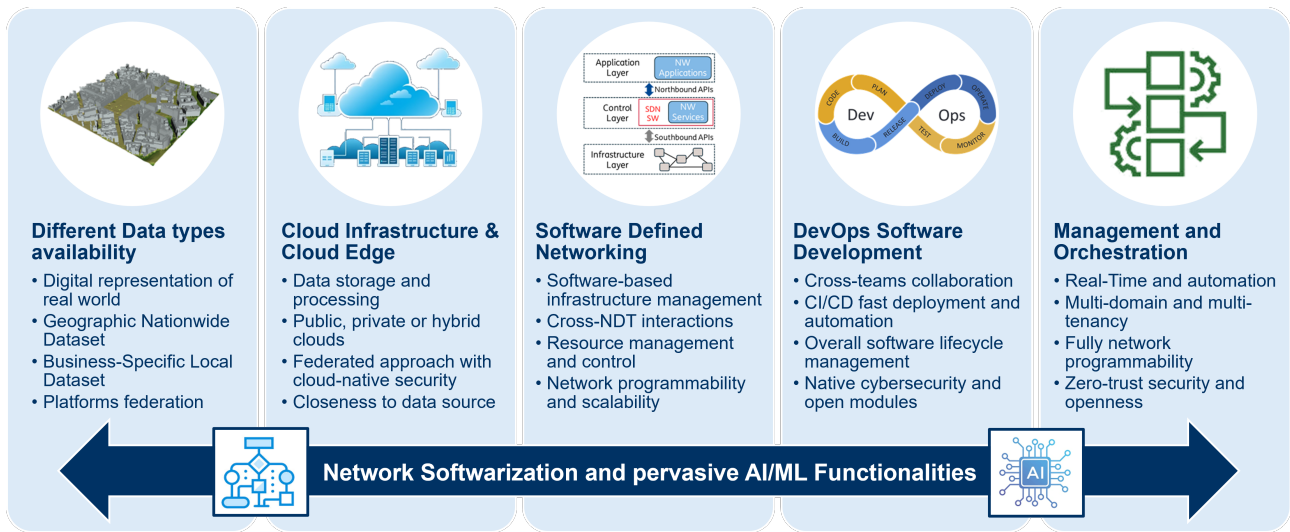


Figure 2: Main valuable NDT enablers.

2.1.1 Geographic Nationwide Data

In the modern data-driven landscape, accurate digital modeling of geographic and network infrastructures is fundamental for strategic decision-making. The ability to create detailed, real-time Three-Dimensional (3D) digital representations has transformed how various sectors - including telecommunications, urban planning, and utilities - visualize and manage spatial data.

The advent of Geographic Information Systems (GIS) has revolutionized spatial data visualization, providing an interactive and dynamic representation of terrain, infrastructure, and urban environments. Unlike traditional 2D maps, 3D digital models offer a more comprehensive and intuitive understanding of geographic features, facilitating improved planning and operational efficiency. To develop high-fidelity digital representations, data is sourced from multiple technologies, including (i) satellite imagery and aerial photography, offering broad coverage of terrain and infrastructure, (ii) Light Detection and Ranging (LiDAR) technologies, enabling precise elevation mapping and object detection, and (iii) vehicle-based and drone-captured geospatial data, providing high-resolution, real-time updates. By integrating these technologies, 3D models enhance decision-making across multiple domains, supporting applications such as smart city development, telecom infrastructure deployment, and disaster management.

One of the most significant advantages of digital geographic networks is their ability to create and share databases across multiple applications and stakeholders. A nationally standardized, open-access database can serve as a centralized resource, enabling cross-industry collaboration and reducing duplication of efforts. Key benefits of a unified digital repository include:

- Optimized resource allocation, minimizing redundant data collection and storage efforts.
- Reduced operational costs, as stakeholders can access shared geospatial data instead of building independent datasets.
- Improved regulatory compliance, ensuring data consistency for governmental oversight and urban development initiatives.
- Enhanced coordination across industries, including telecom providers, smart city planners, and utility companies (e.g., electricity, gas, and water sectors).

- Enhance the effectiveness of AI/ML models using techniques like transfer learning, which utilizes datasets from different contexts to improve model performance in specific scenarios.

A nationwide approach to geographic data sharing would unlock significant benefits across multiple industries, fostering efficiency, transparency, and strategic planning. Key sectors that would directly leverage such a framework include:

- *Electromagnetic Field (EMF) Monitoring and Compliance:* by integrating real-world network measurements into a digital model, stakeholders - including mobile operators and regulatory agencies - can efficiently map, monitor, and manage electromagnetic exposure levels at a national scale. This would standardize compliance verification, reducing the need for fragmented and time-consuming assessments.
- *Fixed and Mobile Network Infrastructure Planning:* a continuously updated nationwide telecom infrastructure map would support real-time network planning, expansion strategies, and investment decisions. For mobile networks, such a system would aid in coverage optimization, spectrum allocation, and interference management. For fixed access networks, this up-to-date view would provide valuable insights into fiber deployment, last-mile connectivity strategies, and market analysis for both private and public stakeholders.

By leveraging shared geographic digital models, network operators, government agencies, and businesses can collaborate within a unified digital framework, enhancing operational efficiency and supporting data-driven decision-making. Moreover, standardizing data formats and ensuring interoperability would foster greater transparency and trust between businesses, regulatory bodies, and public administrations, ultimately streamlining infrastructure deployment and governance.

2.1.2 Business-Specific Local Data

On top of digital models encompassing geographical and network information, each market sector requires tailored data acquisition to create robust digital representations of their respective infrastructures and applications. For certain datasets, adopting a transnational, European Union (EU), or global approach could enhance the capability of NDT that spans beyond national boundaries. For instance, in an industrial context, NDTs integrate information, models, and behaviors derived from different sources, such as sensors, robots, network infrastructure, and Internet of Things (IoT) devices.

The real-time collection and analysis of data from all sensors and systems within a specific business-related environment is essential for developing accurate digital models of the physical world. This comprehensive approach addresses every aspect of production processes, ranging from machine operating conditions to product performance. Furthermore, to effectively manage and optimize operations, NDTs must be synchronized with all the systems that provide information on the characteristics and status of a real environment, such as inventory, management, and assurance.

In some cases, NDTs proprietary data, modeling, and services can also be leveraged by third parties to enhance their own business operations. Therefore, establishing efficient and shared channels for cross-partner communication and collaboration is essential for maximizing the potential of these digital solutions.

2.1.3 Federated Data Exchange and Interoperability

Facilitating the seamless exchange of Geographic Nationwide Data and Business-Specific Local Data requires a federated approach that leverages interconnected NDT platforms. This strategy ensures controlled access to information based on user rights while maintaining data consistency, standardized cross-communication, and robust security measures. Moreover, beyond serving as intermediaries for

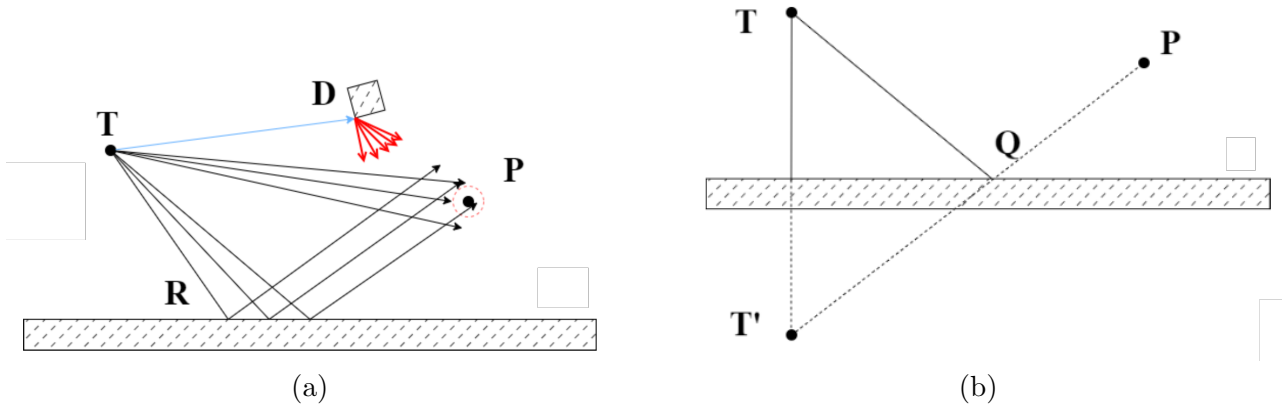


Figure 3: Schematic representation of (a) the Shooting and Bouncing Rays Method (SBR) and (b) the Image Method (IM).

SBR (a): R indicates reflection points while D is a diffraction point at an edge. A path is received if it satisfies the reception condition, exemplified by hitting a reception sphere (red circle) at receiver P. IM (b): T' is the image of transmitter T with respect to the reflection plane hit on point Q.

data exchange, NDT platforms play a pivotal role in providing advanced services, including network simulations, AI/ML-driven analytics, and lifecycle management tools.

Achieving interoperability across diverse systems demands a carefully designed architecture, incorporating well-defined data models, exposed services, and standardized communication protocols. To this end, a strong commitment to shared standards is essential, as it fosters operational efficiency, reliability, and cross-industry collaboration. By embracing this approach, the limitations of traditional one-to-one interactions, such as those between mobile operators and network vendors, are eliminated, paving the way for a more open, transparent, and secure data-sharing ecosystem. This vision aligns with the future trajectory of next-generation telecommunications, as outlined in [16], reinforcing the shift towards a collaborative, standards-driven digital infrastructure.

2.1.4 Ray Tracing

A particularly advanced use case of geographic and contextual data sharing lies in radio environment modeling, where techniques like ray tracing push physical accuracy to the next level. The availability of high-fidelity 3D digital representations of the physical environment significantly enhances the characterization of wireless signal propagation, which is a fundamental requirement for the realization of a NDT. In particular, deterministic ray-based techniques can exploit these digital assets to compute physically consistent channel responses that account for the interactions of electromagnetic waves with surrounding obstacles.

More specifically, ray-based simulators create an electromagnetic DT by deterministically modeling how rays, a representation of waves under the high-frequency approximation of Maxwell's equations, interact with the environment when traveling from a transmitter to the receiver. As a result, ray-based techniques yield a list of complex gains and delays that can be summed incoherently, thus comprehensively taking into consideration the effect of constructive and destructive interference at the receiver. Each ray may also be associated with a Doppler shift, allowing for deterministically capture the time-varying effects due to their relative mobility. This enables precise reconstruction of the wireless channel's multipath structure and dynamics. Integrated into a NDT, this physical-layer accuracy enables realistic simulation of wireless systems, especially in complex, time-varying scenarios where legacy probabilistic approaches fall short. Moreover, in this context, such physical-layer precision is not merely a modeling detail but a critical enabler of end-to-end system fidelity. The

accuracy of application-level outputs in a DT framework fundamentally depends on the realism of the underlying propagation model. As a result, ray-based tools are not optional in this setting: they play an essential role in ensuring that the simulated data reliably mirrors the behavior of the physical network, thus supporting valid and trustworthy decision-making across layers.

Ray-based models can be broadly classified based on their level of detail:

- *Ray Launching (RL)*: an approximate, empirical method in which a fixed number of rays are emitted from an electromagnetic source in predefined angular directions. After a limited number of interactions with the environment, the simulator evaluates whether each ray reaches the receiver, typically by verifying if it intersects a predefined region surrounding it. A common implementation of the RL approach is the Shooting and Bouncing Rays Method (SBR), schematically represented in Figure 3a. The objective of this approximate technique is not to identify the exact propagation paths, but rather to enable scalable simulations across large environments. One typical use case is the generation of radio coverage maps in cellular network planning.
- *Ray Tracing (RT)*: a deterministic, exhaustive approach that models wave propagation by computing the exact geometric paths between a transmitter and a receiver. A common implementation is the Image Method (IM) (Figure 3b) in which reflective surfaces generate virtual sources to construct propagation paths. This process is recursively extended to account for multiple reflections. The IM models the surfaces as flat as mirrors; for this reason, RT simulators also account for diffuse scattering due to surface roughness to better match real-world conditions. Unlike RL, this method aims at high-fidelity modeling of multipath propagation, making it particularly accurate in complex and dense environments.

This distinction underscores the trade-off between accuracy and scalability in ray-based modeling: while RT with IM offers unmatched precision by exhaustively tracing all plausible paths, its computational cost grows rapidly with the number of surfaces and interactions. Current research in this direction explores the development of hybrid approaches that combine the precision of RT with the scalability of RL with SBR, aiming to balance accuracy and computational efficiency. This computational burden holds particular significance in the context of a NDT, where real-time execution is crucial to accurately mirror and predict the dynamics of the physical network. In this context, performance is not a secondary concern but a fundamental requirement. The trade-off between physical fidelity and computational efficiency thus acquires a new dimension: it is not merely a technical choice but a foundational challenge in the realization of scalable, reactive, and predictive NDT.

