IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 28 March 2025, accepted 30 April 2025, date of publication 12 May 2025, date of current version 21 May 2025.

Digital Object Identifier 10.1109/ACCESS.2025.3569314

RESEARCH ARTICLE

Migrate or Not: Medical Digital Twins in the Era of 6G Edge-Based Networks

CHIARA SURACI[1,2], (Member, IEEE), OLGA CHUKHNO[1,2], (Member, IEEE), GABRIEL-MIRO MUNTEAN[3], (Fellow, IEEE), ANTONELLA MOLINARO[1,2], (Senior Member, IEEE), AND GIUSEPPE ARANITI[1,2], (Senior Member, IEEE)

[1]DIIES Department, University Mediterranea of Reggio Calabria, 89124 Reggio Calabria, Italy
[2]CNIT, 43124 Parma, Italy
[3]School of Electronic Engineering, Dublin City University (DCU), Dublin, D09 V209 Ireland

Corresponding author: Chiara Suraci (chiara.suraci@unirc.it)

This work was supported in part by European Union under Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU partnership on "Telecommunications of the Future" (Program "RESTART") under Grant PE00000001. The work of Gabriel-Miro Muntean was supported by the Research Ireland under Grant 12/RC/2289_P2 (Insight).

ABSTRACT As the deployment of fifth-generation (5G) cellular networks progresses worldwide, researchers are already delving into the potential of sixth-generation (6G) systems. One promising 6G-focused solution that has garnered significant attention of both researchers and healthcare providers is the integration of the digital twin (DT) paradigm with the digital health (eHealth) sector. This paper examines this solution, highlighting the challenges that must be overcome to fully unlock its potential, particularly in managing patient mobility. Specifically, the following contributions are provided. First, we explore the value of the deployment of DTs in eHealth, reviewing global initiatives, standards, potential applications, challenges, and 6G-enabled solutions. Next, we focus on the placement of medical DTs at the network's edge and their migration in response to patient mobility. Finally, we present findings from a simulation campaign, showing key insights into the trade-offs involved in medical data transfer strategies. These results deepen our understanding of DT migration complexities and highlight the transformative impacts that mobility-driven medical DTs could have on healthcare services and patient outcomes.

INDEX TERMS 6G, digital twin, eHealth, edge computing, mobility, migration.

I. INTRODUCTION

Sixth-generation (6G) networks are emerging as a critical research frontier, driven by the limitations of the fifth-generation (5G) technology. 6G will rely on cutting-edge, often synergistic technologies to meet the demanding requirements of upcoming services. The evolutionary path of cellular networks has proved that services themselves are the determining factor shaping the design of new generations. Furthermore, a cornerstone of 6G will be its emphasis on the quality of physical experience (QoPE), a comprehensive metric that integrates quality of service (QoS), quality of experience (QoE), and human perception [1]. In the field of digital health (eHealth), achieving a high QoPE is crucial for the success and transformation of healthcare services.

eHealth was created with the aim of expanding healthcare access to the global population, overcoming geographic, social, and economic inequalities. However, the COVID-19 pandemic has exposed the limitations of the rapidly growing eHealth sector, amplifying the digital divide and highlighting the urgent need for universal broadband connectivity to ensure equal access to digital services [2], [3]. Addressing this challenge is a key objective for 6G networks [4], which may offer solutions, particularly through the application of the digital twin (DT) paradigm.

DTs, which enable the digitalization of physical entities, are emerging as a promising approach to enhancing QoPE in eHealth. DTs of organs, patients, or medical devices could

The associate editor coordinating the review of this manuscript and approving it for publication was Bilal Khawaja.

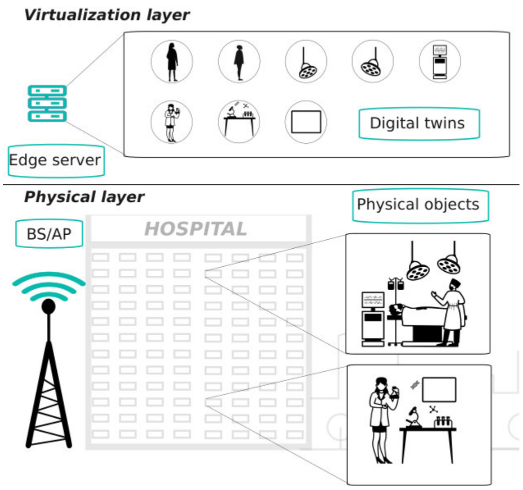


FIGURE 1. Digital twins in the realm of eHealth.

be designed with various functionalities using architectures like the one shown in Fig. 1. This paper explores potential applications of DTs in eHealth, the challenges y pose, and the solutions 6G can offer to create a seamless integration between physical and digital entities. The considerable potential of 6G-enabled DTs in eHealth is reflected in the growing body of literature on the subject, including works such as [5], [6], and [7].

