Digital Twin for 5G and Beyond

Huan X. Nguyen, Ramona Trestian, Duc To, and Mallik Tatipamula

With the support of artificial intelligence, development of digital transformation through the notion of a digital twin has been taking off in many industries such as smart manufacturing, oil and gas, construction, bio-engineering, and automotive. However, digital twins remain relatively new for 5G/6G networks, despite the obvious potential in helping develop and deploy the complex 5G environment.

Abstract

Although many countries have started the initial phase of rolling out 5G, it is still in its infancy with researchers from both academia and industry facing the challenges of developing it to its full potential. With the support of artificial intelligence, development of digital transformation through the notion of a digital twin has been taking off in many industries such as smart manufacturing, oil and gas, construction, bio-engineering, and automotive. However, digital twins remain relatively new for 5G/6G networks, despite the obvious potential in helping develop and deploy the complex 5G environment. This article looks into these topics and discusses how digital twin could be a powerful tool to fulfill the potential of 5G networks and beyond.

Introduction

Thanks to recent and notable improvements in technologies such as the Industrial Internet of Things (IIoT), wireless sensor networks, deep learning algorithms, cloud-based platforms, and high-performance computing, a new data-driven paradigm, digital twin (DT) [1–3], has emerged and is currently receiving increasing attention. The DT represents a high-fidelity digital mirror of the physical entity where the former evolves synchronously with the latter throughout their entire life cycle [4]. Operators rely on DT data and a virtual prototype to enhance preventive maintenance programs, pioneer next generation business models, rapidly improve product development, and maximize a product's sustainability and efficiency in the field. DT helps create comprehensive digital models of physical environments with full support for two-way communication between the digital model and the physical object to enable real-time engineering decisions. One can build one-way data-driven/analytics-based DTs by connecting assets to an Internet of Things (IoT) platform on the cloud. However, these simulation-based DTs are often not as accurate as we want in real life. Thus, one should use physics-based DTs to get an emulated model of the asset as it goes through environmental impact, thereby producing a much more accurate prediction. The very initial concept of DT dates back to when NASA used basic twinning ideas during the 1960s for their space programs (e.g., Apollo 13). However, only around 40 years later did the concept start being developed through different names such as virtual space, digital mirror, digital copy, and then finally the term "digital twin." Only as recently as 2017 has the DT become one of the top strategic technology trends, widely investigated in many industries, including manufacturing, energy, industrial assets, and structures, such as a dual fault diagnosis method based on DT in [5] for high diagnosis accuracy in predicting the trend of production throughput, and a DT-based real-time monitoring system in [6] for mechanical structures to improve the safety of the work environment using IoT and augmented reality.

General Electric developed their Predix IoT platform denoted as a DT that has the capability of ingesting large volumes of sensory data, running analytic models, and performing business rules at the same time, allowing detection of abnormal phenomena and improving plant reliability. Siemens integrates its DT solutions into smart operations at key stages throughout the product life cycle, from product design and production to operation. Microsoft also enables DT support through its ubiquitous IoT platform that models the interaction between people, spaces, and devices. The adoption of DT technology by tech leaders opens up new opportunities of DT integration for more advanced engineering applications [7].

It is expected that 5G will enable $12.3 trillion global economic output and support 22 million jobs by 2035 [8]. Manufacturing is expected to see the largest share of 5G-enabled economic activity ($3.4 trillion out of $12.3 trillion, i.e., 28 percent), while information, communications, and technology (ICT) is second with $1.4 trillion. The potential advantages from 5G are significant, but realizing them remains a challenging task. Despite all the promises, customers and investors remain skeptical of the technology maturity. There are prohibitive complexities with hybrid network deployment challenges, with multi-vendor scenarios and with security risks. Minimizing the risk for life-critical manufacturing and robotic doctor applications is essential, especially with the evolving security risks. Some market challenges with open questions exist:

1. How do we speed up the deployment of new (but complex) 5G technologies?
2. How do we provide flexible testbed facilities with high availability?
3. Who is willing to invest in the expensive 5G deployment with uncertain returns?

