Network digital twins – outlook and opportunities

Digital twins that are tailored to the requirements of individual use cases have significant potential to create value in telecommunications processes, ranging from R&D to network operations such as deployment, management and site engineering.

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A digital twin is a digital representation of a real-world object synchronized at a specified periodicity and fidelity. The original concept emerged decades ago, based on ideas that first arose in science fiction and in the Apollo program [1].

■ The digital twins used today in industries such as aerospace, automotive, energy and manufacturing have been created fit for purpose to improve processes, products and business outcomes by replicating the relevant aspects of reality in a virtual environment. They add value by combining data and knowledge with various analytics and visualization tools, and they are regularly synchronized to keep the real and virtual worlds in sync with each other.

In recent years, there has been a growing interest in applying the digital twin concept on a much broader scale. In the case of mobile networks, digital twins can be applied to a broad set of use cases within both the communication service providers' and the vendors' own organizations, making it possible to both enhance existing capabilities and introduce entirely new functionality.

Characteristics of a digital twin

Both the high interest in digital twins and their diverse applicability have resulted in many definitions of the term [1]. At Ericsson, we have adopted the Digital Twin Consortium's [2] definition for mobile networks. This considers a digital twin to be a virtual representation of real-world network entities and processes, along with their environment and users, which is synchronized at a specified periodicity and fidelity, and which provides added value for specific purposes.

A digital twin is based on having access to accurate, relevant and timely data, and it utilizes advanced analysis, simulation and visualization tools. Interaction with a digital twin results in the creation of a knowledge base related to the twin and its real-world counterpart. Irrespective of the realization, there are a couple of characteristics of digital twins that are essential. First, a suitable data structure is needed to represent the real-world state and knowledge at a level of detail that is appropriate to the scenario, ranging from low-level hardware through to aggregated characteristics of services and networks.

Second, there must be a continuous synchronization between the real world and the twin, and the two must evolve in parallel. Depending on the scenario, the time scale can be from milliseconds to days or longer. In most use cases, the dominant data flow is of measurements and events from the real world asset to the twin, which are needed to characterize performance and behavior. Configurations and control actions can also be pushed back to the real world using appropriate control mechanisms.

Overview of digital-twin use cases in mobile networks

There are several use cases with varying scopes where network digital twins (NDTs) have the potential to create value. A good way to categorize NDTs is to identify the real-world target for the twin, the process to which it applies and its purpose. The considered processes can be diverse, ranging from R&D to network control to network operations such as deployment and site engineering.

In some cases, a real-world NDT target can be the physical environment such as a cell site [3], accurately modeling the site structure, cabling and equipment. This gives the operator a complete view of the site,

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which can be used to simulate rollout and design processes, and to support troubleshooting and site upgrade processes.

NDTs can also represent multiple cell sites in a geographic environment, creating models for radio propagation based on measurements and physics-based simulations. The use of an NDT to optimize transmit power levels in network operations [4] is a good example. Similar approaches could be applied to other key performance indicators (KPIs) like coverage and throughput, in city districts, factory sites, workplace environments or combinations thereof.

The NDT target could also be the logical network – a single node, a network domain or the end-to-end (E2E) network, depending on the target use case. Here, the NDT can be used to observe and experiment with network configuration to improve network operations. A comprehensive NDT implementation will often incorporate aspects of both the logical network and the physical environment.

NDTs can be a huge help in simulating network expansion processes, to select site locations and model the impact of new technologies, new equipment and radio frequency (RF) expansion, as well as helping to predict upcoming capacity

Terms and abbreviations

AGV – Automated Guided Vehicle | **AI** – Artificial Intelligence | **BSS** – Business Support Systems | **CSI** – Channel State Information | **E2E** – End-to-End | **GPU** – Graphical Processing Unit | **KPI** – Key Performance Indicator | **LA** – Link Adaptation | **MCS** – Modulation and Coding Scheme | **MIMO** – Multiple-Input, Multiple-Output | **NDT** – Network Digital Twin | **NR** – New Radio | **OSS** – Operations Support Systems | **RAN** – Radio-Access Network | **RF** – Radio Frequency | **RRM** – Radio Resource Management | **SINR** – Signal-to-Interference Noise Ratio | **URLLC** – Ultra-Reliable Low-Latency Communication