Numerous initiatives worldwide highlight the growing interest in DT technology and its increasing relevance to the healthcare sector. These efforts highlight the potential correlations between DTs and enabling technologies and verticals of 6G, such as the Internet of Things (IoT), artificial intelligence (AI), and Industry 4.0. The healthcare industry is significantly investing in medical DTs, with a projected compound annual growth rate (CAGR) of 25.6% in the global DT healthcare market from 2022 to 2030 [8]. Several R&D projects, such as MeDiTATe (funded by the European Union's Horizon 2020 research and innovation programme) and MyMDT (developed at the Norwegian University of Science and Technology, NTNU) are focused on creating personalized medical DTs for preventive and therapeutic healthcare. The global technological transformation driven by 6G is set to bring these projects to fruition. Other active initiatives include: *ISO/IEC JTC 1/SC 41* – Internet of things and digital twin; *ISO/IEC JTC 1/SC 42* – Artificial intelligence; *ISO/IEC AWI 30172* – Digital Twin – Use cases; *ISO/IEC AWI 30173* – Digital twin – Concepts and terminology; *ISO/TR 24464:2020* – Automation systems and integration – Industrial data – Visualization elements of digital twins; *ISO 23247-1:2021* – Automation systems and integration – Digital twin framework for manufacturing; *IEEE SA-P2806* – System Architecture of Digital Representation for Physical Objects in Factory Environments; *IEEE SA-P2806.1* – Standard for Connectivity Requirements of Digital Representation for Physical Objects in Factory Environments; *IEEE 2888* – Interfacing Cyber And Physical World Working Group; *IEC 62832–2020* – Industrial-process measurement, control and automation – Digital factory framework; *IETF* – Digital Twin Network: Concepts and Reference Architecture. Additionally, the National Institute of Standards and Technology (NIST) in the United States and the National Research Council (CNR) in Italy have formed working groups to establish guidelines and regulations for DTs in industry.

The initiatives are detailed in Table 1, along with their respective reference links.

A. MOTIVATIONS AND CONTRIBUTIONS

Motivations: Hitherto, the key topics of this paper (i.e., 6G, eHealth, and DT) have been introduced, supported by relevant works from the literature highlighting their timeliness and significance. The evidence indicates that the DT technology holds great promise for enhancing applications across various verticals expected to be prevalent in 6G networks. A compelling example is the eHealth vertical, where the implementation of medical DTs can revolutionize telemedicine by enabling precise, real-time monitoring and personalized care. However, to realize this potential, several challenges must be overcome, including the management of patient mobility. Accurately and consistently representing a patient in motion is a non-trivial task. This issue is discussed in [9], where the benefits and challenges of using human digital twins (HDTs) for personalized healthcare are explored. The authors emphasize that mobile HDTs must be implemented to ensure that patient mobility — whether positional (moving from one location to another), or postural (making small body movements) — does not hinder the efficient and successful application of medical DTs. These considerations form the basis of our work, which aims to explore the potential applications of DT in the medical field, identify the challenges that could prevent their successful implementation, and propose technological solutions that 6G systems and their enabling technologies might offer. A key focus of our research is the specific problem of DT migration, that is, the seamless transfer of all DT components within the network in response to patient positional mobility.

Contributions: The current body of literature offers a thorough overview of DT applications in healthcare, discussing both the associated challenges and potential solutions. However, there remains a notable gap in research focused on 6G-oriented approaches that also address the complexities of managing patient mobility. This paper aims to fill that gap by providing the following key contributions:

- *Comprehensive analysis of 6G-enabled applications.* We explore potential applications of DTs in eHealth, focusing on the specific challenges they pose and identifying tailored solutions enabled by 6G technologies.
- *Analysis of patinet mobility issues.* We analyze the challenges that arise when a patient, associated with a

TABLE 1. Global initiatives related to Digital Twin.

Organization	Initiative	Reference link
EU	MeDiTATe - the Medical Digital Twin for Aneurysm Prevention and Treatment	https://meditate-project.eu
NTNU	MyMDT - My Medical Digital Twin	https://www.ntnu.edu/digital-transformation/twin
ISO	ISO/IEC JTC 1/SC 41 - Internet of Things and digital twin	https://www.iso.org/committee/6483279.html
ISO	ISO/IEC JTC 1/SC 42 - Artificial Intelligence	https://www.iso.org/committee/6794475.html
ISO	ISO/IEC AWI 30172 - Digital Twin – Use cases	https://www.iso.org/standard/81578.html
ISO	ISO/IEC AWI 30173 - Digital twin - Concepts and terminology	https://www.iso.org/standard/81442.html
ISO	ISO/TR 24464:2020 - Automation systems and integration - Industrial data - Visualization elements of digital twins	https://www.iso.org/standard/78836.html
ISO	ISO 23247-1:2021 - Automation systems and integration - Digital twin framework for manufacturing	https://www.iso.org/standard/75066.html
IEEE	IEEE SA-P2806 - System Architecture of Digital Representation for Physical Objects in Factory Environments	https://standards.ieee.org/ieee/2806/7524/
IEEE	IEEE SA-P2806.1 - Standard for Connectivity Requirements of Digital Representation for Physical Objects in Factory Environments	https://standards.ieee.org/ieee/2806.1/10370/
IEEE	IEEE 2888 - Interfacing Cyber And Physical World Working Group	https://sagroups.ieee.org/2888/
IEC	IEC 62832-2020 - Industrial-process measurement, control and automation - Digital factory framework	https://webstore.iec.ch/publication/65858
IETF	IETF - Digital Twin Network: Concepts and Reference Architecture	https://datatracker.ietf.org/doc/draft-irtf-nmrg-network-digital-twin-arch/

medical DT, changes position by moving from the radio coverage of one base station to another. This issue is of no minor relevance for maintaining a consistent and accurate DT that truly reflects the characteristics of the physical twin.

