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The concept and use of the 5G network infrastructure digital twin

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Client's logo

Contents

Definition of terms

Digital Twin (DT): A digital twin is a virtual replica of a physical entity or process that enables real-time monitoring, simulation and optimisation through bidirectional data transfer between the digital and physical versions. This connectivity enables scenario testing and improved decision-making processes.

Network Digital Twin (NDT): A network digital twin is a digital twin specifically designed for network infrastructure, representing the entire network architecture in real time. It enables network operators to monitor, test and optimise network configurations without interfering with the live environment.

Bidirectional Data Transfer: An important function of digital twins that enables a continuous flow of data between a physical object and its digital twin. It ensures that both versions are kept up to date in real time, allowing the digital twin to influence physical operations and vice versa.

Predictive Maintenance: This function uses historical and current data to predict when a machine or system will require maintenance. Predictive maintenance optimises resource allocation and reduces unexpected downtime.

Simulation: In the context of digital twins, simulations enable ‘what-if’ scenarios to be modelled, where virtual models test various operational strategies, settings or responses to potential problems. Simulation is essential for preventing costly errors and optimising real-world operations.

Emulation: Emulation replicates the behaviour of a system in real time and creates a realistic testing environment; however, unlike simulation, emulation mimics the full functionality of the system, rather than just selected behaviours or responses. Whilst simulation is often used to explore different scenarios, emulation serves to faithfully replicate real-world operations, particularly when testing software or integrating systems.

Industrial IoT (IIoT): This term refers to the application of IoT technologies in industrial environments, where devices collect and transmit data for monitoring, maintenance and process optimisation. IIoT is key to the creation of digital twins in industrial environments.

Edge Computing: A distributed computing framework that brings data storage and processing closer to the source (e.g. IoT devices), thereby reducing latency. Edge computing supports digital twins by enabling rapid data processing in close proximity to the physical twin.

Network Slicing: A function that creates multiple virtual networks on a shared physical network infrastructure. Each ‘slice’ can be tailored to specific applications, such as requirements for low latency or high reliability.

Cyber-Physical Systems (CPS): These systems integrate physical processes with digital monitoring and control via a network. Digital twins are a form of CPS that help to synchronise and optimise both digital and physical environments.

Real-Time Monitoring: The ability of digital twins to continuously monitor the current state of a physical entity, enabling immediate decision-making and timely adjustments based on up-to-date data.

Connected Digital Twins: A future concept in which different digital twins interact with one another within a single system (such as a smart city), creating a complex, interconnected virtual environment that optimises large-scale operations.

Prescriptive Analytics: An advanced analytical process used by digital twins not only to predict outcomes but also to recommend specific actions to optimise processes or resolve problems.

Machine Learning (ML): A subset of artificial intelligence that enables digital twins to learn from data, recognise patterns and gradually improve. ML in digital twins enhances the accuracy of predictive and prescriptive analytics. This paves the way for the emergence of autonomous digital twins.

Digital Thread: A digital thread is a continuous flow of data and information linking various digital twins and systems throughout the life cycle of a product or process. It enables monitoring and traceability, which supports end-to-end optimisation.

Data Synchronisation: The process of maintaining consistency between a digital twin and its physical counterpart. It ensures that the digital model reflects changes in real time, which is crucial for accurate simulations, real-world applications and informed decisions.

Executive Summary

A digital twin is a virtual replica of physical entities and/or processes. Digital twins have the potential to transform many sectors, from industry and energy to telecommunications and smart cities, as they accelerate comprehensive understanding, help optimise decision-making and streamline operations. Key attributes of digital twins include two-way data transfer between the physical entity and its digital replica, and the ability to model various scenarios.

Digital twins are already a reality today and are helping to boost efficiency in many sectors. Between 2020 and 2025, the market is set to grow tenfold, and in the industrial digital twins sector alone, the market is valued at over USD 6 billion.

However, most digital twins in existence today are still at a low level of maturity. They are often digital representations of reality capable of supporting certain analyses, but lack the ability to recommend optimal solutions and to directly influence the physical entity. As the necessary skills, AI models and the ability to transmit and process large volumes of data develop, the level of digital twins will evolve towards prescriptive and autonomous digital twins capable of independent decision-making and optimising physical entities.

Digital twins can help us explain various phenomena, predict behaviour, explore alternatives, generate data for us, or even make changes in the physical world. As a result, they can bring a range of benefits to businesses and other users, particularly in the areas of new product development, improving operational efficiency and reducing costs, enhancing system performance and, last but not least, increasing resilience and cyber security.

Data and its real-time transmission are essential for the implementation of digital twins. Therefore, 5G technology, including its IoT variants, is the ideal tool for implementing digital twins in virtually all sectors and verticals. Furthermore, 5G plays a vital role in the concept of interconnected twins, where the network twin forms part of a complex system that will encompass, for example, entire logistics hubs, smart cities or factories.

5G technology brings many new possibilities not only for end users, but particularly for businesses and their advanced digitalisation. However, the key benefits of 5G technology also come at a cost in the form of significantly greater complexity in network architecture, as well as the challenges involved in designing, operating and optimising the network for various use cases. It is precisely in addressing these challenges that a Network Digital Twin (NDT) – a virtual model of the physical 5G network that is constantly updated with real-time data – can help. The NDT provides a live simulation of the physical network, enabling operators to assess performance, optimise resource utilisation, and detect and resolve faults in a controlled environment.

The development of 5G network digital twins will be characterised by close integration and mutual reinforcement with traditional tools such as network inventory, monitoring tools and testbeds. The NDT will expand and unify their capabilities, enabling a more comprehensive and proactive approach to network management. This convergence will enable operators to harness the power of each tool whilst utilising NDT's advanced analytics, predictive modelling and interactive capabilities.

The evolution of 5G technology towards 5G Advanced will bring new capabilities to support the creation of digital twins. In particular, the improved uplink and low-latency technology will enable a more detailed and realistic replication of physical environments. Network digital twins are also a key topic in discussions regarding the new 6G standards. It can be expected that the role of NDT will grow further with the new planned functionalities of 6G networks, such as network sensing and ubiquitous communication.

Management summary

Digital twins are virtual replicas of physical entities and/or processes. Digital twins have transformative potential across various sectors, from industry and energy to telecommunications and smart cities, as they accelerate the understanding of complex systems, support optimised decision-making, and improve operational efficiency. Key attributes of digital twins include bidirectional data transfer between the physical entity and its digital replica, as well as the ability to model various scenarios.

Today, digital twins are already a reality and are helping to increase efficiency across many areas. Between 2020 and 2025, the market is projected to grow tenfold, with the market for manufacturing digital twins alone estimated at over $6 billion.

However, most of today's digital twins are still at a low level of maturity. Often, they are digital representations of reality with limited analytical capabilities, lacking the ability to recommend optimal solutions and directly influence the physical entity. As capabilities, AI models and the ability to transmit and process large volumes of data continue to develop, digital twins will evolve into prescriptive and autonomous systems capable of independent decision-making and the optimisation of physical entities.

Digital twins can help explain various phenomena, predict behaviour, explore alternatives, generate data, or even initiate changes in the physical world. Through these capabilities, digital twins can deliver numerous benefits to companies and other users, particularly in the areas of new product development, increased operational efficiency, cost savings, improved system performance and, not least, enhanced resilience and cyber security.

Data and real-time transmission are essential for implementing digital twins. Therefore, 5G technology, including its IoT variants, is an ideal tool for implementing digital twins across virtually all fields and sectors. Furthermore, 5G plays a crucial role in the concept of connected twins, where a network twin forms part of a complex system that may include entire logistics hubs, smart cities or factories.

5G technology opens up many new possibilities, not only for end-users but particularly for enterprises and their advanced digitalisation efforts. However, the substantial benefits of 5G technology also come at a cost in the form of significantly greater complexity in network architecture and increased demands on network design, operation and optimisation for various use cases. The Network Digital Twin (NDT), a virtual model of the physical 5G network that is continuously updated with real data, can help address these challenges. The NDT provides a live simulation of the physical network, enabling operators to evaluate performance, optimise resource utilisation, and detect and resolve issues in a controlled environment.

The development of 5G network digital twins will be characterised by close integration and mutual enhancement with traditional tools, such as network inventory systems, monitoring tools and testbeds. NDT will expand and unify their capabilities, allowing for a more comprehensive and proactive approach to network management. This convergence will enable operators to harness the power of each tool whilst utilising advanced analytics, predictive modelling and NDT's interactive capabilities.

The advancement of 5G technology towards 5G Advanced will bring new capabilities to support the creation of digital twins. Improved uplink performance and low latency will enable a more detailed and realistic replication of physical environments. Network digital twins are also a significant topic in discussions on new 6G standards. It is expected that the role of NDT will grow further with new functionalities planned for 6G networks, such as network sensing and ubiquitous communication.

1 Introduction

1.1 Aims of the study

The objectives of the study are defined in light of the fact that the term 'digital twins', frequently mentioned in connection with digital transformation, requires a more in-depth explanation, including the entire concept behind it and the potential it can bring to businesses across various sectors. Furthermore, we aim to clarify the role of 5G technology in the concept of digital twins, including the digital twin of network infrastructure and its applications.

The objectives of the study are therefore set out as follows:

1. To provide an overview of the concept of digital twins.
2. To analyse the types, purpose and benefits of digital twins across various sectors.
3. To assess the role of 5G technology within the context of digital twins.
4. To provide a more in-depth insight into the digital twin of 5G network infrastructure.
5. To provide a vision for the future development of digital twins.

1.2 Structure of the study

5G technology plays a dual role in the field of digital twins:

- It is an important tool for implementing digital twins across various sectors and verticals.
- The digital twin of 5G network infrastructure plays a significant role in network design and optimisation, as well as in the design and testing of new services.

The structure of the study reflects this, focusing on two main areas:

- The general concept of digital twins.
- Digital twins of network infrastructure.

The study also provides insights into the further evolution of 5G and 6G technology and the implications for the concept of digital twins.

The appendices to the study consist of case studies in the form of specific projects and solutions in the field of digital twins. We are pleased to have been able to include solutions from Czech companies and universities in the case studies.

2 The general concept of digital twins

2.1 Definition and key attributes of digital twins

2.1.1 Definition of digital twins

The term ‘digital twin’ is one of the most popular terms in today’s technological world. Nevertheless, this term is often used for systems and solutions that are not, in fact, digital twins in the true sense of the word.

There are a number of definitions of the term ‘digital twin’. For example, Gartner’s IT Glossary provides the following:

“A digital twin is a virtual representation of a real-world entity or system. A digital twin implementation is a encapsulated software object or model that mirrors a unique physical object, process, organisation, person or other abstraction. Data from multiple digital twins can be aggregated to provide a comprehensive view of a range of real-world entities, such as a power station or a city, and their associated processes.”

In this otherwise clear definition, certain essential attributes of a digital twin relating to data transfer are missing. These are further supplemented by the definition provided by the Digital Twin Consortium[1]:

“A digital twin is a virtual representation of real-world entities and processes, synchronised at a specific frequency and with a specific level of accuracy. Digital twin systems transform business by accelerating comprehensive understanding, optimal decision-making and efficient operations. Digital twins use both real-time and historical data to represent the past and present, and to simulate predicted future states.”

The key attributes of a digital twin can be considered to be:

- Real-time data transfer: Synchronisation at a specific frequency ensures that the digital representation is constantly updated using real-time data from its physical counterpart.
- Two-way communication: The concept of synchronisation implies a two-way flow of information, which enables the digital twin to influence the physical entity and vice versa.
- Simulation of ‘what-if’ scenarios: The ability to simulate predicted future states allows for the exploration of different scenarios and outcomes, facilitating informed decision-making.

A solution that does not incorporate these three attributes cannot be considered a fully-fledged digital twin. At present, the majority of solutions fall into this category. Models that are faithful replicas of a physical entity are commonly referred to as digital twins; data from the physical entity is often fed into such a model, which is then used for specific analyses. However, what is missing in many cases is:

- Real-time data transfer: data is usually fed into the model in batches, and the model works with historical data.
- Two-way communication: data is transferred from the physical entity to the digital one, but not the other way round.
- Influencing the physical entity (related to the previous point): the model completely lacks the functionality that would enable the digital twin to influence the physical entity.

*For example, in the case of **a digital twin of network infrastructure**, this would involve a function that would automatically optimise the physical network’s settings depending on traffic and other factors (self-optimisation/self-healing).*

[1]https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin

- Simulation of 'what-if' scenarios: many models are either an advanced representation of reality or offer certain analytical possibilities, but do not provide comprehensive solutions to scenarios.

Does this therefore mean that using the term 'digital twin' for models that do not meet all the above parameters would be entirely incorrect?

Not quite. Many models that do not meet all the parameters represent a certain stage of development. Digital twin technology is still in its infancy, and digital twin developers must proceed in incremental steps. By using the term 'digital twin', it is at least clear where the model is heading and what its ambitions are.

On the other hand, it would be more effective for all involved if a digital twin were labelled according to the phase it is in. This is similar to autonomous vehicles, which are classified by the Society of Automotive Engineers (SAE) methodology on a scale from Level 0 (no automation) to Level 5 (fully autonomous).

2.1.2 Digital twin levels

In the field of digital twins, attempts are also being made to classify their levels, in this case usually according to their level of maturity. There is no single recognised classification (as is the case with autonomous vehicles); we therefore present one possible framework for distinguishing between levels of digital twins.

Level 0: Basic model

This is a simple digital representation of a physical object or system, which is often static and limited to basic 3D visualisations or diagrams. There is no integration with real-time data or interaction.

Example: A 3D model created using CAD, which serves only for visualisation and is not linked to current data.

Level 1: Descriptive digital twin

The digital twin receives data from the physical asset and enables real-time monitoring and visualisation. It displays the current state of the physical entity but does not include advanced analytics or predictions.

Example: A digital twin that monitors the temperature or pressure of a machine in real time, but only displays the data without further analysis.

Level 2: Predictive digital twin

This level includes predictive capabilities that use historical and real-time data to forecast future states and behaviour. The digital twin may be enhanced with machine learning or statistical models to predict potential problems or changes in performance.

Example: A digital twin that predicts a machine's maintenance requirements based on data trends and usage patterns.

Level 3: Prescriptive digital twin

At this level, the digital twin not only predicts future states but also provides practical information and recommendations. It can suggest optimal settings, adjustments or actions to prevent problems or improve efficiency.

Example: A production line digital twin that recommends adjustments to reduce energy consumption or increase production capacity.

Level 4: Autonomous digital twin

The most advanced level, where the digital twin is capable of autonomous decision-making and action. It has a closed-loop connection with the physical asset, enabling real-time, two-way data exchange and automatic adjustments based on simulations, 'what-if' scenarios and insights driven by artificial intelligence.

Example: A fully autonomous digital twin in a smart factory that optimises operations, schedules maintenance and adapts to changes in the environment without human intervention.

In the field of network digital twins, this would involve a twin that uses real-time data to predict necessary adjustments to the network configuration and implements these configurations directly on the physical network.

Overview of key features by digital twin level:

- Real-time data integration: Present from Level 1 onwards, becoming progressively more complex with each subsequent level.
- Predictive analysis: Introduced at Level 2. Enables the digital twin to anticipate potential problems.
- Prescriptive insights: Available at Level 3. Enables the twin to recommend optimal actions.
- Autonomous decision-making: Present at Level 4, where the digital twin can act independently and manage its physical counterpart.

2.1.3 A brief history of digital twins

The concept of the digital twin – a virtual representation of a physical object or system – has evolved over several decades and is linked to advances in simulation, modelling and information technology in general. During the Apollo missions in the 1960s, NASA developed physical replicas of spacecraft for simulation and analysis of conditions. It thus created early forms of digital twins. This approach proved crucial during the Apollo 13 mission, where simulations on Earth helped to resolve problems directly during the flight. In 1991, computer scientist David Gelernter introduced the idea of 'Mirror Worlds' – a vision of digital representations of real-world systems – which laid the conceptual foundations for today's digital twins.

The term 'digital twin' was formally introduced by Michael Grieves in 2002 during a presentation on Product Lifecycle Management (PLM) at the University of Michigan. Grieves described a model comprising three components: the physical product, its digital counterpart, and the data links between them. John Vickers of NASA subsequently expanded on Grieves' work and incorporated the concept of the digital twin into NASA's technology roadmap, where he highlighted its potential for use in the fields of aerospace.