However, the value of high-quality data can only be fully realized if supported by a scalable and responsive infrastructure capable of storing, processing, and delivering it where and when it is needed. This brings to the next enabler: cloud and edge computing.

2.2 Cloud Infrastructure and Cloud Edge

Cloud storage and cloud edge are key components for the realization of the NDT. Data Centers (DCs) provide the essential infrastructure for centralized computation and storage, enabling extensive data processing capabilities necessary for building accurate digital representations of network environments. These facilities can be located on-premises, i.e., through private cloud solutions, or in public clouds.

The first approach can be exploited by organizations requiring enhanced control and security, especially when dealing with sensitive data or specific use cases. In the second solution, data from multiple network sources can be collected and analyzed more easily, using their massive computing resources to create efficient models NDT. The public cloud market is mainly operated by hyperscalers (e.g., AWS, Microsoft Azure, Google Cloud), which typically also offer additional services on top of data storage. These providers are currently making huge investments in DCs and transport networks

to ensure very high scalability and flexibility for businesses of all sizes. Furthermore, they not only guarantee a large and solid infrastructure, but also develop and supply software platforms to fully support data management and related processing. In this way, companies can derive actionable insights from their data by ensuring cost-effective computational resources and facilitating the introduction and the extension of the massive use of AI in network management and automation processes. The hybrid model of public cloud and private cloud enables the creation of interconnected NDTs, capable of managing and meeting the diverse requirements of users in a flexible and efficient manner.

A crucial aspect to consider on data storage and processing is the relationship between the NDT and nationally/internationally significant geographic information. The management of such data should occur at a national/international level, utilizing distributed DCs that can be federated to maximize efficiency and resilience. This federated architecture would enable scalable and secure management of information that requires a global view and coordinated management. It follows that an effective NDT framework should provide mechanisms for accessing both shared DCs, which can operate at a national/international level, and private DCs through standard-based data exchange and relying on defined agreements for specific use cases. In this view, data security is fundamental, and it is therefore necessary to implement robust systems to ensure that information remains protected and accessible only to authorized users. Alongside the increased resources needed for the adoption of the most innovative technological solutions, it is also important to emphasize the need for a strategic vision, including public initiatives, capable of guiding and supporting the development of this essential sector for the growth of the national/international framework.

The exploitation of edge cloud computing complements DCs infrastructures by extending processing power towards a decentralized logic, i.e., moving closer to the data source. From a functional point of view, the creation of new proximity infrastructures (i.e., edge computing) is aimed at reducing latency in data transmission. This decentralized approach accelerates response times and improves the efficiency of data transfer. This is particularly beneficial for applications that require real-time analytics and decision-making, such as those found within IoT environments. Edge solutions allow for faster iteration of DT models by enabling localized data processing and immediate feedback loops. The advent of edge DCs marks a turning point in the way data is processed and managed, bringing also significant benefits in terms of efficiency, dependability, security, and innovation. Indeed, decentralizing DCs allows for more controlled data management, reducing the risk of large-scale breaches and improving data privacy. Moreover, edge DCs can be easily added or removed as needed, offering a scalable solution that adapts to evolving data processing demands. Cloud storage and cloud edge are therefore key components for the efficient realization and interconnection of NDT platforms. Intermediate solutions that leverage both remote and edge computing approaches are also feasible. Edge computing optimizes local decisions from the point of view, e.g., of latency and real-time requirements. Additionally, edge computing maintains the strict privacy requirements of some data by sending only selected information to centralized DCs. On the other hand, remote elaborations better reach the global optimization that is required in many application contexts of NDTs.

Yet, while cloud and edge platforms provide the physical and virtual resources, they still require intelligent control and programmability to dynamically manage the underlying network fabric. This is where SDN plays a pivotal role.

2.3 Software Defined Networking

NDT leverage digital modeling and advanced software functionalities to create virtual replicas of physical entities, facilitating enhanced monitoring, analysis, and simulation. A crucial technology driving the potential of NDT is SDN. By employing software-based controllers and APIs, SDN streamlines the management of the underlying infrastructure layer, enabling more efficient and responsive network operations.

The importance of evolving towards software-based networks is strategic, as they offer a framework that fosters innovation and flexibility in data handling. Through the SDN logic, communication and information exchange is facilitated not only between different NDT modules but also among NDT platforms and between NDT platforms and the real network. This interconnected approach optimizes data flow and interoperability, while also offering expected benefits such as scalability in adding or removing functionalities, regardless of whether they are deployed in public or private cloud environments, and increased flexibility in network management and control.

Additionally, by managing the Control Plane via software, SDN empowers organizations to achieve flexible, straightforward data transfer across multiple locations, dynamically adapting to varying demands. NDT platforms can exploit this capability to gain comprehensive control over network infrastructure, allowing for seamless adjustments in configuration settings and efficient resource provisioning through a centralized interface. The synergy between SDN and DT technology exemplifies the transformative potential of modern networking and software solutions in creating smarter and more responsive systems. This programmability translates into greater operational efficiency, cost reductions, and improved service quality of real networks. Furthermore, softwarization allows for easier integration of advanced algorithms and ML, capable of predicting potential issues and optimizing network performance.

With SDN laying the groundwork for programmable and flexible infrastructures, it becomes essential to adopt development methodologies that match this agility. DevOps emerges as a natural approach to streamline the development, integration, and deployment of NDT capabilities.

2.4 DevOps-Driven Software Development

To fully realize the potential of NDT platforms, adopting efficient software development practices is crucial. In today's rapidly evolving digital landscape, the combination of integrated development and operations, commonly known as the DevOps approach, creates a transformative synergy aimed at enhancing operational efficiency and agility. DevOps fosters collaboration among cross-functional teams and supports continuous integration and rapid deployment, which are essential in the advancement of NDTs. This methodology breaks down traditional barriers between development and operations, accelerating the creation of DT models that accurately mirror physical network infrastructures. The iterative nature of DevOps, which includes automated testing and continuous feedback loops, guarantees that DTs stay updated with the integration of real data. This ensures a precise representation of the dynamic conditions within network environments. By implementing these methodologies, organizations gain the agility and scalability to fully leverage the capabilities of NDTs, thus driving innovation and facilitating improved decision-making.

One of the primary benefits of incorporating DevOps into the development of NDTs is the enhanced agility it provides. Teams can rapidly iterate on their models, keeping the NDT aligned with the evolving network landscape. This flexibility allows organizations to simulate various scenarios, optimize performance, and proactively address potential challenges before they impact physical infrastructure. Furthermore, automation features such as Continuous Integration and Continuous Deployment (CI/CD) enable the fast rollout of updates and improvements, ensuring that DTs reflect the most current state of the network.

Effective collaboration between development and operations teams also boosts the accuracy and reliability of DTs' predictive capabilities. By integrating data analytics and ML within the DevOps pipeline, organizations can extract actionable insights from DTs, enhancing their decision-making processes. This proactive management of network resources aids strategic planning and capacity management, enabling organizations to meet current demands and anticipate future needs. Additionally, the DevOps approach incorporates cybersecurity measures throughout the application lifecycle, from design to deployment and maintenance. This practice safeguards NDTs against vulnerabilities, ensur-

ing robust protection of sensitive data and maintaining stakeholder trust. The DevOps approach can furthermore exploit open-source models (e.g., TensorFlow for deep learning, PyTorch for flexible model development), presenting significant advantages for the development and enhancement of NDTs. By utilizing modular open-source solutions, it is possible to create adaptable and scalable DTs that integrate seamlessly with third-party systems or platforms. This openness promotes collaboration among stakeholders, creating an ecosystem favourable to the sharing of knowledge, innovations, and advancements to continuously improve NDTs. DevOps ensures continuous delivery of NDT components, but without a robust orchestration framework, these components would remain isolated. To truly enable intelligent, coordinated behavior, the role of management and orchestration becomes fundamental.

2.5 Management and Orchestration

Orchestration is a key capability within a NDT platform, facilitating comprehensive management across complex network infrastructures and functionalities. By enabling real-time data synchronization, orchestration ensures that information from different sources and systems is harmonized, providing an accurate and up-to-date representation of the network. This capability is essential for effective monitoring and decision-making in dynamic network scenarios.

An effective orchestration can also enable a federated approach where digital modular entities are interconnected with each other. Each DT operates as an autonomous entity with clearly defined interfaces and data models, but collectively contributing to a fully programmable digital infrastructure. A seamless integration and management across various domains can also be orchestrated, ensuring that actions taken in one area of the network are appropriately reflected throughout the entire ecosystem (e.g., between fixed and mobile access, cloud infrastructure, transport network, IoT and sensors network, etc.). Moreover, orchestration allows for managing and coordinating advanced simulations through NDTs and taking decisions by means of *what-if* analyses powered by AI and ML. These simulations allow for forecasting potential outcomes based on different scenarios, thereby facilitating proactive management and strategic planning. This overall management and control framework enables a closed-loop automation, whereby information derived from NDTs can be acted upon in real-time, creating a reactive system that adapts network operations based on evolving conditions. This capability not only optimizes resource utilization but also enhances overall network resilience. It follows that orchestration within a NDT platform transforms complex network management into a streamlined, intelligent process, driving innovation and efficiency in today's interconnected digital landscape.

To ensure an effective orchestration, a design relying on a Service Based Architecture (SBA) approach should be pursued. The SBA paradigm facilitates the exposure of various services and data and provides a flexible framework for connecting digital platforms, whether managed by a single owner or multiple entities (e.g., Fixed/Mobile Operators, Tower Companies (TowerCos), Private Network Owners, Public Administrations).

Each platform is built on service-oriented principles (i.e., based on producer/consumer or publisher subscriber paradigms), hence exposing data and its functionalities as services, which other platforms can then discover and consume. This relationship not only enhances the capabilities of individual platforms but, thanks to a high level of programmability, also fosters an ecosystem of integrated services that can respond dynamically to user needs. Programmability is a key feature that empowers platforms to adapt and evolve. This concept operates on two distinct levels:

- *Programmability internal to the platform*: within each platform, developers can build customized applications that enhance or extend the platform's functionalities. This internal programmability allows for the creation of tailored solutions that meet specific user requirements or operational challenges. By leveraging NDT capabilities and related APIs, developers can develop sophisticated applications that fully utilize the underlying services provided by the platform, ensuring

that users have access to the most relevant and effective tools for their needs;

- *Programmability among different platforms*: beyond individual platforms, there exists a layer of programmability that facilitates interaction among various platforms. This is achieved through mutual service exposure and data exchange, allowing platforms to integrate and compose services across organizational and technological boundaries. By adhering to SBA principles, platforms can offer services that are easily discoverable and consumable by other platforms according to a collaborative approach, leading to the creation of innovative, cross-platform solutions that harness the overall power of different systems.

With the exploitation of SBA and its programmability, platforms are evolving towards a state of potential autonomy. Leveraging advanced algorithms, AI, and ML, these platforms can self-manage, optimize, connect, and adapt their services based on changing conditions without necessarily requiring direct human intervention. This autonomy enables opportunities in efficiency and responsiveness, enabling platforms to dynamically adapt their operations in line with user needs, market trends, and performance metrics. Within the NDT orchestration, a SBA is characterized by its flexibility in being able to allow communication among platforms also exploiting different cloud environments, hence ensuring performance optimization based on specific cloud capabilities. This open and modular framework not only supports multi-tenancy but also enhances scalability and flexibility, as each component can operate independently with its own lifecycle, thus enabling tailored upgrades and maintenance without impacting the entire system. A zero-trust security model is integral to this architecture, facilitating secure interconnections among users, assets, and resources across networks, thereby ensuring that data integrity and confidentiality are maintained. Moreover, the collaboration and reference to open-source communities (e.g., ONAP, GSMA, TMForum, Nephio, 3GPP Forge, O-RAN SC, etc.) stimulate software reuse and promote best practices among different platforms, creating a rich ecosystem for innovation. In addition, the SBA approach facilitates incorporating AI and ML technologies in a distributed and pervasive manner across all platforms, hence fostering a federated approach, enhancing decision-making capabilities and operational efficiencies. Furthermore, a sandbox environment can be leveraged that allows researchers to rapidly prototype algorithms, accelerating the development of innovative solutions within the NDT space. Finally, by adhering to standard interfaces, this architecture ensures seamless interaction with networks and infrastructure, promoting interoperability and reducing integration complexities. Overall, the SBA architecture for NDT orchestration enables significant advances in network management and operational intelligence.