- *Simulation-based insights*. We delve into how mobility-driven medical DTs might transform healthcare delivery and enhance patient care, presenting the results of a simulation campaign that provides valuable insights into the trade-offs involved in the edge-based migration of medical DTs.

II. ADVANCEMENTS IN MEDICAL DIGITAL TWINS: POTENTIAL APPLICATIONS

This section examines the potential applications of DTs in eHealth, for which the current availability of clinical implementations remains limited, as evidenced by recent research [10]. To enable a comprehensive understanding, this section will: *(i)* describe each application of medical DTs; *(ii)* address the challenges related to the described application; *(iii)* present possible technological solutions that 6G networks could enable. This final point specifically aims to highlight potential synergies between 6G and medical DTs, as the proposed solutions consist in features and enabling technologies of 6G. To highlight the validity of these forthcoming applications, Fig. 2 compares traditional and DT-assisted medical applications.

A. PRECISION MEDICINE

1) DESCRIPTION

One of the most impactful uses of medical DTs is in precision medicine, also known as personalized medicine. The level of detail in the creation of patient-specific digital replicas can vary, ranging from basic to more sophisticated representations. According to the authors of [10], DTs can be structured hierarchically, representing the physical entity at different levels: unit, system, or system-of-systems. For example, a DT of the heart could serve as a unit-level model; a DT of the entire cardiovascular system could represent a system-level model; and a DT of the whole patient would be a system-of-systems-level model. The ability to leverage a digital representation of the patient at varying degrees of detail offers numerous advantages to physicians – and, by extension, to patients – including the capability to detect diseases earlier, create personalized preventive treatments, test therapies on digital patient models to assess their effectiveness and safety, and facilitate the design and customization of prostheses and implants.

2) CHALLENGES

The application of medical DTs in personalized medicine presents several challenges, as relying on an inaccurate digital model could have severe consequences for the patient. To ensure a reliable connection between the physical twin (PT) and its digital counterpart, the following key requirements must be met: *(i)* a seamless link between the two twins, *(ii)* continuous, real-time data integration into the DT to accurately reflect the current state of the PT, and *(iii)* effective modeling of the PT to ensure its representation is both accurate and up to date.

3) SOLUTIONS

The Internet of Everything (IoE) is a key paradigm for 6G, representing an evolution beyond traditional IoT by integrating people, processes, data, and things into a hyper-connected ecosystem, where heterogeneous interactions – such as machine-to-people, machine-to-machine, and people-to-people – can be enabled [3]. Several advanced 6G technologies are fundamental to realizing the IoE and supporting its use in innovative scenarios. For example, the IoE will feature ultra-low latency ($< 1ms$), enabling near-instantaneous communication between devices and architectural components. This can be particularly valuable for ensuring seamless connections and real-time data integration between DTs and their PTs. Additionally, the expected high data rate ($> 1Tbps$) will facilitate the transfer of large volumes of data between medical devices, sensors, and DTs. Other IoE properties that can address the challenges of implementing medical DTs for precision medicine include high connection density ($> 10^7 devices/km^2$) and energy

Without DTs	Application	With DTs
Cons: Reliance on physical entities for testing therapies and treatments.	PRECISION MEDICINE	**Pros**: Availability of digital representations of entities related to patients. **Challenges:** Seamless connection; real-time data integration; effective modeling. **6G-aided solutions:** IoE; hybrid modeling; holography; XR; metaverse.
Cons: Access to data limited by physical support; risk of mismanagement of operations on data (e.g., updating, deletion, etc.).	DIGITAL MEDICAL RECORD	**Pros**: Shared and remote access to data; efficient management of operations on data. **Challenges:** High-storage edge resources; accuracy, timeliness, and security of data. **6G-aided solutions:** Edge computing; AI/ML; NTNs; FL; 6G security.
Cons: Limitations in exploring alternative strategies; suboptimal surgical outcomes.	DIGITAL SURGERY TESTING	**Pros**: Pre-operative simulations for improved surgical techniques; reduced risks. **Challenges:** Realistic organ modeling; real-time simulation; integration of patient-specific data. **6G-aided solutions:** Advanced imaging; high-performance computing; edge computing; AI; XR.
Cons: Time-consuming and costly; limited virtual trials and real-time insights.	CLINICAL TRIALS	**Pros**: Streamlined drug trials; accelerated recruitment; reduced costs. **Challenges:** Reliable connectivity; data security; remote monitoring; interoperability. **6G-aided solutions:** Robust network infrastructure; cybersecurity; telehealth.

FIGURE 2. Traditional Vs. DT-aided medical applications.

efficiency. The former will enable the efficient management of millions of connected devices simultaneously, leveraging the vast amounts of data required to create accurate, PT-faithful DTs. The latter is particularly suited for autonomous medical sensors and long-lasting wearables, eliminating the need for frequent charging. Together, these advancements will enhance the accuracy of personalized medicine applications. Furthermore, with the 6G's advanced computational and communication capabilities, hybrid modeling approaches can be effectively applied to the modeling of physical entities, facilitating the creation of high-precision DTs for precision medicine [11]. A hybrid modeling approach integrates two key components:

- Statistical models (AI/ML-based) that enable learning from patient data, medical records, and biosignals to predict disease progression.
- Mechanical models (physics-based simulations) to accurately replicate physiological processes (e.g., blood flow, organ behavior) based on fundamental physics laws.

