**SURVEY**

# Empowering 6G Communication Systems With Digital Twin Technology: A Comprehensive Survey

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**ABSTRACT** The global roll-out phase of the fifth-generation of mobile communication systems is currently underway. The industry and academia have already begun research on potential sixth-generation (6G) communication systems. The 6G communication system is anticipated to provide network connectivity for an extensive range of use cases in a variety of emerging vertical industries. Consequently, a new set of challenging requirements and more stringent key performance indicators have to be considered, a novel architecture has to be designed, and unique enabling technologies shall be developed in order to fulfill the technical, regulatory, and business demands of the communication service customers. These requirements place enormous pressure on the players in the telecommunications industry, including network operators, service providers, hardware suppliers, standards development organizations (SDOs), and regulatory authorities aimed at developing, standardizing, and regulating an energy-efficient, cost-effective, performing, and sustainable 6G communication ecosystem. One area of focus for 6G communication systems is the digital twin (DT) technology, which is a well-defined set of tools designed to create virtual representations of physical objects that serve as their digital counterparts. This article explores the applicability of the DT technology in the context of 6G communication systems by viewing it as a promising tool to make research, development, operation, and optimization of the next-generation communication systems highly efficient. The major contribution of this article is fivefold. Firstly, we provide critical analysis of the state-of-the-art literature in the field of DT technology in order to capture its essence in several application areas since its inception. Secondly, we conduct a comprehensive survey of the research concerning the deployment of DT technology in 6G communication systems. Thirdly, we discuss potential use cases and key areas of applications (along with detailed examples) of 6G communication systems that can benefit from DT technology. Fourthly, we present an overview of the activities of several SDOs that are active in the field of DT technology. Finally, we identify several open research challenges and future directions that need to be addressed before the end-to-end deployment of DT technology in 6G communication systems.

**INDEX TERMS** 5G, beyond 5G, 6G, automation, communication systems, digital twinning, digital twin network, digital twin technology, intelligence, physical twin.

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## I. INTRODUCTION
Mobile communication systems have evolved through several generations. The fifth-generation (5G) communication systems are currently in the deployment phase, while research

activities as well as standardization efforts towards the potential 6G communication systems, are in progress [1], [2]. The first-generation (1G) mobile communication systems exemplified the transmission of analog mobile telephony utilizing cellular concepts. In the 1980s, voice calling services were made available to subscribers through 1G mobile communication systems [3]. By 1990, the second-generation (2G) digital cellular networks began replacing the analog 1G mobile communication systems. The most important features of 2G communication systems included but were not limited to digital voice telephony, short message service (SMS), and low-rate data services [3]. The third-generation (3G) mobile communication systems based on code-division multiple access (CDMA) technology were introduced around the year 2000 [4]. The primary feature of 3G communication systems was to deliver better data rates in comparison to their predecessor, 2G. The fourth-generation (4G) cellular systems were commercially deployed around 2010. The 4G communication networks were designed to support mobile broadband services with much higher data rates. The primary enabling technologies for 4G communication systems were orthogonal frequency division multiplexing (OFDM), multiple-input and multiple-output (MIMO), and software-defined radio (SDR), among several others [5]. The evolution of mobile communication systems has revealed that every ten years, new technological standards were released, upon which new communication networks were offered to the market in order to meet the growing requirements of the communication service customers.

Prior to the commercial launch of 4G, the primary focus of mobile communication standards was on human-centered services and higher data rates. However, the 5G communication services, which were first commercially deployed in 2019 [6], go beyond human-centered applications by concentrating on machine and vertical industry connectivity as well. 5G communication networks are anticipated to provide network connectivity to a large number of vertical industries with diverse performance, functional, and operational requirements. These vertical industries and service sectors include but are not limited to healthcare, agriculture, automotive, public safety, finance, and many others. The Third Generation Partnership Project (3GPP) has classified 5G communication services into five categories as of the date of this writing: enhanced mobile broadband (eMBB), ultra-reliable and low latency communication (URLLC), massive Internet of things (mIoT), vehicle-to-everything (V2X), and high-performance machine type communication (HMTC) [7]. These communication service categories are standardized to allow a network operator to provide network connectivity to user equipments (UEs) with stringent performance requirements in a variety of vertical industries at various scales while utilizing a single but shared telecommunications infrastructure. In order to suit these varied requirements, several novel, and revolutionary technologies have been integrated into the 5G communication infrastructure, including network function virtualization (NFV), software defined networking (SDN), mobile edge cloud (MEC), millimeter wave (mmWave), massive-MIMO, amongst others [8].

Following the roll-out of 5G communication systems, it has become evident that there are many new use cases where 5G networks are unable to meet the extremely stringent technical and commercial requirements. As shown in Figure 1, these use cases include: extended reality (XR), augmented reality (AR), virtual reality (VR), holographic telepresence, collaborative robots (cobots), telemedicine, multi-sense experience, tactile internet, pervasive intelligence, and many others [1], [2]. In order to provide network connectivity for these novel use cases and address the societal needs for information and communications technology (ICT) in the 2030s, the communication society has already begun research and development on the 6G telecommunications ecosystem. The proliferation of 5G communication systems, as well as the impending research and development of 6G communication systems, place significant pressure on the major stakeholders of the telecom industry, such as mobile network operators (MNOs), equipment vendors, communication service providers, etc., to conduct research, testing, standardization, deployment, network up-grades, optimization, and network operation in an energy-efficient, fast-paced, cost-effective, and sustainable manner. Therefore, novel key enabling technologies and architectural solutions (as depicted in Figure 1) that aid in achieving the aforementioned objectives are urgently required.

The DT technology is one of the most promising technologies that can be instrumental in realizing the technical and business objectives of 6G communication systems. DT technology was originally devised for industrial and manufacturing applications [9]. It is the concept in which a physical object or process can be fully and precisely represented by its twin in the digital domain. This encapsulates various physical objects in the system, their interactions, environment, and other features to the desired level constituting a physical twin (PT). There is a bi-directional communication between the DT and the physical world and attributes from the physical world are captured into the digital representation in near real-time. On the other hand, the DT can perform tasks of storage, modeling, learning, data analytics, prediction, simulation, etc., and provide the feedback to the PT [9], [10]. Thus, several tedious and non-trivial tasks could be performed in a faster, more efficient, and cost-effective manner using a DT.

There are several concepts that resonate with the principles of a DT, though, with varied degrees of difference. In the strict sense, a DT is the digital representation or model of a single physical object. It is a system that focuses on producing a virtual model of a physical entity with high fidelity. Such a system needs to be intelligent and persistently evolving [11]. On the other hand, a digital twin network (DTN) is applicable in modeling a group of physical entities with complex interactions among themselves. Thus, a DTN is an extension of the DT concept by having multiple DTs communicating with each other [11]. Furthermore, digital twinning is the process of synchronizing the physical and virtual states of the
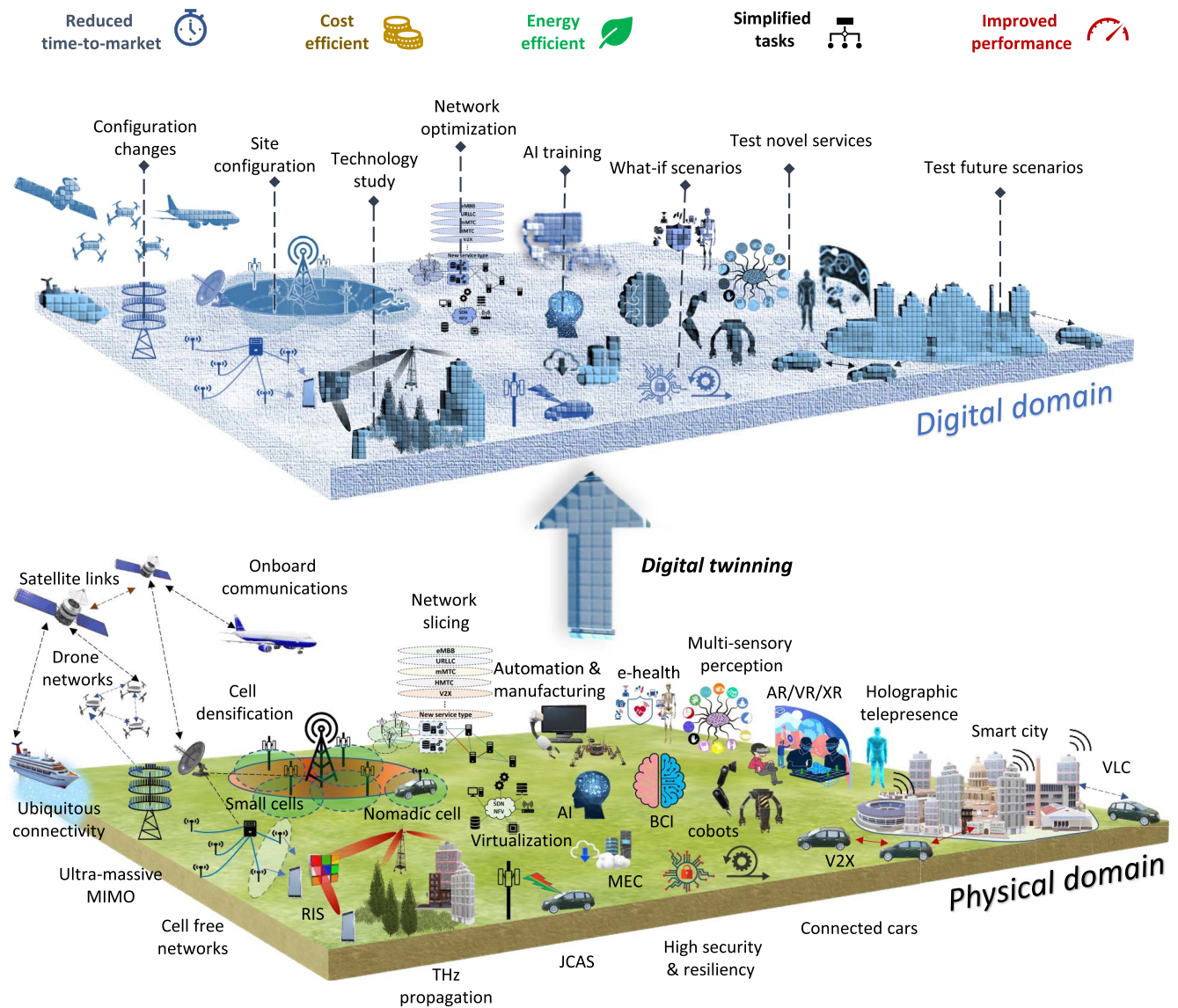
**FIGURE 1.** The potential novel services, future scenarios, capabilities, and technological enablers for the 6G ecosystem, as well as the implications of DT technology for communication systems. The definition of terms used in figure 1 not defined elsewhere in the paper are as follows: VLC, BCI.

considered physical object or system [12]. The term DTN is used by SDOs to refer to the DT of a network. It is also termed as network DT in the context of cellular networks.

DT technology is intensively used in the fields of manufacturing, aviation, industry, healthcare, and smart cities (as observed in Table 1). There are several technologies that are foreseen to play a major role in the proliferation and advancement of DT technology. Some well-known examples are high fidelity computer modeling, virtualization, fast and cost-efficient artificial intelligence (AI) algorithms, cloud and fog computing, and Internet of things (IoT) technologies. In addition, the DT technology requires a fast and reliable communication network to carry out the bilateral exchange of information between the physical and the digital domains. Thus, there is a unanimous opinion in the research commu-

nity that the forthcoming 6G communication networks are going to play a significant role in efficiently deploying DT technology in the vertical industries. There are several works that list advancements in mobile communication technology including 5G, beyond 5G (B5G) and 6G as one of the major enablers for an effective operation of a DT [11], [13].

Finally, yet importantly, the application of DT technology can significantly benefit the research and development of 6G communication systems. There are various network domains, such as radio access network (RAN) and network edge, and solution areas, such as radio resource management (RRM); edge computing; network slicing; etc., that can significantly improve their performances using DT technology. As a result, researchers, MNOs, equipment vendors, service providers, and consumers can all reap the benefits. These include,

for instance, efficient modeling and simulations, fast and cost-effective tests, shortened time-to-market, reduced capital expenditure (CAPEX) and operational expenditure (OPEX), superior quality of service (QoS), etc. Thus, it is crucial to look into DT technology from the perspective of the telecom industry. To accomplish this goal, we study the integration of DT technology into 6G communication systems and provide a thorough analysis of fundamental concepts, potential application domains, use case scenarios, relevant standardization initiatives, and future research prospects in this domain.

## A. REVIEW OF RELATED WORKS

To this end, several survey papers have been published on the deployment of DT technology in various service sectors, manufacturing, industrial applications, etc. These survey papers concentrate primarily on the modeling and design of a DT in these application areas and list various technological enablers. We provide a detailed summary of the contributions of each of the survey papers in Table 1. The methodology through which we obtained these survey papers is described in the next section. Based on our examination, we found that the majority of the studies on the deployment of DT technology have focused so far on smart cities, healthcare, manufacturing, aviation, and Industry 4.0. Despite the widespread interest in the deployment of DT technology in the telecommunication sector, it has not been thoroughly studied in the literature yet. Nevertheless, some of the survey papers briefly highlighted wireless communication technologies as the key enabling technologies for the realization of the DTs in various sectors [13], [15], [21], [23]. Articles [24], [29], [30] do consider the impact of DT technology for the applications in the 6G communications era. However, to the best of our knowledge, no survey paper considers elaborately the application of DT technology in the research and development of 6G communication systems. One of the most critical reasons for such a literature gap is that DT technology is still in its infancy in the telecommunication sector. Therefore, in contrast to the DT-related survey papers described in Table 1, this survey article presents a more comprehensive literature review and critical analysis of the deployment of the DT technology in the telecommunications sector, specifically in 6G communication systems.

## B. KEY CONTRIBUTIONS

In light of the aforementioned gap in the literature, the following are the principal contributions of this article:

- This paper recognizes the importance of DT technology for the research and development of 6G communication systems and performs a state-of-the-art survey of major survey papers in on the topic of the DT. Through this, it offers insights into different application areas of DT and narrows the focus down to DT in 6G communication systems.

- The paper conducts a state-of-the-art review of the DT applications in mobile communication systems (e.g., 5G and beyond). The paper also outlines different domains and solution areas within mobile communication systems where DT technology has been applied so far.

- A thorough historical background is provided, facilitating the application of DT technology in areas of the telecom industry and the implications it has on the research and development of 6G communication systems. The paper also highlights the integration of intelligence and automation into DT technology in 6G communication systems.

- It presents a comprehensive list of potential use cases and areas for the application of DT technology in the context of 6G communication systems. It discusses several domains, such as the RAN; edge network; and end-to-end (E2E) network, solution areas including RRM; traffic steering; RAN moderation; etc., and potential rewards in terms of time-to-market; energy consumption; ease of use; financial gains; safety; and so on.

- The paper discusses the activities of SDOs, such as the International Telecommunication Union - Telecommunications Standardization Sector (ITU-T), Internet Engineering Task Force (IETF), European Telecommunications Standards Institute (ETSI), International Organization for Standardization (ISO), among others, in the field of DT technology from the perspective of the telecom industry. It presents the state-of-the-art literature on these activities with major definitions of DTNs and their key elements. It also highlights the requirements to develop functional and serviceable DTNs with a reference architecture of a DTN.