With the advent of the Internet of Things (IoT) and Industry 4.0 technologies in 2010, a new chapter began for digital twins. These technologies enabled real-time data exchange between physical systems and their digital counterparts, which significantly enhanced the functionality and usability of digital twins across various industrial sectors. In 2018, the US Department of Defence, in its Digital Engineering strategy, defined a digital twin as "an integrated, multi-physics, multi-scale and probabilistic simulation of a system as-built", thereby emphasising its significant role in the simulation of complex systems.

At the current stage of digital twin development, technologies that were previously unavailable, such as machine learning (ML), artificial intelligence (AI) and cloud services, play a crucial role. These technologies enable the collection and analysis of large volumes of data in real time and provide the computing capacity required for demanding simulations. AI and ML give digital twins the ability to learn from historical and current data. This enables digital twins not only to predict future behaviour, but also to autonomously optimise operations and propose solutions in real time. Thanks to cloud services, data from various sources can be efficiently stored, processed and shared, enabling digital twins to collaborate across geographically dispersed systems and devices.

2.2 Types, purpose and benefits of digital twins

2.2.1 Types of digital twins

We have defined digital twins, including their categorisation by maturity. This categorisation already represents a form of classification. However, digital twins can be classified according to a number of different criteria. For example, by scope, purpose, lifecycle, real-time interaction, specific industrial applications or the complexity of data sources. Categorising digital twins into different types is useful for understanding their further applications.

Listed below are common classifications, each with an explanation of the criteria used for each category.

Classification by scope and level of integration

This classification focuses on the extent to which a digital twin represents a physical asset or system, ranging from individual components to complex systems:

- Component twins: These represent individual components or parts of a system, such as a specific part of an engine or a sensor. They are useful for monitoring specific elements and carrying out localised predictive maintenance.
- Asset twins: These cover entire assets, such as a complete machine, vehicle or turbine. They enable the performance of the entire asset to be monitored and predictive maintenance to be planned.

- System twins: These represent an entire system, including multiple assets and their interrelationships, such as a production line or transport network. They provide insight into the interactions between assets, enabling optimisation at the system-wide level.
- Process twins: These model entire processes or workflows, such as a manufacturing process or a supply chain. These twins enable end-to-end process management and optimisation, helping to identify bottlenecks, inefficiencies and opportunities for improvement.

Classification by life cycle phase

This approach classifies digital twins according to the specific phase of an asset's life cycle that they support:

- Design twins: These are used in the conceptual and design phases to simulate and test new products, prototypes or systems before they are built. These twins help to reduce development time and improve design quality by identifying potential problems at an early stage.
- Twins for operation and maintenance: These are deployed during the operational phase to monitor, control and optimise asset performance in real time. They are suitable for maintenance, troubleshooting and performance monitoring in day-to-day operations.

Classification by level of real-time interaction

This classification is based on the level of real-time interaction and synchronisation between the digital twin and its physical counterpart:

- Static twins: These do not incorporate real-time data inputs and are primarily used for analysing historical data, often based on data snapshots. These twins are useful in scenarios where real-time data is not required, such as post-event analysis.
- Synchronised twins: Regularly updated with near-real-time data, they provide an accurate representation of the physical asset's current state. These twins are commonly used for monitoring and decision-making, providing useful insights without the need for continuous synchronisation.
- Real-time twins: These maintain continuous synchronisation with the physical asset, enabling immediate decision-making and control. These twins are essential in fast-paced environments where a rapid response is required, such as in manufacturing or transport.

Furthermore, it is certainly possible to classify digital twins according to the field in which they are used. This is described in more detail in the following chapter.

2.2.2 The Purpose and Role of Digital Twins

Regardless of the type of digital twin and the field in which it is used, it is possible to define, in general terms, the purpose or purposes for which it can serve. This is very useful for understanding the full scope of their potential applications.

In particular, digital twins can fulfil the following roles:

Explaining phenomena: Digital twins can be used to explain what has happened in the past. For example, with sensor-based digital twins, one can look for patterns and anomalies in sensor readings.

Predicting behaviour: Digital twins can be used to predict future behaviour. For example, based on the historical behaviour of a specific sensor, its future readings can be predicted.

Exploring options: The power of a digital twin becomes apparent when we can explore various alternatives in the digital world and evaluate them according to our desired criteria.

Changes in the physical world: When we can implement changes in the physical world based on our exploration in the digital world, we are utilising the full potential of digital twins.

Data generation: Whilst we can explore alternative scenarios, if we have historical data, we can also generate potential values for testing in the physical world. This use of digital twins provides a powerful tool for working with incomplete and uncertain data.

2.2.3 The benefits of digital twins

The purpose of digital twins and the roles they can play when utilised are also closely linked to the benefits that digital twins can provide to businesses.

Digital twins can play a huge role in the lives of companies across a range of sectors and significantly influence their competitiveness in the future. It is no coincidence that this is such a frequently mentioned concept in the context of digital transformation. Digital twins can assist with innovation and product development, as well as with improving operational efficiency and resilience. Furthermore, the benefits of digital twins are divided into the following main areas.

Supporting innovation and product development

Digital twins make it possible to simulate and test new products, systems and processes in a virtual environment before they are actually deployed. By simulating 'what-if' scenarios and analysing the results, companies can develop new products or improve existing processes more quickly and cost-effectively. This process shortens the development cycle and minimises design errors.

Example: In the automotive industry, a digital twin of a new car prototype can be created, enabling the simulation of various operating conditions. In this way, performance and safety can be optimised even before a physical model is produced, thereby reducing the costs and time required for development.

Increased operational efficiency and cost savings

Through real-time monitoring and analysis, digital twins can optimise operational processes, reduce energy consumption and minimise maintenance costs. They provide valuable data for accurate planning and resource management, helping to achieve greater operational efficiency at lower cost.

Example: In the energy sector, a power station's digital twin can monitor energy production and optimise operations based on demand and conditions. This reduces energy consumption, minimises equipment wear and tear, and optimises operating costs.

Improving system performance

Digital twins enable the continuous monitoring and analysis of system performance and the identification of areas for improvement. Thanks to predictive analytics, digital twins can anticipate potential problems and suggest optimisations.

Example: In transport, a digital twin of infrastructure – such as a road network – can monitor traffic flow and recommend changes to traffic routing. It can thus help to improve traffic flow.

Risk mitigation

Digital twins help to identify and mitigate risks before they occur. Through simulations and predictive analytics, organisations can model various scenarios, such as outages, accidents or cyber-attacks, and develop contingency plans. This approach contributes to greater security, ensures business continuity and protects sensitive information.

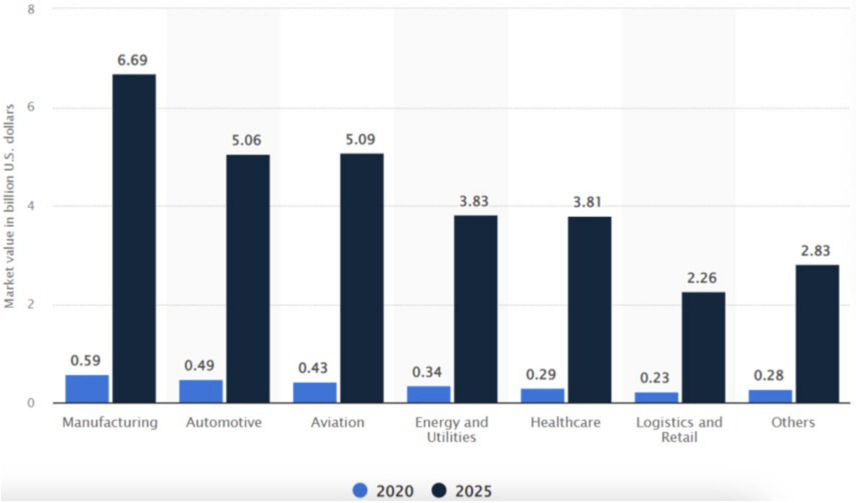
Example: In the field of cyber security, a digital twin of a network infrastructure can simulate cyber attacks, thereby testing the system's resilience and enabling the implementation of protective measures.

2.3 Use cases and applications of digital twins across various sectors

2.3.1 Market overview and the use of digital twins across sectors

Digital twins are finding applications across a range of sectors through a wide variety of use cases. According to data from Statista, the digital twin market has seen dramatic growth, particularly since 2020. In the manufacturing sector alone, the digital twin market is valued at over 6 billion USD.

Chart 1: Market value of digital twins by vertical in billion USD.



Source: Statista[2]

Other verticals, such as the automotive, aerospace, energy and healthcare sectors, are not far behind.

Let us take a closer look at the individual verticals and their typical use cases. Telecommunications and their use cases are summarised in Chapter 3.5.

1. Manufacturing

Digital twins have become an indispensable tool in smart manufacturing and Industry 4.0. By creating virtual replicas of machines, production lines or entire factories, manufacturers can monitor performance, predict equipment failures and optimise operations.

Examples of use:

- Predictive maintenance – Digital twins enable manufacturers to monitor machines in real time, detect early signs of wear and tear, and schedule maintenance before a breakdown occurs.
- Process optimisation – In complex manufacturing processes, digital twins help to optimise workflows, identify bottlenecks and streamline production. By simulating different configurations or settings, manufacturers can identify the most efficient approach to production.

As this is the most significant sector for the use of digital twins, the following chapter is devoted to it.

2. Healthcare

In healthcare, digital twins can be used to create personalised models of patients or medical devices to improve treatment planning, patient monitoring and predictive healthcare.

[2] https://www.weforum.org/stories/2022/05/digital-twin-technology-virtual-model-tech-for-good/

Example of use:

- Patient-specific models – Digital twins of organs, such as the heart or lungs, can be created to simulate a patient's response to different treatments. This enables doctors to develop personalised treatment plans that reduce risks and improve outcomes. For example, Philips uses digital twins in cardiology to simulate procedures and improve surgical planning.
- Medical equipment management – Hospitals can use digital twins to monitor the performance and condition of key medical equipment, such as MRI scanners or ventilators. This enables timely maintenance and ensures that equipment is available when needed.

3. Energy and utilities

The energy sector uses digital twins to optimise the generation, distribution and consumption of energy. This is particularly important during the transition to renewable energy sources, which require precise control and monitoring.

Example of use:

- Power grid management – Digital twins of power grids enable operators to monitor electricity flow, detect faults and optimise energy distribution. With the integration of renewable sources, digital twins help to balance the grid and manage variable sources such as solar or wind power.
- Predictive maintenance in power stations – Digital twins of power generation equipment (such as turbines and substations) provide insights into potential performance degradation and enable predictive maintenance, which reduces downtime and increases efficiency.

4. Transport and the automotive industry

The automotive industry uses digital twins for the design, testing and, where applicable, operation of vehicles. In transport infrastructure, digital twins help to monitor and maintain assets such as roads, bridges and rail systems.

Example of use:

- Vehicle design and testing – Car manufacturers, such as BMW, use digital twins to simulate and test vehicle designs. In this way, they can test the performance, safety and reliability of vehicles in a virtual environment before they are manufactured.
- Smart transport infrastructure – Cities and transport authorities use digital twins of transport infrastructure to monitor condition, manage traffic flow and plan maintenance. For example, the city of Singapore uses a digital twin of its transport network to optimise traffic patterns.

5. Smart cities

Digital twins will be an integral part of the development of smart cities, where they can be used to create virtual models of entire urban areas, integrating data from buildings, transport and utilities.

Example of use:

- Urban planning and development – Urban planners use digital twins to simulate and assess the impacts of new developments, infrastructure projects and population growth on transport, pollution and resource use. This helps cities plan and deliver more sustainable and resilient urban spaces.
- Crisis management – Digital twins enable cities to simulate crisis scenarios, such as natural disasters or infrastructure failures. This helps authorities prepare crisis management plans, ensuring a faster and more effective response to emergencies.

6. Logistics and retail

In the retail and warehousing sectors, digital twins provide insights into stock management, layout optimisation and customer behaviour, helping to streamline operations and improve customer satisfaction.

Example of use:

- Inventory and supply chain optimisation – Digital twins monitor stock levels, forecast demand and optimise warehouse layouts. This ensures stock is available when needed and minimises storage costs. For example, Amazon uses digital twins to efficiently manage complex logistics and warehousing operations.
- Optimising shop layouts – Digital twins of shops enable the testing of different layouts and product placements to optimise customer flow and maximise sales. By analysing customer movement patterns, retailers can make data-driven decisions about shop layouts.

7. Aviation industry

In the aviation industry, digital twins are used for the design, maintenance and operation of aircraft and aviation infrastructure, including applications in air traffic management.

Example of use:

- Aircraft condition monitoring – Digital twins of aircraft monitor the condition of critical components, such as engines and landing gear, in real time. By analysing flight data, they enable predictive maintenance, which reduces unexpected downtime and improves safety. For example, Airbus uses digital twins to monitor the condition of aircraft parts and optimise maintenance schedules.
- Air traffic management – Digital twins of airport infrastructure and air traffic networks help manage air traffic flow, minimise delays and ensure efficient routing. Digital twins simulate various scenarios, such as weather disruptions or high-traffic conditions, thereby optimising air traffic management.

Digital twins have become valuable tools across various industries, enabling better monitoring, predictive maintenance and operational efficiency. With the development of technologies such as AI, IoT and cloud computing, digital twins will continue to expand and offer even greater value in transforming how organisations design, operate and maintain their assets and systems.

2.3.2 Applications of digital twins in manufacturing

Digital twins are transforming decision-making processes in manufacturing. With growing challenges such as supply chain issues, high energy costs and a shortage of skilled labour, digital twins offer solutions to increase efficiency, scale operations and improve resilience. They provide deeper insights into manufacturing processes, optimise planning and enable 'what-if' scenario testing. Digital twins contribute to faster, smarter and more cost-effective decisions.

Main types of digital twins in manufacturing.

Digital twins in manufacturing can be categorised according to their scope (this is similar to the classification set out in section 2.2.1, but applied directly to the specific manufacturing sector) [3] :

1. Product twins: These twins capture detailed information about individual products and support quality control, product development and improvement.
2. Asset twins: These represent production assets such as machinery and equipment. Thanks to IoT devices and sensors, asset twins provide a real-time overview, enabling predictive maintenance and the optimisation of energy consumption, yields and throughput.
3. Factory twins: These cover entire production lines and integrate data from manufacturing information systems (MES), ERP and other systems. They are useful for dynamic production planning and 'what-if' scenario analysis of production set-ups and layouts.
4. End-to-end digital twins: These cover the entire supply chain, from suppliers through to manufacturing and distribution. They offer advanced planning capabilities and help manage supply chain complexity.

[3] Sean Camarella, Michael P. Conway, Kevin Goering, and Mark Huntington. *Digital Twins: The Next Frontier of Factory Optimisation.* McKinsey & Company, January 2024.

The role of digital twins in manufacturing.

Digital twins create a comprehensive model of the manufacturing environment, use real-time data to simulate outcomes, and perform ‘what-if’ analyses across various production scenarios. Advanced digital twins also support automated production planning, either under human supervision or through full automation.

In newly built factories (so-called ‘greenfield’ sites), digital twins validate layout designs, optimise space utilisation and estimate stock requirements. In existing factories, they identify bottlenecks, manage stock and optimise the flow of materials using up-to-date data. Digital twins support both long-term decisions, such as continuous improvement projects, and real-time decisions, such as adjustments to production plans.

Implementing a scalable digital twin.

A successful digital twin requires a modular and scalable technology stack that integrates data from various sources and creates a single source of truth. Key steps in building a scalable digital twin include:

1. Data integration: Collecting data from MES, ERP, inventory systems and IoT sensors, and cleaning and structuring it for simulation purposes.
2. Creating a unified data model: Data integration software standardises and categorises the information. This enables the efficient use of data across different factory operations.
3. Simulation and optimisation: Discrete simulation software creates an accurate virtual model of the factory, whilst optimisation software identifies the best production sequences. Modern techniques such as machine learning (ML) and transfer learning enable digital twins to adapt to changes in real time and dynamically improve production performance.

The successful implementation of digital twins is a highly demanding process. An iterative approach to digital twin development is therefore recommended, beginning with a concept to verify the feasibility and impact of the twin, followed by the creation of a minimum viable product (MVP) and its connection to real-time data sources.