Thus, there is demand for a virtual solution that could create a digital model to replicate as accurately as possible the 5G ecosystem and help tackle all the above obstacles to satisfy the 5G needs. Using DT for 5G networks has recently

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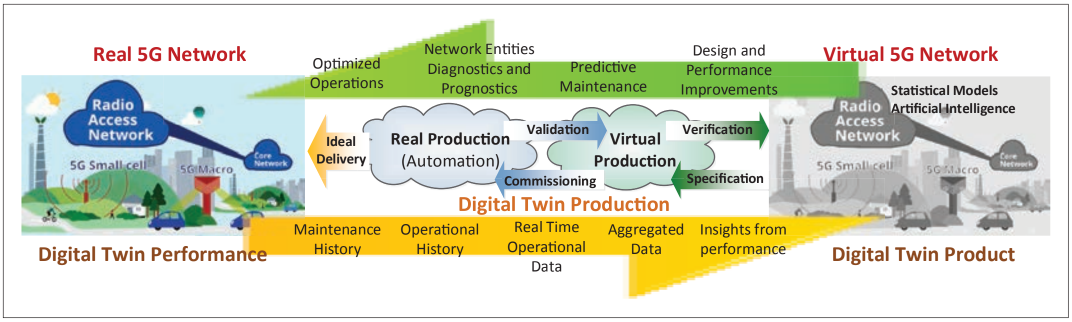

FIGURE 1. Cloud digital twin for 5G — example scenario.

The DT technology allows for easy and cost-effective access to 5G with highly flexible and repeatable development approaches. It enables proactive modeling of data traffic and security risks for test/validation purposes, driving operational and energy efficiency, helping accelerate the research and time to market for new disruptive services.

gained significant interest, including from the leading telcos (e.g., Ericsson [9] and Huawei [10]), being a new topic where sensor/network data, traffic data, data mining, data visualization, and data interpretation are integrated into one system to facilitate the live replica of a process or whole 5G network. The DT has the potential to assess the performance, predict the impact of the environment change, and optimize the 5G network processes and decision making accordingly. Consequently, this study presents a concept of cloud DT for 5G networks, as illustrated in Fig. 1, aiming to perform continuous assessment, monitoring, and proactive maintenance through the closed-loop data from physical entities to the virtual counterparts and vice versa. Within the 5G DT, the digital 5G model will run alongside the physical 5G network to perform operational predictions and enforce optimized decisions into the living network and associated services.

Artificial Intelligence to Sharpen the DT Concept for 5G Networks

Digital Twin Concept

When developing a complex physical system like a plane, an oil rig, a hydroelectric station, or a 5G network, one would want to learn all possible outcomes before proceeding to the production/manufacturing stage. Ideally, the behavior of the system should be well known for any potential inputs and the outcomes can be predicted with certainty. Taking the 5G rollout as an example, it would be too expensive to deploy a trial 5G network, particularly in developing countries where the 4G rollout is still ongoing. If the impact of deploying 5G cells can be predicted accurately in advance, it would greatly help the decision makers to find the appropriate strategies for their own country, avoiding costly and irreversible investment mistakes. However, it is often not easy to achieve such accurate prediction in complex systems.

A simulator, designed aiming to replicate and assess a physical object, is often developed based on a mathematical model and/or the computational counterpart. Those models are not independent of each other.

Unfortunately, a simulator producing inaccurate outcomes can create a confusing situation, which may not be helpful for a quick turn-around development cycle. For example, a low correlation between actual data tested in the field and the data generated from the model in the lab can delay the production process significantly. There is a dilemma in developing a simulator: The computational model should be simple to keep the simulator light, enabling fast response, while the mathematical model should be complex to be close to the true object. However, these two objectives cannot go hand in hand, thus requiring a trade-off. Furthermore, an advanced computational model, that is, one based on the artificial intelligence (AI) concept, requires data for self-configuration. This leads to several questions, including:

1. What is the sufficient level of simplification/complexity in those two computational/mathematical models?
2. How representative are the data required for the input of the virtual object?

To this extent, we believe that the approach of using DT has great potential in providing the answer to these questions. This is because the virtual model within a DT is aimed to self-learn the data pattern to optimize the physical system's configuration on a live basis. This helps the DT to reach its true potential and become a live data model that spans across ecosystems. A 5G DT architecture involves three main components: the physical 5G network, the virtual 5G DT, and the two-way interaction between them, as seen in Fig. 1. The key difference between the DT and the conventional simulation methods is represented by the two-way data connection and updating process. The 5G DT would handle how data is produced throughout the network maintenance, operation, design, development, testing, and validation as well as how is it routed and utilized by the destination object. More importantly, a 5G DT architecture allows the virtual 5G DT to start with a simple form and then, by employing AI mechanisms, evolve to become a more comprehensive model achieving better precision through the assistance of data updating. DT technology allows for easy and cost-effective access to 5G with highly flexible and repeatable development approaches. It enables proactive modeling of data traffic and security risks for test/validation purposes, driving operational and energy efficiency, helping accelerate the research and time to market for new disruptive services.