- The paper also highlights the open research challenges in the area of DT technology pertaining to its application for the research and development of 6G mobile communication systems and highlights future directions for improvements.

## C. THE STRUCTURE OF THE ARTICLE

The rest of this article is organized in the following manner. In Section II, we commence by providing a historical background, the definitions of several key concepts, a summary of the relevant state-of-the-art literature, and a detailed discussion related to the realization of DT technology in 6G communication systems. In Section III, we discuss a variety of potential use cases and areas of application that can be empowered by DT technology across different administrative domains in the 6G network. We then delve deeper, in Section IV, into the activities and efforts of the relevant SDOs involved in the standardization and development of DT technology in telecommunications as well as other sectors. In Section V, we present open challenges and future research directions for the E2E deployment of DT technology in 6G communication systems. Finally, we summarize the main conclusions of the article in Section VI.

**TABLE 1.** A summary of the key contributions of state-of-the-art survey papers concerning the deployment of DT technology in various service sectors and vertical industries.

| Ref. | Publication Date | Summary of Key Contributions |
|---|---|---|
| [22] | 15 October 2021 | This paper reviews articles related to DT technology and its application in the field of smart cities. The paper also compares its vision with that of applying the DT technology in the areas of manufacturing and Industry 4.0. The open challenges in smart cities are highlighted and an argument is made that the application of DT technology in smart cities should be treated as a cyber-physical "system of systems" given the dissimilar complexity, system sizes, etc. when compared to other application areas of the DT. The domains under smart cities, such as energy, comfort, structural health in buildings, traffic, mobility and fleet management, urban planning, sustainability, etc., are discussed in detail. |
| [23] | 07 December 2021 | A survey on the relevance of DT technology in the field of autonomous driving is presented. The paper presents a brief literature review of DT in application areas such as manufacturing, industrial applications, and health care. Then, a framework for autonomous driving test based on DT technology is proposed. The applications required for self driving are reviewed and the self-driving test framework based on DT is presented. The processes involved such as, collection of real driving data, transport through 4G/5G networks (V2X), data fusion, generation of complex scenes, simulation, feed back information to vehicles, etc., are detailed. Different testing phases and levels using DT namely, pure virtual testing, sensor data testing, and real vehicle test are discussed. The challenges pertaining to latency constraints from communication networks, need for AR/VR integration, rich traffic data base, standardized protocols and data formats are outlined. |
| [24] | 15 December 2021 | This tutorial paper proposes an architecture to support holistic network virtualization and pervasive network intelligence for the 6G networks. The holistic network virtualization includes the concepts of network slicing and DT to facilitate service-centric and user-centric networking respectively. The paper focuses on the modeling aspects such as data collection, abstraction, processing and control, etc., to conceptualize a six layer holistic network virtualization architecture to facilitate interplay between DT and network slicing paradigms, between model and data-driven methods, and between AI and virtualization. The proposed architecture is envisioned to enhance flexibility, scalability, adaptability, and intelligence in 6G networks. Further, challenges related to DT such as need for quantitative performance characterization of acpDT, the optimal DT model, DT migration, and data security are discussed. |
| [25] | 20 December 2021 | This paper carries our survey on DT and its integration into power systems to improve efficiency, functionality, and reliability. The paper focuses on the applications of DT in power systems related to utility, fault diagnosis, operation centers, energy management, batteries system, and energy generators. The composition of a DT from the perspective of a power system is presented and key functional blocks are highlighted. The vulnerabilities of a DT from security perspective such as data injection, man-in the middle attack, denial of service, etc., are discussed. The need for standardized smart grid cybersecurity mechanisms is emphasized. |
| [13] | 11 January 2022 | This paper reviews the literature related to the DT and finds gaps in research pertaining to communication and computational technologies. The functional aspects, benefits, and applications of DTs in industrial tasks are discussed. The recent research trends in next-generation wireless technologies (5G, B5G), relevant tools (e.g., data analytics, federated learning), and networked computing paradigms (e.g., fog- and cloud computing), are elaborated. Further, strategies of DT technology deployment at various communication layers are needed to satisfy monitoring and control aspects of industrial applications are investigated. Issues related to privacy and security, general design paradigm, multi-source data fusion, advanced computation, quantum-enhanced machine learning (ML), B5G adaption to industrial DTs, etc., are presented in detail. |
| [26] | 05 February 2022 | This paper focuses on providing an overview of the technical aspects enabling wireless systems to be self-sustaining and proactive-online-learning enabled systems. The DT technology is established as the logical solution for these tasks with key examples. The fundamental concepts of design, high-level architecture, and frameworks of DTs of wireless systems are presented. A comprehensive taxonomy is developed for twins for wireless and wireless for twins. The former considers aspects such as the design of twin objects, prototyping, deployment trends, device design, interface design, etc., whereas, the latter discusses aspects of security, privacy, air interface design, etc. In the end, open research challenges related to dynamic twins, interoperability, twin object migration, true prototyping, incentives for entities enabling twinning, security, etc., are elaborated. |
| [27] | 20 April 2022 | This paper looks into the use of VR with DTs to facilitate better representation and interaction for various DT application scenarios. The application areas including Industry 4.0, robotics, automotive, health, aerospace, education, infrastructure, and so on are reviewed to find areas relevant for combining VR and DT. Subsequently, key use cases are determined namely evaluation and user studies, remote operation, remote collaboration, decision making, and training. Major challenges for combing VR and DT technologies such as cybersickness, security, communication bottleneck, cables and hardware, etc., are discussed. |
| [28] | 29 April 2022 | The paper considers the extensive application of DT technology in the Industry 4.0 and performs a survey of potential security risks. The paper provides a summary of DT applications in areas such as manufacturing, automotive, healthcare, transportation, etc., and provides functional layers and enabling technologies. Four discrete layers are identified for data acquisition, management, modeling, and visualization, and operational requirements of a DT are discussed. A detailed list of security attacks in each layer are presented ranging from software attacks, physical damage, denial of service, man in the middle, DT service tampering, privacy leakage, privilege escalation, rogue virtual resources and servers, to visualization tampering. Finally, some security approaches are explored to combat the threats such as hardening of DT infrastructure, resource decoupling, software security, authentication, authorization, intrusion and deception detection, situational awareness, recovery, trust management, and so on. |
| [29] | 29 July 2022 | This paper provides a vision for the integration of DT in smart city applications. The wireless networks are considered as key enablers for this task. The integration of DT and smart city paradigms are envisioned from a wireless perspective with use cases such as zero-touch networks for healing smart cities, terahertz (THz) communications for smart manufacturing, satellite communications for autonomous driving, sensing as a service, intelligent surface-enabled smart buildings, optical wireless communication for intelligent transport systems, and so on. Finally, open research gaps including trust, security, data communication limitations, advancements required in AI algorithms are presented. |
| [30] | 10 August 2022 | This paper performs survey on digital twin edge networks (DITEN) that combines concepts of MEC and DT. The focus is towards the 6G communications era and key applications that are envisioned in it. The paper provides basics of DITEN including concepts and framework. The potential of DITEN in enhancing communications, computation, and simulation are highlighted. The design aspects of DITEN are outlined including DT modeling, updating, and deployment options (cloud, edge, physical entity and hybrid mode). Key design issues related to efficiency, fault-tolerance, real-time constraints, and security are discussed. Key enabling technologies including communications, data processing, machine learning, blockchain, and incentive mechanisms are discussed. Typical applications of DITEN namely IoT, vehicular networks, space-air.ground-integrated networks, health care, and wireless systems are discussed. Challenges such as high precision modeling, synchronization, migration, security and privacy are discussed. |
| [31] | 22 September 2022 | This paper presents a comprehensive survey on the enabling technologies, trends, challenges and future prospects for the DT technology. An overview of DT definitions are provided followed by detailed discussion on the market potential of DT. The key enabling technologies for DT such as ML, cloud/fog computing, IoT, cyber physical system (CPS), VR/AR, etc., are surveyed. The DT frameworks are reviewed across use cases namely, smart factory, infrastructure and new generation mobile networks. A closer look is taken at DT services including anomaly detection and predictive maintenance. Real use cases of DT in manufacturing industry, cyber-physical factory and structural health monitoring are studied. Challenges related to investment costs, social and ethical issues, standardization, data ownership, data security, etc., are discussed. |

**TABLE 1.** *(Continued.)* A summary of the key contributions of state-of-the-art survey papers concerning the deployment of DT technology in various service sectors and vertical industries.

| Ref. | Publication Date | Summary of Key Contributions |
|------|-----------------|------------------------------|
| [9] | 01 October 2018 | This paper conducts a systematic review of DT applications in the industry. The review examines key components of a DT, recent developments in DT technology and main applications of DT technology in industry. Theoretical foundations of DT technology with respect to DT modeling, simulation, verification, validation and accreditation, interaction, data fusion, collaboration, and service from an industrial perspective are detailed. Industrial applications of DT technology in product life cycle (product design, production, prognostics, health management, etc.) are examined. The key patents in the area of DT in industry are highlighted, and well-established DT applications by industrial leaders are outlined. Challenges related to cyber-physical fusion such as robustness and applicability of fusion algorithms, mass data processing, and security threats are discussed and potential areas for future work are outlined. |
| [10] | 14 November 2019 | The paper presents state-of-the-art definitions of a DT and discusses the key functional traits to be possessed by a DT such as seamless connection, continuous data exchange, data storage capability, exploitation of ontologies, ability to treat high dimensional data, continuously improving AI models, etc. The application of DT technology in domains such as manufacturing, aviation, hospital management, and precision medicine is presented. Implications of the different studies on DT design aspects and life cycle are presented. Finally, open research challenges pertaining to ethics, security and privacy, development costs, technical limitations, regulations, etc., are addressed. |
| [14] | 16 December 2019 | This paper conducts a survey to justify the need for a DT of production systems in the automotive production plant. The paper provides definitions and state-of-the-art of DT technology and body-in-white production system of automotive manufacturing pipeline. Then the survey is conducted on the need for a DT in production planning. Discussions are made regarding automatically created DT in production planning and requirements such as easy data access, faster updating of plant information, extracting information for integration planning, etc., are outlined. The merits of using DT technology in the considered use case are highlighted including time savings, better product adaptation, cost reduction, higher design quality, etc. |
| [15] | 28 January 2020 | This paper reviews the techniques and methodologies pertaining to the modeling of a DT. The value of a DT in different applications such as efficiency, safety, fast control and monitoring, predictive maintenance, risk assessment, etc., is presented. Applications of DT technology in diverse domains ranging from healthcare and manufacturing to meteorology and education are discussed with concrete examples. Challenges such as data management, privacy, data quality, latency, real-time modeling, scalability, etc., are discussed. The key enabling technologies addressing these challenges such as digital platforms, cryptography, blockchain technologies, data compression, 5G communications, edge cloud computing, etc., are presented. The infrastructure and platforms relevant for modeling a DT, such as big data technologies, IoT, communication technologies, computational infrastructure, etc., are investigated. In the end, the socio-economic impacts of DT technology are examined. |
| [12] | 09 March 2020 | This paper carries out a systematic literature review to characterize a DT, identify research gaps, and recognize future research directions. A complete framework and a consolidated vision of a DT are produced by studying the applicability and operations of a DT in different areas such as computer integrated manufacturing, virtual manufacturing systems, predictive control, prognostics and machine health management, advanced control systems, etc. The knowledge gaps are outlined with regard to perceived benefits, product life cycle, use cases, technical implementations, etc. |
| [16] | 28 May 2020 | This paper performs a categorical review of articles related to DTs. Various definitions of a DT are presented and the difference between a DT, a digital shadow, and a digital model is discussed. The application of DT in the areas of smart cities, healthcare, and manufacturing is discussed with several example scenarios (smart cities: city planning, utility usage, etc.; manufacturing: real-time machine performance monitor, product test environment, etc.; and healthcare: simulating drug effects, surgical procedures, etc.). Further, the challenges associated with DT technology, such as the information technology (IT) infrastructure cost, obtaining noise-free and high-quality data, privacy and security, expectations and trust issues, modeling issues, etc., are discussed. |
| [17] | 18 June 2020 | This paper provides a survey of DT technology starting from its original definition in the manufacturing industry to the more recent and relevant proposals in other sectors such as AR/VR, multi-agent systems, virtualization, etc. The article investigates the key characteristics to be possessed by a DT, especially in the context of IoT architectures. Four major application scenarios of a DT are elaborated, namely: IoT virtual sensors, e-health, digital city, cultural heritage, and a generic architectural model of a DT. The future directions for DT research are presented, highlighting its potential to become a key enabler for the softwarization process of physical objects and their interactions within a physical system. Research gaps hindering the full exploitation of DT technology are outlined. Furthermore, some of the industrial and academic platforms that assist in building consolidated DT solutions are highlighted. |
| [18] | 05 October 2020 | This paper reviews DT applications for maintenance. The applications of DT technology across various domains are examined, and the major implications of this on maintenance strategies are studied. Different maintenance strategies considering what steps or activities need to be carried out and when are elaborated. The concepts covering reactive, preventive, condition-based, predictive, and prescriptive maintenance are presented. Predictive and prescriptive maintenance are shown to be the candidates yielding better results with the digitalization efforts and use of DTs technology. Open issues related to the availability of historical data, quality of data, data generation in a synthetic way, defining the maintenance process in detail, cybersecurity, real-time data collection, etc., are discussed. |
| [19] | 05 October 2020 | The paper provides a comprehensive survey on the use of DT technology for efficient verification and validation processes in several application domains. The paper provides the basics of verification, validation, and testing and a brief overview of DT. The key elements of DT essential for verification and validation are outlined and unexploited potential is discussed. Methodological clusters are determined based on the extent of similarity in approaches of using DT for verification and validation. Key application domains such as Aviation, aerospace, manufacturing, product design, robotics, power systems, etc., are explored for the aforementioned purpose. |
| [20] | 11 May 2021 | This paper does a systematic literature review in the area of DT technology, considering technicalities in various application domains, tools, historical uses, definitions, etc. The concept of the DT is described with a wide set of definitions and examples. The context and use cases of a DT in several sectors, such as healthcare, maritime and shipping, manufacturing, etc., are described. The work on DT applications and relevant platforms in the industries (e.g., GE Predix, Microsoft Azure, Siemens PLM, etc.) are highlighted. Insights are provided on the design and implementation of the DT technology, encompassing at least the physical, network, and computing layers. Further, research challenges such as improving sustainability performance using DTs, DT life cycle, and functions, architecture, etc., are discussed. |
| [11] | 12 May 2021 | This paper conducts a survey on DTNs and outlines the differences between a DT and a DTN. The paper establishes the DT as a digital replica of an individual physical entity, whereas a DTN is considered to be the digital representation of an overall physical system, capturing interactions among different physical entities in the considered system. Applications of the DTN in the sectors of manufacturing, aviation, healthcare, etc., are presented. The applicability of a DTN in 6G networks is briefly discussed. The key technological enablers for a DTN, such as edge and cloud computing, communications, data analytics, etc., are examined. The technical challenges in a DTN related to communications among DT entities, data processing, modeling, and computing are analyzed. |
| [21] | 09 July 2021 | This paper considers deployment of DT technology in industrial Internet of things (IIoT) and presents guidelines for the creation of DT in such a setup. The paper emphasizes the need for collection of sufficient amount of relevant data for DT services such as production analytics and predictive maintenance. A detailed study on the relevant digital interfaces for data collection is carried out. A detailed review of digital industrial network protocols including fieldbus, , industrial ethernet protocols, and wireless protocols is provided. A note on the use of 5G networks for communication is also made. Finally, the guidelines for creating a DT in IIoT are outlined in aspects including, data gathering, connectivity, interoperability, scalability, edge node balancing, and security. |

## II. BACKGROUND ON THE KEY CONCEPTS FOR REALIZING DT TECHNOLOGY IN 6G COMMUNICATION SYSTEMS

In this section, we provide an in-depth overview of several critical aspects and key concepts required for the successful deployment of DT technology in 6G communication systems. To that end, we will begin by looking into the historical background of DT technology. Following that, we will discuss the potential implications of DT technology on various aspects of the next generation of communication networks. Then, we will look at the impact of automation and intelligence on DT technology, as well as their combined impact on 6G communication systems. Finally, we will summarize the state-of-the-art literature on the deployment of DT technology in 6G communication systems.