2.4 The role of 5G technology in the digital twin concept.

The digital twin has the potential to become a significant tool for the digitalisation of businesses, particularly industrial ones.

However, the key attribute of a digital twin is **data and its transmission** – ideally in real time – between the physical object and its digital replica. As the sophistication of digital twins increases, so too do the demands on the volume, quality, reliability and security of these data flows.

The massive collection of data from assets enables the development of (particularly industrial**) IoT**. **5G** is therefore the ideal technology for the reliable transmission of this data. Depending on the requirements of a given system, this may also involve various IoT variants of 5G technology, such as RedCap, NB-IoT or Cat-M. 5G is a technology that is sufficiently powerful, secure (particularly when compared with other mobile technologies) and, at the same time, flexible and scalable (when compared with fixed data technologies). This makes it the ideal tool for implementing digital twins in virtually all sectors and verticals.

A detailed description of the use of 5G technology in the IoT sector can be found in the study **‘Integrating elements of the Internet of Things (IoT) and 5G networks’.**

A description of the characteristics of 5G networks and their use in the digitalisation of businesses can be found in the study **“The Use of 5G and Other Electronic Communications Networks for the Digitalisation of Businesses, Including the Use of Modern Information Systems”.**

Both studies were prepared for the Ministry of Industry and Trade of the Czech Republic. The digital twin

thus combines the themes of using 5G for business digitalisation and the subject of the IoT. However,

the role of 5G in the concept of digital twins is even broader. It can be broken down as follows:

1. 5G as a technology enabling the effective creation of digital twins for various verticals and use cases.
2. The 5G network digital twin as part of interconnected digital twins.

Interconnected digital twins are among the anticipated future trends shaping the development of digital twins and their applications, as described in more detail in Chapter 4.4. Networked digital twins will often be one of the elements of an interconnected system. This is because, in the context of digitalisation across various verticals, connectivity will almost always play a key role. Networks – often 5G networks – can be found in smart factories, logistics hubs, hospitals and smart cities. The digital twin of these networks will, logically, be a key component of the entire system of interconnected digital twins, enabling the optimisation of the operation of such complex systems as entire factories or cities.

3 The digital twin of 5G network infrastructure

3.1 Challenges associated with 5G and why a digital twin is needed for 5G networks

5G technology brings many new possibilities not only for end users, but particularly for businesses and their advanced digitalisation. It offers not only high transmission speeds, high reliability and low latency, But also the ability to utilise MEC for processing large volumes of data close to the source, guaranteed QoS parameters thanks to network slicing or private networks. These are all beneficial features of 5G associated with the new architecture of 5G networks, which is based on software-defined networks, virtualised network functions and the separation of the user plane and control plane.

A detailed description of the features of 5G networks and private 5G networks can be found in the study **"The Use of 5G and Other Electronic Communications Networks for the Needs of Business Digitalisation, Including the Use of Modern Information Systems"**

The essence of software-defined networks and the principles of network slicing are explained in the study **"The Use of 5G Network Slicing for Public and Non-Public Networks".**

Both studies were prepared for the Ministry of Industry and Trade of the Czech Republic.

However, the significant benefits of 5G technology also come at a cost in the form of a markedly more complex network architecture and greater demands on network design, operation and optimisation for various use cases.

<u>The main challenges of 5G are therefore:</u>

- Increased network complexity: 5G networks are designed for ultra-high speeds, low latency and massive connectivity demands, which must support various sectors and advanced applications such as Industry 4.0, autonomous vehicles, e-health, and critical communications (PPDR). Managing such heterogeneous requirements whilst maintaining high performance in dynamic environments is extremely demanding.

- Network slicing and virtualisation: Dynamic resource allocation across multiple virtual network slices increases operational complexity. This means that optimal performance must be ensured for various applications, each of which has different service level agreements (SLAs) and quality of service (QoS) requirements.

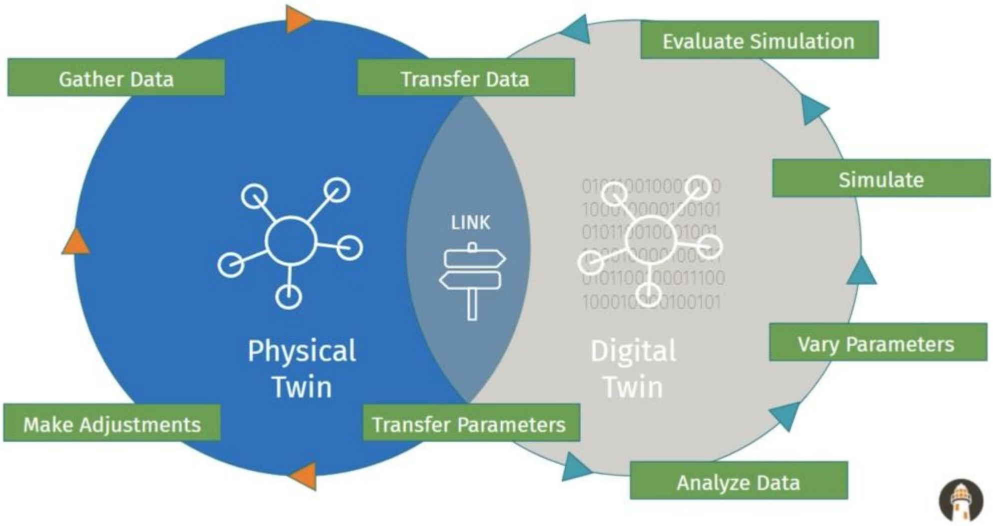
- Rapid development and frequent updates: The rapid evolution of software and infrastructure in 5G, including frequent updates, new services and advances in virtualisation, requires a robust, cost-effective testing environment that minimises deployment risks.

- Cyber security: As networks become more complex, their vulnerability also increases, making it more difficult to ensure comprehensive cyber security.

A Network Digital Twin (NDT) can help address these challenges. Let's first look at its definition:

A 5G network architecture digital twin (NDT) is a virtual model of a physical 5G network that is constantly updated with real-time data. This enables a two-way flow of information between the physical and virtual environments, ensuring that the digital twin evolves in parallel with the real network. The NDT provides a live simulation of the physical network, enabling operators to assess performance, optimise resource utilisation, and detect and resolve faults in a controlled environment.

Figure 1: Digital twin and bidirectional interconnection with the physical twin.



Source: Spirent

NDT is therefore a virtual replica of a mobile network that can mirror the real-world behaviour of the physical network, enabling operators to:

1. Simulate and predict network performance: NDT helps operators model network behaviour, such as traffic congestion, before implementing changes in real-world conditions.

2. Carry out virtual testing: The twin enables the testing of new services and updates in a secure simulated environment. Operators can simulate various network conditions, such as cyber-attacks, high network load and hardware failures, without compromising the live network.

3. Improve decision-making: NDT enables automated network management and optimisation through real-time analytical data, which is fed back into the network to improve service delivery.

4. Accelerate deployment: New services, updates and enhancements can be tested and fine-tuned virtually, reducing the time needed to bring new 5G use cases to market.

The joint initiative by Spirent and Ericsson[4]confirms the defined purpose of the 5G digital twin and demonstrates that it can genuinely contribute to addressing the aforementioned challenges associated with the deployment and operation of 5G technologies. These companies and their project have the following objectives with digital twin technology:

1) to reduce the validation time for new 5G use cases from months to hours, or even minutes;

2) to share test results between development and operations within a matter of minutes;

3) to reduce the costs of deploying new services, as well as support and maintenance/troubleshooting;

4) enable proactive assurance and maintenance by testing virtual 5G network infrastructure to identify potential issues;

5) to support network automation and optimisation;

6) facilitate network slicing using software-defined networking (SDN) and network function virtualisation (NFV);

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[4] H. X. Nguyen, R. Trestian, D. To and M. Tatipamula, "Digital Twin for 5G and Beyond," in IEEE Communications Magazine, vol. 59, no. 2, pp. 10–15, February 2021, doi: 10.1109/MCOM.001.2000343.

7) test multiple slicing paths simultaneously by deploying the functions required for a new use case. For example, in a shared infrastructure scenario in 5G networks, a digital twin capable of monitoring network changes in real time would enable artificial intelligence tools to simulate and predict future outages.

3.2 Distinguishing NDT from existing tools used in the field of 5G infrastructure.

If we look at the definition of NDT and its purpose, we find that operators are already using tools that assist them in these areas and thus have a certain overlap or similarity with the Network Digital Twin. These tools include, in particular:

- **Network inventory**, i.e. a record of the network that is a faithful digital representation of the actual physical network and all its components.
- **Network monitoring**, i.e. systems for monitoring the network's status in real time.
- **Testbed**, i.e. a test environment that, to a certain extent, replicates the production environment for testing new configurations, scenarios, etc.

Let us therefore take a closer look at where they overlap with NDT and where, conversely, they differ:

1. Network management systems – Network inventory:
   - Overlap: Network inventory systems maintain detailed records of the physical and logical elements of the network, including configurations, interconnections and network topology. They provide a static view of the network. This includes visualisations and relationships between assets, similar to the basic functions of NDT.
   - Differences: Whilst network inventory systems are primarily static and descriptive, NDTs are dynamic and focus on real-time modelling. NDTs can adapt to real-world changes in network conditions, update their model and provide predictive insights. This capability enables NDT to simulate the impacts of changes in near real time, going beyond mere visualisation.
2. Network monitoring tools:
   - Overlap: Monitoring tools continuously collect telemetry and performance data from the network. They provide real-time status overviews, fault detection and mechanisms for sending alerts. This real-time view of the physical network's status overlaps with the visualisation provided by NDT.
   - Differences: Traditional monitoring tools often focus on narrow areas, such as tracking specific metrics or KPIs. NDT, by contrast, integrates data from various sources to create a holistic model. Not only does it detect problems, but it also simulates and analyses the outcomes of network configurations or interventions, enabling predictive maintenance and proactive planning. Furthermore, NDTs provide a bidirectional link between the physical network and its digital replica, enabling real-time interactions.
3. Testbed:
   - Overlap: A testbed is used to experiment with new services and configurations, and to test the network's resilience in various scenarios. This corresponds to one of the key functions of NDTs, which is to enable the safe testing and evaluation of network changes without impacting the live environment.
   - Differences: Although testbeds are capable of simulating real-world conditions, they are often isolated and static environments. They do not offer the same level of real-time interaction and synchronisation with the physical network as NDTs do. NDTs go beyond isolated test environments by maintaining real-time synchronisation with the physical network, enabling continuous performance tuning, predictive simulations and fault diagnostics based on real data flows.

So what distinguishes NDTs from traditional network tools?

1) Real-time synchronisation and bidirectional interaction:

NDTs create a continuous, bidirectional link between the physical network and its digital replica. This means that when the physical network changes (e.g. due to a topology modification or changes in data traffic), the digital twin is automatically updated to reflect these changes. Conversely, actions or configurations tested on the digital twin can be applied directly to the physical network. These dynamic, synchronous connections enable operators to identify potential issues proactively and make data-driven decisions.

2) Comprehensive multi-domain integration:

NDTs integrate various data sources and domains under a single unified framework, encompassing inventory data, monitoring data, historical performance records and even user behaviour data. This integration enables comprehensive modelling and predictive analysis, which traditional tools may not be able to achieve due to their more specialised and isolated nature.

3) Predictive and prescriptive analysis:

NDTs are not merely reactive (like traditional tools that detect and alert users to faults), but are also proactive and prescriptive. They can simulate 'what-if' scenarios, carry out impact analyses and automatically optimise network configurations. This predictive capability enables operators to prevent potential outages, optimise resource allocation and simulate future network conditions.

4) Advanced use of artificial intelligence and machine learning:

NDTs utilise AI/ML algorithms to perform in-depth analysis of network behaviour and offer self-healing, anomaly detection and optimisation. Whilst traditional tools may use rule-based monitoring or simpler algorithms, NDTs utilise AI/ML to identify complex patterns, deduce correlations and autonomously propose solutions or adjustments.

In summary, NDTs differ from traditional tools in their dynamic, synchronous integration, predictive analytical capabilities and comprehensive coverage of multiple areas. Whilst traditional tools are highly valuable for displaying network status, visualising network inventory and testing isolated scenarios, NDTs extend these capabilities to include continuous synchronisation, optimisation-based simulations and proactive risk mitigation. Essentially, NDTs function as an advanced intelligent layer that continuously monitors, simulates, optimises and adapts the network – going beyond the scope of existing network inventory systems, monitoring tools and testbed environments.

What is the likely future of the coexistence of traditional tools with 5G network digital twins?

The development of 5G networks and the emergence of network digital twins (NDTs) will lead to a transitional phase in which traditional tools, such as network inventory systems, network monitoring tools and testbeds, will continue to play an important role, whilst NDTs will complement them. Furthermore, traditional tools may be utilised to a certain extent in the implementation of NDTs.

Let's take a closer look at their potential role in relation to NDT:

Network Inventory Systems:

- **Benefits for NDT:** These systems maintain basic data on the physical and logical configuration of the network. During the initial creation of an NDT, this detailed data is essential for the accurate construction of a digital replica of the network topology and its configuration.

- **Coexistence:** Network inventory systems will continue to exist alongside NDT. They provide the basic static data upon which NDT builds. Conversely, NDT can offer an additional layer of real-time visualisation and analysis on top of this static inventory. This coexistence is therefore complementary, as inventory systems act as static reference points, whilst NDT offers dynamic views and simulations.

Network monitoring tools:

- **Benefits for NDT:** Monitoring tools generate real-time telemetry and performance data. This data is essential for NDT to maintain an up-to-date view of the network's status and operational condition. Furthermore, historical data from monitoring tools can assist in training predictive models within NDT.

- **Coexistence:** NDTs rely heavily on monitoring tools as sources of real-time data. Whilst NDTs can enhance the overview through predictions and recommend optimisations, traditional monitoring tools remain essential for the continuous collection of raw telemetry data. NDTs therefore act as a higher layer for analysis and decision-making rather than as a replacement.

Testbed:

- **Benefits for NDT:** Testbeds provide a controlled environment for validating new services, network configurations and failure scenarios failures before their deployment. This environment provides key data for building and validating NDT models, particularly when creating simulations of unusual scenarios that occur only rarely in a live network.

- **Coexistence:** Although NDTs can simulate and predict the impacts of changes in a virtual environment, testbeds remain useful for validating scenarios that are too complex or risky to test in a production environment or require interaction with specific hardware components. Over time, testbeds may become more integrated with NDTs, enabling a seamless transition between simulated and real-world environments.

Will NDT replace traditional tools? The short answer is no, at least not in the foreseeable future.

The roll-out of NDTs is likely to be gradual, rather than revolutionary. Implementing NDTs requires significant investment in data integration, modelling capabilities and system interoperability. Traditional tools provide key data sources and the infrastructure for building these digital twins. As NDTs mature, they will expand the capabilities of these tools rather than render them obsolete.

The development of 5G network digital twins will be characterised by close integration and mutual reinforcement with traditional tools. Network inventory systems, monitoring tools and testbeds will continue to play a key role in building and validating NDTs. Rather than replacing these tools, NDTs will extend and unify their capabilities, enabling a more comprehensive and proactive approach to network management. This convergence will allow operators to harness the power of each tool whilst utilising the advanced analytics, predictive modelling and interactive capabilities of NDTs.

3.3 Architecture and design process of the 5G network digital twin

3.3.1 Architecture and components of the 5G network digital twin

The architecture of the 5G Network Digital Twin (NDT) [5]is designed to be modular and scalable to reflect the dynamic and distributed nature of 5G networks. Key components of the architecture include:

1. Data

NDT requires a large amount of data to maintain synchronisation with the physical network. This data includes:

- Configuration data (routing tables, interface metrics, device details).
- Telemetry data (real-time performance metrics).
- Topology information (network structure and interconnections).

2. Models

NDT uses data-driven models that emulate the behaviour of network components. These models replicate network functions such as base stations (gNodeBs), the network core and user devices. The models ensure that the virtual network behaves like its physical counterpart, enabling accurate simulations of traffic, routing and service-level interactions.

3. Interfaces

Standardised interfaces are essential for connecting the digital twin to both the physical network and external applications. These interfaces ensure the free flow of data between systems, enabling continuous updates and real-time interactions. There are two main types of interfaces:

- Physical-to-digital: Interfaces enabling the exchange of data between physical network elements and their virtual representations.
- Application layer: Interfaces enabling external applications, such as network orchestration systems and artificial intelligence tools, to interact with the NDT.