Support of AI Tools

5G is viewed as an ambitious internetwork of everything. Its applications vary from ones with demanding data rate (e.g., video game), ultra-reliable and fast-response interconnection (e.g., in an autonomous factory) to ones using bat-

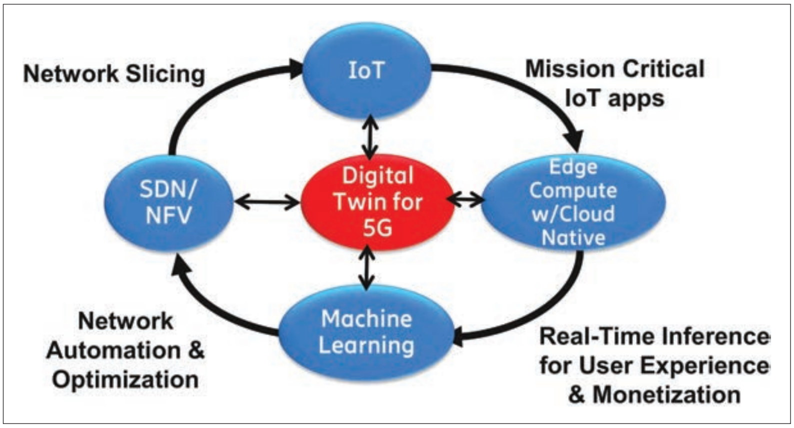

FIGURE 2. Digital twin for 5G.

tery-powered machine-type devices. For this reason, the elements in 5G networks are highly complex, and their development and deployment will come with certain risks, both technical and commercial. Thus, in order to learn 5G's data patterns, AI tools are seen as indispensable elements of the DT architecture. There is no universal approach for optimal 5G DT architecture, but there is a common property: 5G networks and associated applications must often work with richness of diverged data in different formats. Fortunately, advanced AI tools can soften the data diversity issue by allowing a virtual 5G network to be built from a baseline model, not from scratch. For example, machine learning (ML) could be used to create models for 5G traffic/network behavior using historical data as well as real-time IoT data from multiple sources. These ML-based models could help detect anomalies in 5G networks and predict any potential bottleneck for traffic performance.

AI algorithms are executed periodically in order to update the DT operational model. A DT will integrate several different surrogate models representing different aspects of the actual 5G network, such as physical 5G network components including radio access network (RAN), core, and so on, the customer/service aspects, and the operation processes. These models need to interact seamlessly for optimized functionality of the 5G DT. ANSYS' Twin Builder is one example of a DT design tool that supports multiple modeling domains and languages.

Figure 2 shows the coherent relationship between different components in building a 5G DT. The ML supports the DT for continuous prototyping, testing, assurance, and self-optimization of the live 5G network for different use cases. From Release 15, 5G has enabled cloud native core and virtualized RAN (Cloud-RAN). Thus, the AI/cloud-based DT technology has the potential to contribute to speeding up the processes. In particular, the 5G teams from Spirent and Ericsson have the following design targets with the DT technology:

1. Accelerate the validation time of a new 5G use case from months to hours, even minutes.
2. Share the tests results between development and operation within minutes.
3. Save deployment costs for new services, care, and maintenance/troubleshooting.
4. Allow active assurance and maintenance by testing the virtual 5G network infrastructure to find potential issues.
5. Support network automation and optimization.
6. Facilitate network slicing via software defined networking (SDN) and network function virtualization (NFV).
7. Test multiple slicing paths at once by deploying the functions required for a new use case only.

For example, in a shared infrastructure scenario in 5G networks, the DT that has the capability of real-time tracking of the network changes would allow the AI tools to stimulate and predict future outage events. A rollout of 5G can be trialed virtually via the DT even before a site visit. A new network slicing formula can be optimized quickly to shorten the time to market for new use cases. AI-based DT can also be powerful at predicting potential performance bottlenecks. Viavi Solution and Ericsson are targeting the DT approaches for their 5G base station solutions to shorten the time of resolving their clients' issues.