### A. THE HISTORY BEHIND THE DEPLOYMENT OF DT TECHNOLOGY IN TELECOMMUNICATIONS SYSTEMS

David Hillel Gelernter, an American computer scientist, predicted the emergence of DT technology in his book *Mirror Worlds* published by the Oxford University Press in 1991 [32]. In Mirror Worlds, David Hillel Gelernter initially did not use the term DT. Instead, he used the terms Mirror, Mirror Worlds, and Mirroring in order to refer to a computerized model of a product that would be obtained through the application of computer technology, programming, and communication systems in the near future. However, the concept, model, and elements of DT technology within the context of manufacturing were first introduced by Michael Grieves in a presentation at the University of Michigan in 2002 [33]. It was later officially documented by the National Aeronautics and Space Administration (NASA) in a white paper published in 2012, laying the groundwork for the development and deployment of DT technology in the astronautics and aerospace domains [33], [34]. Following that, DT technology has remained one of the most important strategic technological trends in a wide range of industrial applications and businesses around the globe.

Since 2012, advancements in DT technology have garnered considerable attention from industry, academia, and SDOs. We learned during this survey that Industry 4.0, manufacturing, smart cities, aviation, and healthcare are currently the most actively researched and developed areas for the deployment of DT technology within the research community. The use of DT technology in Industry 4.0 is expected to dramatically accelerate product and service innovation, optimize product life cycle management, and enable near real-time diagnostics at previously unthinkable rates [16]. Manufacturing is believed to benefit remarkably from DT technology by reducing maintenance costs, accelerating time to market, and adapting operational processes to the industrial revolution [10]. DT technology is regarded as one of the essential tools for smart cities because it enables cities to be analyzed, planned, managed, monitored, and optimized across a broad range of applications, including mobility and sustainability [22]. In aviation, DT technology enables the construction of a three-dimensional virtual model of an airplane (or a part of one) for the purpose of conducting various types of experiments to predict the outcomes of avionics processes and operations under varying weather and environmental conditions, thereby undoubtedly improving passenger safety, product quality, and design cost [35]. Finally, the potential use of DT technology in healthcare could create a digital replica of human physiology, medical devices, drugs, and chemical substances, enabling doctors, clinicians, and scientists to diagnose a variety of severe and life-threatening diseases, improve treatment planning, provide patient-specific treatment, and conduct research on new diseases and drugs, among other things [11].

In addition to the aforementioned fields, we noticed during this survey that the development and deployment of DT technology in the telecommunications sector has gained considerable attention, most notably from industry since 2018. Numerous start-ups have been founded around the world, various vision statements from telecom vendors have been released, and several technical panel meetings have been scheduled to promote the possibility of the deployment of DT technology in communication networks. These early-stage research and development initiatives unequivocally demonstrate that there is a widespread consensus throughout the communication society that DT technology has the potential to play a revolutionary role in the empowerment of communication systems, particularly 6G networks [36]. It is strongly believed that advanced digital modeling and twinning of nodes and transport links within a telecommunications system enable an operator to maintain complete real-time control over the entire network infrastructure, as well as to acquire comprehensive, up-to-date knowledge of network performance and end-user behavior [37]. The primary benefits of deploying DT technology in a telecommunications network are that it empowers network planning and design, enables predictive maintenance techniques, simplifies management and orchestration of complex network infrastructures, and provides on-demand network optimization through the creation of customized DTs for each process and layer [13]. As a result of these advantages, network operators can decrease total costs, resources, and time spent on a network, while increasing operational efficiency during the network planning, design, run-time, optimization, and termination phases.

### B. THE IMPLICATIONS OF DT TECHNOLOGY ON THE OPERATION AND PERFORMANCE OF 6G COMMUNICATION SYSTEMS

The goals of 6G communication systems are to significantly increase capacity, support extremely low latency, enable advanced industrial use cases, and address emerging societal challenges compared to their predecessors by leveraging a new generation of revolutionary technologies and network architectures [2]. In order to accomplish these objectives, the 6G communication systems must overcome numerous challenges, including those relating to performance, operation, architecture, and cost. The deployment of DT technology

plays a critical role in addressing these challenges by visualizing the entire 6G ecosystem and operating environment with the goal of managing network services and resources autonomously, as well as analyzing the behavior of vertical industries and end users in real-time. Taking into consideration the complexity and scale of the underlying infrastructure, the entire 6G communication systems and their physical and logical assets, such as, base stations, network services, transport networks, network elements, etc., can be digitally twinned [38]. Therefore, compared to state-of-the-art planning, monitoring, controlling, and optimization technological instruments, the pairing of DTs and physical objects of the above assets of 6G communication systems allows network operators to plan, monitor, analyze, control, and optimize resources and services in an efficient and cost-effective manner.

In order to exemplify the implications of DT technology on the performance and operation of a 6G network, we assume two distinct DTs that network planners can create: one for the underlying infrastructure layer and another for the end users or non-public networks (NPNs). These virtual doppelgängers can be deployed independently or in conjunction with one another. In either case, the network operator must ensure that there is strong isolation between them and that the data associated with one DT is not accidentally exposed to the data associated with the other. Finally, these DTs enable network operators to perform virtual system testing prior to implementing changes in a real 6G network [38]. Lessons learned in the virtual world can be extremely beneficial when optimizing the performance and operation of the nodes and links in a physical 6G communication environment [2].

The DT of the underlying infrastructure layer can be used to visualize physical objects from a 6G core network (CN) down to the extreme edge with the purpose of autonomously managing all network elements and resources involved in the realization of a 6G communication system [38]. This E2E twinning of the underlying infrastructure layer can be obtained in several sub-twinning phases. For instance, a number of DTs for the CN, transport network, and RAN could be created and then combined to form an E2E DT for the 6G infrastructure layer. Among them, let us assume the DT of the RAN, which could be created to facilitate the effective management of a 6G RAN [39], specifically for twinning base stations. These base stations are composed of various physical resources and equipment, including antennas, optical and coaxial cables, power systems, towers, sensors, and surveillance cameras [40]. The RAN management function collects a variety of data pertaining to performance, functional, and operational metrics, which can then be analyzed using advanced ML algorithms and subsequently fed into the DT of the RAN. Therefore, viewing the DT of the RAN as replicas of these equipment would enable network operators to provide predictive maintenance, further improve performance, and optimize operations (including those of openness, disaggregation, virtualization, cloudification, network slicing, and intelligentization) of the emerging 6G RAN architecture [7].

The DT belonging to the end user or NPN can be utilized to simulate the coverage areas, anticipate the required QoS and quality of experience (QoE) of end users/NPNs in real-time, provide more accurate status of the current operational status of a 6G network, and prevent the 6G network from becoming congested [26]. For example, a DT for eMBB end users can visualize the demographic composition of a coverage area, the nearby base stations, the interconnections between base stations and eMBB end users, and the mobility of end users, among many other aspects. This virtual representation enables network operators to model and predict the operating environment, radio interfaces, network traffic, and allocated frequency with pinpoint accuracy. Similarly, a DT that is designed for an NPN, such as V2X communication services, can visualize roads and highways, full-road network coverage, traffic lights, speed limits, rush hours, and many other metrics [41]. These characteristics of both end user and NPN DT instances can help improve the performance of a 6G network, enhance the delivery of personalized content and value-added services to end users, and optimize the operations and processes within NPNs [26].

To enable a network operator to design and instantiate the aforementioned or any other type of DT for 6G networks, a number of requirements must be met. The first and foremost requirement is allegiance. Each DT must accurately imitate the behavior of the physical object by capturing service configuration, network topology, traffic volume, and dynamics of a 6G network [26]. The second requirement is intuitiveness. The software and tools for digital twinning should be able to automatically instantiate, manage, and terminate DTs of a 6G network in a time, resource, and effort efficient manner utilizing SDO-defined models [13]. The third requirement is amalgamation. The DTs of a 6G network must be capable of merging with live digital twinning software models. This enables the DTs to evaluate plausible operation-related scenarios in 6G networks [13]. The fourth requirement is rapid and real-time implementation. The DTs in a 6G network must use cutting-edge simulation techniques in order to achieve execution speeds faster than real-time [42]. To dynamically enable such an integrated test bed with digital twinning equipment, the DTs in the 6G network must be capable of synchronizing live and simulated components in real-time. Finally, the fifth requirement is visualization. The DTs must contain tools for efficiently and accurately visualizing network traffic, underlying infrastructure, and end users (or NPNs) in order for the analysts and planners to gain deep insight into the operations of a 6G network [13]. Additionally, it must generate detailed statistics and timely reports that can be used to compare various deployment options.

## C. THE INTEGRATION OF INTELLIGENCE AND AUTOMATION INTO DT TECHNOLOGY IN 6G COMMUNICATION SYSTEMS

Each DT in a 6G network requires the collection of large amounts of data in real-time. The DTN collects this data using a variety of data collection methods from the various

**TABLE 2.** A summary of state-of-the-art contributions related to the deployment of DT technology in 6G communication systems.

| Ref. | Publication Date | Topics | Major Contributions |
|------|------------------|--------|---------------------|
| [43] | 05 June 2020 | DT and vehicular networks | The paper considers software defined vehicular networks facilitating extension of computation resources in vehicular networks. DT is used to construct a virtual intelligent network space envisioned to realize the iterative update of the networking schemes in an adaptive way. |
| [44] | 19 June 2020 | Metasurface and THz | The authors propose a THz signal guidance system in which the DT technology is used in order to model, predict, and control the characteristics of signal propagation of an indoor space in futuristic 6G communication systems. |
| [45] | 12 July 2020 | Relationship between DT and 5G | The relationship between 5G and DT technology is examined with the goal of demonstrating their value in the context of Industry 4.0, manufacturing, and smart cities in order to facilitate the digital transformation of future societies. |
| [46] | 18 August 2020 | Edge computing and intelligence | Integrates DT technology into the edge of 6G wireless networks with the goal of migrating computation and real-time data processing, as well as proposing an ML-assisted solution for improving security and reliability. |
| [47] | 24 August 2020 | Task offloading at network edge | Puts forward a paradigm in which the DTs of servers at the edge of a 6G network represent edge server states, and the DTs of edge computing offer training data for effective task offloading. |
| [48] | 24 November 2020 | DT empowered Internet of vehicles (IoV) | This paper considers edge computing and DT empowered IoV to achieve intelligent transportation capabilities. The problem of overloading at the edge devices is dealt with a service offloading method based on deep reinforcement learning (DRL). |
| [49] | 20 December 2020 | Deploying DT technology in 5G systems | The article discusses the integration of DT technology into 5G systems, with a particular emphasis on network operation and service simplification. It also introduces several characteristics of DT technology and highlights several 5G use cases that leverage it |
| [50] | 29 December 2020 | DT for network slicing | This paper develops a scalable DT for network slicing with the goal of capturing the intertwined relationships between network slice instances and monitoring their E2E metrics in a variety of network environments. |
| [51] | 01 January 2021 | DT and optical communication | In this paper a DT framework is proposed for intelligent fault management, flexible hardware configuration, and dynamic transmission simulation with assistance from deep learning (DL), for optical communication as a potential 6G component. |
| [52] | 16 February 2021 | Integrating Industry 4.0 into 5G | Provides a comprehensive overview and critical analysis of the deployment of DT technology in Industry 4.0, followed by a discussion of how these two concepts can be integrated into 5G and beyond mobile networks. |
| [53] | 10 March 2021 | Network optimization | Introduces DT technology for the optimization and development of 5G and beyond networks, investigates a variety of functions and design options of DT, and extends DT to several mobile network use cases. |
| [54] | 15 March 2021 | Building a network of DTs | Overviews the concept of establishing a network of DTs to address real-world issues in telecommunications. The authors also demonstrate two applications: information organization in a telecommunications network and data traffic monitoring. |
| [55] | 23 March 2021 | DT review and requirements | This article provides a comprehensive overview of DT technology and its application aspects, as well as a detailed discussion of the networking requirements for DT deployment and the key enabling technologies to meet those requirements. |
| [56] | 07 May 2021 | 6G network self-optimization | By designing and instantiating a DT for a 6G network, this article proposes a combined approach of expert knowledge, reinforcement learning (RL), and DT technology for self-optimization of wireless communication networks. |
| [57] | 11 May 2021 | Creation of DTs for Networks | This white paper discusses the importance of creating an accurate DT for communication networks, using topology information, accurate network traffic, and analyzing the networking requirements of larger systems. |
| [58] | 15 May 2021 | DT communication framework | Describes the DT communication models, demonstrates how DT communication can be used to create a novel framework for mobile agent systems by integrating communications, AI, and cloud computing, and discusses open research challenges. |
| [59] | 10 June 2021 | Vehicular edge computing | Incorporates DT technology and AI into the design of a vehicular edge computing network, schedules compute task offloading and edge resource allocation, and proposes a graph-driven vehicular task offloading solution for 6G. |
| [60] | 18 August 2021 | Performance analysis of DT edge networks | This paper proposes using DT to offer training data and optimize task offloading from the devices to edge servers. The Lyapunov's optimization approach and enhanced actor-critic learning are employed for cost and latency reduction in MEC mobility scenario. |
| [61] | 22 September 2021 | Security training in 5G and 6G | Under the DT technology, it combines the demand for a cybersecurity training playground with ML applicability, introduces ML tools that can be integrated into cybersecurity, and enhances the model training process applied to cyber space. |
| [62] | 28 September 2021 | E2E service level agreement (SLA) | A DT-assisted solution is proposed to enable the mapping and full lifecycle management of the physical objects. To ensure SLA compliance, all network operation policies are generated and verified within the proposed DT-assisted framework. |
| [63] | 06 October 2021 | DT architecture for IoT in 6G | Proposes an IoT-centric cyber-PT architecture in 6G systems. The proposed framework is claimed to be capable of addressing the challenges inherent in deploying DT technology in 6G in a reliable, adaptable, and affordable manner. |
| [64] | 12 October 2021 | DT for road traffic using 5G | The paper presents the results of a highly accurate DT of a real-world road traffic project between two German cities, Aachen and Düsseldorf, taking three different scenarios into account through the use of 5G and beyond networks. |
| [65] | 21 October 2021 | DT service demand and MEC response | This paper considers the problems of service congestion and long-term DT service stability in the Digital Twin Edge Networks and proposes incentive-based congestion control scheme for stochastic demand response. |
| [66] | 08 November 2021 | DT and federated learning (FL) | This paper looks into deployment of DT in IoT and exploits blockchain to propose DT edge networks framework for enabling flexible and secure DT construction. Co-operative FLis developed to assist smart devices in building DT at network edges belonging to different MNOs. |