[5] M. Sanz Rodrigo, D. Rivera, J. I. Moreno, M. Àlvarez-Campana and D. R. López, "Digital Twins for 5G Networks: A Modelling and Deployment Methodology," in IEEE Access, vol. 11, pp. 38112–38126, 2023, doi: 10.1109/ACCESS.2023.3267548.

4. Mapping

Mapping refers to the relationship between physical network elements and their digital twins. This relationship can be:

- One-to-one: Direct synchronisation between a single physical element and its virtual counterpart.
- Many-to-one: A situation where multiple physical elements are mapped to a single virtual twin, enabling the modelling of large-scale networks.

5. NFV (Network Functions Virtualisation)

NFV is essential for the virtualisation of network services, such as firewalls and routers, by replacing traditional hardware with software-based network functions. NFV enables operators to deploy these functions dynamically within the digital twin.

6. Management and Orchestration (MANO)

The MANO framework manages the lifecycle of virtualised network functions (NFV) within the NDT. It encompasses orchestration, resource allocation and monitoring, ensuring that NFVs are deployed and managed efficiently.

7. Security gateways

To ensure secure communication between the physical and digital twins, NDTs incorporate encryption protocols such as TLS and post-quantum cryptography (PQC). These gateways protect sensitive data transmitted between the two environments.

3.3.2 Creating a network digital twin: Process and steps

The process of creating a 5G network digital twin involves several specific phases that ensure an accurate representation and real-time synchronisation of the network. The following steps outline a possible methodology for creating a digital twin[6] :

Phase 1: Data Collection

This phase involves collecting data from the physical network using agents. These agents gather data on topology, hardware resource configuration, routing tables, bandwidth and other relevant parameters using protocols such as SNMP, ALTO and ICMP. This data is then sent to a central management system, which creates a comprehensive model of the physical network.

Phase 2: Modelling

Once the data has been collected, it is used to create a semantic model of the network. This model abstracts the complexity of the physical network into a manageable virtual representation. The aim is to optimise resource utilisation without replicating every element of the physical network, thereby ensuring the efficiency and cost-effectiveness of the digital twin.

Phase 3: Adaptation

The data model is adapted for deployment within an NFV architecture. In this phase, templates such as VNFDs (Virtual Network Function Descriptors) are used to define virtual resources and ensure compatibility with virtualisation platforms such as OpenStack.

Phase 4: NFV Deployment

The digital twin is deployed using NFV infrastructure. The architecture supports flexible deployment options, either monolithic (all VNFs in a single instance) or distributed (VNFs deployed across multiple virtual instances). Deployment is managed by MANO systems, which orchestrate virtual elements to mirror the behaviour of the physical network.

Phase 5: Provisioning

Provisioning involves configuring the digital twin so that it behaves in the same way as the physical network. Tools such as Ansible automate the deployment process by running specific playbooks designed for virtual environments.

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[6] M. Sanz Rodrigo, D. Rivera, J. I. Moreno, M. Álvarez-Campana and D. R. López, "Digital Twins for 5G Networks: A Modelling and Deployment Methodology," in IEEE Access, vol. 11, pp. 38112–38126, 2023, doi: 10.1109/ACCESS.2023.3267548.

Phase 6: Interconnection

This phase ensures real-time communication between the physical and digital twins. Security gateways are used to transfer data between the two environments, ensuring that both systems remain synchronised. Communication is managed using messaging protocols such as MQTT or RabbitMQ.

Phase 7: Feedback and Continuous Optimisation

The final phase involves establishing a feedback loop, whereby the digital twin is continuously updated based on real-time telemetry data from the physical network. This enables NDT to detect issues in the network, optimise performance and enable proactive responses to network events such as outages or security threats. This phase also supports the testing of new services and updates before they are deployed on the live network.

3.4 Risks and challenges in implementing digital twins for 5G

Creating a network digital twin (NDT) for 5G infrastructure presents a number of challenges and risks. Below is an analysis of the key challenges and associated risks based on available evidence[7] .

Main challenges and risks:

1. Cybersecurity risks:

The NDT replicates the entire 5G network infrastructure, including its data, protocols and operations. This means that sensitive data from the physical network is mirrored in the digital twin, making it vulnerable to cyber threats. A breach of the digital twin could lead to unauthorised access and the potential exposure of network configurations, traffic patterns and sensitive user data. For this reason, it is crucial to ensure robust cybersecurity measures, such as encryption, secure communication protocols and post-quantum cryptography. However, implementing these measures increases the complexity and maintenance costs of NDT.

2. Interoperability and compatibility:

The 5G ecosystem is characterised by heterogeneous technologies and a multi-vendor environment. Ensuring that NDT can accurately emulate various elements (e.g. base stations, network core, IoT devices) and technologies (e.g. network slicing, virtualised functions) presents a significant challenge. A multi-vendor environment leads to different communication standards and data formats, which requires sophisticated integration capabilities within the NDT to maintain seamless interoperability.

3. High complexity and resource demands:

NDT must accurately model the dynamic and evolving components of the 5G network, including real-time configuration changes, hardware updates and network slicing. This high level of complexity requires advanced data modelling and constant synchronisation between physical and digital counterparts. Furthermore, establishing realistic synchronisation and data flow between the physical network and its digital twin requires significant computing power and storage capacity, which increases costs.

4. Costs and uncertainty regarding return on investment (ROI):

The deployment and maintenance of NDT require significant investment in both technology and human resources. The need for advanced software-defined networks, emulation tools and secure gateways results in substantial upfront costs. Given that NDT is still a relatively new technology, assessing its return on investment is speculative. Many organisations face challenges in justifying these investments without clear evidence of long-term savings or increased efficiency.

5. Risk of incomplete or inaccurate replication:

The success of NDT depends on its ability to accurately replicate the real-world network. Inadequate data collection or insufficient emulation of certain network functions can result in a digital twin that behaves differently from its physical counterpart. This inaccuracy could undermine the value of NDT, as decisions based on a flawed digital twin would lead to sub-optimal results or failures.

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[7] Huan X. Nguyen et al., “Digital Twin for 5G and Beyond,” *IEEE Communications Magazine* 59, no. 2 (1 February 2021): 10–15, https://doi.org/10.1109/mcom.001.2000343.

6. Dependence on evolving standards:

5G technology is constantly evolving, with standards and protocols frequently updated or amended. This adds a further layer of complexity, as the NDT must be continually updated to comply with the latest standards. If these changes are not implemented regularly, a mismatch may arise between the physical network and its digital twin.

Possible conceptual measures to mitigate risks and challenges:

1. A comprehensive cybersecurity strategy:

The implementation of robust security measures at every communication layer between the physical and digital twins, using post-quantum cryptography and Transport Layer Security (TLS) protocols, is essential. Regular assessments of the NDT's security posture, including penetration testing and simulations of real-world attacks, should be a priority.

2. A standards-based interoperability framework:

NDT should adhere to recognised standards, such as those proposed by ETSI or the IETF for the virtualisation and integration of network functions. This would enhance compatibility and integration with various 5G technologies and multi-vendor environments.

3. Use of agile development:

Given the rapid pace of progress in the field of 5G, a flexible approach to NDT development is essential. The use of agile methodologies, including a continuous integration and continuous deployment (CI/CD) framework, enables organisations to update and optimise their digital twins in response to changes in standards, protocols or hardware.

A phased deployment strategy is also in line with agile principles. Early-stage validation using modular prototypes and extensive simulations can help fine-tune the NDT before full-scale implementation.

These measures, if implemented effectively, can help companies better navigate the complexities and risks associated with creating and utilising a digital twin of a 5G infrastructure network.

3.5 Use cases and case studies of 5G infrastructure digital twins

Chapter 3.1 outlined the reasons for using 5G infrastructure digital twins and their purpose. Broadly speaking, these include simulating various network states, supporting network status monitoring and optimisation, accelerating decision-making, deploying new features and, last but not least, taking testing to a new level of quality.

Let us, however, look at the specific use cases that 5G NDT can help address. Given that this is a very new technology, this is an illustrative list that will certainly expand rapidly.

The following examples demonstrate how digital twins contribute to developments in C-V2X testing, smart factories, CSP traffic management, and further advances in Open RAN, radio channel emulation and 5G network security:

1. **NDT for C-V2X vehicle testing[8] :**

Digital twins enable virtual testing of connected and autonomous vehicles (CAVs) by simulating various road conditions and network parameters. A digital twin helps to reduce the number of kilometres travelled during physical testing and allows for the exploration of different scenarios, such as weather conditions, traffic patterns and handover between 5G base stations.

2. **NDT for modelling and optimising private 5G networks for Industry 4.0:**

Industry 4.0, for example in the form of smart factories, has demanding requirements such as ultra-low latency, high reliability and secure communication. Digital twins provide a mechanism for modelling, planning and optimising private 5G networks, thereby ensuring high device synchronisation and minimising network interference.

3. **The use of NDT by communications service providers (particularly MNOs) for planning and managing quality of service (QoS):**

Communications service providers (CSPs) can use digital twins to continuously model and validate how network functions and processes should behave in real time. Digital twins enable CSPs to test different network configurations and proactively optimise them. This allows them to maintain service quality (QoS) at the required level, even under dynamically changing conditions.

4. **Cloud-delivered NDT for 5G:**

Global cloud service providers (so-called ‘hyperscalers’) host cloud-based versions of 5G CORE and, where applicable, Open RAN (O-RAN). They face interoperability challenges due to the need to collaborate with multiple suppliers, as well as the requirement to ensure low latency even when services are deployed in the cloud. Digital twins provide a sandbox environment for testing and validating the performance of various cloud-based 5G infrastructure configurations.

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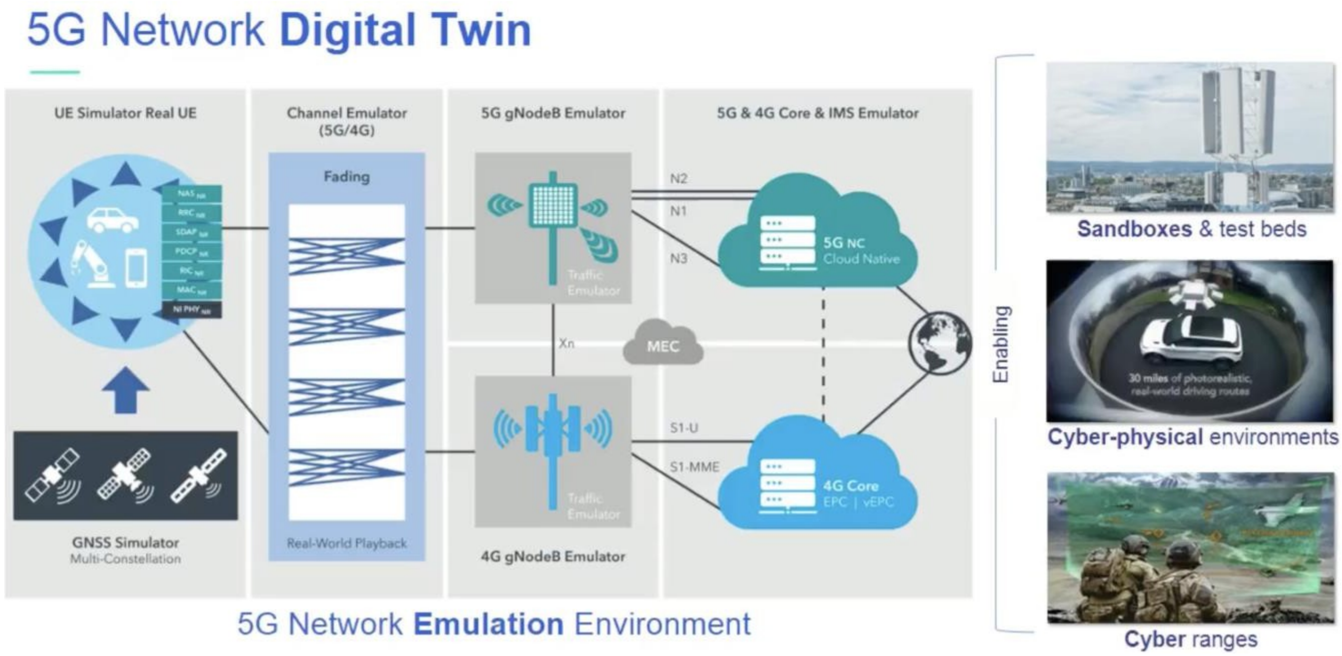
[8] Spirent, *Simplifying 5G with a Network Digital Twin* (White paper), 2022.

5. **Emulation of 5G radio channels:**

Digital twins emulate various RF channels (below 6 GHz and mmWave) and RAN technologies, such as Massive MIMO and beamforming. This emulation enables the testing of base stations and network performance under complex radio conditions. NDT thus accelerates 5G deployment through RF performance validation and network configuration optimisation under realistic conditions.

Figure 2: Use of 5G NDT for the emulation of radio channels and other network elements



Source: Spirent

6. **Security threat emulation:**

Digital twins are used to emulate security threats in a 5G environment. By creating and testing various attack scenarios, the twins help to proactively identify vulnerabilities and propose countermeasures. NDTs thus help to enhance the security of 5G networks by providing continuous assessment and proactive threat management.

7. **Network slicing emulation:**

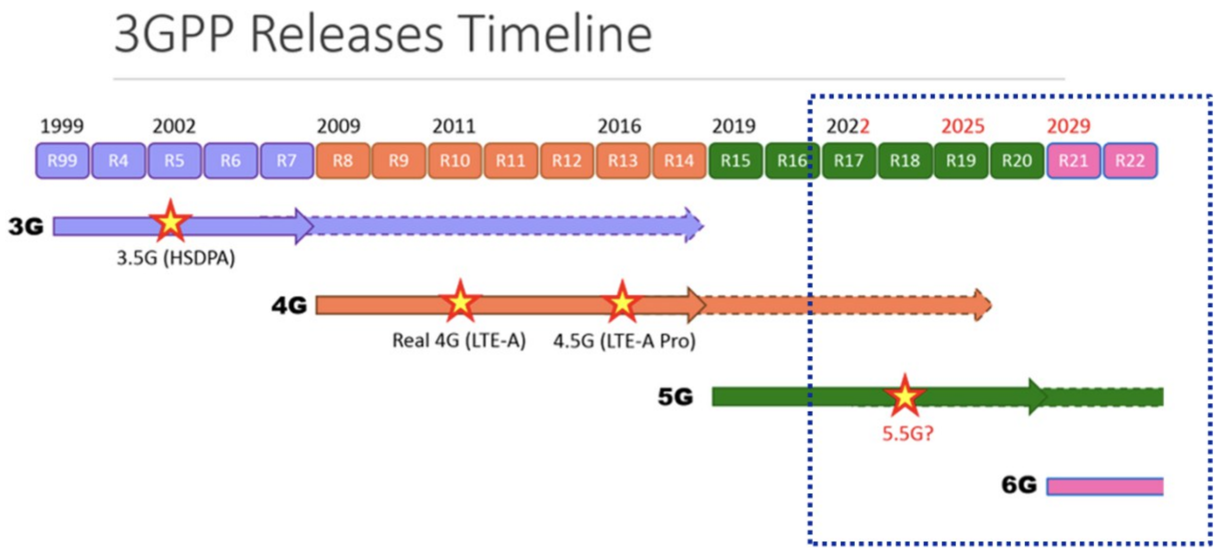
Digital twins emulate multiple network slices with different configurations and performance criteria. This enables service providers to test and validate applications specific to particular network slices without affecting the entire network. In this way, digital twins help to identify efficient resource allocation and performance optimisation for critical 5G services.

4 The future of digital twins

4.1 The evolution towards 5G Advanced and new capabilities for creating digital twins

Although the full potential of fifth-generation mobile networks has not yet been realised – with some functionalities not yet commercially available or only available to a limited extent (such as network slicing), and others not yet fully standardised (such as passive IoT) – discussions on standards leading towards 6G are already in full swing. As the following figure shows, we are currently in the 5G Advanced development phase, which serves as a bridge to 6G.