Finally, 6G technologies such as holography, extended reality (XR), and the metaverse could provide interactive and visualization tools to examine and assess medical DTs, thus enhancing decision-making and fostering collaboration in personalized medicine applications.

B. DIGITAL MEDICAL RECORD

1) DESCRIPTION

By employing DTs, medical records — encompassing crucial patient information like vital signs, medical history, and treatment specifics — can be digitalized to enable remote access to information, resulting in so-called digital medical records or electronic health records. This advancement would ensure seamless continuity of care. This is particularly valuable in emergencies such as the COVID-19 pandemic, and promotes collaborative efforts among healthcare professionals.

2) CHALLENGES

The management of a significant volume of clinical data within DT-enabled medical records requires substantial storage resources located as close as possible to users. This proximity helps reduce latency, ensuring quick access to information and providing adequate memory space to keep patient data up-to-date and readily available to physicians at any time. In addition to data storage, data transmission presents significant challenges. Latency and unreliable coverage in remote areas must be effectively addressed to prevent inaccuracies in patient information. Furthermore, due to the high sensitivity of health data, ensuring the security and confidentiality of patient information is crucial, both in terms of data storage and transmission.

3) SOLUTIONS

Edge computing, device-to-device (D2D) communications, non-terrestrial networks (NTNs), and cutting-edge 6G security measures provide effective solutions to the challenges of using DTs as digital medical records. In particular, edge nodes can offer efficient data storage and processing capabilities in close proximity to users, allowing the entire DT or relevant data to be locally stored before being sent to central servers. where DTs are placed. This setup has the potential to significantly reduce latency in updating digital medical records, thereby improving their accuracy and timeliness. The integration of edge computing and AI can further enhance the efficiency, security, and responsiveness of DT-based electronic medical records. For example, AI-powered edge nodes can analyze a patient's vital parameters in real time, promptly detecting abnormalities and helping to alleviate network congestion. Additionally, federated learning can be applied to detect patterns in patients' data through a distributed approach enabling predictive health insights while preserving information security.

Data transmission performance can be considerably improved through D2D communications, which allow direct communication between devices in close proximity. For instance, a sensor on a patient could send data directly to an edge server, bypassing the base station. This would reduce energy consumption, increase throughput, lower transmission power, and minimize latency. Similarly, NTNs can extend network coverage to remote or underserved areas, ensuring reliable data transmission even in challenging environments.

Regarding security, 6G's advanced security features – such as quantum cryptography, biometric authentication, federated learning, and blockchain – would ensure robust protection of health data within DT-based medical records. For example, post-quantum encryption algorithms could safeguard digital medical records from future quantum computing threats. In addition, blockchain-based encryption could ensure the traceability and immutability of operations performed on medical records, preventing data tampering. 6G-AKA (Authentication and Key Agreement) could facilitate secure authentication between devices and 6G networks, while biometric-based authentication would ensure secure, personalized access to DTs without relying on vulnerable passwords. Lastly, federated learning would allow health data to be trained locally, minimizing the need for data transmission over insecure channels.

C. DIGITAL SURGERY TESTING

1) DESCRIPTION

The use of medical DTs, which accurately replicate human organs, has the potential to enable risk-free simulations of complex surgical procedures [12]. This application would allow surgeons to identify possible complications in challenging surgeries and explore alternative strategies in a virtual environment before performing them in the real-world. Additionally, it would facilitate virtual information sharing among multidisciplinary teams, fostering the development of collaborative. precision-driven surgical strategies.

2) CHALLENGES

Accurate and realistic modeling of organs or anatomical areas is essential for reliable surgical simulations. This demands access to high-quality anatomical data and the capability to convert it into precise digital models. Furthermore, real-time simulation and interactive engagement with virtual organs are critical to enable surgeons to visualize realistic outcomes.

3) SOLUTIONS

To address the aforementioned challenges, several key solutions must be implemented for *(i)* accurate modeling, *(ii)* real-time simulation, and *(iii)* data integration. Advanced imaging techniques, including high-resolution magnetic resonance imaging (MRI), computed tomography (CT), and real-time three-dimensional (3D) holography, enable the acquisition of detailed anatomical datasets. These can be transmitted over the 6G's ultra-high bandwidth ($\geq 1Tbps$) with near-zero delay, enhancing the precision of patient-specific DTs. Terahertz (THz)-based wireless transmission ensures the lossless and real-time delivery of these high-fidelity models for preoperative planning. For real-time digital surgery testing, the integration of edge computing and AI-driven rendering can enable instantaneous interaction with virtual surgical environments. Furthermore, AI and high-performance computing can enable hypercomputing, accelerating simulation processes and allowing more accurate and timely digital surgery testing. A native 6G network infrastructure, featuring advanced transmission techniques, such as beamforming, reconfigurable intelligent surfaces (RIS), and AI-enhanced connections, would ensure ultra-reliable low-latency communication (URLLC) between DTs and remote healthcare providers. Additionally, XR technologies, supported by 6G systems, can significantly improve surgeon interaction with virtual organs by providing haptic, visual, and auditory sensory integration. The haptic Internet in 6G enables precise force-feedback mechanisms, allowing surgeons to "feel" virtual tissues with near-zero latency, closely mimicking real-world surgical conditions. Collaboration with experts in human-computer interaction, robotics, and AI-empowered surgical training will drive the development of immersive, intelligent interfaces for next-generation 6G-enabled digital surgery platforms.