**TABLE 2.** *(Continued.)* A summary of state-of-the-art contributions related to the deployment of DT technology in 6G communication systems.

| | | | |
|---|---|---|---|
| [37] | 15 November 2021 | Edge network and association | Proposes a model for a DT-assisted edge network based on the integration of DTs and edge networks to enable new functionality, as well as develops a RL-based algorithm for efficiently solving the DT placement problem. |
| [67] | 19 November 2021 | DT in 6G empowered industry | The challenges to DT-driven industry by human existence in the industrial environment are identified; novel human-machine interface solutions are surveyed as pillars in the context of 6G communication systems. |
| [68] | 06 December 2021 | Vision for 6G and Industry 5.0 | Inquires about a future vision for the digital society that incorporates DT technology and intelligence into Industry 5.0 and 6G mobile communication systems. |
| [42] | 15 December 2021 | Relationship between 6G and DT | Examines the relationship between 6G and DT technology, describes DT technology and its characteristics and requirements, discusses the application of DT technology in 6G, and concludes with a number of future research directions and observations. |
| [69] | 04 January 2022 | Challenges and opportunities of DT | An architectural framework is proposed for the efficient management of futuristic networks. It is argued that ML algorithms in combination with DT technology enable the accurate and efficient construction of physical networks. |
| [70] | 12 January 2022 | Resource and service management | Proposes a DT-enabled architectural framework, augmented by AI, to handle the variability and complexity inherent in 6G networks, while also providing intelligent resource management and service orchestration. |
| [13] | 19 January 2022 | Edge computing and layers | Discusses the functional and innovative use of DT in smart industries, expands on this perspective by reviewing and reflecting on recent research trends, and highlights DT technology deployment in various communication layers of 6G networks. |
| [71] | 24 January 2022 | DT-empowered network slicing | In this paper a DT-enabled framework is proposed to create a digital mirror of a physical slicing-enabled B5G network in order to simulate its environment and forecast the network's dynamic properties. |
| [72] | 25 January 2022 | Edge computing architecture | Studies a DT-enabled edge computing architecture and its application to industrial automation, in which multiple IoT devices intelligently offload computing tasks to multiple servers with the goal of reducing E2E latency. |
| [73] | 04 February 2022 | Efficient energy consumption | Focuses on efficient energy consumption in 5G and B5G cellular systems from two distinct aspects: minimizing the energy consumption of wireless systems and designing energy-efficient architectures for communication systems using DTs. |
| [26] | 05 February 2022 | Survey and challenges | Provides key concepts and a comprehensive overview of the architectural frameworks and high-level design aspects of DTs for wireless and wireless for DTs, discusses open research challenges, and proposes possible solutions. |
| [36] | 11 February 2022 | Vision and architecture | Presents several critical design requirements, compares various DTs, proposes an architectural framework for 6G communication systems enabled by DT technology, and discusses future research directions. |
| [74] | 03 March 2022 | DT assisted resource allocation in IoV | This paper considers edge devices sharing communication, computation, and caching resources to support low latency applications for IoV. DT technology is leveraged to construct a virtual digital space and the relevant data is used to train the AI model for optimal resource allocation. |
| [75] | 24 March 2022 | Innovations enhanced by DT | Explores the challenges confronting telecommunications, demonstrates how experimentation-driven innovation combined with AI can improve speed and effectiveness, and discusses the benefits of using realistic DTs of a network. |
| [76] | 03 April 2022 | RL in DT technology | The source-to-target problem is solved using DRL algorithms in DT-enabled mobile communication systems. According to the authors, such algorithms are significantly effective for domains with varying blockage dynamics. |
| [77] | 10 April 2022 | Representation of physical objects | An optimal learning environment is modeled at the edge of 6G wireless networks in order to accurately evolve the affinity between a DT and its respective physical object with the primary goal of maintaining synchronization among them. |
| [78] | 20 April 2022 | Reducing data traffic in 6G | DT technology is proven to benefit emergent intelligence (EI) in wireless scenarios by improving the information exchange efficiency. A swarm-based solution of multi-agent localization and routing is implemented and evaluated for demonstration. |
| [79] | 21 April 2022 | DT and satellite-terrestrial networks (STN) | The paper considers the problem of frequent handovers in STN and reduced link utilization and proposes using DT to map the physical network to virtual space. Subsequently, optimal inter-satellite routing scheme is designed to improve the quality of data delivery between satellites. |
| [80] | 31 May 2022 | DT assisted routing in vehicular networks | The paper looks into the intelligent DT-based software-defined vehicular networks where virtual network in DT is used for training and policy generation. Subsequently, deployment and relay selection is done in physical networks and an intelligent DT hierarchical routing is designed. |
| [81] | 04 July 2022 | DT empowered IIoT and FL | This paper proposes DT based IIoT architecture assisting real-time processing and intelligent decision making by capturing the properties of industrial devices. An optimized FL scheme with a DT assisted DRL is used to tackle data transmission overhead and privacy leakage. |
| [82] | 25 August 2022 | FL for DT in air-ground 6G networks | The paper considers deployment of DT in unmanned aerial vehicles having energy limitations and scarce computational capabilities. A FL and distributed incentive based lightweight DT architecture is proposed leveraging high performing diverse ground network devices. |
| [83] | 12 September 2022 | DT driven blockchain in 6G networks | The paper considers using DT in the 6G networks for enhanced performance. The problems of data privacy and security due to use of AI and ML are addressed using transfer learning and blockchain technology. |
| [84] | 12 September 2022 | DT enabled resource allocation | This paper considers a FL framework in a heterogeneous cellular network and integrates DT and MEC technologies to combat congestion. The DT assisted framework is used joint optimization of resource allocation to the user devices and user device-base station association. |
| [85] | 21 September 2022 | DT assisted task offloading in IoV | This paper proposes a DT framework for vehicular task offloading and re-configurable intelligent surfaces (RIS) configuration in IoV. DT enables digital representation of physical IoV environment assisting DRL in joint optimization of task offloading and RIS configuration. |

domains, layers, nodes, and links that exist in a 6G network. Since the collected data might be in a variety of formats and structures, it is critical for the DTN to "perform filtering, correlation, cleansing, anonymization, pseudonymization, augmentation, and labeling operations on [input data collected from the aforementioned parts of a 6G network]" with a high degree of accuracy [7]. Following the completion of the data collection process, the input data is normalized and translated into a standard and unified data format that the DTN could understand for further processing. This common data format enables the DTN to rapidly learn about the network performance parameters for each component of a 6G network, simplify complicated computational tasks, and leverage data analysis techniques to find network traffic trends and detect aberrant traffic in advance.

The DTN then employs AI techniques such as supervised, semi-supervised, RL, DL, FL, and other advanced ML-assisted algorithms to accurately, reliably, and efficiently create the corresponding DTs for the physical components in the 6G network [86]. Following that, the 6G network makes use of these DTs and the information provided by the DTN to anticipate and test various network conditions in advance, to evaluate various network deployment scenarios and algorithms, and to analyze various performance improvement methods. Before the 6G network can use the commands and recommendations generated by the DTN, they must be converted into a format that the 6G network understands using specialized data formatting and conversion techniques. On the basis of these recommendations, the 6G network is expected to take the necessary course of actions in order to reserve resources, improve security and privacy, and enhance network performance, among many other improvements.

This interaction between DTN and 6G communication systems must be performed through a set of trusted, authorized, and well-defined application programming interfaces (APIs). The APIs of the DTN must communicate with the APIs of the 6G communication systems through the use of an API broker [7]. The API broker defines a proper and well-defined method of interaction that enables automated and zero-touch requests for information, DTs, and services between the DTN and 6G communication systems. This automation significantly reduces the costs and complexity of the interactions between the two systems. Finally, in order to accurately create a DT for a 6G network in an intelligent and automated manner, there is a need to define a standardized architectural framework. To that end, a number of SDOs are working towards this goal. We delve deeply into the architectural framework of DT technology in the context of 6G communication systems in Sec. IV.

### D. A SUMMARY OF THE STATE-OF-THE-ART LITERATURE RELATED TO DT TECHNOLOGY IN 6G COMMUNICATION SYSTEMS

This subsection summarizes the state-of-the-art literature on the deployment of DT technology in 6G communication systems in order to compile a list of all selected articles along with their associated category classifications. A summary of the literature is provided in Tab. 2, which is made up of four columns: (a) *Reference*, which contains a link to the publication; (b) *Publication Date*, which indicates when the publication was made; (c) *Topics*, which highlights the main topics of the publication; and (d) *Major Contributions*, which provides a brief summary of the major contributions of the publication. The primary objective of producing a summary of relevant literature for this section is to highlight the academic and industrial contributions to the deployment of DT technology in 6G communication systems. We purposefully omit contributions from SDOs. Section IV of this article summarizes the contributions of SDOs to the topic.

On the basis of the foregoing assumptions, we conducted a systematic search for relevant publications using a variety of literature search engines, including Google Scholar, Semantic Scholar, and ResearchGate. In contrast to several survey papers listed in Tab. 1, we did not limit our search to a specific time period. Additionally, unlike some of the survey papers compared in Tab. 1, we did not select any specific database in order to avoid bias in favor of certain scientific publishers, such as IEEE Xplore, ScienceDirect, Springer, Elsevier, Hindawi, and others. In light of this, we used a variety of search strings such as *digital twin(s)*, *digital twinning*, *digital twin in 6G*, *digital twin in wireless communication*, *digital twin in mobile networks*, and *digital twin survey*. This search was conducted in September 2022. We compiled a list of around four hundred publications on the subject which, we strongly believe, provides a fairly accurate snapshot of the current state-of-the-art in this particular area of research.

Having the above in mind, we excluded all publications from this study that were not written in the English language. We then divided the list of found publications into two categories. The first category included all DT-related survey papers that were then summarized in Tab. 1. The second category included all non-survey DT-related publications, such as research papers, white papers, position papers, and technical reports. Due to the scope of this article, we also removed all publications from the second category that focused on the deployment of DT technology in areas other than telecommunications systems, such as manufacturing, smart cities, healthcare, etc. Hence, we found a list of only those publications that are focusing on the deployment of DT technology in 6G communication systems. We also obtained numerous articles to include in our analysis by browsing through the reference lists of all acquired publications that met the above criteria. We discontinued our search once no new publications were discovered.

From the results, it can be observed that practically all publications relating to the deployment of DT technology in telecommunications systems, specifically in 6G communication systems, have been published after 2020 as indicated in the *Publication Date* column of Tab. 2. We are also observing that DT technology is gradually being integrated into a variety of critical research areas in 6G networks, such as network slicing, resource management and orchestration,

site configuration, security and resiliency, and many others, as shown in the *Topics* column of Tab. 2. Likewise, it has also gained considerable attention for being developed and deployed from the CN down to the extreme edge of 6G communication networks. Finally, we arranged the publications included in this survey based on their publication date in ascending order and provided a brief summary of the contributions of each of the publications in the *Major Contributions* column of Tab. 2.

## III. POTENTIAL USE CASES AND KEY APPLICATION AREAS EMPOWERED BY DT TECHNOLOGY IN 6G COMMUNICATION SYSTEMS

In this section, we discuss the key areas related to the deployment and operation of B5G or 6G networks, that can significantly benefit from DT technology. This section highlights potential application areas across different domains such as, RAN, edge, CN, E2E and all layers of the network such as, physical layer (PHY) and medium access control (MAC), as well as the key benefits of deploying DT technology in each area. To begin with, we will look into the application of DT technology in accelerating the deployment of 6G services as well as evaluating future scenarios and deployment possibilities in 6G communication systems. Then, we will explore the prospects of applying DT technology for training ML algorithms that are envisioned to optimize the operation of 6G systems. This will be followed by the usage of DT technology in studying the impacts of configuration changes in a 6G system. Further, we will address the application of DT technology in simplifying 6G deployment site configurations, followed by assistance of DTs in THz propagation studies and operation of RIS in 6G communication systems. Then, we will present the benefit of using DT technology for RRM, RAN moderation, and traffic steering in 6G communication systems. After this, we will look into improving the performance of MEC in co-operation with DT technology. In addition, we will investigate the use of DT technology in handling challenges pertaining to security and resiliency in 6G communication systems. In the end, we will discuss the application of DT technology in making the management of network slices easier and more efficient.

### A. LEVERAGING DT TECHNOLOGY FOR TESTING AND RAPID DEPLOYMENT OF NOVEL 6G SERVICES

In 6G mobile communication systems, a variety of novel services with varying degrees of requirements are anticipated. These services range from VR, AR, XR, holographic telepresence, cobots, re-configurable and self-assembling robots to telemedicine and healthcare services [1]. They can be oriented to a smaller group of users (e.g., emergency personnel, self-assembling robots, etc.) or tailored for mass market. For instance, event-customizable AR/VR for immersive and interactive sports events. These futuristic services have stringent performance requirements, and the related SLAs have extremely challenging key performance indicators (KPIs) to fulfill [87].

A DTN must be modeled carefully by taking into account all the relevant network entities, domains, existing services, network dynamics, etc., in order to capture the current network state as closely as possible. The new service being considered for launch on the actual network can be deployed on the previously established DTN. The performance of the new service and its effect on services that are currently being handled by the network, can be simulated and investigated using various analytical models [88]. It is possible to gain valuable insights into the potential conflicts or issues that may arise as a result of deploying the new service under the given network circumstances. It enables the network operators to take appropriate decisions regarding the launch of a new service. Further, necessary steps such as tuning the service parameters or adjusting the network for an increase in load, to alleviate any potential issues that are indicated by the DTN can be tested to make a conclusive decision on solutions (e.g., network upgrades, revised usage assignments, etc.) before launching a new service on the network [88].

### B. DT TECHNOLOGY FOR ASSESSING FUTURE SCENARIOS AND DEPLOYMENT OPTIONS IN 6G COMMUNICATION SYSTEMS

As a consequence of the plethora of new services that will be added within the context of 6G communication systems, new subscriptions at an unprecedented pace, new vertical industries, and businesses demanding operational support from the network, making pro-active upgrades to the network or building out the network will become essential for the industry to adapt and sustain. It becomes critical for the network operators to be aware of this and be well equipped to make pro-active decisions. The timing of the 6G network deployment or upgrades is as equally important as their execution. Careful analysis of ongoing trends as well as anticipating new developments is necessary to predict service requirements in the future. After the required capabilities and compute capacity for the network are deduced, it becomes important to evaluate these deductions against diverse future scenarios and conditions.