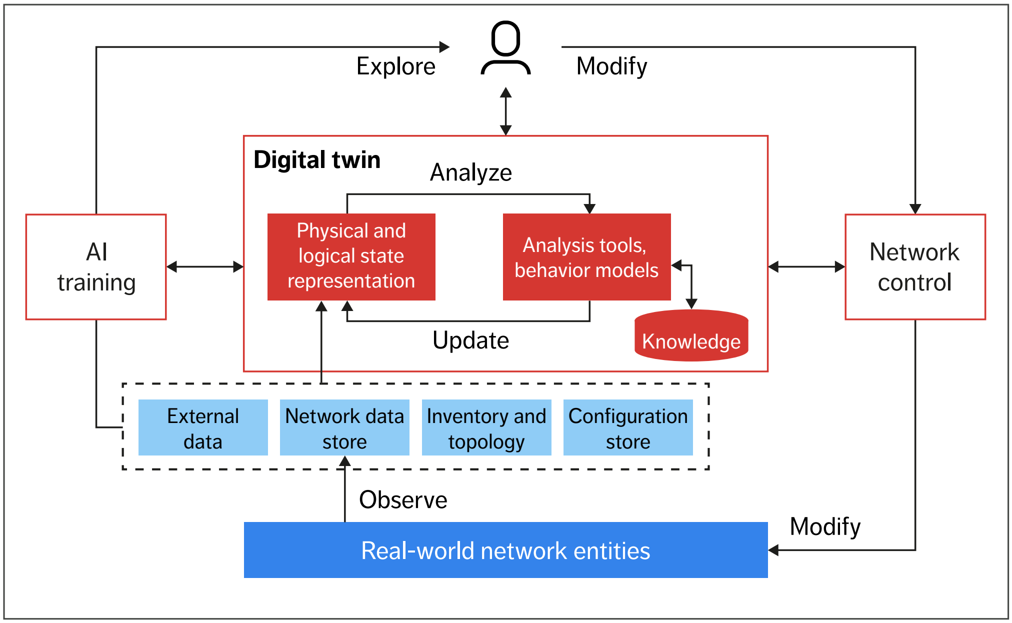

Figure 1 A network digital twin's main elements and environment

bottlenecks, enabling preemptive recommendations for network growth.

Another way that NDTs can add value is by predicting the impact of operator actions – either by humans or by autonomous systems [5] – that might have detrimental side effects. Using an NDT, potential actions could be evaluated before they are implemented. Similarly, new machine-learning algorithms can be safely trained and validated in the twin environment and only introduced in the real network once they have achieved a satisfactory level of performance.

The twin of the E2E network can add value by analyzing changes in consumer services. This type of NDT can evaluate the cost and performance of a new network slice before deployment and assess its impact on existing services. Based on this analysis, workload placement and network configuration can be further optimized to meet the required characteristics.

Yet another type of NDT can add value by evaluating various what-if scenarios such as equipment failures, security attacks or power loss to define contingency plans and network improvements.

NDTs can also address the need to represent traffic and user behavior. In these cases, the NDT needs to be tuned according to its use, from aggregate or detailed traffic characteristics and application flows to behavior in relation to subscription offerings and plans. By using anonymization techniques of sufficient accuracy, it is possible to realize these types of twins while also respecting privacy and safeguarding personal data.

Beyond the many benefits that NDTs can deliver for public networks, they also have great potential to add value in industrial connectivity use cases. To enable the integration of a mobile network in Industry 4.0 environments, the 5G Alliance for

Connected Industries and Automation (5G ACIA) has defined the 5G network asset administration shell [6], which extends digital twins for factory management to include representation of industrial 5G.

Realization of a network digital twin

In an ideal world, an NDT would be a perfect copy of its real-world entity. But in reality, some degree of simplification based on domain knowledge is usually needed to make it feasible. At the core of the NDT are the data and knowledge that describe the relevant aspects of the real world, complemented with tools that create insights from the data captured, as depicted in *Figure 1*.