D. CLINICAL TRIALS

1) DESCRIPTION

Medical DTs represent a promising solution for accelerating drug testing, particularly in urgent scenarios such as the development of the SARS-CoV-2 vaccine. By enabling faster results and contributing to regulatory compliance, DTs can save both time and money. Using DTs for clinical trials can simplify the assessment of drug efficacy, associated adverse effects, and optimal dosing, potentially reducing the reliance on traditional, resource-intensive methods. Moreover, DTs can help model diverse patient profiles, overcoming the challenges of recruiting physically heterogeneous patients, thereby providing a more comprehensive understanding of how drugs interact with different individuals.

2) CHALLENGES

Ensuring reliable connectivity and robust network infrastructure, especially in underserved areas, is a critical challenge for conducting virtual clinical trials. The sensitive nature of patient data in these trials emphasizes the need for strong security measures and advanced encryption techniques to safeguard privacy and ensure compliance. Additionally, the real-time transmission of data from numerous IoT devices requires systems that can accurately and efficiently monitor and collect this information. To ensure seamless integration and communication across various platforms and devices, interoperability and standardization are essential. Finally, the high costs associated with implementing DTs for clinical trials remain a significant challenge.

3) SOLUTIONS

A 6G-driven network infrastructure can be realized through advanced technologies like Terahertz (THz) waves, RIS, multicast communications, and NTNs. These innovations enable ultra-fast, low-latency data transmission, even in remote or underserved areas, which is crucial for implementing DTs in clinical trials. For example, RIS-assisted THz communications can enhance transmission quality, ensuring instantaneous data exchange between DTs and medical AI models used in clinical trials. NTNs can extend network coverage to rural or isolated regions, facilitating comprehensive data collection, enabling efficient remote monitoring of all patients, and allowing for a more diverse and large participation pool in clinical trials.

To protect patient data and ensure regulatory compliance, post-quantum encryption and federated learning can be integrated into 6G-native security frameworks. These technologies prevent data breaches in digitalized clinical trials while enabling distributed AI training on medical datasets without exposing sensitive patient information. Blockchain-enabled smart contracts could further ensure data integrity and regulatory compliance by automating the verification of informed consent and clinical trial protocols.

Regarding cost reduction, the architectural evolution of 6G, shaped by research initiatives like the Hexa-X project, aims to create a highly flexible and cost-efficient network. The Hexa-X project, Europe's flagship 6H initiative, envisions a future of connectivity that bridges the human, physical, and digital worlds [13]. The architectural trends identified by Hexa-X highlight that the programmability, virtualization, and cloud-native design of the 6G Radio Access Network (RAN) and Core Network (CN) will enable dynamic resource allocation, reducing operational expenses (OPEX) in DT-based clinical trials. For instance, network slicing can create dedicated virtual infrastructures optimized for real-time medical simulations, lowering the cost of data processing and transmission. In addition, the exploitation of AI and ML can reduce network management costs by enabling intelligent network resource [14] and configuration management. This is particularly relevant when considering the use of THz frequencies in 6G networks, which require denser networks for broader coverage, but may also increase energy consumption, raising OPEX [15]. Implementing intelligent RANs, powered by AI and ML, can help mitigate this issue, ensuring both efficient and cost-effective 6G-powered clinical trials.

III. ROLE OF DT MIGRATION FOR MOBILE PATIENTS

Effective coupling between the PT and the DT relies on meeting specific conditions, particularly the effective DT placement to minimize latency. This has been a subject of extensive research. For example, in [16] the dynamic placement of social DTs within edge IoT environments is investigated to minimize data transmission delays, while accounting for device mobility, network deployment, device types, and social characteristics. Similarly, the authors in [17] focus on optimizing DT placement to minimize maximum application interaction delays, ensuring timely data delivery. However, latency is not the only factor to consider. In [18], the sustainability-conscious DT placement in wireless networks is addressed, aiming to reduce both system delay and energy consumption. Additionally, work in [19] proposes an architecture in which computing entities and DTs cooperate to provide computing services, introducing a DT placement and transfer scheme to adapt to fluctuating resource demands. This approach demonstrates improvements in latency, DT error rates, and resource utilization. These diverse strategies highlight the complexity of DT placement, which is further emphasized in [20], where the authors compare edge-based, cloud-based, and hybrid (edge-cloud) approaches. Each method comes with its own trade-offs, and the study concludes that the optimal solution depends on the specific characteristics of the application.

Once the optimal DT placement strategy is established, managing patient mobility becomes a critical challenge in the creation of medical DTs, particularly in edge computing environments. Edge servers, while advantageous for their low latency, typically have limited coverage, making them unsuitable for supporting continuous patient movement [21]. To ensure that the DT remains in close proximity to the referring patient at all times, it is necessary to transfer it from one edge server to another. This process, known as DT migration, is crucial for maintaining synchronization between the digital and physical twins as patients transition between different environments [9]. By allowing the DT to seamlessly follow the patient, continuous access to real-time data about their condition is ensured. This enables uninterrupted monitoring, reducing the risk of delayed treatment or misdiagnosis caused by outdated information. Ultimately, DT migration has the potential to revolutionize patient management and continuity of care, enhancing healthcare systems by reducing latency and fostering a more connected, responsive, and efficient approach to patient care, especially during mobility.