A DT representing the newly deduced network capabilities and functions can be used to test these new scenarios before the actual build-out of the network [88]. It is possible to thoroughly explore different options for improving network coverage, extending the transport and cloud infrastructure, and comparing the resulting performance gains. Further, it is feasible to investigate the effects of various failure events on the services. The DT makes it possible for the network operator to determine the weak spots and assists in gauging the ramifications of failure events. It allows an in-depth evaluation of customer expectations and the financial risks associated with SLA violations. This knowledge proves to be valuable in the planning phase so that the investment can be optimized and steered to the areas of maximum benefit.
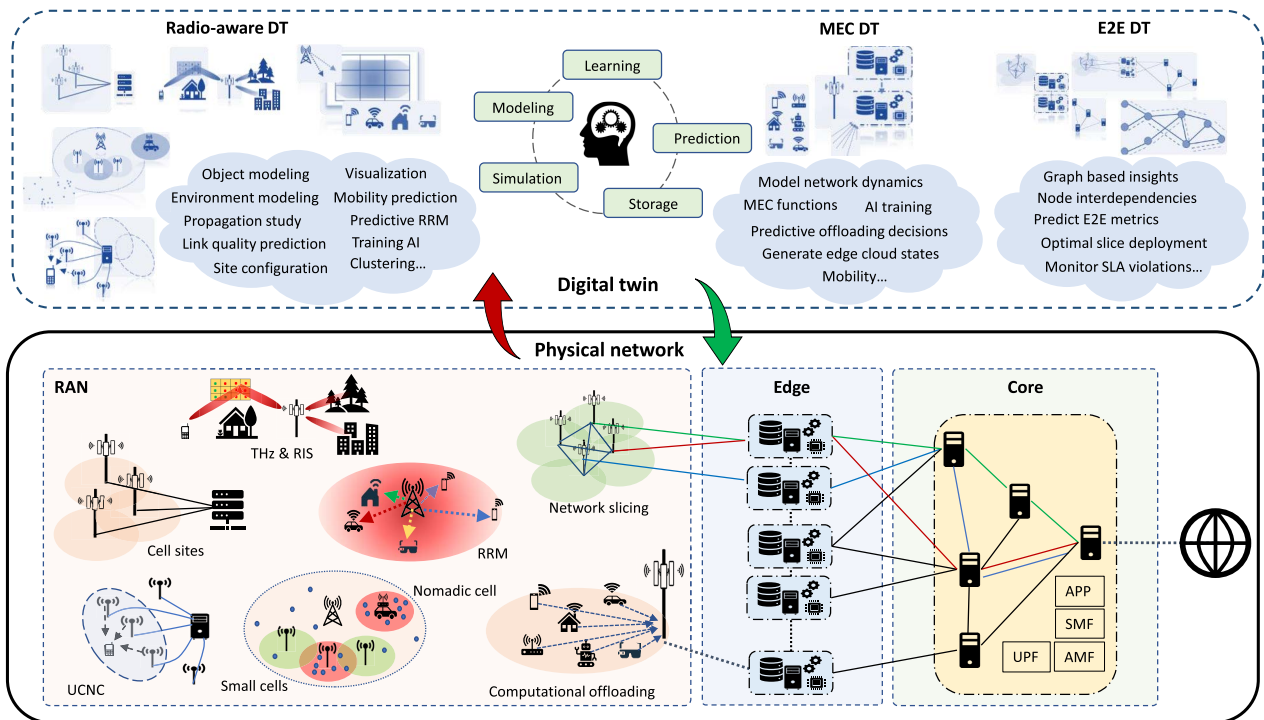
**FIGURE 2.** The application of DT technology in various domains and solution areas of the envisioned 6G communication system thereby achieving enhanced system performance and simplifying system operation. The definitions of terms used in Fig. 2 that are not defined elsewhere in the paper are as follows: UPF, AMF, SMF, APP.

## C. DT TECHNOLOGY FOR BUILDING PLATFORMS TO TRAIN AI MODELS USED IN 6G COMMUNICATION SYSTEMS

AI is anticipated to play a pivotal role in the technological advancement of B5G and 6G mobile communication systems. The ML algorithms can significantly enhance the performance of the network in several domains and layers, including optimization of PHY layer operation, power control, modulation and coding scheme (MCS), waveform selection, RRM based on signal-to-interference-plus-noise ratio (SINR) predictions, caching in MEC, slicing of the network, etc. [89]

However, the key to the efficient and accurate functioning of the AI engine is the availability of versatile and realistic data in large quantities. It allows the ML algorithms to become well-trained so that the resulting predictions can be highly accurate under all circumstances. Accumulating diverse data from the live network is not only time-consuming but also expensive. Further, certain situations or irregularities in the network are rare, and it is non-trivial to capture those in network measurement campaigns. The DTN can generate simulated data by undergoing a number of iterations and diverse scenarios. This rich data helps the training of the ML algorithms, thereby teaching the AI models about real-world situations that otherwise turn out to be very rare in the testing phase [88]. Supervised ML is the most commonly used ML technique, where the model is trained based on labeled data. However, it is beneficial to obtain unforeseen patterns from the available data in some cases. RL is one such ML technique

that allows the model to learn in an unsupervised fashion, relying on the rewards obtained when specific actions are taken in a given environment. However, deploying such a model for training in a live network is risky, as it may negatively impact network performance while learning to obtain rewards. In addition, training such a model against certain rare situations or failures is non-trivial in a real network. Nevertheless, a DTN can be used as a safe virtual network environment to train the RL agents, which also permits testing the same rare scenario multiple times and allows the learning agents to find different novel ways to obtain rewards.

## D. DT FOR TESTING THE IMPACT OF CONFIGURATION AND FUNCTION CHANGES IN 6G COMMUNICATION SYSTEMS

Before implementing a new network configuration, upgrading the software, or applying a new AI model to the network, it is crucial to test its functionality and performance. The actions are only then applicable to the entire network. In the context of modern cellular networks (5G and B5G), the telecom industry recognizes continuous integration and continuous deployment (CI/CD) as a requirement for managing the increasing influence of the digital value chain on it. The CI/CD is a framework that enables the continuous building of software, as well as testing, deployment, and validation throughout its lifecycle. The telecom vendors are employing CI/CD practices to enhance feature flexibility and improve software quality [90].

Canary testing is frequently performed as part of the continuous integration and deployment pipeline to ensure that the services are performing as expected [88]. Canary testing allows release of new configurations or changes to a selected small group of users and validates functionality and performance before rolling it out to all users. A DT representing a live network can act as an efficient tool for validating these new configurations, upgrades, and AI models with the advantage of operating in a safe virtual environment. For instance, assessing the desired steps required for deploying the new software in the cloud environment and ensuring that there are adequate resources to conduct the test. On a successful test, the network can switch to this new version [88]. In the case of autonomous networks, the network management entity independently decides the steps to ensure the expected performance of the services and to achieve the goals defined for network operations. It becomes crucial to understand the effect of these steps, and a DT can assist with testing these steps by evaluating their consequences and estimating any degradation in relevant KPIs. Thus, a DT can facilitate the selection of the optimal steps or actions prior to their application with live services [88].

### E. DT TECHNOLOGY FOR SIMPLIFYING AND ACCELERATING SITE DEPLOYMENT CONFIGURATION IN 6G COMMUNICATION SYSTEMS

Before the deployment of a network at a given site, it is essential to carry out radio planning by studying the environment where the radio units will be deployed. Determining the appropriate placement and optimal configuration for the site will yield the best coverage and enhance the network performance. Modeling a DT inheriting all the essential properties and dynamics of the deployment-ready environment (cell sites) is highly valuable for the aforementioned task as depicted in Fig. 2. Physically precise models scaling up to the city level can be built, considering the location of buildings, materials used in construction, foliage, vegetation, etc. It is possible to append the components of the network and their attributes such as, base station position, height, elevation, antenna patterns, etc., on top of this layer. Then, the incorporation of the radio propagation data is viable. For this purpose, advanced techniques such as ray-tracing can be used, which enables prompt calculation of signal quality at all points in the considered environment (e.g., city) as well as opens doors for visualization.

A DT that has a virtual representation of buildings and other physical objects and is capable of mimicking the behavior of actual materials as closely as possible enables accurate calculation of the intensity of reflections. Further, it allows for simulation as well as visualization of signal paths and antenna beamforming. For instance, lobes can represent transmitter beamforming, straight lines can denote signal paths, and a coloring scheme with blue depicting the weakest and red being the strongest can show signal strengths in decibels. Similar illustrations are possible for other performance indicators such as link throughput, latency, coverage, etc.

Using such a visualization capability in tandem with VR or XR allows the network engineers to explore any part of the model and remotely analyze the entire site from anywhere. The effects of tuning or adjustments made to the network can be seen by the engineers in real-time, which would otherwise be invisible, such as, signal paths, lobes, strength indicators, etc. This way, a true-to-reality remote simulation of the entire network is possible, which equips the network operators to design highly efficient and reliable networks, conduct remote field trials, and accelerate deployments. Such efforts are already underway to speed up 5G deployments [91] and is foreseen to become a trendsetting tool for the future B5G or 6G tests and deployments.

### F. DT TECHNOLOGY FOR ASSISTING STUDIES OF TERAHERTZ PROPAGATION AND OPERATION OF RE-CONFIGURABLE INTELLIGENT SURFACES IN 6G COMMUNICATION SYSTEMS

6G mobile communication envisions highly challenging use cases requiring extreme radio performance regarding communication metrics, such as coverage and throughput, localization/sensing metrics (e.g., positioning accuracy), or joint metrics, including energy efficiency, and latency. For instance, immersive telepresence with AR/VR applications requires approximately data rates up to 20 Gbps, whereas fully immersive holographic communications require around 1 Tbps [1]. Further, localization precision below 1 cm with a latency of less than 1 ms is anticipated to satisfy stringent conditions on haptic and visual feedback [1]. Use case families of massive twinning, cobots, etc., foresee similar requirements.

The ideal way to fulfill these needs is to use larger bandwidths (in the magnitude of 2-20 GHz), which are abundant only at higher frequencies, namely the upper mmWave band (100-300 GHz) and the THz band (300 GHz-1 THz) [1]. From the perspective of coverage and performance, 6G is expected to operate not only at higher frequencies but use a combination of several frequency bands. Thus, studying the radio operation in the range of 100 GHz to 1 THz becomes pivotal from both scientific and commercial standpoints. The line-of-sight (LOS) signals and reflections from metallic objects highly influence the received power at these high-frequency ranges. Only the concepts of small-scale fading and shadowing that are traditionally used to characterize the channel will not be adequate for 6G system design and evaluation purposes. Additionally, at such high frequencies, the channel is prone to molecular absorption, which negatively impacts the communication link [92]. Thus, carefully studying the propagation aspects and modeling the channel at these frequency ranges becomes crucial.

With a concept similar to Section III-E, a DT mimicking the actual physical environment can be used to carry out THz propagation studies as shown in Fig. 2. A DT can be instrumental in testing the non-trivial or expensive test scenarios in the physical environment. It benefits the study of

THz propagation characteristics and contributes to creating accurate propagation models for a plethora of cases.

As previously stated, THz signals require LOS propagation in order to achieve an adequate signal-to-noise ratio (SNR) for sustaining a reliable communication link. The RIS is proposed as a practical means of supporting such criteria. These unique surfaces can be reconfigured to reflect or redirect transmitter beams as needed [93]. This property is essential for establishing a wireless connection between the source and the target by avoiding obstacles that cause signal attenuation.

A DT that captures the physical propagation space and all the objects in it can assist in optimizing the operation of RIS. With the knowledge of obstacle attributes, such as size, position, material composition, surface roughness, mobile device/access node positions, user mobility, environmental factors (e.g., water vapor concentration), etc., it is possible to efficiently predict the effects of the obstacles and the propagation environment on the quality of the received THz signals. Thus, a DT can be used to model the THz propagation and realistically simulate the effects of the environment on the received power. Furthermore, such DT can explore various signal paths and find the most promising one that maximizes the resulting SNR at the receiver. Subsequently, the RIS in the physical environment can be pro-actively adapted to modify the beam paths in the live network. In this direction, a DT of the physical indoor space equipped with a top-view camera has been implemented in [44]. This DT exploits advanced image processing to obtain obstacle and receiver attributes and adapt beam paths accordingly. Such models are scalable to a city-level and other challenging outdoor environments, and they are desirable to build DTs capable of managing the RIS operation for THz communications.

### G. DT TECHNOLOGY FOR ENHANCING RADIO RESOURCE MANAGEMENT IN 6G COMMUNICATION SYSTEMS

A radio-aware DT (depicted in Fig. 2) is realizable by capturing the intricate details of a radio network. This includes PHY and MAC layer operation of mobile devices as well as access points. Furthermore, it takes into account the attributes of these transmitting/receiving nodes, including physical co-ordinates, trajectories, speed, node capabilities, and RRM procedures, beam patterns, and radio link quality in the entire network. For instance, reference signal receive power (RSRP) or SINR on a grid basis, which can be stored and periodically updated in a database as radio environment map (REM). The key benefit of such a DT is a predictive and pro-active RRM [94]. The DT enables the network to work out preemptive solutions in anticipation of possible errors or failures. For example, the prediction of poor link quality for a mobile device availing URLLC service, at a certain point in the future (time or distance) will enable the network to prepare for such an event with pro-active measures such as allocating more resources, switching to different frequency bands, preparing for new beams, etc. It is beneficial over the conventional reactive measures at the network (e.g.,

re-transmissions), which often fail to satisfy the QoS constraints, such as the delay budget.

Furthermore, a radio-aware DT is equipped with a precise REM that is continuously updated. Efficient propagation prediction mechanisms, such as ray-tracing and extended measurements, aid in constructing and updating the REM. In controlled environments like private factory networks, the radio-aware DT knows the current and future positions of mobile devices and traffic patterns, e.g., sensors transmitting packets of a fixed size at regular intervals. It enables the prediction of interference patterns, and the estimation of SINR in a specific location is thus possible. This aids in designing an efficient RRM mechanism [94].

Another advantage of a radio-aware DT is its capability to predict the link quality between mobile devices and access nodes without the need for full-scale measurements. The digital replication of the PHY layer of the network allows for the usage of data-driven models or enhanced ray-tracing algorithms to precisely estimate the corresponding channel conditions. It can reduce channel estimation overhead, requiring fewer to no channels for direct measurements, thereby improving spectral efficiency [94]. In addition, energy efficiency can also be enhanced, given that the power consumed by the data-driven models or ray-tracing algorithms is lower than the power needed for comprehensive measurements.

With the accurate knowledge of future link conditions, it is possible to carry out RRM on the mobile devices for the entire duration, consisting of a fixed number of transmit time intervals (TTIs), and deliver this information to the mobile device in one go. Such persistent short-term RRM decisions make it possible to signal several radio parameters that are constituents of control signaling in advance to the mobile devices, such as transmit power control, modulation and coding scheme, active bandwidth-part (BWP) selection, time-frequency resource allocation within a BWP, etc. [94]. Nevertheless, the DT requires the knowledge of device trajectories and estimation of transmit buffers of device/access nodes over the considered number of TTIs, to make these short-term RRM decisions efficient. Again, such a technique is more reasonable in quasi-deterministic controlled environments like factory automation. These short-term RRM decisions can reduce the overhead associated with conventional RRM procedures by eliminating the periodic measurements carried out by mobile devices/access nodes to perform RRM reactively.