Digital Twin as a Highly Interactive 5G Emulator

5G Automotive

The latest developments in both the automotive and communications industries, especially related to the rollout of 5G networks, the Internet of Vehicles, and adoption of cellular vehicle-to-everything (C-V2X) connectivity, are fueling significant transformations on the roads in terms of autonomous driving where 5G connected vehicles will negotiate traffic, motorways, roundabouts, and so on, without human intervention behind the steering wheel. Thus, 3rd Generation Partnership Project (3GPP) Release 16 targets Industry 4.0 and C-V2X services.

The deployment of 5G aims to enable effective connected cars communication as well as fully automated driving that could increase road safety and improve traffic management. The provisioning of ultra-reliable low-latency communication (URLLC) through 5G will enable the support for these connected cars services as well as a new set of related applications (traffic prediction, intelligent navigation systems, cooperative collision avoidance systems, etc.). The highly dynamic nature of vehicular networks along with the heterogeneity of wireless infrastructures for connected cars and the variety of vehicular applications (e.g., safety, traffic management, infotainment, etc.) make the resource management and low-latency communication requirements a significant challenge. It is expected that thousands of millions of miles of expensive driving setup is required for testing and validating the connected autonomous vehicles. Consequently, one promising solution in the automotive sector is the use of DTs to create the virtual model of a 5G connected vehicle. The DT could analyze the overall performance of the 5G connected vehicle and enable the delivery of personalized services. AI is used to predict the vehicle's performance under various dynamic conditions, identify problems, and apply solutions, making the driving experience safer for the user. However, before taking the solution out on the public roads, it has to be tested thoroughly through emulations. The Spirent 5G DT [11] aims to emulate the 5G network for testing the behavior and performance of the connected vehicles within a controlled realistic environment using a 3xD drive-in simulator. The 5G emulator would enable car manufacturer understand how is the vehicle behaving under different road specific scenarios (e.g., parking, pedestrians, road traffic, weather conditions) as well as under various 5G connectivity specific scenarios (handover, network traffic load, radio propagation, etc.). As the automotive industry relies on 5G to power core functionalities, this level of testing could speed up the adoption and integration of autonomous vehicles in a safe, reliable, and secure manner. The advantages of 5G DT integration within the automotive industry include efficient use of road capacity in real time, reduction of carbon emissions, reduction of road accidents, as well as limiting the need for emergency services in case of accidents. However, some significant questions still remain open, such as: In a critical scenario, should the autonomous car value the life of its passenger over a pedestrian's?

5G Radio and Channel Emulation

Being able to emulate 5G entities with more complex antenna systems such as multiple-input multiple-output (MIMO) that cover a boarder spectrum of frequencies (e.g., millimeter-wave, mmWave) and using realistic radio propagation models could dramatically speed up the 5G deployment process by eliminating the trial and error in the field and reducing the number of antennas actually required.

Taking advantage of the different digital ecosystems within the city, Bristol, United Kingdom, is making progress toward becoming a smart city [12]. To this end, the Smart Internet Lab in Bristol builds a DT to visualize and predict how 5G radio signals will flow around the city, to connected and autonomous vehicles, creating 5G radio models and mapping tools. The 5G DT uses an accurate 3D model of the terrain, buildings, and trees of the city, and together with advanced radio propagation models, it traces how radio waves travel/bounce off/diffract over buildings/corners/rooftops. Using complex radio propagation models, the 5G DT can accurately predict the coverage area for each base station across the city, which is key for the successful deployment of 5G.

Once the 5G network is deployed, the 5G DT could continuously monitor and test the network's performance applying near-real-time optimizations when required. The integrated 5G DT and emulators proposed by Spirent [11] enable continuous prototyping, testing, assuring, and self-optimization of the real 5G network. Consequently, a part of the network could be emulated to test the performance of other real network entities. For example, the performance of a 5G New Radio could be tested by emulating the next-generation 5G core network. Spirent's 5G DT integrates multiple emulation processes, traffic, and signal generation functions, as seen in Fig. 3, to mirror an actual 5G network. The main emulated components of the 5G DT are devices, traffic, 5G/4G base stations, 5G RF channels, satellite connectivity, real-world captured signals and traffic, network impairments, security threats, core network, cloud edge, fronthaul, and network slices. In this way, the performance of the 5G network could be tested on demand under various dynamic scenarios and context (e.g., traffic congestion, security threats, network failure).