Figure 3: Timeline of standardisation towards 6G

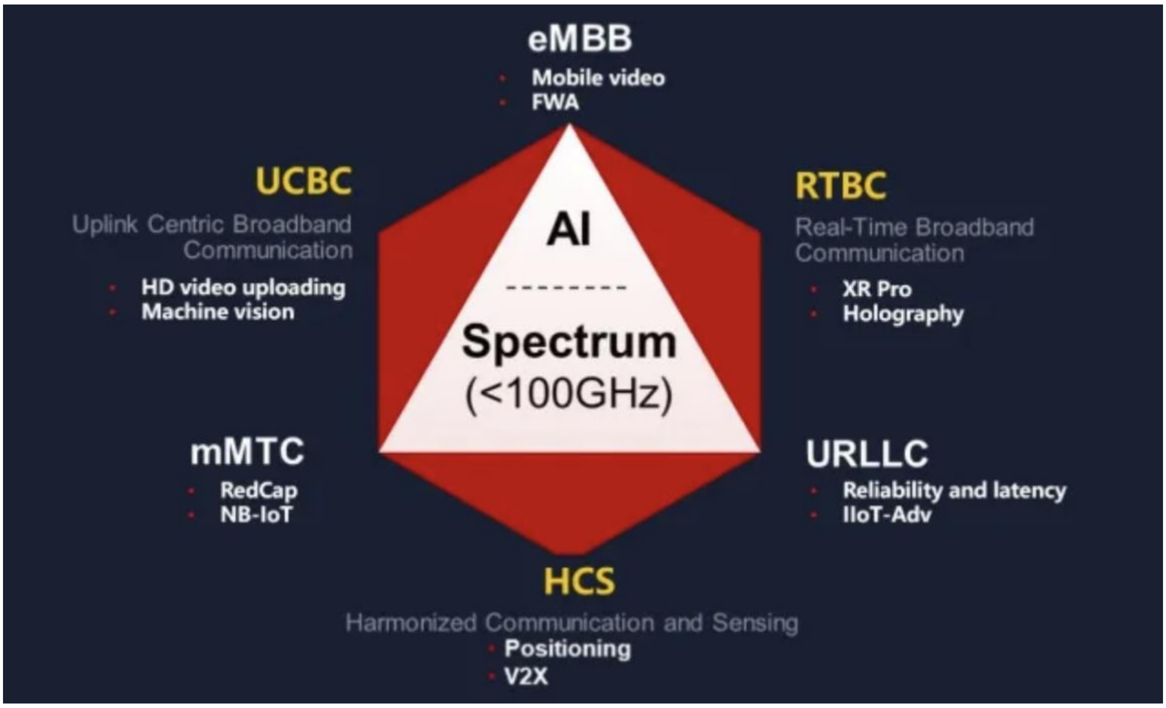


Source: Business Finland

5G Advanced

5G Advanced represents a significant development in 5G technology, aimed at overcoming the limitations of existing 5G networks and paving the way for further progress towards 6G. It enhances key aspects of 5G to meet the growing demand for innovative services.

Figure 4: The triangle used to define 5G has become a hexagon for 5G Advanced



Source: Tech Junction[9]

The main technological improvements within 5G Advanced are as follows:

Three new use cases:

- Uplink Centric Broadband Communications (UCBC): UCBC improves uplink performance, which is essential for applications requiring high volumes of upstream data transmission, such as machine vision.

- Real-Time Broadband Communications (RTBC): RTBC offers ultra-wide bandwidth and high reliability, supporting applications such as holographic communication that require high data rates and minimal latency.

- Harmonised Communication and Sensing (HCS): HCS integrates communication with precise sensing, which is key for applications such as connected vehicles, drones and industrial automation, where low latency and accurate localisation are essential.

By adding these scenarios, 5G Advanced extends the original IMT 2020 model and transforms the 5G performance triangle into a hexagon, thereby covering a broader spectrum of applications.

Increased network capacity and performance:

- Uplink speeds are expected to reach up to 1 Gbps, whilst latency is set to fall from 20 ms to 5 ms. This will enable more efficient and reliable data transfers, which is essential for real-time applications.

- These network enhancements enable 5G Advanced to handle a significantly larger number of connections – up to 100 billion connected devices by 2030, compared with the current 1.3 billion.

[9]https://techjunction.co/tech-question/new-5g-advanced-use-cases/

Expanded support for advanced applications:

- Holographic communication: Thanks to low latency and high throughput, 5G Advanced enables immersive experiences such as holography, enhancing both personal and professional communication.
- Autonomous vehicles: With centimetre-level positioning accuracy and ultra-low latency, 5G Advanced enhances the reliability and safety of autonomous vehicles.
- Augmented and virtual reality (AR/VR): Higher data rates and lower latency make AR/VR experiences more realistic and immersive, supporting applications in education, healthcare and entertainment.

Smart cities and urban connectivity:

- 5G Advanced supports the dynamic operations of smart cities, enabling real-time data flow across the city, thereby optimising services, increasing efficiency and reducing environmental impact.
- High connection density will enable new urban applications such as intelligent traffic management, energy-efficient infrastructure and public safety systems.

The impact of 5G Advanced on digital twins:

In the case of digital twins, the improved uplink and low latency of 5G Advanced technology enable a more detailed and realistic replication of physical environments. This supports complex applications in sectors such as manufacturing, logistics and healthcare. The higher network capacity also enables digital twins to manage and synchronise large volumes of data from various IoT devices. This capability is important as digital twins are increasingly becoming an integral part of interconnected systems.

4.2 The path to 6G and the Hexa-X project.

Within the European Union, the Hexa-X project[10]plays a key role in the transition towards 6G.

The Hexa-X project is a key European research initiative focused on developing the underlying technologies for 6G networks. The project is funded by the European Union under the Horizon 2020 programme and aims to consolidate Europe’s position as a leader in 6G research and innovation. The Hexa-X project is paving the way for 6G by defining early standards, addressing technical challenges and establishing key performance requirements. The results of the Hexa-X project will influence the design of 6G networks. It is intended to ensure alignment with Europe’s strategic objectives in the areas of technological sovereignty, environmental sustainability and digital transformation.

The Hexa-X project has defined the following key objectives:

1. Research into use cases and applications for 6G: Hexa-X identifies potential applications for 6G, including smart transport, advanced healthcare, industrial automation and immersive extended reality (XR).
2. Development of key technologies for 6G: The project focuses on key 6G technologies such as:
    - Artificial intelligence (AI) and machine learning (ML) for network management, automation and optimisation.
    - A network of networks for the seamless integration of terrestrial and non-terrestrial networks (such as satellite, drone and maritime networks).
    - Sub-terahertz frequency bands to support ultra-high-speed and low-latency communications.
3. **Support for digital twins and human-machine interfaces** (HMI): Hexa-X is exploring digital twin technologies and new HMIs as ways of connecting the physical and digital worlds, enabling real-time feedback and control.

[10]https://hexa-x.eu

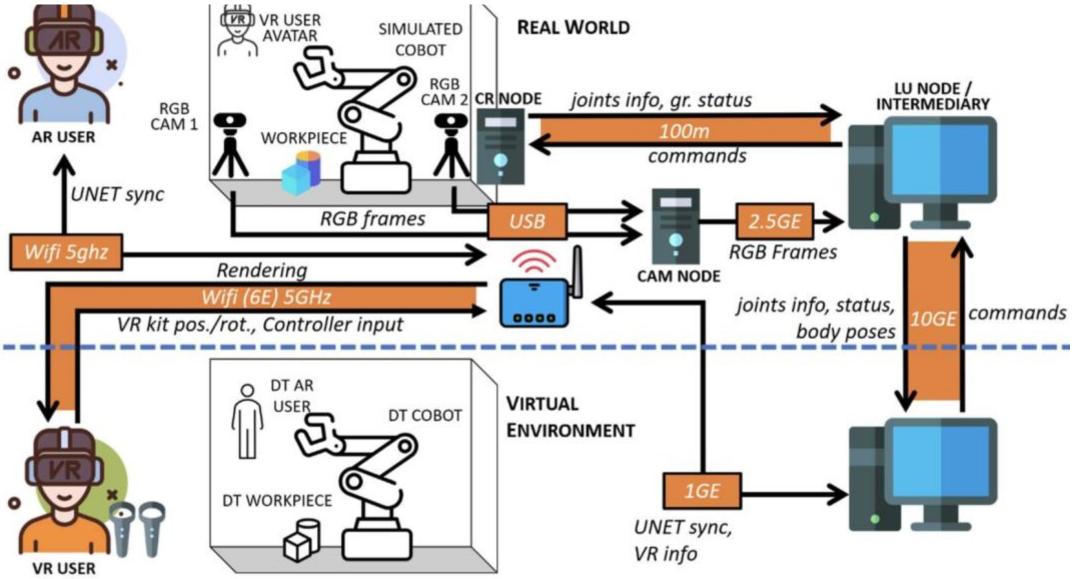
4. Support for sustainability and energy efficiency: The project aims to make 6G networks more energy-efficient and environmentally friendly, and therefore focuses on the development of green technologies and energy-saving mechanisms.

5. Ensuring security and privacy: Hexa-X is dedicated to building secure architectures for 6G, taking into account emerging cyber threats and privacy challenges.

Supporting digital twins and the convergence of the physical and digital worlds is therefore one of the main objectives of the Hexa-X project.

New digital twin and human-machine interface (HMI) technologies play an important role in enabling new 6G use cases and realising the convergence of the physical, digital and human worlds. The Hexa-X project presented and analysed new HMI and digital twin technologies and explored their applications in future 6G systems.[11]

Figure 5: Architectural overview of an example of human-machine interaction in an industrial environment using digital twins



Source: Hexa-X D7.2

Within the Hexa-X project, the following use cases for digital twins in 6G systems are defined in particular:

Collaborative robots with digital twins: Digital twins in the workplace can be enhanced in terms of localisation and visualisation, whilst the digital twin of a local user can be enhanced by enabling full-body pose reconstruction using computer vision (CV) and AI techniques. This enables more sophisticated HMI scenarios, but requires additional connected hardware and may necessitate a reassessment of network requirements.

Adaptation of digital twin-based functional partitioning for industrial networks: The concept of a digital twin-based control system is designed to determine the optimal functional partitioning in a large-scale industrial RAN comprising heterogeneous cells. This RAN is responsible for providing connectivity to both fixed stations and mobile AGVs deployed for various tasks, such as parts transport and monitoring activities within an industrial area.

Digital twins for emergent intelligence: Extensive access capacity and full 6G coverage enable the emergence of emergent intelligence (EI) in large-scale networks. However, scaling the system and ensuring efficient communication between agents presents challenges. To address this issue, massive twinning can be deployed, enabling the decision-making engine of EI agents to reside in their digital twins. Agents communicate with cloud servers hosting their digital twins, thereby reducing signalling overhead, improving resource efficiency and reducing latency.

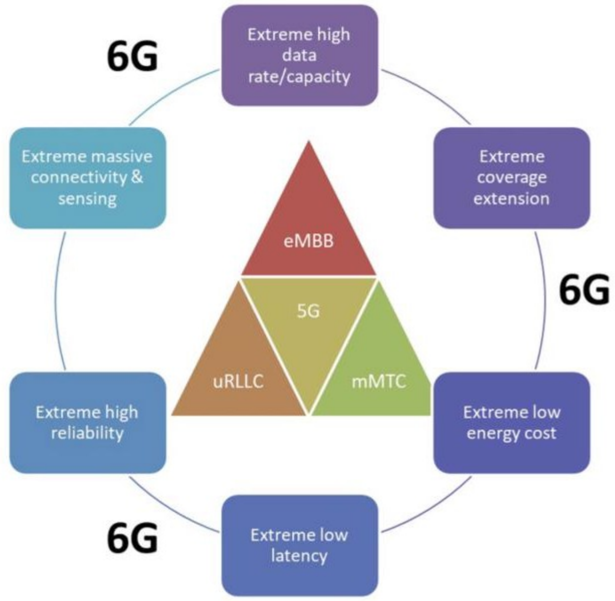
4.3 New 6G functionalities will also bring new challenges

The development of 6G networks will introduce several key features that go beyond the capabilities of 5G. These new features are designed to support more demanding applications, enhance connectivity and utilise real-time data in ways that were previously impossible. However, these innovations

[11]https://www.ericsson.com/en/blog/2023/6/hexa-x-laying-the-foundation-for-6g

also significantly increase network complexity – even beyond that of 5G. This further highlights the need for tools such as digital network twins, which can effectively manage and optimise these new systems.

Figure 6: Expansion of network capabilities from 5G to 6G



Source: Asghar, Memon & Hämäläinen[12]

The following overview presents the key features of 6G, as currently discussed and planned. It includes the level of complexity they entail and the potential role of digital twins in addressing these challenges.

1. Network Sensing

In 6G, the network infrastructure can function as a massive sensing tool by using and analysing radio waves to detect the surrounding environment. This capability enables networks to collect data on movement, object detection and even surface textures, supporting applications such as autonomous driving, environmental monitoring and city management.

Network sensing places demanding requirements on real-time signal processing and data analysis. The network must distinguish between standard communication data and sensing information, which requires advanced AI algorithms and high computing power.

The potential role of digital twins: Digital twins can simulate network sensing capabilities and provide a virtual environment for testing sensing algorithms, assessing their accuracy and optimising signal processing strategies. This will enable operators to fine-tune sensing protocols before deploying them in real-world networks.

2. Ubiquitous Communications and the integration of satellite communications

6G will aim for seamless global connectivity by integrating terrestrial, aerial and satellite networks. This capability will ensure coverage in remote and underserved areas, enabling access for applications such as disaster response, remote healthcare and global IoT connectivity.

Managing connectivity across different environments – for example, when switching between terrestrial and satellite links – will require highly dynamic routing protocols and advanced handover mechanisms. Furthermore, interoperability between different network standards and communication protocols between satellites and terrestrial networks will be essential.

[12] Asghar, Z.A.; Memon, S.A.; Hämäläinen, J. Evolution of Wireless Communication to 6G: Potential Applications and Research Directions. *Sustainability* 2022.

The potential role of digital twins: Digital twins will help to model and test seamless handover between terrestrial and satellite connectivity and assess performance across different environments. This simulation will reduce the risk of network failure during real-world deployment and ensure service stability, which will be crucial for applications requiring reliable connectivity in remote areas.

3. AI-driven network automation and autonomous systems

6G will rely heavily on AI for network automation, enabling the network to optimise itself, self-heal and even anticipate user requirements. The network will thus be able to adapt in real time to changing conditions and ensure optimal performance and resource allocation.

AI-driven automation will introduce layers of decision-making algorithms and machine learning models, which will require continuous updates and large volumes of real-time data. The implementation of self-optimising networks will also require complex communication between individual units for collective decision-making, as seen in emergent intelligence.

The potential role of digital twins: Digital twins will provide a controlled environment for testing AI models and decision-making algorithms, enabling engineers to observe how autonomous systems respond to simulated changes in the network. This will help identify potential issues in AI algorithms and support the continuous improvement of autonomous network functions.

4. High-precision positioning and localisation

Going beyond traditional GPS-based localisation, 6G networks will aim for centimetre-level accuracy through advanced radio wave sensing and analysis. High-precision localisation will be essential for autonomous vehicles, drone control and augmented reality applications.

Achieving this level of accuracy will require advanced localisation algorithms, precise sensor calibration and the integration of multiple sources of localisation data. This will place further demands on network infrastructure and require ultra-low latency to provide real-time localisation information.

The potential role of digital twins: Digital twins will enable the simulation of high-precision positioning in a virtual environment and allow testing of how various variables (such as weather conditions, obstacles or building density) affect positioning accuracy. This will help refine positioning algorithms and ensure reliable performance prior to deployment in live networks.

5. Integrated communication and sensing for IoT and smart environments

6G will aim to integrate communication with sensing across billions of IoT devices, enabling networks that support smart cities, factories and homes. For example, sensors will be able to monitor environmental conditions and transmit data in real time for applications such as pollution monitoring or energy management.

Simultaneously processing communications and sensing data across a massive number of IoT devices will require a robust network capable of managing high volumes of data traffic and ensuring synchronisation between devices. Furthermore, achieving energy efficiency will be challenging, as IoT devices often operate on limited power.

The potential role of digital twins: Digital twins will be able to emulate smart environments with interconnected IoT devices, enabling the simulation of data flows and interactions between devices. This will help operators identify potential bottlenecks, optimise device synchronisation and ensure efficient data processing.

6. Extended Reality (XR) and Holographic Communication

6G networks will support fully immersive experiences, including virtual and augmented reality (VR/AR), and holographic communication for applications in education, healthcare and entertainment.