### H. DT TECHNOLOGY FOR ACHIEVING RAN MODERATION AND EFFICIENT TRAFFIC STEERING IN 6G COMMUNICATION SYSTEMS

6G mobile networks envision services with varying requirements, and the service demand can change over space and time. Designing the radio topology for peak service requirements is therefore unnecessary and inefficient. The network should adapt to the fluctuating demands as necessary [95]. Such intelligent RAN moderation ensures optimal, energy-efficient, and adaptable usage of the radio resources and infrastructure.

Deployment of small cells can offload the macro cells and serve a high density of users concentrated in smaller areas such as shopping malls, offices, stadiums, etc. Keeping these small cells always active irrespective of the user density under its service area is not energy efficient [96]. A DT of the service area covered under the small cells, considering the corresponding mobile devices, their mobility history, running applications, service demands, etc., will be beneficial to predict the resulting user density and data demands for small cells in the near future (refer to Fig. 2). This assists in the proactive activation and deactivation of corresponding small cells, thereby minimizing the wastage of power and spectral resources.

Contrary to the fixed small cell deployments, nomadic nodes (NNs) envision allowing the integration of low-power access nodes with wireless backhaul into vehicles such as private cars and taxis. These movable access nodes help extend coverage or increase network capacity based on data demand [97]. Conventionally, these nodes intend to be stationary during their operation (e.g., parked vehicle), and their availability is random. Nevertheless, they can be activated and deactivated based on coverage, capacity, or energy demands. A DT of such a system in a given service area assists in optimal node selection, taking into account backhaul link qualities at different available NNs and base stations, modeling factors of shadowing, multi-path fading, and co-channel interference, and predicting capacity demands, mobility of users, etc. Additionally, it is possible to moderate the movement of these access nodes proactively based on the real-time projections of service demands from the DT. Thus, network planning is possible on the fly.

Advanced traffic steering procedures are also beneficial in enhancing the energy efficiency of the networks, as they optimize the active operation time of the access points in the network. A user-centric cell-free massive MIMO network architecture is a promising feature of future mobile networks (6G or B5G) [98]. In dense deployment of distributed units (DUs), fewer users are served in these systems, with a serving cluster defined explicitly for each user. Such user-centric no cell (UCNC) architecture eliminates cell edges, providing performance and coverage uniformly for users across the network area.

However, for high mobility users, there exists a mismatch between the estimated channel quality at the time of estimation and the time of application for data transmission. This deviation is known as channel aging [99]. A DT of such a distributed antenna system is applicable for dynamic clustering of DUs and resource allocation as shown in Fig. 2. This DT must take into account the mobility attributes and user history and incorporate channel aging effects using time-varying modeling of the channel that relates the temporal autocorrelation function of the channel with user velocity, frequency, propagation geometry, antenna characteristics, and so on [98]. This way, exploring various methods for RAN moderation and traffic steering is practicable with the capability of testing these methods and comparing them in

real-time using a DT of the considered solution environment before enforcing these actions in the live network.

## I. DT TECHNOLOGY FOR ENHANCING THE OPERATION OF MOBILE EDGE CLOUDS IN 6G COMMUNICATION SYSTEMS

MEC is a promising technology that brings the computational resources, storage, and desired functionalities closer to the device and at the edge of the network (co-located with the access nodes or base stations) [100], [101]. MEC assists in satisfying strict service requirements, including ultra-low latency, high reliability, low energy consumption, etc., and envisions providing novel functions and intelligent services in the B5G or 6G networks by integrating AI tightly into the network [102].

Mobile devices offload their computational tasks to the MEC, playing a significant role in ensuring low energy consumption (e.g., IoT devices). However, the increasing demand for MEC-supported services with diverse requirements has led to heterogeneous edge server deployments [101]. Thus, the network dynamics have become harder to anticipate. Furthermore, plenty of mobile IoT devices demand that they offload their computational tasks to the MEC servers. Hence, it is challenging to devise an optimal task offloading scheme for network management [103].

The network management module needs to perform offloading decisions based on the information of the time-dependent user environment as well as long-term user mobility [101]. 6G foresees several high-mobility use cases with stringent latency and energy constraints, thereby inevitably requiring the usage of MEC at high mobility. It becomes a challenge to plan the sequence of offloading choices since the offloading action at present influences the subsequent offloading decisions.

A DT of the MEC system capable of representing the crucial functions of edge servers and dynamics of the network in real-time can provide an energy-efficient platform for the network management module to train its decision-making potential. DTs are suitable for determining the states of edge clouds and providing the AI algorithms (e.g., RL agents) with valuable training data for making optimal mobile offloading decisions (see Fig. 2). For instance, [47] has developed DTs in this direction and considers the DT of edge servers and the DT of the entire MEC system, depicting the overall complex interactions of the MEC environment. It tackles the issue of computational offloading from mobile devices and aims to minimize the offloading latency with the constraint of an accumulated migration cost.

## J. DT TECHNOLOGY FOR TACKLING ISSUES OF SECURITY AND RESILIENCY IN 6G COMMUNICATION SYSTEMS

6G networks anticipates tight integration of AI into the network to improve the network performance by leveraging the large amounts of data collected from various network entities, layers, and domains [102]. Furthermore,

a large number of IoT devices would be connected to the network with a demand for low power and low latency communication to support desired operations [104]. The intelligent transportation system (ITS) is another vertical industry having a substantial interest in availing communication services from the 6G network to support low latency and high-reliability safety-critical services [105]. In this way, multiple businesses and vertical industries are intertwined with mobile communication technologies and are anticipating maximum support and utilization from 6G networks.

Security becomes a key concern due to multiple parties and several factors including, IoT devices, network components, entities from the vertical industries, etc., involved in the process. The AI engine is one of the promising elements in futuristic networks, which is prone to security attacks [106], [107]. The consequences can range from data breaches, identity theft, and malfunctioning of the network to total network failure. Preparing all the entities involved in the system for such scenarios becomes crucial while designing new and improved security solutions. A DT of the overall system can act as an arena to play out various security breach scenarios in the network. It helps in understanding repercussions as well as designing enhanced security protocols. The same concept is applicable in designing resilient networks that are robust against security attacks, degradation, failures, and other unforeseen factors such as natural calamities. A DT capturing intricate details and dynamics of the network can assist in studying the effects of several what-if scenarios that can cause system damage and degradation. It helps in devising the steps to ensure an operational system despite an adverse situation.

### K. DT TECHNOLOGY FOR EFFECTIVE ORCHESTRATION AND NETWORK SLICE MANAGEMENT IN 6G COMMUNICATION SYSTEMS

The state-of-the-art cellular communication systems are anticipated to support use cases with diverse and challenging QoS requirements concerning throughput, latency, reliability, and many others. Therefore, a one-size-fits-all approach to designing communication networks is inefficient in terms of resource utilization, energy efficiency, network deployment and maintenance costs, and network performance [108]. Network slicing is a revolutionary architectural solution that allows flexible customization of the communication network to serve individual applications and ensures support for a wide range of services using a softwarized and virtualized network design [109].

Network slicing enables the sharing of the physical network and its infrastructure among different tenants as logically isolated E2E virtual networks and manages them autonomously to facilitate the provisioning of robust and flexible services. The NFV and SDN are the main enablers for such flexible and efficient network slicing solutions [109]. However, the wide range of services with diverse and stringent requirements, sharing the same infras-

tructure, and traversing different domains makes it hard to ensure E2E performance for the slices. Efficient monitoring of the network and generating precise E2E metrics are critical for carrying out dynamic and independent network orchestration, satisfying corresponding QoS requirements.

A DTN can benefit the management and orchestration of network slicing in several ways [50]. A DTN can create a digital replica of the physical slicing network and test several what-if scenarios, resource allocation schemes, and such, without impacting the physical network. Further, a DTN can produce and process data of its own by interacting with the physical network. It also estimates QoS performance following any changes in its configuration. A DT for network slicing is crucial in attaining slicing management that is optimally performing and cost-effective. It is also instrumental in continuing performance checks across several operating conditions without affecting the live physical network.

A DTN should consider the physical entities in the slice-enabled networks and the corresponding virtual components. These virtual components are generated or destroyed in real-time, causing them to fluctuate. It makes the development of such a DTN even more complex. Typically, graphs can depict the communication networks with the underlying information structured in a non-Euclidean domain as a result of the inter-dependency among the various network nodes and the irregular topology of graphs. Under such conditions, many well-established ML architectures, such as convolutional neural networks, recurrent neural networks, auto encoders, and their variants, fail to function efficiently [50].

In this direction, [50] proposes a DT for network slicing management based on a graph neural network (GNN) to explore the intricate dynamics and inter-dependencies among network slices, resource utilization, and network infrastructure. This GNN-based DT employs an inductive graph framework to produce feature embedding of the network slices represented as graphs. Subsequently, it predicts the E2E metrics for each slice under a variety of scenarios. The DT monitors the E2E performance of slices by making precise slice latency predictions. This DT functions as a cost-efficient tool to monitor SLA violations as resource utilization increases. The DT also proves to be beneficial in mitigating the effect of link failures by finding the best alternative path (after predicting the new E2E latencies) and migrating the impacted slices accordingly. The concept of such an E2E DT is depicted in Fig. 2. In addition, the DT leverages the optimal deployment solutions for slices in the case of SLA violations. In the same vein, [71] presents a DT of network slicing represented as a graph, using GNN to learn the intricate dependencies of the network slice. A DT-enabled deep distributional Q-network agent learns the optimal network slicing policy based on the graph-based network states derived from the DT. Consequently, DT technology can optimize the complex tasks of network slicing.

**TABLE 3.** A summary of the state-of-the-art activities of the SDOs related to the DT technology.

| Ref. | SDO | Number | Type | Sector | Status | Description |
|---|---|---|---|---|---|---|
| [110] | ISO | 23247 | standards series | manufacturing | published | This standards series provides an overview of the framework for the creation of DTs of observable manufacturing elements such as personnel, equipment, manufacturing processes, among others, in order to achieve functional objectives such as real-time control, predictive maintenance, etc. |
| [111] | IEC | 30173 | standard | IoT | under development | This standard document is currently in the preparatory phase and aims to define concepts and terminology for a DT used in IoT to support six of the United Nations (UN)'s sustainability goals [112]. |
| [113] | IEC | 63278-1 ED-1 | standard | Industry 4.0 | under development | The standard document defines asset administration shell (AAS) as an implementation of DT technology in Industry 4.0. Developed with the help of Plattform Industrie 4.0, this document describes the AAS structure for industrial applications. |
| [114] | ITU | Y.3090 | rec. | telecom | published | This recommendation describes the requirements and provides a reference architecture of a DTN. |
| [115] | IETF | Draft 07 | internet draft | telecom | work in Progress | This draft provides an overview of the concepts of DTNs, i.e., definitions, reference architecture, application scenarios, advantages, and key challenges. It is intended for informational purposes only. |
| [116] | ETSI | CIM 009 | spec. | multiple | published | This group specification provides a formal definition of the next generation service interfaces-linked data (NGSI-LD) specification. ETSI views this framework as bringing standardized access to DTs, as the users can subscribe and access applications-specific context information, which is modelled as attributes in the framework (i.e., DTs of physical entities). |
| [117] | ETSI | CIM 017 | report | multiple | work in Progress | This group report is intended to investigate the feasibility of the NGSI-LD framework for DTs in multiple sectors such as robotics, aeronautics, mobility, etc., and consequently add scenario-specific features to the NGSI-LD framework. |
| [118] | IEEE-SA | P3144 | standard | industry | under development | This standard aims to define DT assessment methodologies, including content, processes, and maturity levels for industries, DT capability domains, and sub-domains. |

## IV. THE ACTIVITIES OF THE STANDARDS DEVELOPMENT ORGANIZATIONS ON DIGITAL TWIN NETWORKS

SDOs have been standardizing terminologies, protocols, architectural frameworks, and technologies in different vertical industries and business sectors to create uniformity amongst vendors, government agencies, consumers, and other relevant third-parties. In this section, we investigate the ongoing activities and efforts to standardize DT technology or DT-related technologies, such as data formats, standardized interfaces, application services, etc., of some of the major SDOs, including ITU-T, IETF, ETSI, ISO, IEC, IEEE-SA, among others. Moreover, we also look at the development of DT technology in different sectors by the different stakeholders. To that end, we begin by exploring different documents from various SDOs and other stakeholders, such as standards, specifications, recommendations, white papers, technical reports, etc., that are made available to the public by the respective organizations. Furthermore, keeping in line with the scope of this article, we focus on the ongoing and planned SDO activities that promote the usage of DT technology in mobile communication networks. Following that, we focus on how a DTN is defined and characterized, and discuss certain requirements needed for its better functionality and serviceability. Finally, we conclude by looking at the proposed reference architecture and discussing its different domains.

### A. STATE-OF-THE-ART LITERATURE ON THE STANDARDIZATION ACTIVITIES FOR DIGITAL TWIN TECHNOLOGY

This subsection provides a summary of different standards and ongoing discussions of the SDOs related to DT technology. With this survey, our aim is to offer a thorough summary to the reader to showcase the ongoing efforts to standardize and provide a unified definition or framework to support the creation of DTs in different sectors. This summary can be seen in Tab. 3 which consists of 7 columns: (a) *Ref.*, which contains the reference link to the publication; (b) *SDO*, which indicates the name of the organization responsible for the corresponding reference; (c) *Number*, which indicates the standard/specification/document number for the DT technology; (d) *Type*, which indicates whether the document is a standard, recommendation, or draft; (e) *Sector*, which indicates the area of interest for which the corresponding standard is written; (f) *Status*, which indicates whether the document is available publicly or is still under development; and (g) *Description*, which provides a brief summary of the document. We conducted this survey using the most relevant search terms such as *digital twins in SDOs, digital twin standards, network digital twin standardization,* and *digital twin frameworks*. The documents are accessed at different online standards databases, including the IEC webstore, ETSI portal, ITU-T recommendation database, and others.

Based on our search results, we have selected the documents that are written in the English language and divided them into three categories. The first category consists of documents that either seek to define DTs with their benefits, challenges, and architecture in different domains, or provide a framework upon which DTs can be created. The second category deals with the applications and use cases of DTs in different sectors. The third category is comprised of documents that formally describe technologies that can assist or act as building blocks for a DT. Based on the scope of this article, we focus on the first category to show the ongoing efforts of the SDOs in formally defining DTs or a DT framework in different domains and sectors. The documents that are selected are either publicly available or the SDOs have provided an overview and summary of them. SDO documents describing individual building blocks and elements of a DT

are not considered for this summary. A comprehensive survey of the different elements of a DT can be found in [119]. Moreover, only the latest versions of the documents are selected.

Our search results are not limited to the listed SDOs (see Tab. 3). As the research work towards standardization, to provide a unified definition of a DT, is still in its infancy; at the time this paper was written, no documentation or links could be found that indicate efforts (ongoing or planned) from SDOs, such as 3GPP, European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC), Alliance for Telecommunications Industry Solutions (ATIS), China Communications Standards Association (CCSA), Association of Radio Industries and Businesses (ARIB), Telecommunication Technology Committee (TTC), Telecommunications Standards Development Society India (TSDSI), Telecommunications Industry Association (TIA), Open Mobile Alliance (OMA), Global System for Mobile Communications Association (GSMA), and others in order to formally define a DT.