Together, these enablers constitute a holistic ecosystem where data becomes actionable, infrastructure becomes agile, and orchestration becomes autonomous. Building effective NDTs is not about selecting one of these pillars, but it is about weaving them into a coherent, interoperable fabric.

3 Standardization Landscape

The successful deployment of NDTs at scale depends not only on technological enablers, but also on the availability of common standards and reference models. While Chapter 2 introduced the foundational technologies that underpin NDTs, this chapter examines the current landscape of standardization efforts across key organizations, including 3GPP, ETSI ZSM, ITU-T, and TM Forum.

Understanding the scope and limitations of these ongoing initiatives is essential to identify gaps, avoid fragmentation, and guide the development of interoperable, future-proof NDT architectures.

3.1 3GPP

The 3GPP is a global collaboration between telecommunications standards organizations aimed at developing and maintaining technical specifications and standards for mobile communication systems. Established in 1998, 3GPP defines standards across multiple domains, including Radio Access Networks (RANs), Core Networks (CNs), service capabilities, and terminal interfaces. Its primary objectives are to ensure interoperability, promote innovation, and facilitate the deployment of new mobile technologies, such as 5th Generation (5G), to enhance user experience and enable advanced services.

3.1.1 3GPP SA5

The 3GPP SA5 group is responsible for management, orchestration, and charging in 3GPP systems, covering both functional and service-related aspects. Notably, SA5 is at the forefront of standardization efforts related to NDT, driving its integration into future network architectures.

Key SA5's responsibilities include:

- **Network Management:** developing standards and specifications for managing telecommunications networks effectively, ensuring that they operate efficiently and reliably.
- **Service Assurance:** establishing guidelines for monitoring and ensuring the quality of services provided over mobile networks, which is crucial for maintaining user satisfaction.
- **Integration of New Technologies:** addressing the integration of new technologies, such as Network Functions Virtualization (NFV) and NDT, into existing management frameworks.

By focusing on these areas, SA5 drives the evolution of mobile network management and orchestration, enabling more automated, efficient, and user-centric telecommunications systems. It collaborates closely with other 3GPP groups and external organizations to align standards and ensure comprehensive coverage of all aspects of service and network management.

3.1.2 3GPP TR 28.915 V19.0.0 (2024-12)

Overview

Within the scope of SA5, 3GPP TR 28.915 [17] addresses the management and orchestration of NDTs in mobile networks, specifically under Release 19. It addresses the growing need for advanced management solutions in telecommunications, particularly as networks become more complex and demand more efficient operational strategies. The report outlines a comprehensive study on NDTs, detailing their potential applications in network management and automation. It emphasizes a dual approach that combines both emulation and simulation techniques to accurately model network behavior. The document identifies key requirements for NDTs, including their ability to provide insights into network performance, verify configurations, and predict outcomes under different operational scenarios. The

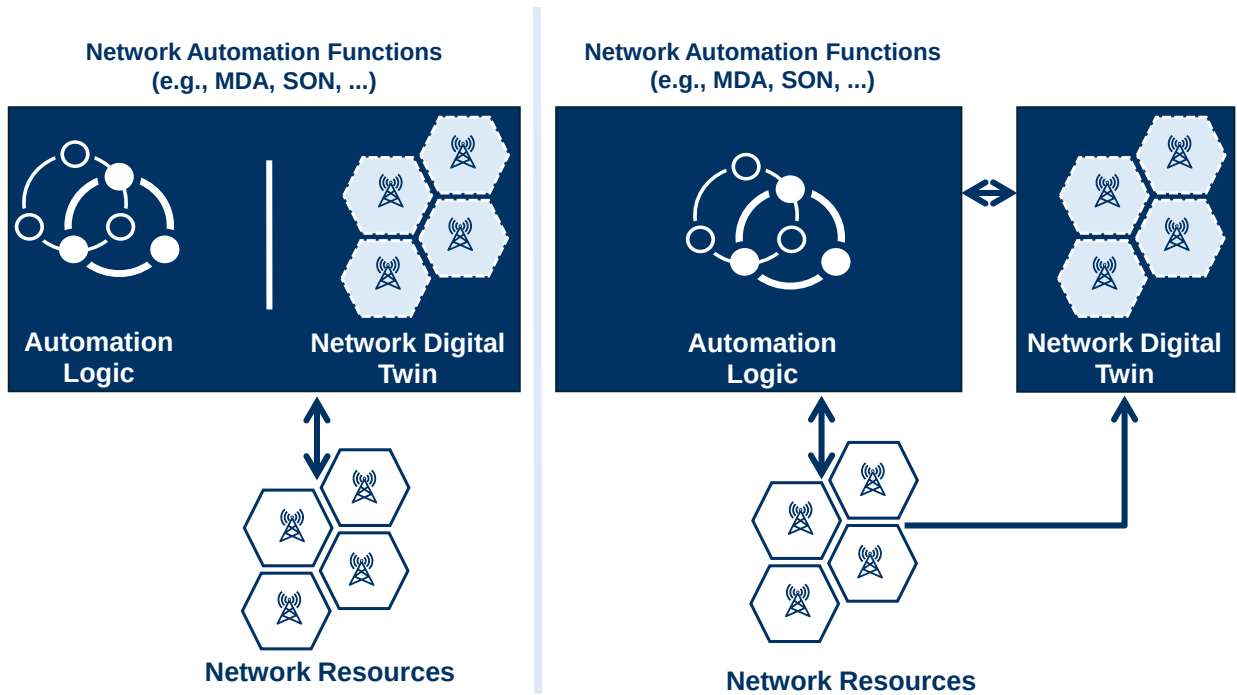


Figure 4: NDT relation with Network Automation Functions according to 3GPP TR 28.915 [17].

Option 1 (left): NDT internal/integrated into existing Network Automation Functions.

Option 2 (right): NDT separate from existing Network Automation Functions.

Double-headed arrows represent bidirectional data and control flows between the network, NDT, and management functions, while single-headed arrows indicate unidirectional control flow.

study also highlights the importance of integrating various data sources to enrich the NDT models, ensuring they can effectively support the management of real-world network conditions.

NDT Framework

In the 3GPP framework, the concept of NDTs is introduced as a means to create virtual replicas of mobile networks that can simulate and analyze various scenarios without impacting the actual network, thus enhancing decision-making processes and operational efficiencies. Herein, NDT follows a service-based architecture, where network functionalities are provided and consumed as modular services. 3GPP TR 28.915 defines a structured interaction model between NDT consumers and providers, enabling scalable, on-demand operation for dynamic network management and optimization.

The NDT provider creates, manages, and maintains the NDT instance, ensuring accurate network replication through data synchronization, continuous updates, and performance monitoring. Upon request, a Management Service (MnS) consumer is provisioned with an NDT instance, which is managed through its lifecycle phases: creation, configuration, operation, reconfiguration, deactivation, and deletion. If the NDT consumer is a network automation function (e.g., software components such as Management Data Analytics (MDA), Self-Organizing Network (SON)), NDT supports these functions by providing critical modeling capabilities that enable impact evaluation and predictive analysis. In this context, two approaches can be pursued: the network function automation capabilities remain available regardless of whether the NDT models are integrated within the automation function or operate externally, as illustrated in Figure 4.

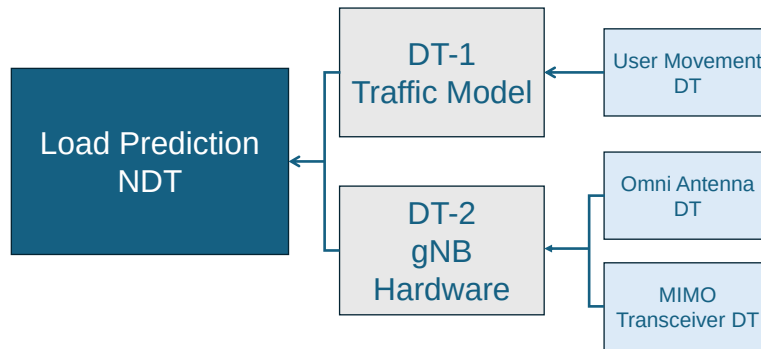


Figure 5: Example of a Nested NDT for Load Prediction from TR 28.915 [17].

The NDT predicting load (e.g., for RAN energy saving) relies on DT-1 that models network traffic based on a user mobility DT, while DT-2 represents active cell equipment, integrating separate DTs for the omni-antenna system and Multiple-Input Multiple-Output (MIMO) transceiver.

The 3GPP's approach has so far abstracted internal complexities, exposing only high-level modeling and prediction capabilities through a black-box paradigm. Rather than disclosing detailed network mechanisms, the NDT is conceptualized as a service interface that processes inputs (e.g., configurations, policies, traffic loads) and returns outputs (e.g., performance predictions, risk assessments, optimization insights). However, recent developments introduced in [18] mark a shift towards a more open and collaborative direction. In particular, 3GPP embraces the concept of collaborative NDTs, which implies the need to *open the box* and access the internal components of the twin, thereby enabling greater transparency and flexibility in both implementation and management.

Use Cases

3GPP TR 28.915 outlines 11 use cases related to the application of NDT in mobile networks, which we classify as follows:

- **Energy Efficiency and Configuration Management**

1. RAN Energy Policy verification: this use case aims to evaluate the impact of energy-saving policies on the RAN. By simulating different configurations, operators can optimize energy efficiency while maintaining network performance.
2. Configuration Verification: this use case focuses on verifying configuration changes before implementation to prevent unintended network disruptions.

- **Resilience and Risk Mitigation**

3. Signaling Storm Analysis: this use case models signaling storms that can overload network capacities. The NDT helps predict network responses and recommend optimizations to mitigate potential disruptions.
4. Emergency Preparedness: the NDT simulates the effects of natural disasters on network performance, allowing operators to test configurations and improve resilience without risking actual services.
5. Network Failure and Risk Prediction: this use case involves predicting potential network failures due to high-risk operations. The NDT evaluates the implications of configuration changes and helps in planning preventive measures.

- **Service Quality and User Experience Optimization**

6. Measurement of Customer Satisfaction with Network Services: this use case models user experiences and feedback using NDTs to identify areas for service improvement.

- **AI-Driven Network Automation**

7. NDT for ML Training: this use case highlights the ability of NDTs to produce synthetic data for ML applications, addressing the need for diverse and extensive datasets.
8. Integration with Network Automation: NDTs enhance automation functions by providing accurate models of network behavior, enabling better decision-making for network management tasks.

- **Multi-Layer Simulation and Modeling**

9. Nested NDTs: this use case discusses the capability of NDTs to incorporate other NDTs, allowing for layered simulations that enhance the accuracy of network modeling. See Figure 5 for an example of Nested NDT for load prediction.

- **Visualization and Network Diagnostics**

10. Network Topology Visualization: NDTs can be used to visualize network structures and traffic flows, aiding in real-time monitoring and management.
11. Network Issue Inducement: NDTs can simulate network failures to analyze responses and prepare mitigation strategies without affecting live networks.

Way Forward

The report concludes with a call for further development of the NDT framework to support the identified use cases. It emphasizes the need for standardized methodologies for implementing NDTs in different telecommunication environments. Future work should focus on refining technical specifications, improving data integration capabilities, and ensuring that NDT solutions can be seamlessly integrated into existing network management systems. Collaboration among stakeholders in the telecommunications sector will be crucial to advancing the deployment of NDT technologies and maximizing their benefits for network efficiency and reliability. The activity will continue in the new Work Item (WI) context ([18]) approved during the 3GPP SA plenary of December 2024.

3.2 ETSI

The European Telecommunications Standards Institute (ETSI) is a leading standards organization driving globally applicable Information and Communication Technology (ICT) standards. It provides an open, collaborative platform for industry, government, and research to shape telecommunications, broadcasting, and electronic communications standards. As one of the three European Standards Organizations (ESOs) recognized by the European Union (EU), ETSI supports European regulations through Harmonized European Standards. Initially focused on Europe, it now has a global impact, with its standards widely adopted across industries. ETSI is also a key partner in international initiatives like 3GPP, contributing to the evolution of mobile communications.

3.2.1 ETSI GR ZSM

The ETSI Group Report (GR) on Zero-touch Network and Service Management (ZSM) aims at developing standards and frameworks for fully automated network and service management in order to address the increasing complexity and dynamic nature of modern telecommunications networks, particularly with the advent of technologies such as 5G, NFV, and SDN. The primary scope of the ZSM project includes:

- **Automation:** creating a framework for end-to-end automation of network and service management processes to minimize human intervention and enhance operational efficiency.
- **Zero-touch Principles:** establishing guidelines for implementing zero-touch management, which includes self-configuration, self-healing, self-optimization, and self-protection capabilities within networks. In addition, identifying and documenting specific use cases that demonstrate the application of zero-touch management in real-world scenarios.
- **Interoperability:** ensuring that ZSM standards facilitate interoperability among network components and services across different technologies while aligning with and complementing existing telecommunications frameworks and specifications, as well as developing standardized data models for network and service management to enable consistent communication across systems.
- **Service Lifecycle Management:** addressing the complete lifecycle of services, from design and deployment to operation and decommissioning, with a focus on continuous optimization.