However, migrating a DT based on patient mobility is a complex process that presents several challenges. One of the primary issues in mobility-driven medical DT migration is ensuring the accurate replication and synchronization of moving entities [22]. Furthermore, minimizing latency

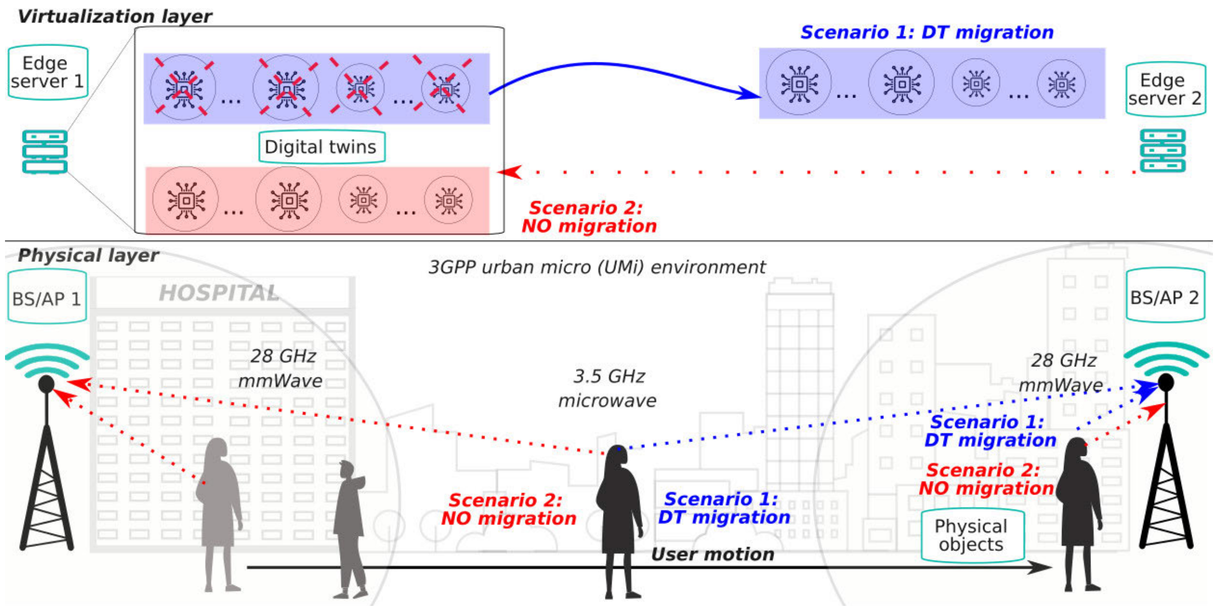


FIGURE 3. Simulation scenario.

is crucial, as processing delays can result in outdated representations, compromising the accuracy of predictions and decisions [23]. A robust and dependable network infrastructure is essential to facilitate the successful migration of medical DTs. Regardless of the entity's location or mobility, the DT system must guarantee seamless communication between the physical twin and its virtual representation [16].

Security is another critical aspect in DT migration. Protecting data and communication channels is paramount [24], and encryption techniques must be properly implemented to safeguard the confidentiality of data during transfer. For example, homomorphic encryption enables the transfer of data without the need for decryption, ensuring security throughout the process. Lastly, the lack of standardized communication protocols and data formats may pose significant hurdles in the migration of medical DTs [25].

Despite these challenges, ongoing research and development efforts are actively addressing these issues. Researchers are exploring innovative solutions for accurate and efficient data synchronization [26], [27], low-latency communication [28], robust network management [29], and enhanced security protocols [30], [31]. In parallel, standardization bodies are working to define common protocols and data formats for medical DTs [32], [33]. These advancements suggest that, while significant hurdles remain, practical and effective DT migration solutions for healthcare applications are becoming more feasible and are expected to be implemented in the near future.

IV. SIMULATION CAMPAIGN

A. REFERENCE SCENARIOS

In this study, we explore data transfer strategies for the DT-enabled application of digital medical records, with a particular focus on the transmission of patient health data

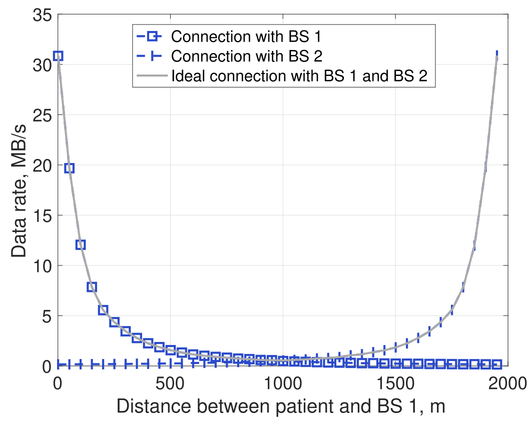


FIGURE 4. Data rate on the radio link between patient and BS.

– specifically ECG and blood pressure readings – into their corresponding DTs. The nature of these data types varies considerably. For example, ECG values, typically represented as time-series signals, can range in size from a few kilobytes to several megabytes per reading, depending on factors like sampling rate, resolution, and duration. In our simulations, we assume a typical ECG reading size of 2 MB. In contrast, blood pressure data, consisting of numerical values for systolic and diastolic pressures, is much smaller, generally amounting to only a few kilobytes. For our purposes, we use a representative size of 0.1 MB for a blood pressure reading. The frequency of data transmission also varies: ECG data may be transmitted periodically (e.g., every hour), while blood pressure readings might be sent at scheduled intervals (e.g., every 3 hours).