Several real-world entities are represented in an NDT. To capture their state and relations, an NDT aggregates data from multiple sources, including inventories, configuration settings and measurements performed at different levels of the network. Depending on the purpose, additional data from external sources, such as geospatial mapping information, may be required to build the full picture.

The inventory and configuration of the network can be accessed through operations support systems (OSS) that can correlate network application topologies with the topology and connectivity provided by virtualization, hardware and transport systems.

The sheer volume and constant flow of new data about measurements in the network make data management systems [7] essential. Data in different forms, including files, streams or discrete events, is all gathered and made available as a common reusable data asset for different consumers. As new data becomes available, a digital twin updates its models.

To perform the analysis in the twin and extract the necessary knowledge, it is necessary to apply a suitable tool or model that can perform the tasks at hand, fulfilling requirements such as response time and accuracy for the given use case. Analysis can be based on calculation, simulation or an artificial intelligence (AI) algorithm. Typically, this involves the prediction of system behavior based on the current state.

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The role of simulators

Our view of the role of simulators is that they are part of the digital twin's analysis toolbox used for knowledge extraction. One of the key differentiators between conventional simulators and digital twins is that the latter has regular synchronization with the real-world entity.

It is possible to make highly detailed simulations. However, there is a trade-off between the size of the simulated scenario, the time it takes to evaluate and the required computing capacity. Smaller scenarios can be simulated quickly, whereas larger scenarios require a longer execution time. In many use cases, fast response times are important, which leads to the need for simplified models focusing on the most relevant aspects, or to limiting the scenario size to a subset of the network.

New simulation models and the evolution of computing hardware continue to expand the boundary of what is possible, enabling more advanced and realistic simulations. More sophisticated models require the data to be captured in greater detail than it is at present. Often, the selection of data and modeling needs to be defined iteratively, where models are refined and data selection is updated until a satisfactory balance between accuracy, evaluation time and cost has been reached. AI models have a significant role to play, whether they are used for predictions, data generation or creating black-box models based on observed behavior, further driving the need for data availability for training and optimization.

> SIMULATIONS OF NETWORKS AND THEIR USERS IS A KEY METHOD EMPLOYED IN RESEARCHING AND DEVELOPING NEW RAN FUNCTIONALITY

The integration of a digital twin within the network operational processes requires some consideration, both to invoke the digital twin and to take advantage of the resulting insights. For human-centered use cases, visualization is an important part of the twin, whereas other use cases require an application programming interface to integrate the twin within an automated process. Depending on the process for which the digital twin is used, it may be located in the operations support system, the business support system (BSS), the network functions or even in the R&D domain of a vendor.

Two promising use cases

Two of the many NDT use cases that have the potential to deliver significant value are those that can carry out network performance evaluations and those that can handle Radio Resource Management (RRM) in factory environments.

Use case #1: Network performance evaluation

Simulations of networks and their users is a key method employed in researching and developing new radio-access network (RAN) functionality, when evaluating network performance of different RAN products and deployment strategies, and when exploring ideas for "the next G." There is a rich history of radio network simulation models both at Ericsson and in the wider telco industry – from 3GPP (3rd Generation Partnership Project) models and common RAN deployment planning tools to more refined proprietary RF propagation models. They all capture deep physical properties of RF transmission and deliver predictive accuracy.

The evolution from today's radio network simulators to NDTs that utilize decades of investment in 3D gaming and computer-generated imagery technologies is expected to unlock significant benefits. New features and functionality will include:

- High-resolution and complex city or indoor geometry (bridges, tunnels, foliage, indoor to outdoor and more)
- Detailed surface materials that influence RF propagation, such as metallic coatings and metal features in places such as factories
- Representation of user mobility and dynamic scene features such as automotive traffic
- The ability to explore complex models visually
- Internal and external collaboration and data sharing
- Extremely high computational complexity of physically accurate models.

When 3D gaming technology is applied to the development of relevant models for 5G radio networks, the result is an attractive combination of gaming and radio technologies – for example, the use of Graphical Processing Unit (GPU) hardware to model radio propagation [8]. Games deal with incredibly detailed and complex scene geometry, apply fine-grained textures, and have highly evolved "actor" AI that provides scene dynamics, which is appealing for representing a network.