The ZSM project collaborates closely with the 3GPP SA5 Working Group (WG), which focuses on management and orchestration. Through this partnership, ZSM and 3GPP SA5 aim to advance the state of network and service management, supporting the transition to more automated and efficient telecommunications networks.

3.2.2 ETSI GR ZSM 015 V1.1.1 (2024-02)

Overview

Within the scope of ETSI GR on ZSM, the 015 V1.1.1 report establishes a structured framework for leveraging NDTs to automate network and service management. The ETSI definition of NDT aligns closely with that of 3GPP, describing it as a virtual replica of a communications network or its subset, designed to support operational decision-making and automation through simulated interactions.

The report highlights the role of NDTs in enabling real-time verification of configurations, retrospective analysis of past network states, and predictive failure detection, ultimately improving operational efficiency and mitigating risks. Furthermore, it emphasizes that access to historical, real-time, and contextual data facilitates proactive decision-making while enabling data sharing for collaborative applications, such as predictive automation for disaster response.

The report also outlines the factors influencing the accuracy of an NDT, primarily the completeness of real-world data and the robustness of its functional and behavioral models. It identifies three key modeling approaches: emulation, simulation, and hybrid methods combining both. The selection of a modeling approach depends on specific requirements, with emulation adhering to strict real-time execution, while simulation offers a more scalable and computationally efficient alternative.

NDT Framework

ETSI categorizes NDT components into four key elements, as detailed in [19]:

- **Data:** encompasses network topology, services, traffic, element status, performance metrics, and historical records, customized for specific use cases.
- **Models:** represent network structure, service configurations, and behavioral patterns to predict performance under varying conditions.
- **Interfaces:** facilitate data exchange and integration with external systems.
- **Mapping:** establishes correspondences between digital representations and their physical counterparts.

These elements define the two primary functional scopes of NDT, distinguishing ETSI's approach from that of 3GPP by incorporating active decision-making and automation capabilities. In particular, while 3GPP primarily views NDT as a passive entity providing outputs on demand through consumer-provider interactions, ETSI differentiates between two distinct operational roles, that are (i) analyzing NDT, focused on predicting network behavior under various conditions, aiding impact assessment and scenario analysis, and (ii) controlling NDT, which extends beyond analysis by enabling operational decision-making and initiating actions in the physical network, facilitating automation and closed-loop control.

Use Cases

The 14 use cases presented in ETSI GR ZSM 015 V1.1.1 are listed below.

- **Energy Efficiency and Network Resource Optimization**
 1. **Radio Network Energy Saving:** this use case leverages NDT to verify and optimize energy-saving actions in mobile networks, ensuring power reduction strategies do not compromise service quality.
 2. **NDT Resource Management and Orchestration:** this use case optimizes resource sharing among multiple NDTs, enhancing efficiency and minimizing redundancy in network operations.
- **Network Reliability, Resilience, and Failure Management**
 3. **Network Slicing Risk Prediction:** this use case employs NDT to predict risks of Service Level Agreement (SLA) violations in network slices, enabling proactive mitigation actions before service degradation occurs.
 4. **Network Playback for Historical Incident Analysis:** this use case enables NDT to replay historical network data, facilitating root-cause analysis and improving future resilience strategies.
 5. **Signaling Storm Simulation and Analysis:** this use case models large-scale reconnection attempts following network failures, allowing operators to anticipate congestion and optimize recovery mechanisms.
 6. **Quality of Transmission for Optical Networks:** this use case utilizes NDT to simulate optical signal performance, aiding network planning, risk assessment, and fault management.
 7. **NDT Fault Injection Analysis:** this use case simulates network faults, supporting self-healing mechanisms and refining anomaly detection models.
- **AI-Enhanced Automation and Data Management**

8. NDT for ML Training: this use case employs NDT-generated synthetic data for pre-training and continuous learning of ML models, reducing time and resource costs.
9. ML Inference-Impact Emulation: this use case provides a sandbox for evaluating the impact of ML-based decision-making before deployment in real-world network environments.
10. Data Generation for NDT: this use case enables synthetic data generation by means of data augmentation approaches when real network data is insufficient, improving NDT model completeness and reliability.
11. NDT Consumer Preference Management: This use case allows consumers to specify their requirements for data sources, accuracy, and synchronization in NDT-based simulations.

- **Continuous Integration, Deployment, and Software Validation**

12. NDT for CI/CD Process Verification: this use case incorporates NDT into continuous integration and deployment pipelines, verifying software updates before live deployment to prevent service disruptions.
13. DevOps-Oriented Certification: this use case integrates NDT into CI/CD pipelines, automating software validation to prevent disruptions in live network environments.

- **Advanced Synchronization and Time-Aware Simulation**

14. NDT Time Management: this use case ensures synchronization between virtual and physical network timelines, maintaining accurate real-time simulations and predictive modeling.

Way Forward

The report suggests expanding ZSM capabilities to fully integrate NDTs, including enhanced data collection, emulation models, resource management, and synchronization capabilities. It also recommends ongoing collaboration with other standardization bodies, such as International Telecommunication Union (ITU) and Internet Research Task Force (IRTF), to unify frameworks and address emerging requirements. Future research will focus on refining NDT precision, scalability, and integration within the ZSM framework to support increasingly complex network management scenarios. Ultimately, this approach promises more adaptable, predictive, and self-optimizing network management for the evolving digital infrastructure.

3.3 IRTF - Network Management Research Group

The Network Management Research Group (NMRG), part of the Internet Research Task Force (IRTF), explores innovative approaches to network management. It focuses on AI/ML, intent-based networking, and DTs to enhance automation, adaptability, and multi-domain interoperability. NMRG fosters research on next-generation network architectures, bridging academic and industry efforts while aligning with IETF standardization.

NDT Framework

According to the IRTF's vision, NDTs represents a virtual replica of a network, designed to enable advanced simulation, analysis, and decision-making. By providing a real-time or near-real-time representation of the network, NDTs support operators in monitoring, optimizing, and predicting network behavior, improving overall efficiency and resilience.

Role of the Network Digital Twin: NDTs play a crucial role in network management by:

- Enhancing predictive capabilities for fault management and optimization.

- Enabling intent-based networking, where network configurations adjust dynamically.
- Facilitating automation, reducing the need for manual interventions in operations.
- Supporting AI/ML-driven analytics for anomaly detection and traffic forecasting.

Relationship with Network Management Processes: The NDT interacts with existing network management and orchestration frameworks to improve decision-making. It integrates with OSS/BSS, SDN controllers, and AI-driven analytics to offer a holistic view of the network state, aligning operational goals with real-time insights. This tight integration ensures proactive management, rather than reactive troubleshooting.

Internal Structure of the Network Digital Twin: The architecture of a NDT consists of several key layers:

- Data Collection Layer: gathers real-time and historical network data.
- Modeling and Simulation Layer: creates a dynamic, virtual representation of network components.
- Analytics and Decision Layer: uses AI/ML to derive insights and optimize performance.
- Orchestration and Actuation Layer: feeds decisions back into the network to adjust configurations dynamically.

This structured approach ensures that the NDTs operates as a continuously evolving system, improving accuracy and responsiveness.

Relation Between Network Data and the Digital Twin: A NDT relies on continuous data flows from various network elements, including:

- Real-time telemetry from routers, switches, and base stations.
- Historical performance data for predictive analytics.
- External data sources (e.g., user behavior, environmental conditions).

The quality and granularity of data directly impact the accuracy and effectiveness of the NDT. By leveraging semantic models and graph-based representations, the NDT can interpret and structure network data efficiently, enhancing interoperability across different vendors and technologies.

3.4 ITU-T

The International Telecommunication Union - Telecommunication Standardization Sector (ITU-T) is a branch of the ITU responsible for developing international standards, or “Recommendations” for telecommunications. Its primary goal is to ensure interoperability, compatibility, and high-quality communication systems worldwide. ITU-T covers a broad range of topics including networking, cybersecurity, Quality of Service (QoS), multimedia, and emerging technologies such as 5G. In terms of collaboration with other Standards Development Organizations (SDOs), ITU-T works closely with 3GPP to harmonize global standards for mobile networks, particularly in the development of standards for 5G and Beyond 5G (B5G). While 3GPP primarily focuses on creating technical specifications for mobile systems (RAN, CN, and network architecture), ITU-T provides the overarching framework for international telecommunications standards, ensuring that 3GPP specifications meet global regulatory requirements and align with ITU’s vision for network interoperability and service quality. Together, they enable a unified approach to mobile telecommunications, enhancing global connectivity and supporting emerging technologies across countries.

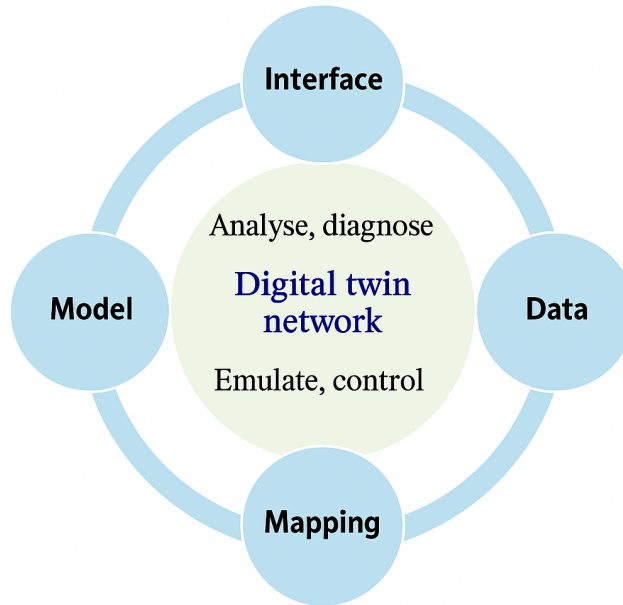


Figure 6: Key characteristics of a DTN according to ITU-T provided in Recommendation Y.3090 [20].

3.4.1 ITU-T SG13

The ITU-T Study Group 13 (SG13) is responsible for developing standards in network management and emerging network technologies, including cloud computing, B5G mobile communications, and DTN. SG13 defines architectures, functional capabilities, and application programming for future networks, as well as network aspects of the IoT and the application of AI and ML in communication networks. Given the data-intensive nature of AI, SG13 also considers privacy and security implications, particularly regarding surveillance, tracking, and profiling risks in digital networks. A key area of SG13's work is the standardization of DTN, aiming to enable predictive management, resource optimization, and network resilience through virtual replicas of physical networks. Within SG13, Working Party 3 (WP3) focuses on automation and intelligence for network management, driving the development of DTN frameworks that enhance efficiency and adaptability in telecommunications infrastructures. To ensure global interoperability, SG13 collaborates with ETSI and 3GPP, aligning DTN and network management standards across the telecommunications and Information Technology (IT) industries.

3.4.2 ITU-T Recommendation Y.3090

Overview

ITU-T Recommendation Y.3090 on “Digital Twin Network Requirements and Architecture” defines the concept, functional and service requirements, and security considerations for DTNs.

While 3GPP and ETSI define NDT primarily as a service-based concept, focusing on its interaction with networks without prescribing its internal structure, ITU-T takes a complementary approach by embedding NDT within a broader architectural framework, known as the DTN. This approach explicitly defines how a NDT should be structured, which interfaces it should expose, and how it should interact with both the physical network and external applications, ensuring a more integrated and standardized implementation.