XR and holographic applications will require extremely high transmission speeds, minimal latency and synchronisation across multiple data streams. Supporting these applications will be challenging, as it will require constant optimisation of network performance and precise data processing.

The potential role of digital twins: Digital twins will replicate the demands of XR and holographic communication in a controlled environment, enabling operators to test the network's ability to maintain consistent performance under high data loads. This simulation will identify performance weaknesses and allow for adjustments prior to deployment to ensure user experience requirements are met.

The high complexity of 6G, due to these advanced features, will make network digital twins virtually indispensable tools, particularly for network operators and the entire associated ecosystem. All in all, the advanced features of 6G will significantly increase the complexity of network operations, making digital twins essential for effective real-time design, testing and management. Digital twins will provide a secure virtual environment for continuous optimisation, thereby ensuring that 6G networks are resilient, efficient and capable of supporting future applications.

4.4 Selected promising applications of digital twins

The application of digital twins will undoubtedly continue to evolve, moving towards increasingly sophisticated and, in particular, more interconnected models. Given that network connectivity is an element common to a large proportion of digitised operations and systems across all verticals, a digital twin of network infrastructure can play a role not only directly in the telecommunications sector, but can also be one of the components of interconnected systems in a number of other areas. Selected promising areas of application for digital twins are described below:

1. Interconnected digital twins and cyber-physical systems

The evolution of digital twins (DTs) is moving towards more interconnected and collaborative systems, often referred to as 'interconnected digital twins'. This concept goes beyond individual DTs and encompasses networks of twins that communicate with one another and share data, enabling more comprehensive and dynamic representations of complex systems.

Interconnected digital twins involve the integration of several DTs, each representing different physical assets or processes, into a cohesive network. This interconnection enables real-time data exchange and collaboration between different components, thereby facilitating a holistic view and management of complex systems.

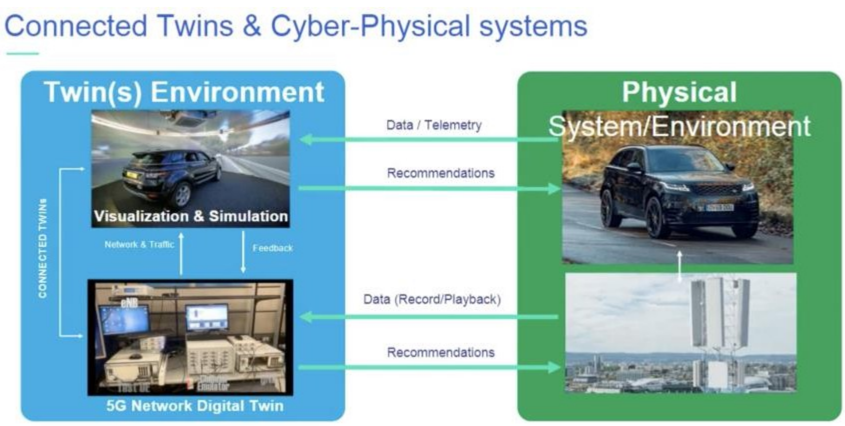
In urban planning, interconnected digital twins can integrate data from transport, utilities and infrastructure to optimise urban operations, enhance sustainability and improve residents' quality of life.

In manufacturing, interconnected DT enables the synchronisation of production lines, supply chains and equipment maintenance.

Connected DTs can represent various aspects of patient care, from individual organs to entire healthcare systems. This integration enables personalised treatment plans, the simulation of medical procedures and improved outcomes for patients. For example, researchers are developing digital twins of organs, such as the heart, to simulate treatment prior to actual procedures.

In the energy sector, interconnected digital twins can monitor and manage energy generation, distribution and consumption. This interconnected approach can increase grid reliability, integrate renewable energy sources and optimise energy usage.

Figure 7: Connected digital twins of the automotive sector and the grid



Source: Spirent

2. Cyber ranges – simulation of risks and corrective measures

Cyber ranges are simulated digital environments that enable the safe testing of cybersecurity strategies and procedures. These ranges will be able to utilise digital twins to mimic the behaviour of an entire network or specific devices.

Using cyber ranges, organisations will be able to simulate various attack scenarios, test the responses of security teams and identify vulnerabilities in their cybersecurity infrastructure. For example, financial institutions can simulate cyberattacks on transaction systems to train staff in how to respond to incidents in a realistic manner.

Cyber simulators will enable organisations to test remedial measures, such as isolating affected parts of the network or deploying automated defence mechanisms. By utilising DT, they provide feedback on the impact of an attack and recovery time, which helps organisations improve their protection and resilience procedures.

These DT-enabled cyber simulators will be particularly beneficial for sectors such as critical infrastructure, networks, energy, defence and healthcare, where cyber security is paramount.

3. Models for recommendations and operational efficiency

Digital twins will enable the creation of recommendation systems that utilise real-time data, historical performance records and predictive analytics to optimise operations and improve decision-making. By simulating various operational scenarios, these systems will be able to offer recommendations leading to increased efficiency and reduced costs.

In manufacturing and the utilities sector, digital twin-based reconstruction engines can recommend maintenance plans based on current equipment data and historical usage patterns. Buildings and factories can reduce energy consumption thanks to recommendation systems. For example, a digital twin model of an HVAC system can recommend energy-saving settings based on building occupancy, weather and historical data. In logistics, reconstruction engines will help to optimise stock levels, transport routes and delivery schedules. By continuously analysing data across the supply chain, DT can predict disruptions and suggest alternative routes or suppliers, thereby increasing the flexibility and resilience of supply networks.

4. CI/CD continuous network testing

CI/CD (Continuous Integration/Continuous Deployment) systems, which are key to agile software development, are becoming increasingly relevant for network operations too, particularly in telecommunications. DT will create virtualised network environments where updates and changes can be tested on an ongoing basis.

For telecoms providers, DTs will enable rapid testing and validation of network updates – ranging from software patches to hardware configurations – within a virtual environment that faithfully mimics the live network. This will minimise downtime and enable faster roll-out of new services.

The integration of DT with CI/CD pipelines will support automated testing, whereby every change to code or network settings is validated in the digital twin before live deployment. This automation will increase accuracy and reduce the risk of human error, which is critical in sectors requiring high availability and reliability.

As networks evolve with the advent of 5G, edge computing and network slicing, DT-enabled CI/CD will support the rapid iteration and testing required to meet the dynamic demands of next-generation applications.

5. Simulation in healthcare and personalised medicine

Digital twins in healthcare will create models of individual patients based on their health data, enabling highly personalised treatment plans. These twins can simulate responses to various treatment options, allowing doctors to select the most effective and least invasive approach.

Surgeons and medical students will be able to use digital twins to practise complex procedures in a virtual environment, thereby gaining the skills and confidence needed before performing real-life operations. In crisis situations, digital twins in healthcare can provide a reliable means of simulating and practising high-risk procedures.

6. Management and optimisation of smart cities

Digital twins for smart cities will collect data from transport, energy, water management and public infrastructure. This will provide a comprehensive overview of the city's operations. They will thus enable the anticipation of problems, such as traffic congestion or energy shortages, and allow for a proactive response.

Digital twins will enable urban planners to model the impacts of various scenarios, such as increased traffic or new construction projects. This will support better decision-making focused on sustainability and help cities reduce emissions and manage resources more efficiently.

7. Retail and consumer behaviour

Retail chains will be able to use digital twins to simulate shop layouts and customer flows, optimising shelf layout, product placement and staff allocation to maximise sales. This approach will be particularly valuable for e-commerce fulfilment centres, where optimising the layout speeds up and improves the accuracy of order fulfilment.

Summary:

The future of digital twins holds transformative potential across various sectors, from autonomous driving and cyber security to personalised medicine and smart city management. Each of these scenarios demonstrates how digital twins are evolving from mere replicas into proactive, predictive and intelligent agents. Thanks to their ability to enable continuous testing, risk management, operational optimisation and real-time data collection, digital twins can become a key driver of growth and innovation worldwide. Leveraging digital-physical integration can deliver unrivalled agility in development across various fields, whilst simultaneously enhancing operational efficiency.

Appendix 1 – Case Study: CTU – Digital Twins for Predicting Signal Quality between Devices

The Department of Telecommunications at the Faculty of Electrical Engineering, CTU, led by Professor Bečvář, has developed a concept for using a digital twin model to predict signal quality between two devices.

This model is described below, including its potential benefits for future use in 5G and 6G networks:

Introduction to the problem

In wireless networks, it is crucial to maintain high-quality communication between devices. Traditionally, channel quality (the strength and reliability of the signal between two devices) is measured directly using reference signals. However, this approach places a heavy demand on radio resources and energy, as it requires frequent transmission of reference signals and measurement of their quality by the receiver, particularly in networks where a large number of devices are communicating.

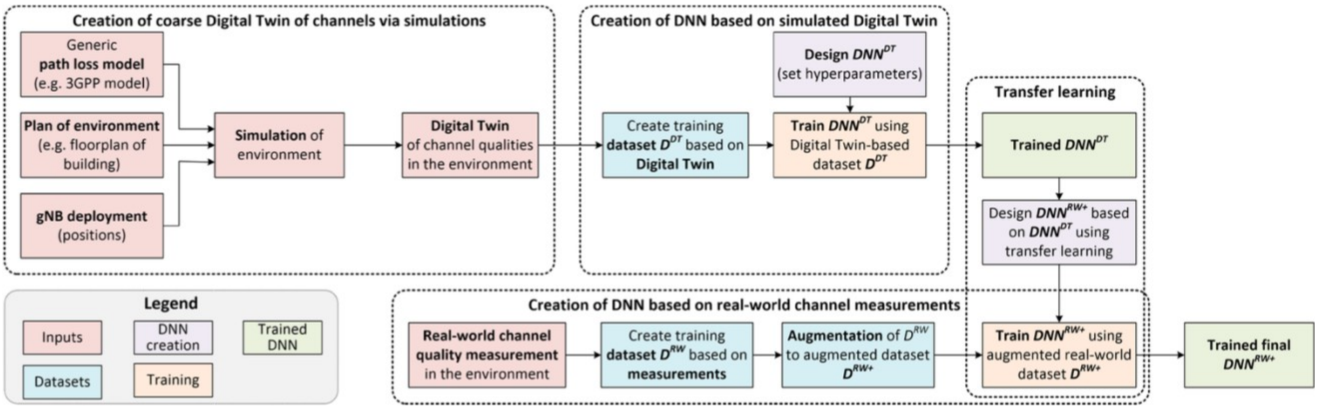
The concept of a digital twin for channel prediction

A digital twin is a virtual model that reflects the characteristics and behaviour of the physical network environment. In this context, it helps to predict channel quality by simulating network conditions. Digital twins for predicting channel quality in wireless communications utilise machine learning, particularly deep neural networks (DNNs), to estimate the signal strength between two devices based on data from neighbouring reference points (such as base stations).

This approach uses the digital twin as a simple virtual representation of the real-world environment, enabling predictions based on a combination of synthetic and real-world data through transfer learning, a technique in which a model trained on synthetic data is improved and refined using real-world data.

Channel prediction procedure using digital twins

Figure 8: Overview of the proposed solution for channel quality prediction based on a coarse, low-complexity digital twin combined with augmented real-world measurements via transfer learning



Source: Becvar et al. [13]

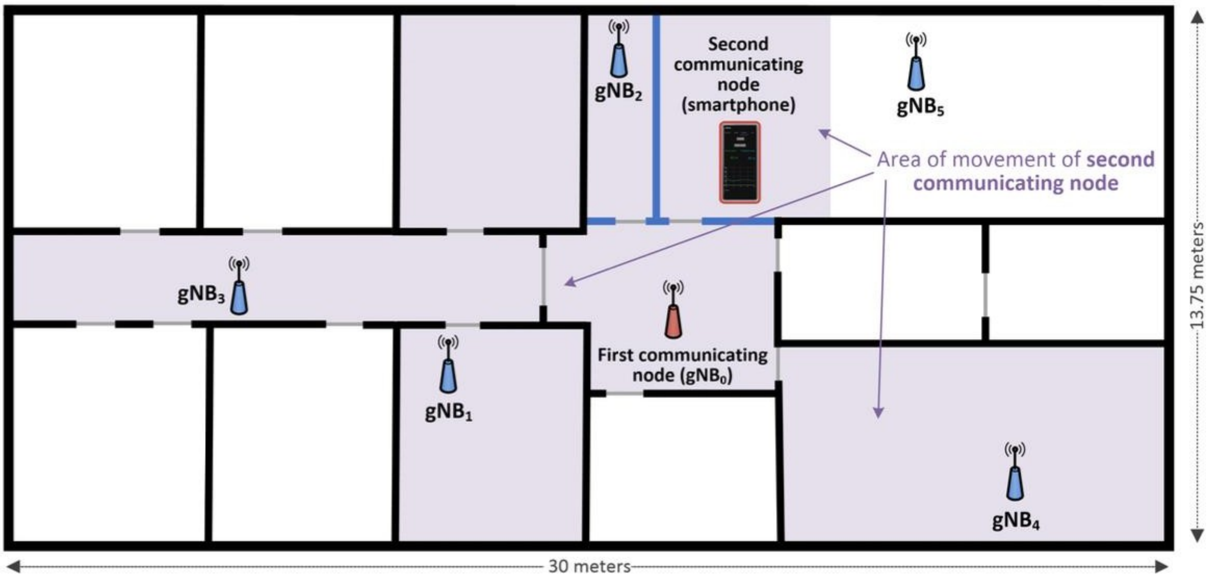
1. The digital twin generates synthetic data to train the DNN model. This data includes channel quality from communicating devices to surrounding reference nodes (base stations or access points). By generating large volumes of synthetic training data, the model becomes sufficiently robust to predict channel quality in various scenarios without the need for extensive real-world data collection.

2. Integration of real data and transfer learning: To improve accuracy, real measurements are integrated into the model trained on synthetic data . Whilst the digital twin provides the foundation, transfer learning fine-tunes the model based on actual network measurements. This combination of synthetic and real data reduces prediction errors, as the model learns to account for practical network conditions that the digital twin does not fully capture.

3. Continuous improvement and validation: The model is continuously validated and updated to ensure reliability. In real-world testing, the developed DNN-based digital twin achieved an error of less than 0.7 dB in channel quality prediction – a level of accuracy sufficient for practical use in wireless networks.

[13] Zdenek Becvar, Jan Plachy, Pavel Mach, Anastas Nikolov, David Gesbert: *Machine Learning for Channel Quality Prediction: From Concept to Experimental Validation* (IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS)

Figure 9: Floor plan for experiments showing the actual positions of the five reference nodes represented by base stations gNB1 – gNB5. Base stations gNB3 and gNB4 are located on the ceiling (≈3 m above the floor), whilst base stations gNB1, gNB2 and gNB5 are situated



Source: Becvar et al. [14]

Advantages of a digital twin for channel prediction

This methodology offers several advantages for network management:

- Prediction, rather than direct measurement of channel quality, minimises the need to transmit reference signals, thereby freeing up bandwidth for the transmission of actual data and saving energy for communicating devices.

- The system is scalable across different network sizes and densities, making it suitable for various communication scenarios, from dense urban networks, through industrial campus networks, to large-scale IoT systems.

- Reducing the need for extensive real-world measurements lowers operational costs, as data can be generated synthetically using a digital twin.

- Digital twins are also suitable for challenging environments, such as indoor spaces, where signals are often reflected and degraded by walls and other obstacles.

Practical applications

The use of digital twins for channel quality prediction supports network operators in several ways:

- Thanks to channel quality prediction, operators can dynamically adjust network resources, balance the load and improve overall network performance.

- As resource-intensive measurements are minimised, devices save energy, which is particularly important for battery-powered IoT devices in large-scale deployments.

- Predictive models enable proactive adjustments to signal strength or device configuration, thereby enhancing user experience through stable connections.

[14] Zdenek Becvar, Jan Plachy, Pavel Mach, Anastas Nikolov, David Gesbert: *Machine Learning for Channel Quality Prediction: From Concept to Experimental Validation* (IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS)

Future potential

Although the current focus is on the use of digital twins for 5G networks, the methodology can be extended to next-generation networks such as 6G. These future networks are likely to encompass an even wider range of applications, from augmented reality (AR) to ultra-reliable low-latency communications (URLLC), making predictive models a valuable asset for network operators. Digital twins will evolve to incorporate more sophisticated machine learning models, possibly utilising reinforcement learning for real-time adaptation.