Technological advances have improved our capability in several aspects: visualization, integration, standardization of formats, collaboration and modeling accuracy. Together, these enable leaps in our ability to accurately simulate a radio network in a digital twin.

To illustrate the power of combining these capabilities, *Figure 2* shows an example from a network simulation study, in which we collected data from the real world, imported it and used it to create a set of simulated models. The real-world section on the left side shows a car that is connected to Ericsson's cellular network driving down a Stockholm street. On the right side of the figure, the digital twin dynamically illustrates the resulting massive multiple-input, multiple-output (MIMO)

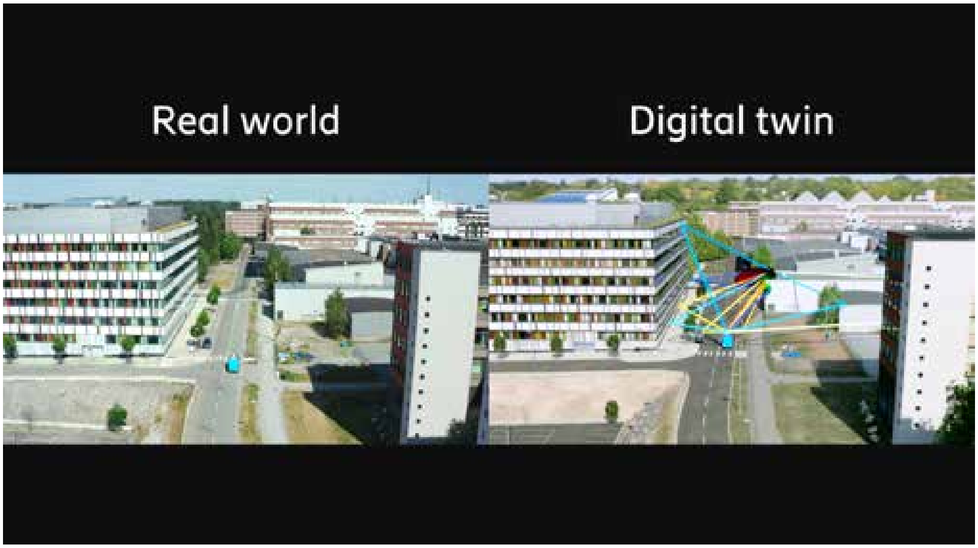

Figure 2 Example of a real-world city environment (left), accurately modeled in a digital twin simulator (right)

antenna and signal propagation paths, thereby making it possible to analyze them.

The data used in the simulation shown in Figure 2 included the city environment details down to the level of building materials, roof shapes and windows. The network deployment included network equipment deployment information as well as the users' mobility pattern. This was combined with detailed ray-tracing models of propagation and models of radios and the 5G New Radio (NR) layer 1-3 as specified in 3GPP to create an NDT representation of the whole system under study, enabling extremely accurate network simulations of the 5G NR system in this "real" environment.

An example of RAN functionality that benefits from this type of detailed evaluation is massive MIMO interference sensing. Using an NDT, we can determine the impact of interference on the beamforming action of the base station. Beyond enabling the extraction of very accurate statistical performance measurements available from ordinary network simulators, the NDT is able to provide such a high level of detail that it is also possible to illustrate concrete beam patterns toward single users, as shown on the right side of Figure 2. Similarly, when an NDT is applied to interference sensing, it can show how the radio network can avoid directing power toward users within its interference range, thereby lowering interference levels and increasing performance.

This simulation capability enables a much more detailed R&D analysis in the digital world, allowing us to develop RAN solutions and products to address the real challenges much faster than before. Further, it enables the early detection of problems that affect product design long before products are deployed, thereby reducing R&D costs, improving time to market and ensuring the reliable performance of products when they are deployed in real networks.

Use case #2: Radio resource management in factories

One important way that NDTs can deliver benefits in factory deployments is by enhancing the

Figure 3 Illustration of a factory floor with 5G-connected stationary robotic arms and moving AGVs

performance of the industrial cellular network. This is achieved through cooperation between an NDT in the RAN system and a factory digital twin with the ability to provide information about stationary and moving factory objects. The NDT uses the information from the factory digital twin to enable better link adaptation (LA) decisions from the 5G base station scheduler.