This approach positions NDT as a fundamental component within the broader DTN architecture,

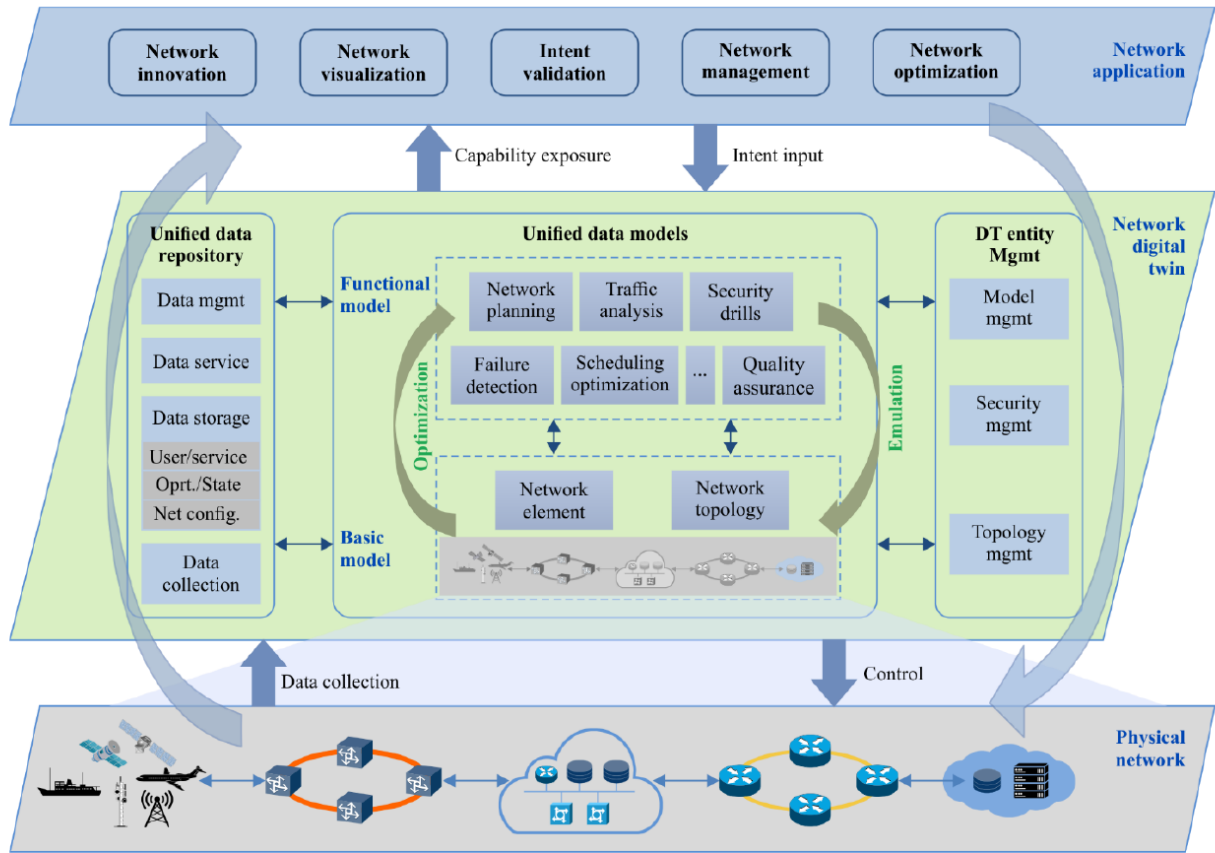


Figure 7: Reference architecture of a DTN according to ITU-T provided in Recommendation Y.3090 [20].

which is characterized by four key elements: data, mapping, model, and interface, as illustrated in Figure 6. This vision is coherent with the content of the ETSI GR ZSM 015 V1.1.1 report described in Section 3.2.2, with which it shares the nomenclature of the four key elements.

- Data is the cornerstone for constructing a DTN system. Massive network data collected from a physical network can be stored in a virtual twin network as a unified data repository, which can be the single source of truth and provide timely and accurate data support for models.
- Mapping between a physical network and a virtual twin network is interactive and real-time. Mapping is the most typical feature where the DTN is different from a network simulation system.
- The model is the source of the capability of DTN. Various data models built in virtual twin networks can be designed and flexibly combined to serve network applications.
- Interface, which is standardized, is the key enabler that can effectively ensure the compatibility and scalability of the DTN system. Southbound interfaces connect physical networks and virtual twin networks, whereas northbound interfaces exchange information between virtual twin networks and network applications.

NDT Framework

The ITU-T's DTN architecture follows a three-layer, three-domain, and double closed-loop model.

- The Physical Network Layer represents the real-world infrastructure (e.g., telecom networks). This layer interacts with the NDT through *southbound interfaces*, enabling extensive data exchange and real-time monitoring. Data collection occurs at this level, with network telemetry, performance metrics, and configuration states being continuously gathered and passed to the NDT.
- The Network Digital Twin Layer forms the core of the DTN and consists of three subsystems:
 - Unified Data Repository: collects and stores real-time operational data from the physical network, ensuring a single source of truth for analysis and decision-making. It manages diverse network data types, including performance logs, configuration settings, and service metrics.
 - Unified Data Models: provides analytical and predictive models for network performance assessment, fault diagnosis, and resource optimization. These models are categorized into basic models, which capture network topology and elements, and functional models, which support advanced operations such as traffic analysis and fault prediction.
 - Digital Twin Entity Management: oversees the lifecycle, visualization, and control of the NDT, ensuring model integrity and security. This subsystem includes topology management, model coordination, and security enforcement for data integrity and access control.

The NDT exposes its capabilities to the Network Application Layer in terms of advanced analytics, simulation, validation, and predictive insights.

- The Network Application Layer interacts with the NDT through northbound interfaces, leveraging the capabilities exposed by the NDT to provide high-level intent inputs and service requirements. Based on these inputs, the NDT executes simulations, validates configurations, and optimizes network strategies. Once validated, control updates can be sent either directly from the NDT to the Physical Network Layer via southbound interfaces or through the Network Application Layer, which refines and applies them to the real network.

The three-domain structure of the DTN consists of the data domain, responsible for collecting, processing, and managing network data; the model domain, which executes predictive analytics, simulations, and optimization functions; and the management domain, which oversees governance, security, and policy enforcement.

Additionally, the double closed-loop mechanism ensures continuous and adaptive optimization. The inner closed-loop operates within the NDT, performing real-time simulations, emulations, and optimizations based on predefined models. Meanwhile, the outer closed-loop facilitates feedback-driven control, enabling automated adjustments to the physical network based on insights derived from the NDT.

Use Cases

ITU-T defines 6 use cases for DTN, demonstrating its role in enhancing network management, optimization, security, and innovation. These use cases are categorized as follows:

- **Intelligent Network Operation and Maintenance**

1. Predictive and Proactive Maintenance: as networks evolve with virtualization, cloud-based resources, and dynamic service orchestration, traditional network operation faces increasing complexity. DTN integrates data acquisition, big data processing, and AI-driven analytics to assess network status, diagnose past issues, predict future trends, and transition from reactive to predictive maintenance.

- **Enhanced Network Optimization**

2. Cost-Efficient Network Optimization: traditional network optimization requires direct implementation on live networks, leading to high operational costs and service risks. DTN enables rapid, cost-effective validation of candidate optimization solutions without impacting real-world operations.

- **Accelerating Network Innovation**

3. Faster Technology Experimentation and Deployment: high-risk environments limit real-world testing of innovative network techniques. DTN creates virtualized replicas of physical networks, allowing researchers to safely test new network protocols, AI/ML applications, and advanced network functions with minimal risk.

- **Comprehensive Network Measurement**

4. Indirect Parameter Estimation: certain network parameters, such as end-to-end latency and path bandwidth, cannot be directly monitored from the physical network. DTN enables estimation of these metrics by analyzing vast cross-domain datasets in a virtualized environment.

- **Intent-Based Networking Implementation**

5. Intent Validation and Automation: future networks will leverage intent-based architectures where users specify high-level goals instead of device-specific configurations. DTN ensures intent assurance by simulating multiple policy adjustments and validating them before deployment, reducing unintended network impacts.

- **Strengthening Network Security**

6. Cybersecurity Strategy Simulation: DTN enables real-time security drills, such as simulating hacker attacks, DDoS threats, and malware intrusions, facilitating proactive security policy development to ensure robust network protection.

3.5 TM Forum

TM Forum is a global industry alliance consisting of over 800 companies, including leading network and communications providers, technology suppliers, consultancies, and system integrators from more than 110 countries. Its primary mission is to foster digital transformation by breaking down technological and cultural barriers within the telecommunications and digital service industries.

By creating an open, collaborative environment, TM Forum enables Communications Service Providers (CSPs) and their suppliers to evolve their business operations, IT systems, and ecosystems. The organization promotes shared experiences, collective problem-solving, and the co-creation of industry-wide solutions, accelerating the adoption of innovative services and technological breakthroughs. TM Forum leads global collaboration among CSPs, technology providers, and industry stakeholders through three main focus areas:

- **Managing the Digital Transformation Journey:** TM Forum provides practical, collaboratively developed resources, including the Digital Maturity Model, the only industry-agreed framework designed to assess and guide digital transformation strategies.
- **Solving Industry-wide Challenges:** the Forum develops toolkits and standardized frameworks, such as Open APIs, to streamline operations and accelerate digital transformation.
- **Accelerating Innovation:** through initiatives like the Catalyst Program (i.e., aimed to support early-stage research and proof of concepts), TM Forum fosters rapid proof-of-concept projects that allow members to experiment with emerging technologies and business models. The Forum also provides insights into evolving trends and strategies through collaborative research.

Key Initiatives are:

- **Open Digital Framework (ODF):** TM Forum's flagship initiative standardizes digital transformation through APIs, data models, and best practices.
- **Agile and Automated Operations:** TM Forum advocates for automation and AI-driven network management, supporting zero-touch operations.
- **Customer Experience and Data Analytics:** the Forum develops tools and metrics to enhance customer experience and optimize service delivery.

TM Forum collaborates closely with 3GPP to align operational frameworks (such as Open Digital Architecture - ODA) with 3GPP's technical standards. This ensures seamless integration of 5G technologies with operators' business and operational processes.

TM Forum's work on NDTs focuses on enabling service providers to leverage DTs for efficient network management, predictive maintenance, and operational automation. Their initiatives in this area align closely with their broader goals of AI-driven automation and zero-touch operations. Here are some key areas where TM Forum is actively developing guidelines, frameworks, and standards for NDTs:

AI-Driven Closed-Loop Automation: TM Forum is incorporating NDTs into closed-loop automation processes to enable proactive and autonomous management, possibly supervised by AI models. Using an NDT, operators can simulate and predict network behaviors in response to various operational changes or faults, facilitating self-optimizing networks. DTs are used to test AI models before applying them to live networks, which ensures a safer deployment of automation technologies and allows providers to evaluate the effectiveness of predictive algorithms.

Digital Twins in the Open Digital Architecture: As part of TM Forum's Open Digital Architecture (ODA), NDTs are being integrated to create a more modular, flexible, and data-driven approach to network and service management. The ODA aims to standardize the architecture and APIs that facilitate interoperability, and NDTs are part of this effort to provide real-time data insights and simulations. NDTs within ODA help ensure compatibility across different vendor solutions, enabling seamless integration of DT functionalities into existing network management systems.

Predictive Maintenance and Performance Management: TM Forum promotes using NDTs to support predictive maintenance by simulating potential network issues and predicting equipment failures. Through historical data analysis and real-time simulation, NDTs can identify components likely to fail and recommend preemptive actions. NDTs are also used for performance management by monitoring network elements and predicting traffic patterns, allowing operators to optimize resource allocation and enhance quality of service proactively.

Standardization of Data Models and Interfaces: TM Forum collaborates with industry stakeholders to create standardized data models and interfaces for NDTs, ensuring that they can

represent physical network elements accurately. This standardization is essential for compatibility and interoperability with other frameworks, including those from 3GPP and ETSI. The goal is to provide standardized APIs for data collection, analysis, and integration into other systems, facilitating widespread adoption of NDTs across networks.

Use Case Library and Catalyst Projects: TM Forum has initiated several Catalyst projects, which are collaborative proofs of concept with industry partners to test real-world applications of NDTs. These projects focus on use cases like fault prediction, dynamic network slicing, and optimization of network resources based on DT simulations. A use case library for NDT applications is also being developed, with examples such as network slicing assurance, signaling storm analysis, and energy consumption reduction in radio networks. This library serves as a resource for industry players looking to implement NDTs effectively.

Cross-Industry Collaboration: TM Forum works with organizations such as 3GPP, ITU-T, and ETSI to ensure alignment on NDT standards and compatibility across telecom and IT infrastructures. This collaboration allows TM Forum to incorporate the latest insights from global standard bodies into its NDT frameworks, promoting consistency and cross-functional operability. Through these efforts, TM Forum is positioning NDTs as a cornerstone of future intelligent network management systems, where digital replicas support automation, fault resilience, and adaptable networks.

DT4DI (Digital Twin for Digital Infrastructure): is a TM Forum initiative that focuses on developing standards and frameworks for using DTs specifically within digital infrastructure. Its goal is to create a DT model that enables telecom and digital service providers to simulate, monitor, and optimize their infrastructure in real-time, covering aspects like network performance, energy management, and fault prediction.

The DT4DI initiative aims to standardize how DTs can be applied to infrastructure management, making it easier for operators to achieve predictive maintenance, enhance network resilience, and support zero-touch automation. It aligns with TM Forum's vision of agile, AI-driven network management, allowing operators to reduce costs and improve operational efficiency through precise, data-driven insights.