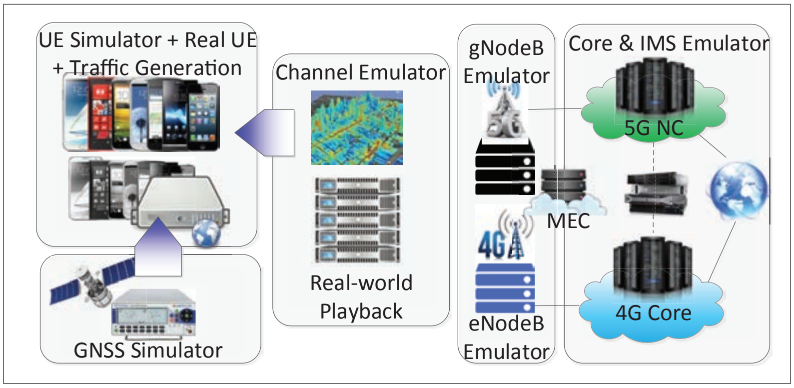

FIGURE 3. Digital twin as emulator.

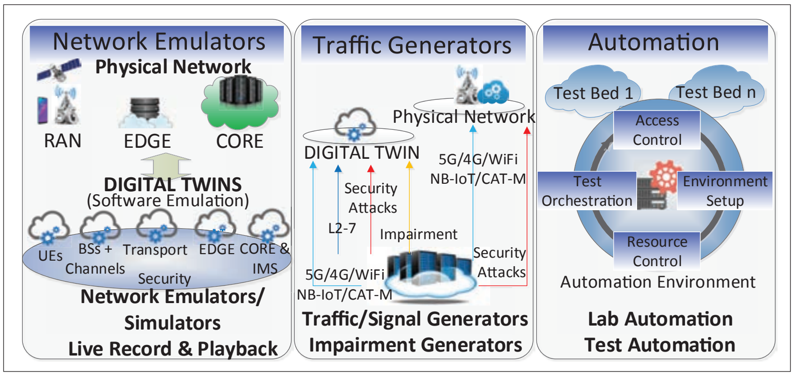

FIGURE 4. Digital twin for test and validation.

5G Continuous Validation and Optimization

5G offers great potential for new business cases. The requirements of various services create many constraints for network deployment. In the context of each business case, each provider requires different objectives, which can be conflicting. Thus, deploying an optimized 5G network in one go is an impossible task due to its complexity, including the lack of data (e.g., user behaviors and channel characteristics). The unavailability of a sufficient amount of accurate data prior to the deployment plan becomes a bottleneck. When rolling out a 5G network, there is no longer a clear boundary between the infrastructure deployment stage and operation and maintenance. More network nodes will be added, links will be upgraded, and new features will be offered later to support additional requirements. Deployment and optimization go continuously together during the network's life cycle. It can take decades to reach the full 5G potential. This is a continuous process in which validation and optimization are crucial to fully deploy 5G (Fig. 4). Consequently, the cost-effective DT solution will play a key role. For continuous validation and optimization, some constraints may be relaxed (e.g., 1 ms latency not strictly required) at the beginning when 5G services are still immature. Data maturity and feedback exchanges between the DT and the physical 5G components are continuously updated through iterations, which could involve the

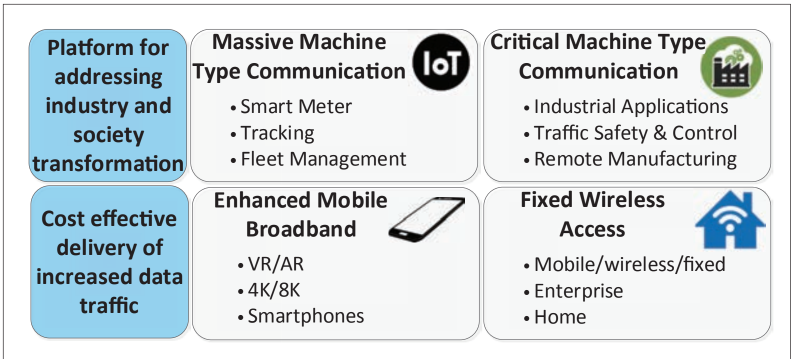

FIGURE 5. Digital twin covers 5G use cases.