Conclusion:

This case study illustrates the significant use of digital twin technology in predicting wireless channel quality. By creating a virtual model combined with real-world measurements, the DNN-based digital twin approach enables accurate and efficient channel quality predictions. This improves network efficiency, reduces costs and optimises resource allocation. As such, the digital twin is becoming an important tool for both modern and future wireless communication networks.

Appendix 2 – Case Study: Digital twin of warehouses using virtual sensors from InovecTech

A virtual sensor is a generalisation of a physical sensor in virtual reality. It is a software application that takes a digital image (e.g. of a production line) as input and produces an easily interpretable and integrable signal over time as output. InovecTech has made this technology scalable, accessible and effective for manufacturing through the development of edge devices with the computing power of a standard computer (e.g. Raspberry Pi) and cameras, as well as through advances in artificial intelligence. Virtual sensors naturally link the digital image of the production process captured by cameras with the production's digital twin, i.e. a model of the production process that can be used for monitoring and optimisation.

Basic information about the solution provider

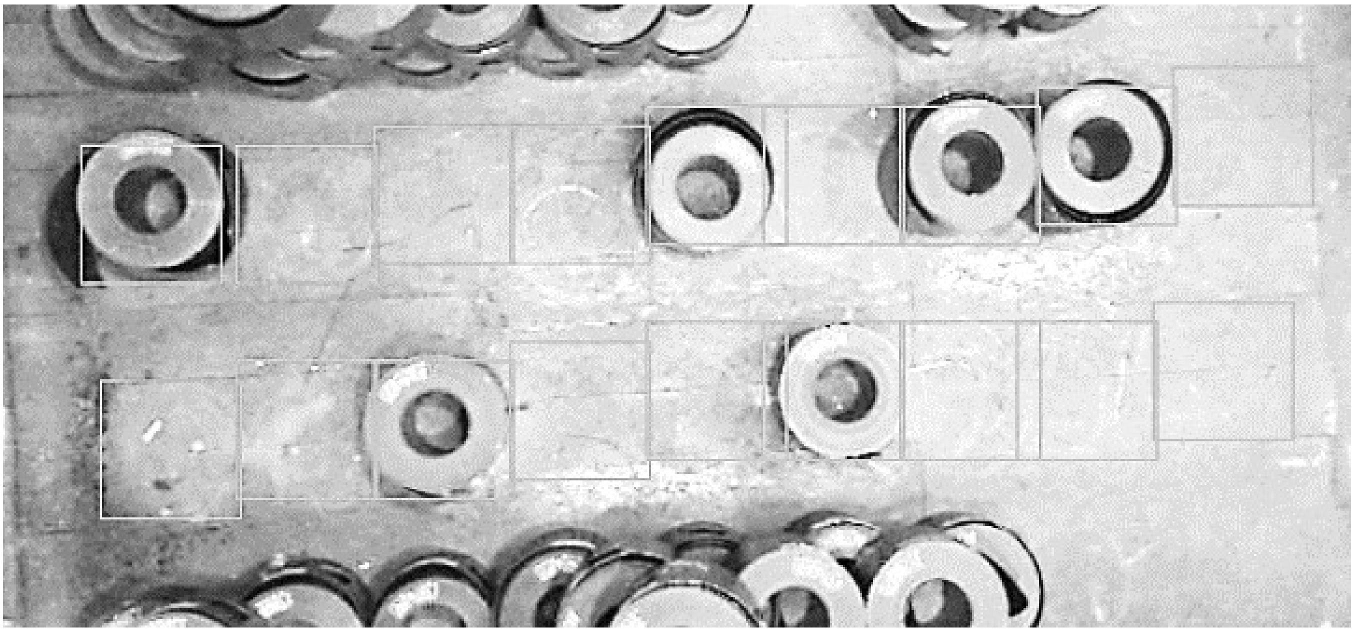
InovecTech is a global pioneer in virtual IoT sensor technology for manufacturing, an approach that utilises artificial intelligence to flexibly collect data from production facilities, warehouses and transport. A versatile edge device equipped with cameras can be rapidly deployed and immediately begins collecting visual data. Artificial intelligence, with human oversight, distributed across multiple layers between the edge and the cloud, analyses this data into easily interpretable and verifiable signals which, in the case of warehouses or internal logistics, contain all the necessary information for tracking the movement of materials and mobile equipment (forklift trucks, cranes, conveyors, etc.).

Customers, users and their needs

Heavy industry in the EU is facing a difficult situation. Unpredictable regulations (particularly regarding CO_2) and a mismanaged European energy policy are causing significant risk and further underinvestment in the sector; aluminium smelters are closing, whilst steelworks face very high capital costs and require an unusually rapid return on investment for their projects. Regardless of decarbonisation initiatives, it makes sense to optimise the internal logistics of both intermediate and final products across all plants. Storage, in particular, is a major challenge in heavy industry, as the high weight of materials increases the necessary investment costs, meaning that fully automated warehouses take decades to pay for themselves. Whilst primary metallurgical production (blast furnace, electric furnace, converter, casting) is interwoven with standard, tried-and-tested sensors for data collection, the storage of individual items (slabs, continuous castings, ingots, billets, etc.) and internal logistics – which absorb production variability – hold enormous potential for digitalisation. Most warehouses do not even have defined storage locations, and the material is placed on the warehouse floor, stacked in heaps, pyramids or towers. As these piles are constantly being rearranged, locating a specific item is challenging, and the solution adopted by most steelworks [ref] worldwide is to send workers into the material, which creates a risk of accidents and overheating for staff, takes up a great deal of time and thus reduces work efficiency. Warehouse staff need to physically locate an item within the warehouse or at least confirm its position. Quality control, logistics and management need a real-time overview and the ability to trace the history of each product. In a digitised warehouse, locating an item is simply a matter of retrieving a value from a database, rather than 'searching high and low' for a coil across areas often spanning several hectares. The situation is exacerbated by the properties of the material, often high temperatures, and the impossibility of attaching a label to, for example, a scrap metal block, etc. The aim of warehouse digitisation is, ideally, to provide a complete overview of the location of any individual item or mobile device at any given time.

Use case

The company is a large steelworks with a complex warehouse behind the hot rolling mill, where material from the rolling mill, cutting lines, customers, the cold rolling mill and other warehouses all converge. It encompasses all methods of coil transport, including cranes, conveyors and trolleys, as well as loading onto trains, conveyors and lorries, and processes such as sampling and stacking. There are no clearly defined storage locations.



The aim of digitisation is therefore to obtain the most accurate representation possible of the warehouse as $x_i(t)$, i.e. the position $\mathbf{x}$ (x, y, z) of each item *i* at every time *t*. From this representation, it is then easy not only to locate an item in the warehouse quickly, but also to carry out further analyses, such as the number of handling operations, lead time (known as 'days of inventory'), and to plan stock-out in detail or optimise layout. Virtual sensors are ideal for this task because no complex integration is required, nor is data from a PLC or any physical sensors needed apart from a single item identification (which we obtain from an existing robot at the warehouse entrance or production line output, etc.).

Technologické vrstvy	**Sběr dat**	**Datová a IT infrastruktura**	**Model**	**Rozhraní**
Digitální dvojče obecně	Fyzické senzory projektovány na míru	IT/OT rozhraní, databáze na míru	Model navržen dle potřeb	Rozhraní navrženy dle potřeb
Využití virtuálních senzorů	Univerzální edge zařízení	Digitální obraz	Model dle potřeb definuje senzory	Rozhraní navrženy dle potřeb
Případ hutnického skladu	Univerzální edge zařízení	Digitální obraz	Databáze všech poloh materiálu	Zobrazení nad databází poloh (2D, 3D, API)

Implementing a digital twin generally requires iterative fine-tuning of all technological layers; each iteration involves significant costs and time, sometimes taking weeks for a single change to the sensor system or model. Instead, the virtual sensor approach limits this iterative fine-tuning to the user interface layer and the installation of virtual sensors, which can take a matter of seconds and be carried out by a production operator. In this case, the model is standardised, so the warehouse digital twin can be delivered as 'plug-and-play'.

3D visualisation reconstructed using a photogrammetric 3D model of the building combined with positional data from the InoWare system database

Product/solution and its implementation

InoWare is a digital twin of internal logistics based on data from virtual sensors that process data from edge cameras using artificial intelligence. The cameras create a digital image in which (virtual) sensors for the occupancy of various warehouse locations and (virtual) sensors for the positions and occupancy of mobile devices are installed. Data from the sensors is integrated into the 3D trajectories of each individual. The concept differs from the well-known Amazon Go concept

It is possible to retrofit older warehouses at low cost (whereas the Amazon Go concept operates in new warehouses and combines computer vision methods with physical sensors, particularly scales)

Only larger objects that are clearly visible from stationary cameras above the warehouse can be tracked

To protect staff privacy, figure blurring is implemented; currently, 100% anonymisation is ensured by artificially reducing the resolution of edge cameras, which limits the minimum size of tracked objects to at least 0.1 m² of surface area (e.g. for a 10,000 m² warehouse, approximately 300 cameras are required).

The interface layer comprises interactive web applications for viewing data and warehouse KPIs, 2D and 3D visualisation, and an API (application programming interface) for customer systems (e.g. company-wide WMS) that automatically utilise data from the digital twin.

5G/P5G

5G is not strictly essential for digitalisation using virtual sensors. However, given that virtual sensors transmit high-resolution images, the use of a private 5G network ensures a truly stable and high-quality service. Another major advantage of using a private 5G network is the ability to flexibly position and relocate virtual sensors.

Reason for choosing this solution

The solution was selected following a six-month trial comparing seven different technologies. Only this technology has the potential to be used across all metallurgical warehouses. Other technologies have already failed completely at this complex warehouse. The advantages of a digital twin using virtual sensors at the edge are:

- Virtually unlimited reliability – the ability to trace individual items retrospectively from records which, thanks to redundancy, continuously monitor all movements within the warehouse
- Suitability for all warehouses, including those storing hot (>300˚C) materials, as well as damp and dusty environments
- Scalability – acquisition costs are directly proportional to the size of the warehouse; it is possible to digitise smaller warehouses (up to 1,000 m²) as well as areas spanning several km²; calibration is carried out quickly using software, and no new specialists are required on the user's side
- Secure installation – over 99.9% of data remains on-premises, so availability is not compromised by minor internet outages, nor are there high demands on data transfer to the cloud
- Integration of additional analytics – the system includes OEE (overall equipment effectiveness) analytics for mobile devices, 3D and 2D warehouse visualisations, and integration with other WMS, ERP or other information systems
- Speed of installation – warehouse digitisation can be completed within a week
- Faster return on investment compared to other technologies, particularly due to standardisation – the standard solution is developed for multiple customers

Project status

The project is currently integrated into operations. InovecTech has already deployed this technology in five production warehouses belonging to two major manufacturers in heavy industry; two further projects are in progress and discussions are underway with a further five companies.

Project evaluation and benefits

- The benefits are being quantified; so far, the following have been confirmed qualitatively
- Savings in staff time spent searching for materials, which automatically improves productivity and safety
- Greater predictability of production schedules and shift planning
- Faster regular stock-taking

Potential uses and future applications

The benefits and costs of tablets for crane operators are being recalculated; work is underway in collaboration with warehouse staff to add coils that were delivered to the warehouse under non-standard conditions (the final 5% reliability threshold) and to enable automatic identification of errors in records, reducing latency (simulations based on data from virtual sensors are currently running only 2–4 times a day) and operating and maintenance costs.

In terms of costs and reliability, the technology already far surpasses alternatives using physical sensors on mobile devices or camera technology on mobile devices. Technology involving the tagging of materials using RFID, barcodes or 2D codes is only applicable in exceptional cases. Virtual sensors have an advantage over a full VR setup in that they require fewer cameras, allow for direct interpretation and facilitate easier human intervention. Autonomous drones are not yet sufficiently safe or developed for the demanding conditions of steelworks warehouses and require reliable and sufficiently visible individual identification. Technologies based on higher-resolution cameras or specialised 2D sensors (e.g. LIDAR or RGBD) suffer from very costly hardware, both in terms of purchase and, above all, maintenance.

As the technology is based on rapidly evolving artificial intelligence technologies, we anticipate further overall improvements in reliability, reduced latency and lower costs over the next five years. At present, the best application is in the steel industry, where it is not possible to use RFIDs, which have low reliability; the technology is currently more expensive than RFID for small non-metallic products stored in boxes that are recycled as part of the production process. However, costs are falling as the technology develops, so it will likely become more cost-effective for a wider range of warehouses as well.

Appendix 3 – Case Study: Spirent – a digital twin for China Mobile's IP network

Basic information about the solution provider

Spirent Communications is a leading global provider of solutions for testing, quality assurance and analysis of networks. It specialises in helping customers manage the complexity of 5G, network infrastructure and cloud services. Drawing on decades of experience, Spirent serves developers, communications service providers and enterprise network operators, enabling them to achieve best-in-class performance and reliability.

Customers, users, and their challenges and needs

In this case study, the key customer was China Mobile, which faced challenges associated with deploying and managing its SRv6-based backbone network, which supports its IPv6, cloud and 5G infrastructure. As part of its transformation strategy, China Mobile needed to validate and optimise its next-generation networks in the face of growing complexity arising from new technologies and the expanding scale of the network.

The main challenges faced by China Mobile included:

- High costs and tight timeframes for testing extensive network infrastructure.
- The need to validate complex network functions, including new protocols such as SRv6.
- Limitations in laboratory test environments, which were unable to effectively emulate a live network scenario.
- Insufficient validation of network stability, reliability and functionality, leading to potential risks during live deployment.

Use case

China Mobile set out to use the Network Digital Twin (NDT) platform to achieve several objectives:

- To emulate and test the behaviour of a large-scale SRv6 network comprising hundreds of routers and numerous access switches.
- Simulate network traffic and real-world conditions to test the resilience and reliability of their SRv6 backbone network.
- Verify network configurations in advance and optimise deployment scenarios without the need for physical testing.

Product/Solution and its implementation

Spirent deployed its Network Digital Twin platform, which included key components such as:

- Spirent TestCenter, a network traffic generator and protocol emulator designed to replicate large-scale network environments.
- The Impairment Tool, which emulated real-world network conditions such as latency, signal fluctuations and congestion.

During the implementation, Spirent worked closely with China Mobile's research and development and operations teams, as well as network equipment manufacturers, to customise and extend the integration of the Digital Twin platform with external devices.

Reasons for choosing this solution

China Mobile selected Spirent's solution due to its unique combination of comprehensive emulation capabilities, flexibility and scalability. The platform's ability to support hundreds of network devices, simulate real-world operating conditions and perform detailed protocol evaluations effectively met their needs. Furthermore, Spirent's proven expertise in network assurance provided significant value.

Project status:

The deployment of the Network Digital Twin platform formed part of an ongoing initiative to enhance and modernise China Mobile's SRv6-based infrastructure. The project began as a Proof of Concept (PoC), which demonstrated the feasibility and benefits of this solution. This was followed by close collaboration for further optimisation and testing, as China Mobile planned for full deployment.

Project evaluation and benefits:

The quantifiable benefits realised by China Mobile included:

Cost savings of up to 90% when setting up and testing large-scale network scenarios.