3.6 Current Challenges and Limitations in Standardization Activities

The standardization efforts related to NDTs conducted by 3GPP, ETSI ZSM, ITU-T, and TM Forum share a common goal: establishing frameworks and standards to enhance network management and automation. However, each organization adopts a distinct approach, scope, and set of objectives, leading to differences in how NDTs are conceptualized and implemented.

3GPP focuses primarily on mobile networks, where NDTs serve as tools for simulation and emulation to optimize network efficiency. However, its approach is inherently tied to mobile network management systems, assigning NDTs a predominantly “passive” role in network operations rather than leveraging them as “active” entities capable of proactive decision-making and autonomous adaptation. This limitation restricts the potential of NDTs as intelligent, self-evolving systems. Moreover, the 3GPP framework has so far not sufficiently emphasized the notion that a NDT can consist of a system of multiple interconnected DTs, flexibly structured and linked according to specific requirements. This limited focus on modularity and interconnectivity has hindered the evolution of NDTs into comprehensive and adaptive ecosystems capable of interfacing with DTs beyond the boundaries of the mobile network domain. This, in essence, aligns with the concept of federated NDTs, where multiple instances, potentially operated by different stakeholders or network providers (e.g., in network-sharing scenarios involving heterogeneous communication technologies), can collaborate while preserving operational independence.

As previously discussed, these dimensions have only recently started to gain traction within 3GPP, largely due to the efforts undertaken within the RESTART Grand Challenge on Network Digital Twins

to promote a more modular and systemic vision of NDT architectures. These efforts contributed to opening the standardization landscape to this vision, supported by a structured methodology of information gathering, analysis, and formal contribution drafting. The approach adopted to bring these inputs into the 3GPP standardization process has been formalized and documented in a dedicated scientific publication [21]. A federated approach is crucial for enabling interoperability, scalability, and cross-domain network management in future multi-stakeholder environments. Expanding the 3GPP framework to incorporate these aspects would be essential for fully unlocking the potential of NDTs in next-generation networks.

ETSI ZSM aligns its approach with zero-touch network management principles, aiming for full automation across multi-domain environments. While the NDT framework in ETSI ZSM does not diverge significantly from the 3GPP perspective, a key distinction lies in its recognition of two distinct roles for NDTs. Specifically, ETSI ZSM differentiates between an Analyzing NDT and a Controlling NDT, where the former is a more passive entity aimed at assessing the expected behavioral impact of changes in network conditions, traffic patterns, service dynamics, environmental factors, or potential operational actions, while the latter, in addition to performing analysis, can autonomously make operational decisions based on its assessments and enforce those decisions on the physical network, thus playing a more active role. Despite this broader conceptualization, the standardization efforts within ETSI ZSM remain in an evolving state. Further collaboration with organizations such as ITU-T and the IRTF is necessary to refine aspects of scalability and ensure broader industry alignment. Furthermore, similar to 3GPP, ETSI ZSM does not yet explicitly address the integration of multiple NDTs to enable more flexible and dynamic network functions. The lack of provisions for a composable NDT ecosystem limits its applicability in scenarios where complex, interlinked DTNs could provide more advanced automation and orchestration capabilities. To fully harness the potential of NDTs across diverse network environments, future standardization efforts must evolve towards a more interconnected and adaptive framework, integrating NDTs not only within individual domains but also across heterogeneous network ecosystems.

ITU-T, particularly through SG13, establishes a high-level framework for NDTs, placing significant emphasis on global interoperability and scalability across diverse network environments. However, ITU-T's approach tends to be broader and more conceptual, offering less specificity in practical NDT applications compared to the more operationally focused frameworks of 3GPP and ETSI. As a result, while ITU-T's vision provides a strong foundational framework, further refinement and closer collaboration with 3GPP and ETSI are necessary to enhance its applicability in addressing concrete technical and operational challenges.

TM Forum's initiatives, including the Digital Twin for Digital Infrastructure (DT4DI), focus on translating NDTs into practical, operational solutions by providing frameworks for predictive maintenance, performance optimization, and AI-driven autonomous network management. A key emphasis of TM Forum's approach lies in the standardization of data models and APIs, ensuring seamless interoperability and facilitating integration across diverse vendor ecosystems. However, while TM Forum's work excels in practical implementation and real-world deployment, it may not explore certain technical intricacies to the same extent as other standardization bodies such as ITU or 3GPP, which provide more detailed architectural and system-level specifications.

In summary, while 3GPP and ETSI ZSM establish technical frameworks primarily tailored to mobile networks and zero-touch automation, ITU-T adopts a broader perspective, focusing on high-level global interoperability. Meanwhile, TM Forum emphasizes the practical and operational aspects required to integrate NDTs into digital infrastructures. However, the true challenge lies not only in the distinct scopes of these organizations but in the lack of a concerted effort to unify their contributions. The absence of strong cross-organizational collaboration hinders the full realization of NDTs, preventing them from evolving into truly dynamic, intelligent, and federated systems. A more cohesive and coordinated approach among these standardization bodies is essential to establish comprehen-

sive, interoperable frameworks that can unlock the full potential of NDTs across diverse network environments.

4 Towards a Unified Architecture for Network Digital Twins

In Chapter 3, we examined how different SDOs approach the concept of NDT, each offering a distinct perspective. On one hand, 3GPP define the NDT from a service-based viewpoint, focusing primarily on the regulatory aspects needed to enable interaction between different modules in a SBA context. In this regard, the 3GPP specification concentrates on defining the necessary rules and interfaces to support interactions such as the configuration, activation, and de-activation of DTs a NDT, as well as potential inter-NDT communication during simulation or emulation phases. The internal structure or composition of the NDT itself remains out of scope. On the other hand, ITU-T adopts a broader architectural perspective by embedding the NDT within the DTN framework, a layered and systemic model that includes the physical network, its digital representation (the NDT) and higher-level applications such as management, optimization, intent validation, and visualization. Crucially, the DTN architecture implicitly supports the notion of nested NDT, as the NDT layer may be composed of multiple interconnected and cooperative DT/NDT entities, possibly spanning different technological or administrative domains. These two perspectives address complementary yet equally critical dimensions of a fully operational NDT, i.e., external interoperability and internal coherence. Both are essential to enable the realization of collaborative NDTs, where multiple entities interact seamlessly across domains. This convergence reinforces the need for a unified standardization effort that integrates both views into a cohesive and interoperable framework.

Building on this foundation, and recognizing the need for greater detail to fully realize the potential of the NDT, this chapter introduces an extended DTN architecture. Developed within the RESTART framework, this proposal takes the ITU-T model as a reference, while enhancing its granularity to better support advanced NDT implementations.

4.1 Concepts and Definitions

Before delving into the details of the proposed architecture, its implementation logic, and key pillars, it is important to clarify foundational concepts and introduce new ones that will recur throughout the architectural description. In particular, the term DT will refer to an entity characterized by the following properties. First, it is digital, meaning it exists in a digital form and adheres to an interpretable standard. Second, it is actionable, allowing it to serve as both the subject and the object of actions within the system. Third, it is connectable, ensuring accessibility and interaction via a network connection.

As a first defining element of the proposed architecture, we introduce the notion of the *Digital Hat (DH)*, defined as the DT that maintains the closest association with a given asset by interfacing with it through a dedicated and direct connection. This abstraction generalizes interface models such as the Asset Administration Shell (AAS), transforming the asset-to-digital interface layer into a flexible and extensible component capable of supporting a wide range of standardized or proprietary protocols. Unlike the AAS, which is tightly bound to the industrial domain and primarily focused on physical assets, the DH accommodates heterogeneous asset types, including digital and hybrid (phygital) entities, which are increasingly relevant in B5G ecosystems. Furthermore, the DH model lays the foundation for hierarchical DT architectures, where a DT can be composed of, or serve as a coordinator for, other DTs. This recursive structure supports scalable and modular system representations, enabling advanced abstraction, orchestration, and cross-domain coordination. Importantly, the DH is not tied to a specific interface specification: while the AAS may be employed as one instantiation, the DH is explicitly designed to support multiple coexisting interface models. This interface-agnostic nature promotes interoperability across domains and ensures compatibility with diverse application requirements. Within the proposed architecture, every asset is associated with at least one DH responsible for its representation and supervision. In more complex scenarios, multiple DHs may be assigned to

the same asset to support distinct monitoring or management functionalities. In such cases, appropriate coordination mechanisms must be implemented to prevent semantic conflicts, for instance, by avoiding double-counting of capabilities and ensuring consistent reporting of the asset's state. This relationship leads to key structural principles that govern the integrity and functionality of a DTN.

Following the DH concept, the proposed architecture introduces an additional element that extends the ITU-T DTN model to explicitly capture the potential for collaborative NDTs. This extension reflects the possibility that a single NDT may actually comprise multiple interconnected DTs/NDTs that collectively support a specific network function or service. The key construct in this regard, within the proposed architecture, is the *Digital Hub (DTH)*, which formalizes the aggregation of multiple DTs, each associated with its own DH, into a coordinated unit. A notable property of the DTH concept is that it supports the self-composite pattern. This means that an interconnection of multiple DTHs constitutes a DTH itself. This composability allows a system or subsystem, which encompasses multiple distinct functions, to be decomposed into multiple DTHs, each responsible for a specific function. Additionally, a single DT can simultaneously belong to multiple DTHs, ensuring flexibility and modularity in network management.

A fundamental tenet underpinning the entire framework is that its effectiveness depends on the adoption of precise and well-structured *models*. These models define the internal organization of each DT, specifying the type of asset represented, its properties and operations, and the logic governing its behavior over time. They also ensure interoperability by providing a shared semantic foundation, often expressed through standardized modeling languages such as Unified Modeling Language (UML) or Yet Another Next Generation (YANG), which enables DTs to exchange meaningful information across heterogeneous domains. In addition, models support automation and intelligent behavior by enabling predictive, structural, and behavioral logic. They also play a key role in enabling the aggregation of multiple DHs into higher-level entities like the DTH, supporting modular development, interface validation, and the construction of composable system architecture.

To further explore the benefits of such an approach, it is important to introduce aspects related to service provisioning within the DTN framework. A key concept in this regard is that of *microservice*, a modular design approach where each DT operates as a self-contained unit, providing a specific service. As stated in this definition, a *microservice* represents the service provided by a DT. Thus, each DT in a given network can be associated with a corresponding *microservice* and vice versa. In cases where complex network assets require multiple services, they can be modeled as DTHs. Since a DTH is composed of multiple DTs, the services provided by these complex assets will be a composite of the *microservices* associated with the DTs within the hub. This modular approach fosters interoperability, scalability, and adaptability within DTNs, ensuring that network functions can be flexibly composed, managed, and optimized in an automated and intelligent manner.

4.2 Architecture Outline

The proposed architecture consists of three primary layers.