Besides the SDOs, other stakeholders are also actively developing frameworks and products, as part of the DT technology, tailored for different businesses and domains. Microsoft is developing the digital twin definition language (DTDL) [120]. It is a data management model based on JavaScript object notation for linked data (JSON-LD) and focuses only on resource description and does not address resource discovery and access. Microsoft already offers DTDL in IoT Hub, Azure DTs, etc., as part of its Azure cloud computing services. Amazon has developed the Amazon Web Services (AWS) IoT TwinMaker framework [121] to help developers create DTs of real-world systems such as buildings, factories, industrial equipment, etc., to optimize operations. Finally, Google's Supply Chain Twin and Pulse [122] build digital representations of the supply chains of an organization, in order to optimize their management with E2E visibility, event management, and analytics.

### B. DEFINING DIGITAL TWIN NETWORKS AND THEIR KEY ELEMENTS FROM THE SDO's PERSPECTIVE

The research work for DTNs is still in its infancy, with current applications focused on simulating specific scenarios such as network optimization, network operation and maintenance, etc. SDOs anticipate DTNs as a means to achieve the ultimate goal of an autonomous network or self-driven network. ETSI foresees a DTN as a stepping stone to achieve this and categorizes a DTN as network intelligence at level 3 automation (i.e., a self-optimization network wherein machines have deep awareness of the current network status and automatic network control, and make decisions to meet the users' intents) to verify and optimize network planning [123]. The IETF defines a DTN as "a digital twin that is used in the context of networking", while the ITU-T defines it as a "virtual representation of a physical network."

Moreover, the IETF and the ITU-T have identified a number of key elements and characteristics for a DTN, including

data, mapping, model, and interface. We discuss each of the elements in the following:

- Data: it is the foundation of DT technology. All types of data collected from the physical network and entities must be stored in a unified data repository. Such a data repository stores both historical and real-time data, which serves as the single source of truth (SSOT). Good and complete data can be leveraged to create accurate models of the physical assets in the virtual world.
- Mapping: DTs are frequently mistaken for simulation platforms. Mapping differentiates DTNs from the traditional simulation platforms. The main difference lies with the interactive virtual-real mapping between the physical network and its virtual counterpart that forms a closed feedback loop. This closed feedback loop can help analyze the actual status of the physical network, which in turn, can enable the DTN to optimize and effectively maintain the physical network.
- Model: Models create virtual representations and can help represent the physical networks and entities. Models serve as the source of ability for the DTN, i.e., they are instantiated upon request both individually and as a group to cater to different applications. Models can help capture the real-time characteristics of the physical network, such as network topology, context information, etc. Moreover, models are useful in various tasks, including analyzing, diagnosing, and emulating the network.
- Interface: Interfaces, both southbound and northbound, act as a medium across which a DTN can perform multiple functions, including real-time data exchange, controlling the physical network elements, making the DTN functionally available to the different network applications, and catering to their intents. Standardized interfaces ensure interoperability and scalability of the DTN.

The SDOs envision these elements to form the core of any DTN. DTNs use these elements to analyze the network status for intelligent decision-making; diagnose the health of network infrastructures for predictive maintenance; emulate different models and new standards for safe, low cost trials; and control the physical network with interactive applications.

### C. THE REQUIREMENTS TO DEVELOP A FUNCTIONAL AND SERVICEABLE DIGITAL TWIN NETWORK

There are a number of SDOs that have discerned a certain set of requirements for the creation of a DTN. These requirements, intended as guidelines or as recommendations by the SDOs, lay the foundation for the necessary build-up of a DTN, including its core elements and functionality. These requirements are classified into two categories: functional requirements and service requirements. We discuss these two categories and their corresponding lists of requirements in the following.

#### 1) FUNCTIONAL REQUIREMENTS

The functional requirements describe certain features and functions that a DTN should possess in order to optimally

accomplish its tasks. Furthermore, these features can help in describing system behavior under specific conditions. The functional requirements, which are recognized by some SDOs, are: data collection policies and tools; data repository; data models; standardized interfaces; and life cycle management. We will discuss each of the requirements as follows:

- Data collection policies and tools: The collection of complete data is necessary and a prerequisite for data to be used as the source of truth. This data should be accumulated with a timestamp, so that its real-time and historical components can be easily maintained and accessed. Moreover, support for data with different collection frequencies, complex measurements, different sources, etc., should also be provided. Such a detailed collection of data requires tools to be as lightweight (i.e., fast and easy to use) as possible to ensure that they do not affect the normal functionality of the network and the applications.
- Data repository: A unified data repository is imperative to handle and manage the massive amount of network data. Such a data repository should have the capability to store various types of data along with the ability to support efficient and real-time extraction, transfer, loading, and storing with application-specific latencies. The repository should also be able to handle high concurrency, i.e., multiple requests from multiple models, by enabling parallel processing. The hardware and software components needed to support such operations should be available at minimal cost. But most importantly, this repository should ensure that the data is accurate, consistent, and secure.
- Data models: DTNs should have the capability to create data models resembling the network elements and topologies. These models should be capable of achieving an accurate and real-time description of the physical network. Data models should interact with the data repository to create different basic and functional models for the DTN. These models should be capable of being instantiated both as an individual item and in a group, as per application request. Furthermore, these models should be capable of iteratively optimizing network applications.
- Standardized interfaces: The interfaces to and from a DTN should be standardized in order to avoid hardware and/or software vendor lock-in and achieve easier integration and interoperable data collection tools and service applications. Besides, the interfaces should be secure and able to provide reliable information with high concurrency. The southbound interface should be capable of exchanging information at high speeds to and from different sources. Moreover, the southbound interface should be capable of controlling the elements of the physical network by delivering control messages and configuration changes at latencies acceptable to the applications. The northbound interface should primarily

be able to cater to all requests from the application side and be able to provide copies of models to third-party applications.
- Life cycle management: The management of data, storage, modelling, and instantiation of virtual models and entities should be managed in a robust manner over the entire life cycle of a DTN. This enables the DTN to accurately store and track transactions of data and models, and also enables the DTN to control elements of the network and its twin, especially the topology, models and security.

#### 2) SERVICE REQUIREMENTS

The service requirements specify certain characteristics that a DTN should possess in order to function optimally depending on different user demands. These requirements are compatibility, flexibility, privacy, scalability, security, synchronicity, and repeatability. We discuss each of the service requirements in the following:

- Compatibility: A DTN should be compatible with the different types of network elements, both hardware and software, developed by different vendors, i.e., interoperable. This ensures that the DTN has the capability to store various types of data to build accurate virtual models, which can then be instantiated by any application developed and used by different vendors. Moreover, a DTN should be compatible with different physical networks such as CN, campus network, RAN, data center, etc. This assures that the DTN can be used for not only single-domain networks, but also cross-domain and end-to-end networks. Besides, DTNs should have backward compatibility with devices from legacy networks.
- Flexibility: A DTN should be flexible to meet the demands of network applications, both single-purpose and multi-purpose, at different operation stages. This warrants that the DTN can collect and store data as needed by the applications, while instantiating and combining different models to serve the applications. Such flexibility can also be extended to information exchange between one or more DTNs.
- Privacy: A DTN should be able to guarantee data protection for all users (of network applications) during its entire life cycle, besides complying with the local laws and regulations on data privacy. Privacy is not restricted only to users' usage statistics or the registration information, but also to information on interaction between the network devices and the DTN, i.e., internet protocol (IP) addresses, MAC addresses, etc. Privacy can be further improved by better modelling techniques in the DTN, which can generate models based on limited amounts of data.
- Scalability: A DTN should be able to handle and replicate networks of any scale. A DTN['s] functionality and performance levels should be maintained even when network shrinks down or scales up. This assumes that the capabilities of each core element can be smoothly
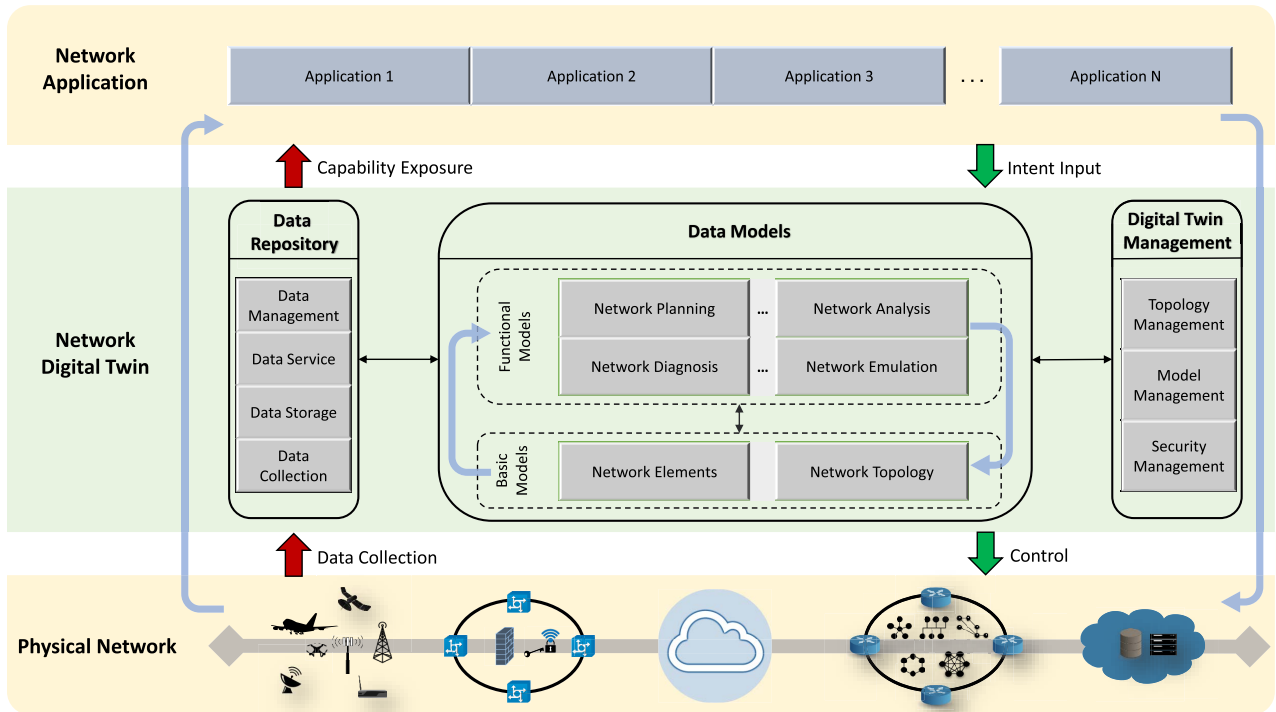
**FIGURE 3.** A reference architecture for a DTN with interfaces between different layers designed to form a closed loop between physical network elements and network applications.

extended depending on the scale of the physical network.

- Security: A DTN should be able to not only prevent preemptive attacks, but also be able to set up necessary defenses after the network has been attacked. This includes mechanisms to secure data throughout its life cycle, thus, making the data repositories and models trustworthy. The interactions across both the northbound and southbound interfaces with the DTN should be kept secure in order to ensure network infrastructure security, DTN layer security, and network application security.
- Synchronicity: A DTN should be synchronized with its real-time counterpart in order to represent the real-time status of the physical elements of the network with acceptable latencies. This should be applicable in both directions across the southbound interface, i.e., data collection and control information execution.
- Repeatability and reproducibility: A DTN should be able to replicate the network conditions and replay them (possibly with slight variations) as required. This allows the DTN to be leveraged as a simulation tool, which enables testing and validation of new technologies on real-time data.

### D. THE ARCHITECTURAL FRAMEWORK OF THE DIGITAL TWIN NETWORK

This subsection presents the reference architecture of a DTN. This DTN architecture, which is shown in Fig. 3, is proposed by the IETF and the ITU-T considering the aforementioned core elements and expected characteristics of a DTN, and the

knowledge extracted from DT architectures (being developed in the industrial domain). This DTN architecture can be best described as a *three-layer, three-domain, and double closed-loop* architecture. The key architectural blocks and their components are as follows:

#### 1) PHYSICAL NETWORK LAYER

All physical elements of the network are part of this layer. The physical network can be a mobile core, campus network, data center network, etc. It can span across a single domain to multiple domains. This layer interacts with the DTN layer via the southbound interface.

#### 2) NETWORK DIGITAL TWIN LAYER

This layer is the core of the DTN. The DTN layer provides an interactive platform based on real-time information and configuration (of the physical network). It interacts with the network application layer via the northbound interface and the physical network layer with the southbound interface. It is comprised of three domains:

- *Data Repository:* This domain houses the data repository that is responsible for the collection of real-time data from the physical layer and stores it in heterogeneous databases. This domain provides data upon request for the creation of models and manages the data during its life time.
- *Data Models:* This domain includes the data modelling services that can be leveraged to improve the agility and programmability of the DTN. This domain can also be referred to as the ability core of a DTN. Models can be broadly classified as:

– *Base Models:* These models are used to replicate the real-time characteristics and state of the physical network elements with respect to its topology, environment information, operational state, etc. These models can be used to emulate control changes and to implement optimized solutions to the physical network in a safe and cost-effective manner, before being implemented on the entire network.

– *Functional Models:* These models refer to models leveraged to perform analysis, prediction, emulation, diagnosis, etc., for various application scenarios. By using the accurate data in the data repository, these models can be built and expanded by multiple dimensions, i.e., by network-type and function-type. Furthermore, this flexibility and scalability in model creation can be leveraged to create new functional models, that currently do not exist.

● *Digital Twin Management:* This domain concerns itself with the life cycle management of the DTN, including visualization of the DTN, by controlling topology management, model management, and security management functions of the DTN.

### 3) APPLICATION LAYER

The application layer is the one that encompasses all applications that intend to use the physical network. A few examples of such applications include network management, network optimization, network innovation, network visualization, etc. These applications make requests, i.e., show intent to the DTN layer. The performance of the applications depends on the capability of the DTN, which is exposed via the northbound interface.

### 4) DOUBLE CLOSED LOOP

A double closed loop is formed collectively by the layers and both the northbound and southbound interfaces. The first inner loop deals with emulation of the physical network elements and optimization of their virtual counterparts based on the data models. The second outer loop includes control and optimization of physical network elements via feedback from network applications.

## V. OPEN RESEARCH CHALLENGES AND FUTURE DIRECTIONS FOR E2E DEPLOYMENT OF DT TECHNOLOGY IN 6G COMMUNICATION SYSTEMS

In this section, we identify a number of critical research challenges that are associated with the deployment of DT technology in the forthcoming 6G networks. These challenges require substantial research efforts and careful planning to enable future 6G networks to meet the ever-increasing requirements of various types of DTs. The challenges we have derived in this work can be broadly classified according to their connection to the envisioned 6G networks as follows.

### A. DATA PROVISIONING

A prerequisite for the optimal functioning of a DT is the availability and provisioning of large amounts of data that capture the attributes of the entities in the physical domain,

their interactions and any state alterations. Additionally, the collected data must also be carefully evaluated and selected upon the exploitable value: data is useful in building a DT only when it is of satisfactory quality, e.g., noise-free, or with a consistent data stream. On the contrary, data with poor quality will only reduce the performance of a DT. Therefore, it is necessary not only to develop liable solutions allowing for merging diverse data of different types and from various sources into a single DT [124], but also to establish effective solutions that are capable of evaluating and filtering the data with reasonable costs.