As illustrated in Fig. 3, the simulations involve two base stations (BS 1 and BS 2), separated by a distance of 2 km.

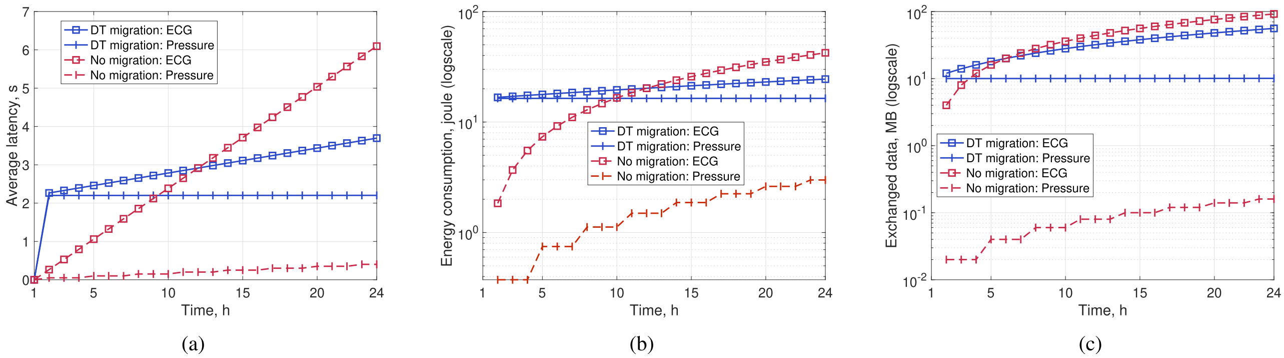


FIGURE 5. (a) Latency, (b) Energy consumption, and (c) Exchanged data(2 km area, 2 BSs).

BS 1 serves the hospital and its surrounding area, while BS 2 covers locations where patients typically spend their time, such as offices or homes. Each BS is co-located with an edge server. Patients' DTs, with a size of 10 MB, are initially deployed as containers on edge server associated with BS 1 [16]. The wired backhaul connecting the two edge servers has a bandwidth of 1 Gb/s.

We use the 3GPP channel model for an urban micro (UMi) environment, defined in [34]. This model is applied to both the mmWave band at 28 GHz and the μWave band at 3.5 GHz. The BS side is configured with a 32x32 antenna array, while the device side has a 2x2 configuration. The transmit power is set to 10 dBm at the device and 23 dBm at the BS. The power consumption of the baseband electronic circuitry at the device and BS side is set to 5.34 W [35]. Patients establish communication with the available BSs and, by extension, with their DTs hosted on the co-located edge servers, using either the mmWave or the μWave radio interface, depending on their proximity to the BS. Specifically, when a patient is within 250 m of a BS, mmWave transmissions are used, otherwise, the μWave interface is employed. Moreover, patients switch from BS 1 to BS 2 while moving, based on the prevailing channel conditions.

We focus on patients who move from the hospital to offices or homes and remain there for a variable time interval duration. During this observation period, the physical devices monitoring the patient's health continuously communicate with the corresponding DT. In detail, we analyze the following two possible scenarios: *DT migration* and *No migration*.

1) *DT migration*; when the patient moves from BS 1 to BS 2, the corresponding DT is migrated from edge server 1 to edge server 2. The migration process involves transferring a container with a data volume of 10 MB. It is assumed that a preallocation of the container at the target edge server (edge server 2) is initiated in advance when the user is expected to move toward BS 2. However, the actual transfer of the container's data volume is activated only after the user's handover to BS 2 [36]. Once the container is started on edge server 2, the monitored health data from the patient's physical devices are directly delivered to the DT via the uplink to BS 2.
2) *No migration*; in this case, although the patient moves from the coverage area of BS 1 to the coverage area of BS 2, the corresponding DT remains on edge server 1. This results in additional backhaul transmission between the two BSs. Once the patient leaves the coverage area of BS 1, the health data collected on the patient is transmitted via the uplink to BS 2, and then it is routed from BS 2 to BS 1 via the backhaul, as the data still needs to be stored in the DT at edge server 1.

The metrics of interest in our analysis include: *(i)* data rate on the radio links, *(ii)* latency for migrating and updating the DT, *(iii)* total energy consumed, and *(iv)* amount of data exchanged over time.

B. NUMERICAL RESULTS

In Fig. 4, we show the data rate (measured in megabytes per second, MB/s) achievable on the cellular links as the distance (measured in meters, m) between the patient and BS 1 increases. Three possible connection options are considered: *(1)* connection patient-BS 1, *(2)* connection patient-BS 2, and *(3)* connection to the best BS, in terms of data rate, potentially utilizing backhaul links. When the patient is within the 250 m range of a BS (BS 1 or BS 2), the mmWave bands are used, providing higher data rates. In contrast, for distances between 250 m and 1750 m, the μWave radio interface is used, and there is overlap between the coverage areas of BS 1 and BS 2. The curve following a parabolic trend in the figure corresponds to connection option *(3)*, where handover is triggered when the patient enters the coverage area of BS 2. In the following analysis, we evaluate the metrics of interest by considering option *(3)* (ideal connection) and assuming perfect switching between the BSs.