1. **Physical Network Layer:** it comprises all physical, digital, and “phygital” components of the network. In advanced programmable networks, this layer is managed by one or more Network Managers/Orchestrators that oversee network operations and resource allocation. These entities maintain comprehensive control over the network, or a specific subnetwork and its nodes, enabled by programmability features provided through SDN and NFV paradigms.
2. **Digital Twin Network Layer:** it is the core of the architecture. It hosts DT instances that are dynamically created, managed, and terminated by a DTN management module, based on structured templates that define the network services required by applications. These templates serve as blueprints that translate application-level requirements into specific DT configurations,

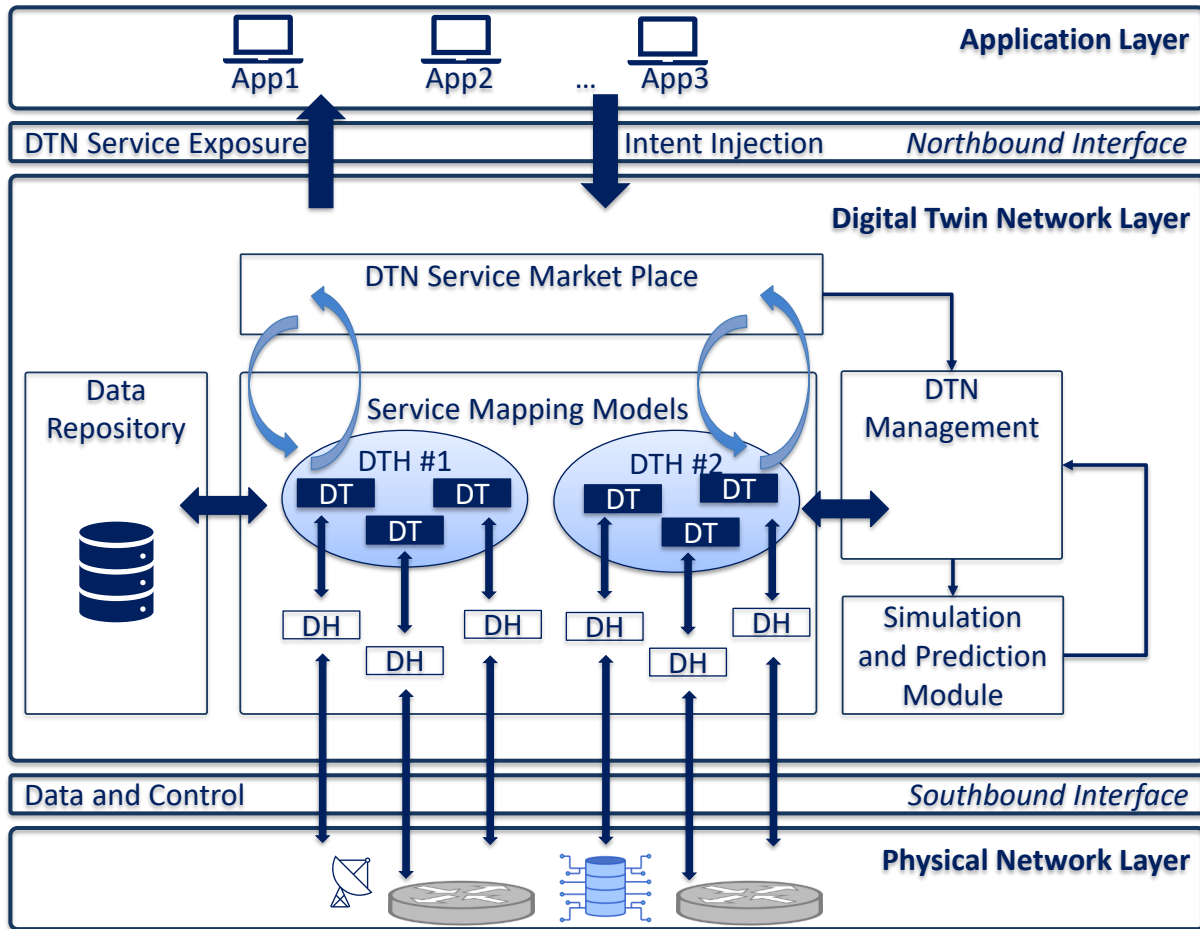


Figure 8: Proposed DTN architecture developed through studies conducted within the COHERENT project under the RESTART framework.

ensuring that each instance is created with a purpose aligned to the functional and performance needs of the underlying service. Once deployed, each DT actively monitors and interacts with its associated asset or service, exposing capabilities such as state reporting, predictive insights, or control actions. These functionalities are made available to the Network Application Layer, enabling applications to dynamically adapt, optimize, or validate their behavior based on the real-time feedback provided by the DTN layer.

3. **Application Layer:** it is responsible for implementing various services that rely on the DTN platform. This layer serves as the primary interface for injecting network intents, which represent high-level objectives and service requirements. The intents are mapped into specific actions and executed through DT mechanisms. The applications within this layer are designed to align with sustainability objectives, ensuring efficient resource utilization and energy-aware networking strategies.

At a more granular level, the DTN layer comprises several key components, including both permanent and dynamic DTs. Each DT represents a specific asset and may form interdependencies with others based on operational needs. A permanent DT is continuously maintained and updated, representing an entity with a long operational lifespan. In contrast, a dynamic DT is instantiated on-

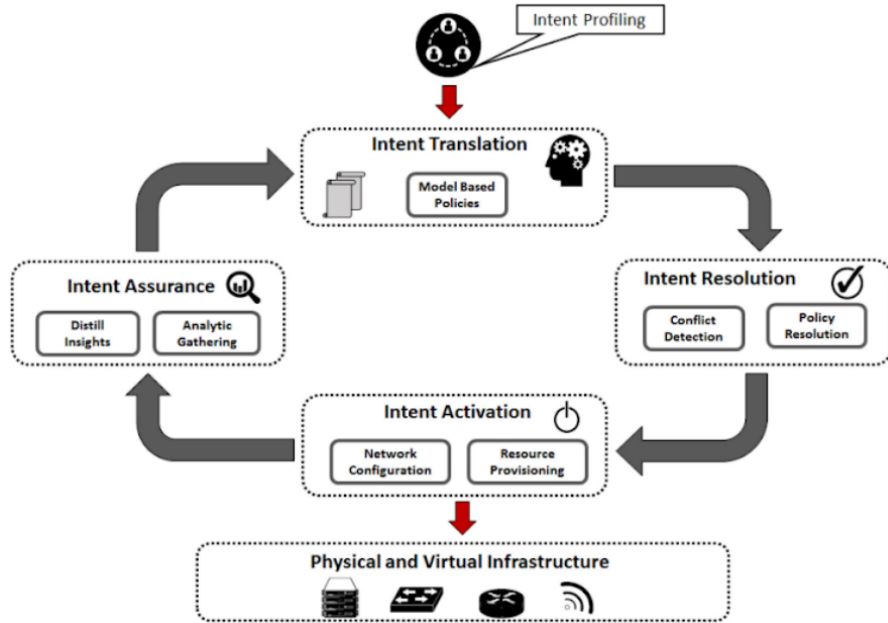


Figure 9: Main steps of an IBN framework. Adapted from [22].

demand and typically used for short-term monitoring, simulation, or analysis tasks. The DH serves as an intermediary between physical network assets and their digital representations, ensuring accurate monitoring and management.

A service marketplace within the DTN layer acts as a repository for network services and functionalities. The marketplace dynamically manages service availability and interactions between different DTHs. Additionally, metamodels are maintained within the service marketplace, capturing digital representations of real-world components. These models provide the necessary abstractions for structuring network services and adapting to evolving network conditions.

4.3 Compatibility with Existing Standards

The proposed architecture builds on existing standardization efforts while introducing additional functionalities aimed at enhancing network intelligence and automation. Similar to reference architectures proposed by standardization bodies, the proposed framework adopts a three-layer structure, in which the DTN occupies the central position. It is worth noting that in the ITU-T model, the central layer is referred to as the NDT, while the term DTN designates the entire architectural stack. In contrast, within the proposed architecture, DTN specifically denotes the central layer. Despite this naming difference, the layered partitioning serves the same purpose in both cases: each layer is assigned distinct responsibilities related to data handling, service provision, and management. The interfaces, supporting both southbound and northbound communication, ensure effective integration with network applications and the underlying infrastructure. Southbound interfaces enable real-time data collection and control over network operations through advanced probing and actuation mechanisms, while northbound interfaces expose capabilities and accept intents, allowing for intent-driven management and service provisioning.

Notably, the proposed architecture extends existing reference frameworks defined by standardization bodies by introducing elements that explicitly advance the realization of collaborative NDTs. In particular, the introduction of the DH concept provides a flexible abstraction layer that acts as a bridge between each asset and one or more associated DTs. This abstraction enables the construction

of hierarchical DT/NDT structures, where digital representations are organized across multiple levels of granularity. Such organization culminates in the concept of a DTH, defined as a coordinated set of DTs, each uniquely associated with a specific microservice, that collectively operate to support a common network function or objective.

4.4 Intent-Based Networking Capabilities

Intent-Based Networking (IBN) introduces a paradigm shift in network management by allowing users to specify high-level objectives—called intents—instead of directly configuring low-level network parameters. These intents describe what the network should achieve (e.g., low latency, secure connection), rather than how to achieve it. A management system then translates these intents into executable policies that guide the behavior of the network.

In the proposed architecture, IBN principles are tightly integrated with the DTN framework. Here, DTs serve a critical assurance role: they continuously monitor the network environment, validate whether the current configuration satisfies the intent, and detect potential conflicts before changes are applied to the real infrastructure. This allows policies to be dynamically adapted, ensuring alignment with the original user intent over time. To enable intent-driven automation, the architecture supports two primary channels through which intents can be communicated to the network system. The first involves domain-to-domain exchanges, articulated through dedicated interfaces using either YANG-based syntax or compact representations such as JSON. This approach facilitates structured interactions between domains, enabling seamless inter-domain orchestration. The second mode concerns external user-to-domain communication, where intents are typically submitted via graphical interfaces or client applications and transmitted through the Business Operations Support System (BOSS) module. In this case, intents are initially expressed in JSON and subsequently translated by the BOSS into a structured format, such as YANG or a semantically equivalent representation, that ensures the preservation of intent semantics throughout the architecture. This translation allows intents to influence specific subsets of DTs or coordinate interfaces across domains, supporting consistency and coherence in the overall network behavior.

5 Enabling Collaboration through Standardization

Building upon the architectural framework and enabling technologies presented previously, this chapter explores how NDTs can address real-world challenges through advanced deployment scenarios. In particular, we introduce the emerging concept of nested NDTs, which extends the traditional digital twin paradigm by enabling cross-domain synchronization, multi-operator coordination, and federated control. While some of these ideas have surfaced in early 3GPP discussions (e.g., TR 28.915), their true potential remains untapped in current standards. This chapter argues that nested NDTs are not merely use cases—they represent a fundamental shift in how digital twins are designed, deployed, and scaled. Without coherent and aligned standardization, however, such capabilities risk fragmentation and inefficiency.

By positioning nested NDTs as a distinct paradigm rather than a mere extension, we emphasize their potential to transform the way DTs interact, scale, and enable unprecedented levels of automation and collaboration in future network architectures. Their ability to facilitate seamless cooperation among multiple NDTs, each operating within different domains yet functionally interconnected, paves the way for highly intelligent, self-optimizing, and interoperable network ecosystems.

5.1 Management of Non-Public Networks

When Non-Public Networks (NPNs) are deployed, there are difficulties in defining standardized approaches for NDTs because of the complex relationships between Mobile Network Operators (MNOs) and vertical industries. In both Public Network Integrated (PNI)-NPNs and Standalone Non-Public Networks (S-NPNs) configurations, network management responsibilities are often shared between the MNO, which operates and maintains the underlying infrastructure, and the vertical industry, which leverages the network to support its industrial processes and services.

One of the most compelling scenarios that highlights the necessity of nested NDTs and their interoperability arises when a vertical industry needs to assess the impact of potential network failures on its critical operations. Unlike conventional network management scenarios, where a MNO ensures service continuity based solely on its own network monitoring, an industrial entity requires a real-time, predictive assessment of network conditions to its own operational framework.

In this case, the DT representing the industrial process must be dynamically synchronized with the NDT maintained by the MNO as depicted in Figure 10, enabling a comprehensive view that integrates both network performance data and industrial process dependencies. This synchronization allows for real-time failure impact assessment, proactive mitigation strategies, and adaptive resource allocation within the vertical's operational environment.

For instance, consider an automated manufacturing plant relying on a NPN for mission-critical industrial automation. A degradation in network quality - such as increased latency, reduced throughput, or loss of connectivity - could disrupt robotic assembly lines, delay critical operations, worsen the quality of products, or even lead to production shutdowns. By leveraging a nested NDT approach, the factory's DT can be continuously updated with network performance insights from the MNO's NDT, allowing it to simulate potential failures, anticipate performance degradation, and trigger automated countermeasures such as traffic rerouting or priority resource allocation.

This use case underscores the fundamental role of standardization in ensuring seamless interactions between NDTs across different domains. This challenge is complex as many factories use digital twins for production processes and manufacturing, which have to collaborate with the quite different NDTs to achieve a common goal. The ability to harmonize DTs across both industrial and network environments enables predictive analytics, optimized failure response, and enhanced service assurance for vertical industries. Without standardized data exchange mechanisms, interfaces, and interoperability frameworks, the potential of NDTs in multi-stakeholder environments remains limited to proprietary

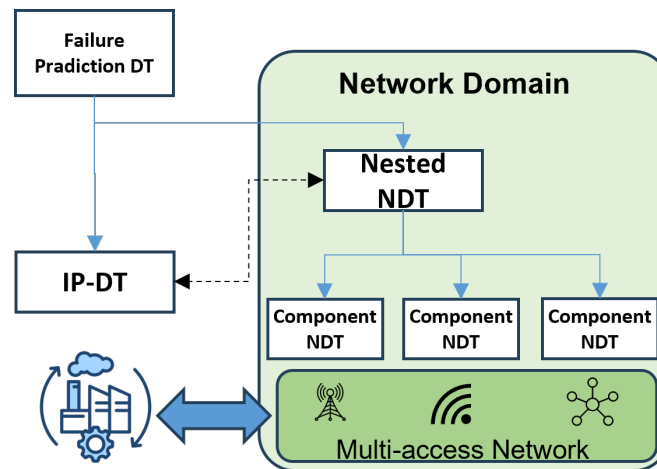


Figure 10: NDT in NPN scenario

implementations, hindering large-scale deployment and adoption.