### B. AI INTEGRATION

With the integration of advanced AI and ML algorithms into the DT technology, the accuracy and performance of 6G communication systems are significantly increased due to the fact that the DTN collects and processes real-time data and subsequently produces recommendations and predictions about their corresponding physical components. However, there are several research challenges that need to be addressed in order to successfully incorporate intelligence in DT technology for 6G communication systems. Such challenges include, but are not limited to: (a) realizing intelligent solutions by combining various types of data from heterogeneous physical objects within the 6G communication systems; (b) refining the architecture and the external and internal interfaces between the AI model generation system, the DTN, and 6G communication systems; and (c) collaboration between the SDOs in charge of AI/ML, DT technology, and the 6G communication system, with the purpose of developing the support needed for dynamic interoperability across all layers and domains of futuristic DT-assisted 6G ecosystem, as suggested in [94].

### C. NETWORK EXPOSURE MANAGEMENT

Enabling the owner of a DTN to create various types of DTs for a variety of physical objects in 6G communication systems and providing them to the service provider of a 6G network is a unique capability that needs to be supported through the use of a well-defined set of APIs. These APIs and the data exchanged between a DTN and 6G networks can be facilitated through the utilization of a standardized functional block within the trust domains of both systems. To this end, the 3GPP has defined a network exposure function (NEF) for beyond 5G communication networks. However, such a functional block is not yet standardized in the context of DTNs, which is regarded as a critical area of research. Additionally, enabling robust, standardized, scalable, trusted, and user-friendly access to applications exposed by DTNs or 6G networks while concealing network topology and protecting the privacy of end users or NPNs are challenging research issues.

### D. CROSS-APPLICATION, LIFE CYCLE, AND ACCESS MANAGEMENT

According to [20], most existing industrial DT applications refer only to a single phase of a product life cycle, e.g., the

design phase, the production phase, or the service phase. In such circumstance, it can become a common case that for the same product, the DT must be repeatedly created and terminated. Furthermore, in the envisaged future DT ecosystem [94], different applications may need to access the DT for the same PT simultaneously, leading to a co-existence of multiple DT instances.

In both cases, a significant amount of computing and communication resources will be wasted, damaging the expected sustainability of 6G systems. Therefore, it becomes essential to manage the life cycle of a DT across different phases of its PT, and to allow different services/applications share access to it. However, this may introduce several technical and business problems, e.g., authentication and authorization in access management, protection and resolution of conflicts among operations to the same DT by different applications, and the ownership of a DT.

### E. MODULARITY AND INTERFACING

Modular design was and continues to be a driving force behind the success of many technologies. It is essential to divide a complex modern engineering system into multiple sub-modules, especially in the design and production phases. For each associated sub-module, an individual DT is usually required, meanwhile, another DT shall be created for the overall system as well. Thus, it is a natural approach to assemble the sub-module DT to construct a joint system DT. However, despite considerable existing research efforts, there is still an open gap to be bridged towards a liable software platform that can flexibly support interfacing between the different sub-module DTs, as identified in [125].

### F. DIGITAL TWINING OF NETWORKS

The efficient operation of a DTN requires constant and real-time updating of the associated attributes and dynamics in the network. It requires a reliable and real-time communication backbone that can support the bilateral exchange of large amounts of data between physical entities and their digital replicas, as well as among the various DTs representing sub-domains (e.g., RAN, edge) themselves. As a result, this can cause significant overhead to the communication network, and maintaining ultra-reliable low latency bilateral communication is challenging in such an environment. Further research is required over all the network protocol layers to satisfy the low latency and reliable data exchange requirements with a focus on the operation of a DTN. Further, several steps in modeling and operating a DTN can significantly benefit from joint communication and sensing (JCAS) capabilities anticipated in the 6G access nodes. The potential availability of sub-THz frequency bands in 6G encourages small cell deployments. Small cells procuring large bandwidths provide an opportunity to engage the mobile network efficiently for sensing. The radio-aware DT can specifically benefit from this with RRM decisions based on captured mobile device attributes (e.g., speed, direction), SINR predictions using obstacle detection and obstacle attributes, and

enhanced link condition predictions using propagation environment modeling, and so on. Though some significant works are looking into JCAS [126], [127], [128], which as a technology is still in its infancy with several of its own challenges (e.g., new waveforms, AI/ML processing, distributed and multi-band sensing, channel modeling, sensor fusion, etc.) [129]. There is a need for further research in these aspects before JCAS can be successfully used to create DTs of physical entities and environments.

### G. STANDARDIZATIONS AND OPEN-SOURCING

On the one hand, having standardized models and technical specifications of DTs will simplify their implementation: by applying standardized templates and design flow, the development cost can be significantly reduced. Furthermore, mature standards will also provide a generic API to different applications to allow them share the same DT. A standardized DT model will pave the way towards a DT brokering mechanism, which allows the exchange and reuse of information among different DTs, e.g., as previously mentioned, to construct the joint system DT by assembling and interconnecting sub-module DTs. On the other hand, pursuing a unified and open architecture with a clear structure and comprehensively defined elements, domains, and standardized interfaces would further support and facilitate scalable operations of DTNs. This indicates that the DT and PT interfaces should not be vendor-locked and that the accessibility to heterogeneous data for storage and accurate creation of virtual models of physical network elements be made uniformly available.

### H. SECURITY AND PRIVACY

While the data and models associated with DTs commonly play a key role in the decision-making of error-intolerant industrial processes, it raises an important issue of dealing with uncertainty and guaranteeing trustworthiness within DT systems. Both these happen to be a part of the open challenges that 6G networks are envisaged to tackle. On the other hand, sensitive user data can be usually stored at a DT, and consistently synchronized between the DT and PT. In some use cases, by having access to the DT, one might even be able to manipulate the associated PT. Serious security and privacy concerns can be therewith raised in the deployment of DT technology: privacy-sensitive data shall neither be exposed to anyone, nor exploited by anyone without the permission of the PT owner. Data transmission between the DT and the PT must be E2E encrypted, integration check and anomaly detection must also be applied to protect a DT from any possible attacks. Finally, paradigmatic solutions are required to determine an optimal level of authentication for the owner of a DTN to access the 6G network infrastructure, to monitor DT-specific events occurring in the 6G network and report them to the DTN in real-time, and to implement advanced ML-assisted solutions for managing the APIs and information exposed between these two systems.

## I. GREENFIELD DEVELOPMENT AND DEPLOYMENT

The development of a DT system requires a solid basis of both system expertise and methodological expertise. The former is demanded to recognize, describe and model the system, while the latter is required to exploit the structural and behavioral models represented by the DT [130]. Both expertise and the associated efforts must be taken into account as part of the development cost. Furthermore, legacy system environment, including both the underlying software platform and the hardware infrastructure, e.g., production machines and their cloud/physical interconnection, may fail to fully meet the performance requirements of a DT system in all aspects, including coverage, user density, latency, reliability, computing capability, and power efficiency. A substantial upgrade or even replacement may have to be invested, in order to support the deployment of a DT. Which is why a greenfield development approach might be a better fit.

The requirements of expertise and environment upgrade are implying huge CAPEX and OPEX hurdles, and might block the way to the spread of DT technology for small and medium enterprises without necessary capital and human resources.

## J. SUSTAINABILITY AND ENERGY CONSIDERATIONS

Given that the DT technology is data-driven, i.e., it relies on the steady provisioning of DTs with abundant data of high quality, energy considerations are thrown into question. As the transmission of every bit of data over the air has green house gas (GHG) emissions associated with it. Sustainability is one of the key pillars for 6G communication systems, and it is of high priority to make 6G network operation energy efficient. Therefore, the data-driven models need to prioritize minimal data collection without sacrificing the accuracy or reliability of desired DT tasks (e.g., virtual modeling, predictions, etc.). For instance, a DTN performs at its best with a more comprehensive and frequent data collection from the network entities and environment. However, this benefit comes at the cost of communication resources and energy consumption making it crucial to calculate the trade-off between expected benefits and data collection costs. Periodic and event-triggered approaches can assist in optimal data collection. The periodic data collection method enables the DTN to request the network to provide the desired data periodically. This period needs adjustments by considering the costs involved in data collection. The event-triggered approach allows the network to transmit data only during a specific event negotiated between the DTN and the network [94]. There is a need to have more adaptable and dynamic data collection methods to control the frequency and volume of data collection without sacrificing a DTN's performance. Further, AI experts need to rethink models which consume less power (e.g., in the training phase) yet provide reasonable predictions. Further research on federated and cooperative learning is in demand to facilitate trust-based joint learning and avoid multiple hubs across several domains performing similar learning tasks.

## K. DEFINING A DT-ASSISTED 6G NETWORK ARCHITECTURE

DTNs are still in their infancy. Efforts to formally describe and define a uniform architecture will help developers and other stakeholders accelerate their efforts to research and develop DTNs in an efficient manner. A DTN in the 6G ecosystem should enable manufacturers, solution integrators, network providers, service providers, and other stakeholders to efficiently compete and cooperate in order to service the unique user demands. To achieve this, adequate research activities into visualisations, standardized and open APIs, standardized interfaces, etc., should be carried out. The SDOs envision that a DTN would be able to seamlessly handle different user intents. To that end, research into the automation of life cycle management of the user's intent and consequently, handling of the DT models involved, should be carried out. Moreover, the architecture should be developed in a robust manner to address newer technologies, business segments and the UN sustainability goals that are being addressed as part of the 6G ecosystem.

## VI. CONCLUSION

Due to the proliferation of 5G communication systems and the commencement of research activities on potential 6G communication systems, the telecommunications industry is exploring the key enabling technologies, use cases, architectures, etc. that can facilitate the delivery of the next generation of communication services in a faster, more cost-effective, energy-efficient, and environment-friendly manner. One of the topics receiving considerable attention from the research community is DT technology. Motivated by its significance in the communication society, we conducted a comprehensive survey of DT technology to capture the essence of its application in the forthcoming 6G communication systems aimed at achieving the performance goals mentioned above. To accomplish these objectives, we began by providing a brief history of DT technology from its inception to its widespread application in manufacturing, aviation, healthcare, and other industries. We reviewed several survey papers in the field of DT technology and outlined the implications of this technology for the research, development, and operation of 6G communication systems. We also surveyed the state-of-the-art literature concerning the deployment of DT technology in 6G communication systems. In addition, we elaborated on a list of potential use cases and areas across different domains (such as radio, access, transport, core, and data center) and solution scopes (including RRM, RAN moderation, RIS, etc.) for the application of DT technology in 6G communication systems. Further, we discussed the most recent activities of several SDOs regarding DTN and DT technology for 6G communication systems. Moreover, we highlighted several open challenges and future research directions for E2E deployment of DT technology in 6G communication systems. Finally, this article is intended to assert DT technology as a key enabler for empowering 6G communication systems and attempted to trigger interest and further research within the

telecommunications sector to facilitate the E2E deployment of DT technology.

## LIST OF ACRONYMS

| | |
|---|---|
| 1G | first-generation |
| 2G | second-generation |
| 3G | third-generation |
| 3GPP | Third Generation Partnership Project |
| 4G | fourth-generation |
| 5G | fifth-generation |
| 6G | sixth-generation |
| AAS | asset administration shell |
| AI | artificial intelligence |
| AMF | access and mobility management function |
| API | application programming interface |
| APP | application |
| AR | augmented reality |
| ARIB | Association of Radio Industries and Businesses |
| ATIS | Alliance for Telecommunications Industry Solutions |
| AWS | Amazon Web Services |
| B5G | beyond 5G |
| BCI | brain-computer interface |
| BWP | bandwidth-part |
| CAPEX | capital expenditure |
| CCSA | China Communications Standards Association |
| CDMA | code-division multiple access |
| CEN | European Committee for Standardization |
| CENELEC | European Committee for Electrotechnical Standardization |
| CI/CD | continuous integration and continuous deployment |
| CN | core network |
| cobot | collaborative robot |
| CPS | cyber physical system |
| DITEN | digital twin edge networks |
| DL | deep learning |
| DRL | deep reinforcement learning |
| DT | digital twin |
| DTDL | digital twin definition language |
| DTN | digital twin network |
| DU | distributed unit |
| E2E | end-to-end |
| EI | emergent intelligence |
| eMBB | enhanced mobile broadband |
| ETSI | European Telecommunications Standards Institute |
| FL | federated learning |
| GHG | green house gas |
| GNN | graph neural network |
| GSMA | Global System for Mobile Communications Association |
| HMTC | high-performance machine type communication |
| ICT | information and communications technology |

| | |
|---|---|
| IEC | International Electrotechnical Commission |
| IEEE-SA | The Institute of Electrical and Electronics Engineers Standards Association |
| IETF | Internet Engineering Task Force |
| IIoT | industrial Internet of things |
| IoT | Internet of things |
| IoV | Internet of vehicles |
| IP | internet protocol |
| ISO | International Organization for Standardization |
| IT | information technology |
| ITS | intelligent transportation system |
| ITU | International Telecommunication Union |
| ITU-T | International Telecommunication Union - Telecommunications Standardization Sector |
| JCAS | joint communication and sensing |
| JSON-LD | JavaScript object notation for linked data |
| KPI | key performance indicator |
| LOS | line-of-sight |
| MAC | medium access control |
| MCS | modulation and coding scheme |
| MEC | mobile edge cloud |
| MIMO | multiple-input and multiple-output |
| mIoT | massive Internet of things |
| ML | machine learning |
| mMTC | massive machine type communication |
| mmWave | millimeter wave |
| MNO | mobile network operator |
| NASA | National Aeronautics and Space Administration |
| NDT | network digital twin |
| NEF | network exposure function |
| NFV | network function virtualization |
| NGSI-LD | next generation service interfaces-linked data |
| NN | nomadic node |
| NPN | non-public network |
| OFDM | orthogonal frequency division multiplexing |
| OMA | Open Mobile Alliance |
| OPEX | operational expenditure |
| PHY | physical layer |
| PT | physical twin |
| QoE | quality of experience |
| QoS | quality of service |
| RAN | radio access network |
| REM | radio environment map |
| RIS | re-configurable intelligent surfaces |
| RL | reinforcement learning |
| RRM | radio resource management |
| RSRP | reference signal receive power |
| SDN | software defined networking |
| SDO | standards development organization |
| SDR | software-defined radio |
| SINR | signal-to-interference-plus-noise ratio |
| SLA | service level agreement |
| SMF | session management function |
| SMS | short message service |

| SNR | signal-to-noise ratio |
|---|---|
| SSOT | single source of truth |
| STN | satellite-terrestrial networks |
| THz | terahertz |
| TIA | Telecommunications Industry Association |
| TSDSI | Telecommunications Standards Development Society India |
| TTC | Telecommunication Technology Committee |
| TTI | transmit time interval |
| UCNC | user-centric no cell |
| UE | user equipment |
| UN | United Nations |
| UPF | user plane function |
| URLLC | ultra-reliable and low latency communication |
| V2X | vehicle-to-everything |
| VLC | visible light communication |
| VR | virtual reality |
| XR | extended reality |

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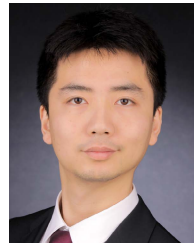
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