We used a dynamic system-level simulator to accurately model the factory scenario illustrated in *Figure 3*. The stationary connected robotic arms, colored according to their connecting cell, periodically send data packets to 5G base stations placed at a height of 6m, while metallic-gray automated guided vehicles (AGVs) carrying 2mx4m containers move around the production shop floor. We evaluated the performance of factory network at millimeter wave frequencies where the impact of blockage on radio wave propagation is especially high.

The conventional LA method uses signal-to-interference noise ratio (SINR) information based on measurement history, delivered in a channel state information (CSI) report. In digital-twin-based LA, the SINR information is gathered with the help of an NDT that predicts the path loss, which is impacted by the locations of the blockers, and performs inter-cell interference coordination. The NDT achieves the former by receiving accurate data about the location of major obstacles from an AGV controller or similar entity. To achieve the latter, the NDT controls the time-frequency resource allocations made by 5G schedulers in each cell. These two capabilities enable the NDT to perform a more optimal modulation and coding scheme (MCS) selection than conventional LA, going beyond performance of the well-known inter-site interference coordination-based scheduling.

The table shown in *Figure 4* presents the results of our evaluation of the two LA algorithms in terms of median spectral efficiency, two different latency percentiles and the reliability of packet transmissions. Although the CSI measurement reporting is delayed by a certain number of NR slots, the conventional LA algorithm performs reasonably well, capturing both interference and path-loss variation to a certain extent. Our results show that the achieved reliability and latency of conventional

Link adaptation algorithm	Median spectral efficiency	Latency 90th percentile	Latency 99th percentile	Reliability % (1-packet error rate)
Conventional LA	0.3 bits/s/Hz	0.5ms	20.66ms	99.89%
Digital-twin-based LA	4.2 bits/s/Hz	0.125ms	0.125ms	99.99%

Figure 4 Performance comparison for conventional and digital-twin-based link adaptation algorithms

LA will be sufficient for most non-URLLC (Ultra-Reliable Low-Latency Communication) industrial applications, but not for URLLC services, which require at least 99.99% reliability and under 1ms latency.

The performance of the DT-based LA algorithm is significantly better than that of the conventional LA algorithm and therefore better suited for industrial URLLC services. This is because the DT-based LA algorithm can make more accurate predictions of the SINR, resulting in higher spectral efficiency, lower latency and two orders of magnitude higher reliability. This performance improvement is particularly important for industrial applications that depend on reliable connectivity, indicating that digital twins have the potential to significantly improve functions such as RRM in industrial 5G networks.

In short, the results of our evaluation show that the DT-based algorithm derives a significant performance gain from the integration between the factory digital twin and the NDT.

Standards and industry alignment

Initial efforts to define a framework for NDTs have been made in standards bodies such as the IETF (Internet Engineering Task Force) [9]. Due to the diversity of potential NDT use cases, we believe that the value of standards for NDTs will be in terms of providing alignment on terminology and defining a high-level architectural framework without being so specific as to inhibit innovation. The various types of NDTs each have their own needs in terms of data and characteristics, as well as different starting points. A high degree of flexibility will be required to support innovation both in terms of evolving existing functionality and introducing entirely new functionality.

Conclusion

Network digital twins (NDTs) have the potential to deliver massive benefits to mobile networks by supporting use cases in areas ranging from R&D to planning, deployment and operations. We foresee that there will be many types of NDTs in the not-so-distant future, each designed to fit the process it is intended to support. Some will emerge as an evolution of existing functionality, while others will be new creations that deliver novel capabilities. Depending on their purpose, NDTs may reside with the communication service provider and/or with their vendors.

To ensure that NDT solutions have the greatest possible impact, we believe it is wise to begin by identifying opportunities to reuse existing functionality such as management functions and simulation and analysis tools, while also ensuring that other necessary enablers, such as access to the required data, are in place. As digital twins proliferate, it is likely that individual NDTs will be combined both with each other and with industrial digital twins to create increasingly sophisticated digital representations that can deliver ever more powerful functionality.

Further reading

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