Therefore, the nested NDT concept extends beyond traditional network monitoring—it provides a unified, cross-domain perspective that aligns network conditions with industrial needs, fostering a more resilient, autonomous, and intelligent network ecosystem. This approach is essential for realizing the full potential of 5G-enabled industrial applications, network slicing, and next-generation NPNs, ensuring that NDTs serve as active enablers of digital transformation rather than passive monitoring tools.

This scenario highlights the importance of exposing NDT services to external actors beyond the MNO. Standardization efforts must address how NDTs interact across different operational environments, ensuring secure and structured data exchange between industrial systems and telecommunications networks.

5.2 Management of Local Area Networks

Local Area Networks (LAN), either wired or wireless, are common subsystems that can benefit from NDTs for NPN, and can sometimes be seen as nested NDTs. They are found across many verticals, including industry and utilities. Since the 1970s, communication among devices (sensors, actuators, controllers) in distributed real-time systems has shifted from analog wiring to fully digital networks, reducing wiring complexity and cost while meeting application demands for reliability, predictability, robustness, maintainability, and safety. For instance, Time-Sensitive Networking (TSN) is increasingly adopted both in wired production backbones and as a replacement for industrial Ethernet and legacy fieldbuses. This shift also supports ubiquitous connectivity, a key feature of the (industrial) IoT paradigm.

To ensure QoS across end-to-end paths, including both geographic and local segments, it's necessary to consider all transmission technologies and their interconnection strategies. Therefore, NDTs used in such settings must be able to interact. LANs are simpler than WANs, and thus have not traditionally required NDTs for performance optimization. Enterprise IT/OT departments usually manage their planning, deployment, and maintenance, intervening reactively when issues arise, often based on user complaints. Diagnostic tools assist troubleshooting via manual reconfiguration. Proactive solutions are rare and typically require specialized (and costly) setups. However, things are changing. New high-performance wireless LANs, based on IEEE 802.11 standards, have grown complex and unpredictable due to interference, electromagnetic noise, and device or obstacle mobility. This unpredictability becomes critical in industrial setups, where control and monitoring applications

demand timely, reliable data delivery.

For this reason, the next Wi-Fi version (Wi-Fi 8), currently being defined by the IEEE P802.11-Task Group bn, also known as Ultra High Reliability (UHR), is focusing on mechanisms aimed at making communication more predictable [23], with the goal to define “*modifications to both the IEEE Std 802.11 physical layer (PHY) and the IEEE Std 802.11 Medium Access Control (MAC) [that add] an Ultra High Reliability capability to a Wireless Local Area Network (WLAN). The Ultra High Reliability capability is defined for both an isolated Basic Service Set (BSS) and overlapping BSSs as:*

- *At least one mode of operation capable of increasing throughput by 25%, as measured at the MAC data service Access Point, in at least one Signal to Interference and Noise Ratio (SINR) level (Rate-vs Range), compared to the Extremely High Throughput MAC/PHY operation, and*
- *At least one mode of operation capable of reducing latency by 25% for the 95th percentile of the latency distribution compared to the Extremely High Throughput MAC/PHY operation and*
- *At least one mode of operation capable of reducing MAC Protocol Data Unit (MPDU) loss by 25% compared to the Extremely High Throughput MAC/PHY operation for a given scenario, especially for transitions between BSSs.*

This amendment provides a mechanism to reduce power consumption for Access Points (APs) (including mobile APs) and improved Peer-to-Peer (P2P) operation compared to the Extremely High Throughput MAC/PHY operation.”

While NDTs are not explicitly cited in the TGbn framework, the call for tight AP coordination across a covered area clearly aligns with NDT principles. Given the inherent unpredictability of wireless channels and the complexity of the MAC layer in modern Wi-Fi (e.g., OFDMA, MU-MIMO, Multi-Link Operation (MLO), trigger frames, overlapping BSSs), network behavior cannot be optimized using only theoretical models or local heuristics. A holistic approach is needed, accounting for all Stations (STAs), traffic flows, QoS demands, positions (and possibly directions), and real-time interference conditions, measured using metrics like frame loss and latency. Using NDTs to guide runtime network configurations, especially when integrated with AI or ML, is likely to become the preferred solution in the mid-to-long term. Most insights developed for NDTs in 5G/6G contexts are transferable to Wi-Fi, with appropriate adaptations. A key difference is that Wi-Fi operates in unlicensed bands, where legacy devices remain common. Environments as university campuses, where students frequently come and go, using devices of various generations, demand robust support for streaming and connectivity, regardless of device age. Coordination mechanisms must enhance newer devices’ performance without penalizing older ones. Backward compatibility is a core Wi-Fi requirement, and, combined with operation in unlicensed bands, it has shaped the protocol’s evolution from early low-speed versions to the forthcoming high-speed ones (up to 100Gb/s). Although there is no standard yet for implementing Wi-Fi NDTs, several IEEE amendments provide useful foundations. Since 2012, amendments 802.11k, 802.11r, and 802.11v have been integrated into the main specification. IEEE 802.11k focuses on radio resource measurement. It exposes relevant radio and network information to support device mobility. The current AP, upon request, provides a list of candidate APs to assist a departing STA, helping reduce roaming delays and balance load. An NDT can guide the creation of this list for globally optimal resource use and QoS maintenance. IEEE 802.11r enables fast handovers by sharing STA context (e.g., authentication, QoS) between APs, reducing reassociation time and minimizing packet loss or delay. This is vital for secure, dependable multimedia and control services. IEEE 802.11v enhances roaming and power saving through network-assisted features. It complements and is compatible with 11k and 11r. While these amendments are insufficient to define a full-fledged Wi-Fi NDT, they provide a solid starting point.

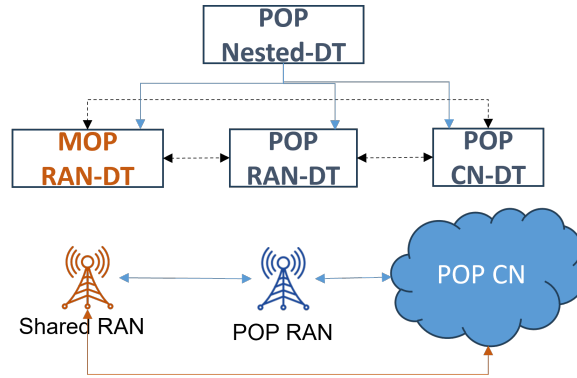


Figure 11: NDT in Network Sharing scenario.

5.3 Network Sharing

Network sharing agreements introduce additional complexities in NDT standardization, as multiple operators manage different aspects of a shared infrastructure while maintaining independent control over their respective network segments. These scenarios typically involve a Main Operator (MOP), which oversees and operates the primary network components, and one or more Participating Operators (POPs), which leverage the shared resources while retaining autonomy over their own network management functions.

One critical use case arises when a POP needs to verify the configuration of a subnetwork that includes both dedicated and shared elements governed by the MOP. In such instances, the POP requires controlled access to the MOP's NDT to interact with its own NDT instance. This interaction enables comprehensive configuration validation, ensuring service consistency, policy compliance, and optimal resource allocation. The necessity for seamless NDT interoperability in such multi-operator environments underscores the importance of standardized frameworks for cross-domain DT collaboration. This process is depicted in Figure 11.

This use case underscores the need for a standardized multi-actor framework, where distinct stakeholders can securely exchange NDT data and services while preserving confidentiality and operational independence. Standardization efforts must define governance models, access control mechanisms, and interoperability protocols to support seamless NDT interactions in multi-stakeholder environments.

5.4 Final Remarks

The advancement of NDT platforms necessitates not only technical progress but also a strategic and collaborative standardization effort. While the discussion thus far has established the need for cross-SDO coordination and highlighted the benefits of standardized interoperability, it is equally important to recognize the broader economic, operational, and societal impacts of such a framework.

A well-structured standardization framework is a catalyst for network automation, resilience, and service innovation, reducing complexity and ensuring cost-efficient deployment of NDTs across different domains. By minimizing vendor lock-in, a unified framework allows for greater flexibility in how operators, enterprises, and vertical industries integrate DTs into their operations. For network operators, this means the ability to deploy, monitor, and optimize resources dynamically, leveraging NDTs not just for real-time performance improvements, but also for long-term planning, such as capacity forecasting, energy efficiency optimization, and service differentiation. Enterprises operating in Industry 4.0, smart cities, and autonomous transport systems stand to benefit from enhanced situational awareness, where DTs ensure predictable, data-driven decision-making. Moreover, the availability of an interoperable NDT ecosystem fosters new market opportunities, enabling the emergence of multi-

party service marketplaces where network operators, technology providers, and application developers can co-create and monetize services built on real-time DT insights. This shift is particularly relevant as networks evolve towards 6G, where dynamic and intent-driven network slices will require collaborative, intelligent, and automated management solutions.

Beyond direct economic benefits, standardization plays a pivotal role in building resilient and sustainable digital infrastructure. In an era where climate impact and energy consumption are major concerns, NDTs offer a pathway to sustainable network operations, allowing for precise resource allocation, predictive fault detection, and adaptive power management. However, these benefits can only be fully realized if NDTs are built on consistent, scalable, and federated architectures, enabling coordinated resource utilization across multiple stakeholders. Regulatory bodies, industry alliances, and research institutions must align their efforts to develop a long-term vision for NDT standardization, ensuring that frameworks evolve in step with technological advancements and operational needs. A unified approach does not imply rigid standardization but rather a flexible yet harmonized ecosystem, where diverse industry players can contribute and evolve together.

6 Conclusions

NDTs are rapidly emerging as a cornerstone for intelligent, adaptive, and sustainable network management. As shown throughout this white paper, their potential lies in providing a real-time, continuously synchronized virtual representation of the network, enabling advanced simulation, predictive analytics, and autonomous optimization across diverse domains. Realizing this potential requires more than technological readiness. It demands a unified architectural framework, shared data models, and cross-domain interoperability grounded in robust standardization efforts. Fragmented approaches lead to silos and inefficiencies—hindering the emergence of a truly collaborative digital network ecosystem.. This white paper, developed as part of the RESTART initiative, has presented a unified view of the NDT paradigm.

Interoperability is the foundation of modern telecommunications, particularly in heterogeneous environments that integrate multiple technologies, architectures, and domains. The adoption of DTs reinforces the need for industry-wide standards that facilitate seamless coordination across the network, edge-computing environments, and satellite systems. Standardization efforts extend beyond purely technical aspects: they drive innovation, economic growth, and strategic investment in digital infrastructure. A unified framework promotes interoperability across multiple platforms and services, fostering an ecosystem in which new applications and business models can emerge. Start-ups, research institutions, and enterprises can develop applications that leverage shared NDT resources for intelligent routing, seamless handover, predictive maintenance, and spectrum management, thereby enhancing network performance and efficiency. Without a cohesive, cross-SDO strategy, the transformative potential of NDTs remains underutilized.

The white paper identified key enabling technologies—ranging from data availability (both geographic and business-specific) to edge/cloud computing, SDN/NFV, and AI/ML-driven analytics and DevOps pipelines—as the foundation for NDT deployment. We also explored the transformative role of nested NDTs through three real-world scenarios: industrial Non-Public Networks, enterprise LANs, and multi-operator infrastructures. These cases illustrate how NDTs can foster cooperation, resilience, and efficiency in highly heterogeneous environments. This document also introduced a comprehensive architectural vision based on the concepts of the DH and the DTH, which enable modular, scalable, and federated NDT deployments. These abstractions support both domain-specific intelligence and coordinated behavior across layers of complexity. Furthermore, the analysis of ongoing standardization activities revealed the need for convergence: while 3GPP and ITU-T provide complementary perspectives, a unified approach is essential to avoid fragmentation and accelerate adoption. The proposed RESTART architecture aims to bridge these perspectives and serve as a reference model for future NDT implementations.

Looking ahead, NDTs will play a critical role in addressing the challenges of 6G networks, sustainability, cybersecurity, and data governance. They are not just a technological innovation—they form the digital fabric that will connect, predict, and optimize the networks of tomorrow. Building them right means enabling networks that adapt, learn, and evolve with the world they serve. To fully unlock this potential, national-level availability and harmonization of geographic data are essential. Enabling trusted access to standardized spatial datasets will empower stakeholders to operate within a shared digital framework—supporting more effective coordination, informed planning, and transparent infrastructure governance. Through these contributions, the white paper lays the groundwork for a structured, extensible reference model for NDTs and underscores the importance of active collaboration with standardization bodies to ensure that evolving implementations remain interoperable, secure, and aligned with global best practices.

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