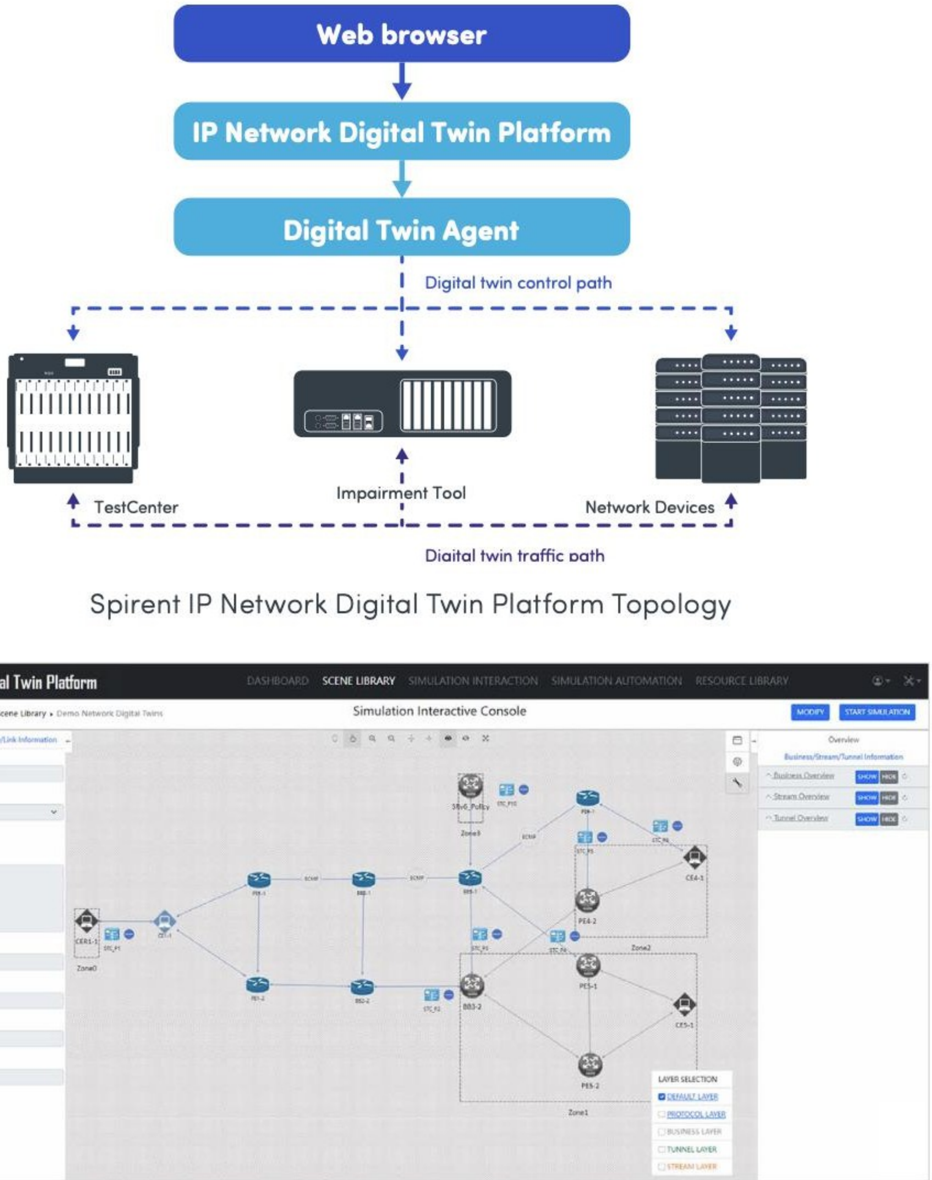
- A 70% reduction in testing time, which significantly accelerated the time-to-market for new services and technologies.
- Improved verification and operational capabilities, which eliminated more than 90 per cent of human error.
- Improved collaboration between research and development teams and operations teams, leading to greater efficiency in deployment and troubleshooting.

Usage and future applications:

Spirent's Digital Twin solution is a scalable, software-defined testing framework that enables China Mobile to continuously test and validate network changes, optimise configurations and proactively identify security vulnerabilities. Future applications include support for new 5G use cases, such as smart factories, autonomous vehicles and large-scale IoT deployments.

The successful deployment at China Mobile demonstrates the scalability and flexibility of the Digital Twin approach, making it a compelling solution for other service providers looking to transition to advanced network protocols and architectures.

Figure 10: Diagram of the IP network digital twin platform



Source: Spirent – IP Network Digital Twin Platform for China Mobile

Summary:

Spirent's Network Digital Twin solution for China Mobile demonstrates how emulated environments can simplify and optimise network validation processes in large-scale, complex deployments. The solution has proven effective in reducing costs, increasing efficiency and minimising risks in dynamic and evolving network ecosystems. This case study highlights the potential for replicating similar solutions across various verticals, such as smart cities, industrial automation and critical communications infrastructure.

Appendix 4 – Case Study: Digital Twin of 5G Infrastructure for the US Department of Defence.

Background information on the solution provider

Spirent Communications is a leading global provider of solutions for network testing, quality assurance and analysis. It specialises in helping customers manage the complexity of 5G, network infrastructure and cloud services. With decades of experience, Spirent serves developers, communications service providers and enterprise network operators, enabling them to achieve best-in-class performance and reliability.

Customers, users, and their challenges and needs

The main user in this case study is the US Department of Defence (DoD). The US defence sector faces a significant challenge: ensuring secure, reliable and fast communications in conflict zones and rapidly changing environments. With the advent of 5G, the Department of Defence sees the potential to improve mission-critical tasks such as command and control, surveillance, logistics and training. The complexity of integrating 5G networks, combined with unpredictable field conditions, interference and cyber threats, poses a significant risk to mission success.

<u>The identified requirements included:</u>

- Reliable communication networks in dynamic and conflict environments.
- Validation of 5G technologies for safe and effective deployment in the field.
- Testing capabilities for complex scenarios involving large numbers of devices or users.
- Management of cyber risks in communications within the defence sector.

Use case

Spirent's Digital Twin solution was used to address the complexities of deploying 5G-enabled networks for defence purposes. Specific use cases included:

- Smart bases and depots: Streamlining operations and logistics using IoT and 5G connectivity.

- Distributed command and control at the tactical front line: Ensuring robust communications for mission-critical operations.

- Augmented reality applications for combat training: Enhancing soldier training through the simulation of realistic conditions and environments.

Product/Solution and its implementation

Spirent deployed its 5G Network Digital Twin solution, which provides a comprehensive testing environment through network and traffic emulation. The solution utilises an emulated twin of the communications network to test the performance, resilience and security of technologies and services in the highly demanding scenarios expected in defence applications.

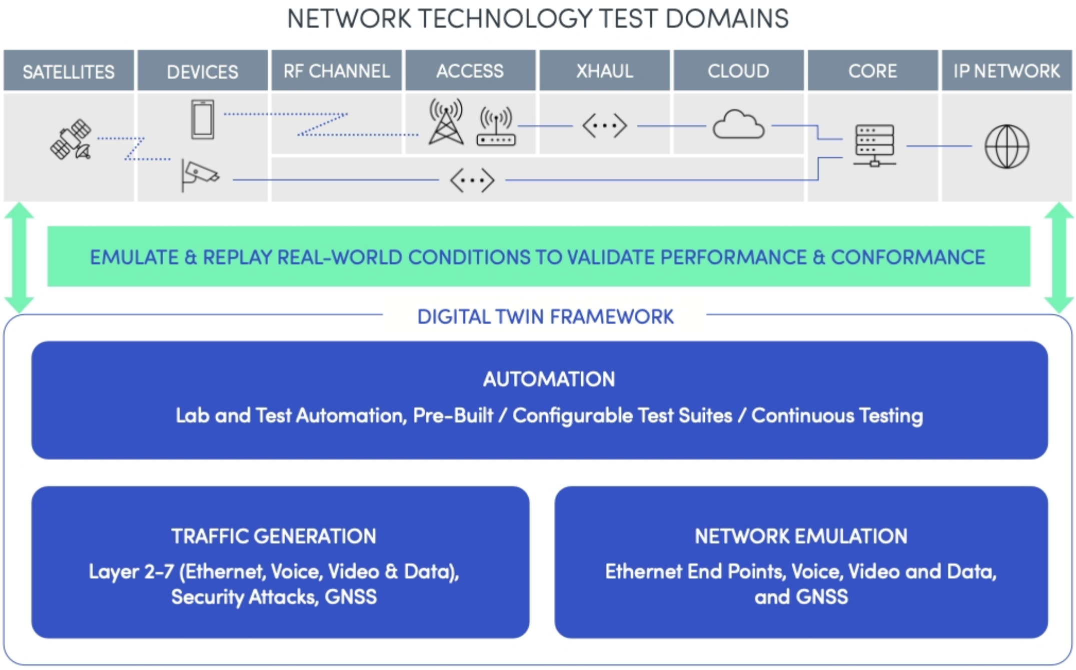
<u>The implementation of the solution included:</u>

- Traffic generation and network emulation, including synthetic traffic, cyber-attacks, signal jamming and simulated outages.

- Integration of commercial and emulated elements, enabling combined test scenarios that reflect both laboratory and real-world conditions.

Orchestration via automation, enabling the efficient coordination and execution of complex test scenarios.

Figure 11: Network technology test areas



Source: Spirent – Digital Twin Solutions for U.S. Defence

Reasons for choosing this solution

The Digital Twin solution was selected for its ability to:

- Provide immediate access to an advanced 5G network testing environment without the need for significant capital investment.
- Ensure end-to-end network validation in a secure and controlled environment.
- Minimise the risks of inefficient testing by providing a fully customisable and repeatable test environment.
- Leverage Spirent's expertise in cyber security and network quality assurance to optimise the design and execution of large-scale network tests.

Project Status

The solution is currently in active use, whilst its refinement and integration into the broader framework of defence communications strategies continues. Spirent continues to collaborate with defence communities to improve 5G deployment and testing capabilities. The aim of the ongoing project is to optimise the transition from laboratory testing to real-world field conditions.

Project evaluation and benefits

The main benefits of the project include:

- Accelerated adoption of 5G technologies in the defence sector.
- Reduced capital investment in physical infrastructure for large-scale testing through the use of advanced digital twin emulation.
- Improved collaboration between the defence and commercial sectors, which enhances the integration of new technologies.
- Increased mission success through reduced risks and improved communication reliability in conflict environments.

Potential uses and future applications

Spirent's Digital Twin solution has proven scalability and versatility, making it ideal for further defence applications and other sectors. The framework is highly adaptable to various environments, ranging from smart warehouses and autonomous vehicles to multi-domain command and control networks. Successful deployment in the defence sector suggests potential for replication in sectors such as public safety, critical infrastructure and smart cities, where secure and reliable communications are crucial.

Summary:

Spirent's Digital Twin solution for the US Department of Defence illustrates the power of emulated test environments in validating and optimising 5G communications. By simulating real-world conditions, Spirent provided a flexible and reliable solution to ensure that mission-critical communications are secure, efficient and resilient.

Appendix 5 – Case Study: VIAVI Digital Twins for cyber threat simulation and 5G network roll-out.

Key Information about the Solution Provider

VIAVI Solutions is a leading global provider of solutions for testing, monitoring and quality assurance of advanced communications networks. The company specialises in providing comprehensive tools for the validation, optimisation and security of 5G networks and other technologies. VIAVI's solutions focus on ensuring high performance, reliability and user experience at all stages of network deployment.

Customers, users and their challenges and needs

VIAVI's primary customers are telecoms service providers, network equipment manufacturers (NEMs) and enterprises that need to manage increasingly complex network architectures. With the advent of 5G and the transition to 6G, customers face several challenges:

- Increased network complexity caused by open and virtualised architectures, edge computing and cloud infrastructures.
- The need to optimise and automate network operations using AI/ML.
- Security risks arising from growing cyber threats and frequent software updates.

Use Case

VIAVI's digital twins, part of the NITRO Wireless portfolio, have been effectively utilised to address two key use cases:

1. Deployment of software updates: Before deploying software updates on a live network, the digital twin enables scenarios to be simulated over the weekend. This allows operators to simulate realistic traffic volumes, detect issues in the Radio Access Network (RAN) and ensure the update proceeds smoothly.

2. Cyber threat detection: VIAVI's Digital Twin solution enables the simulation of cyber attacks and malware scenarios in a secure laboratory environment. This helps operators to test and refine their risk mitigation strategies and ensure that defences remain robust against emerging threats.

Product/solution and its implementation

VIAVI's Digital Twin is built on the TM500 and TeraVM solutions, which emulate base stations, the network core and real-world traffic scenarios. These digital twins replicate the operator's network in a controlled environment using RAN and core network emulators, combined with realistic traffic and cyber threat scenarios. The solution enables comprehensive emulation of all key network elements, including user equipment (UE), base stations (BTS), the network core and the RAN Intelligent Controller (RIC).

Reasons for choosing this solution

The VIAVI solution was selected by several leading telecoms service providers due to its ability to:

- Realistically replicate complex network scenarios in a laboratory environment.
- Provide end-to-end visibility from laboratory testing through to field deployment.
- Validate AI/ML algorithms and network performance under various conditions, which is essential for optimising open and virtualised network architectures.
- Improve decision-making through automated testing and increased intelligence across the network.

Project Status

VIAVI's Digital Twin solution is actively deployed as part of the NITRO Wireless platform and is used by operators and communications service providers worldwide. The solution is not merely a Proof of Concept (PoC), but a commercially available tool that has been widely adopted for various network testing and quality assurance applications.

Key benefits of the VIAVI solution:

- Reduced business risks: Testing software updates and network changes in the digital twin prior to deployment helps prevent costly errors and service outages.
- Enhanced network security: The ability to simulate cyber-attacks and refine risk mitigation strategies has led to more robust defence mechanisms.
- Automation and cost savings: The automated nature of digital twin testing reduces the need for physical resources and accelerates the time-to-market for new services.

Usage and future applications

The success of VIAVI's Digital Twin solution highlights its scalability and versatility for use across various sectors. This approach is not only suitable for telecommunications networks but can be effectively replicated for smart cities, critical infrastructure, private 5G networks and industrial IoT. As the industry moves towards 6G, the Digital Twin is expected to play a central role in validating next-generation applications and optimising operations in real time.

VIAVI's Digital Twin solution demonstrates the benefits of emulating complex network environments for secure and efficient network validation. The solution addresses key challenges such as software reliability, cyber threats and the complexities of open and virtualised networks. As a result, VIAVI's Digital Twin is a valuable tool in the evolution towards 5G and 6G.

Appendix 6 – Case Study: BaseN's Network Digital Twin

BaseN, a company specialising in network management solutions, has developed an advanced digital twin platform focused on network infrastructure. This Network Digital Twin (NDT) offers robust situational awareness and scalability with the aim of optimising network performance and increasing its reliability. BaseN's NDT system processes up to 70 Gbit/s of data in real time from various customer networks. It provides continuous information on network status, performance and potential issues.

Key features of the Network Digital Twin

BaseN's Network Digital Twin technology integrates key features that make it a versatile network management tool:

- Real-time monitoring and situational awareness: By capturing telemetry data in real time, NDT provides an accurate picture of the network's status, including information on device performance, service levels and traffic patterns. Network operators gain situational awareness that enables them to quickly identify potential issues and anomalies.

- Predictive maintenance and proactive fault resolution: Using machine learning capabilities, the digital twin anticipates faults before they occur, enabling predictive maintenance. Operators can address issues pre-emptively, thereby avoiding service outages and ensuring network reliability.

- Network optimisation and capacity planning: NDT supports strategic planning by predicting
, managing network expansion and designing improvements. Using predictive modelling, it can simulate scenarios such as route optimisation and resource allocation, thereby improving the network's efficiency and responsiveness.

- Customer-centric approach: A unique aspect of BaseN's NDT is its customer-centric design, which incorporates digital twins for individual customers. These customer twins (DToC) enhance the personalisation of services by analysing customers' usage patterns, predicting their needs and tailoring the service offering.

Benefits for telecoms service providers

BaseN's network digital twin offers telecoms service providers several benefits:

- A unified view of network assets and operations: NDT consolidates data from various sources onto a single, comprehensive platform. It integrates information from various network management systems, IoT devices and customer databases, providing a unified view of the entire network environment.

- Improved decision-making and resilience: Thanks to a detailed, real-time view of assets and operations, the NDT enables network operators to make informed decisions quickly. This situational awareness supports operational resilience, particularly during unexpected events or periods of high demand.

- Optimised resource utilisation: Through predictive modelling, NDT helps operators allocate resources efficiently. It identifies under-utilised resources and allocates them according to projected demand, thereby maximising cost-effectiveness and minimising operational costs.

- Shared/collaborative view: NDT enables the consolidation of views from the customer, the provider and any third parties, where applicable. Customer twins (DToC) share a common intersection and data foundation with the provider twin and other stakeholders (the customer's or provider's subcontractors). This increases integration, reduces redundant communication, operating costs, speeds up problem-solving and the adoption of new services, and generally increases customer satisfaction with the use of services

BaseN envisions a future in which the digital twin of the network serves as the primary entity autonomously managing and optimising network operations. This approach goes beyond traditional network management by enabling faster innovation cycles, accelerating the roll-out of new services and minimising environmental impact through optimised energy consumption. By incorporating sustainable NDT metrics, it not only improves network efficiency but also fulfils broader corporate environmental responsibility objectives.