addition/removal of entities to/from the network (e.g., removal of entities supporting the previous generation services only). The 5G DT architecture could minimize the human involvement in design and validation of the physical network, which brings two-fold benefits: lower labor costs and fewer human errors. As such, one example is the recently proposed open architecture RAN of 5G (O-RAN). The openness, due to layered architecture and interfaces, eliminates the limitation of interoperation of network components from different vendors. The physical network components can also interact with DT virtual components through defined interfaces during deployment and optimization. Within O-RAN, the AI will play an important role within the network. Overall, without building the full 5G physical infrastructure, the DT could help with the following while the development of 5G networks continues:

1. Test new core functions and slices to meet service level agreements (SLAs).
2. Validate the data rate with real-world call traffic.
3. Test the complex handover scenarios.
4. Test the New Radio performance.
5. Ensure the mobile edge computing (MEC) [13] and NFV end-to-end performance (illustrated in Fig. 2).

Providing Flexibility for New Use Cases

Many countries see 5G as a game changer. 5G is important for not only the mobile operators, but also the vertical industries. There are certainly opportunities for raising revenue, but the uncertainty of strong return can still put off the potential investors. Thus, clear use cases (e.g., Fig. 5) are needed to deliver the full potential of 5G, which justifies investment. Although each country will focus on their own strengths and needs, having the flexibility of a DT model to explore the deployment of a 5G network will be key for policy makers and operators.

The question is who is driving the 5G rollout. There are significant hurdles in technology, regulations, and economics. Many countries have still to decide between the 5G rollout approaches:

1. *Non-standalone*: upgrading from legacy 4G
2. *Standalone*: full 5G implementation

The DT will allow flexibility to test and embrace new models for infrastructure. For example, it can help explore the possible scenarios of the operators sharing the infrastructures and providing *infrastructure as a service* to the vertical industries. The integration of DT-based network slicing through NFV and SDN will enable flexibility for new use cases where only required functions in the edge or core slices will be executed, depending whether they are mission-, throughput-, or coverage-critical.

Beyond 5G and Next Steps

The benefits of 5G DT are significant for many industries because it enables them to build what-if scenarios for new products/services/processes or new network entities and test them under realistic conditions before moving into real-world implementation. 5G DT could also improve ongoing operations by continuously monitoring the real physical systems and use big data analytics and ML to predict any issues before they happen in the real world. This shows that the potential of the 5G DT technology and beyond is limitless. The implementation and automation of IIoT could benefit from 5G DT to reduce maintenance issues and optimize production. Similarly, 5G DT could revolutionize healthcare operations as well as it could provide solutions for intelligent assisted living homes. The future of 5G DT could also envision building AI-powered instructors, teachers, doctors, nurses, and others.

5G DT is seen as an enabler for new emerging services, including city management tools [14] that could help developing countries in addressing the critical challenges in terms of traffic control, water and sanitary management, and urban security. Looking at the current global pandemic situation, a 5G DT could actually help understand the spread of COVID-19, and relying on the AI of 5G DT could anticipate the approximate location of epidemic hotspots. This could be done by creating a DT containing a 3D model of the city and overlaying the 5G network along with other information such as transportation networks, street grids, buildings, IoT data, as well as people's movements and activities along with epidemiological data from current but also past epidemic patterns. By making use of big data analytics together with ML, it is possible to predict outbreak scenarios most likely to happen, enabling 5G DT to take appropriate measures to avoid these situations from happening in the real world (e.g., reroute people in order to avoid an epidemic hotspot). Additionally, blockchain technology could be used to overcome data privacy issues. Having this information at hand could actually help governments to take more efficient steps to manage the size of the epidemic to be at least in line with the healthcare resources available. Even though 5G is still being deployed, works are carried out toward defining the next 6G networks [15]. The idea behind 6G is to enhance even further all the applications and vertical use cases of the 5G network by bringing the intelligence to the edge of the network. Consequently, what lies beyond the 5G DT would be an intelligent interconnected system of DTs that enables the creation of a real-time digital world. Thus, 6G will be represented by connected and augmented intelligence that will change the way data is created, processed, and consumed.

Conclusions

We introduce DT technology for optimizing and developing 5G networks and beyond where the general concept of DT is studied with different functions and designs. DT can certainly help the research community move away from the traditional network designs (which used actual deployment) to approach the digital/virtual one, including testing and validation steps. This DT technology, however, is not yet market ready for 5G, which represents a unique opportunity for the DT and 5G research communities to foster innovations that will enable disruptive 5G use cases for future society.

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Biographies

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