In Figures 5(a), (b), and (c), we analyze the impact of *DT migration* and *No migration* on key metrics, respectively: *latency*, representing the time (measured in seconds, s) needed to update the DT with data readings from the patient; *energy consumption* measuring the energy cost (in joules) and *exchanged data* including both data readings and container's data volume migration (in megabytes, MB). The analysis considers two types of medical data, ECG (labeled as *ECG*) and blood pressure (labeled as *Pressure*). The data point is sent 2 hours after the start of the monitoring interval.

1) LATENCY

Fig. 5(a) shows the latency, which includes both data transfer over the access and backhaul links. Initially, for ECG data, *DT migration* results in higher latency than *No migration* due to the time needed to migrate the DT over the backhaul link. However, as the patient remains away from the hospital, the *No migration* strategy experiences increased latency due to the need for periodic updates transmitted via the backhaul from BS 2 to BS 1. For ECG data, *DT migration* becomes advantageous after 12 hours of patient being away from the hospital, with up to a 41% improvement in latency with regard to *No migration*. This suggests that for time-sensitive data like ECG, minimizing backhaul traffic over long periods is crucial. In a real-world medical application, this would result in faster alerts for critical ECG events, even if the patient has moved from the initial monitoring location.

For blood pressure data, which are sampled less frequently, the latency increase in the *No migration* case is more gradual. Consequently, *No migration* remains the most efficient solution for up to 24 hours, with a performance improvement of up to 81% with regard to *DT migration*. This highlights that for less frequent updates (e.g., blood pressure), the initial *DT migration* overhead might not justify the expected long-term benefits, and maintaining the DT at the original BS may be preferable for short-term monitoring.

2) ENERGY CONSUMPTION

Fig. 5(b) depicts the average energy consumed by the system. We note that the energy spent by device remains the same regardless of the migration strategy, once fixed the type of data (ECG or blood pressure). Clearly, the lower data size (0.1 MB vs. 2 MB) and sampling rate (every 3 h vs. 1 h) in the case of blood pressure readings justify the lower energy spent for such data transmission compared to the ECG case.

On the contrary, the network energy consumption, specifically on the backhaul links, differs significantly with the migration strategy. This difference arises from how data are routed and stored. In the *DT migration* case, the DT is pre-allocated at edge server 2 as the patient moves towards BS 2, increasing initial energy consumption. Then data flows directly from the device to BS 2 and DT, without traversing the backhaul network. In contrast, with *No migration*, the DT remains at edge server 1, forcing data from BS 2 to travel over the backhaul to BS 1, increasing significantly network energy consumption with every data transmission. Here, a similar pattern to the latency analysis is observed: *DT migration* yields performance gains for ECG data after the patient has been away from the hospital for 12 hours or more.

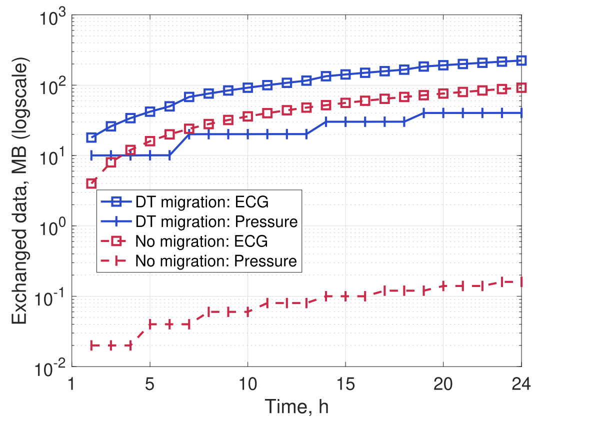


FIGURE 6. Exchanged data for multi-hop network scenario (10 km area, 5 BSs).

3) EXCHANGED DATA

Transferred data volume over the network is shown in Fig. 5(c). For the blood pressure data, which is sampled less frequently, *No migration* is more efficient for 24 hours, aligning with the intermittent nature of clinical readings and resulting in up to 98% improvement in data volume transfer with regard to *DT migration*. For ECG data, with higher sampling frequency, *DT migration* becomes more efficient after 5 hours. Though the initial migration of the DT is larger (10 MB), subsequent updates are smaller, reducing the total data volume compared to continuous transmission of raw ECG data. This results in up to 39% reduction in network load and bandwidth usage with regard to *NO migration* for continuous monitoring.

4) MULTI-HOP SCENARIO

To evaluate scenarios involving patient mobility across a larger area, we considered a multi-hop network. Fig. 6 shows the volume of transferred data across a 10 km area with 5 BSs and multi-hop communication. In this case, *No migration* remains the more efficient strategy for 24-hour monitoring, as keeping the DT closer to the hospital minimizes data transfer overhead. *DT migration* incurs significant data transfer overhead as the patient moves between edge servers. This holds true for both ECG and blood pressure data, where the migration of DT containers introduces unnecessary costs.

In summary, our findings demonstrate that the optimal data transfer strategy depends heavily on both *(i)* the data update frequency, which varies depending on the type of medical data being monitored, and *(ii)* the overall monitoring duration. *DT migration* is generally more effective for long-term monitoring and data types (e.g., ECG) that require frequent updates. Although it introduces a higher initial latency due to the migration process, it ultimately reduces backhaul traffic and network energy consumption. On the other hand, for short-term monitoring and data types with low update frequencies (e.g., blood pressure), *No migration* offers greater efficiency, minimizing the overhead associated with DT migration.

V. CONCLUSION AND LESSONS LEARNED

This article explores the promising convergence of digital twins and 6G networks in the context of eHealth, highlighting the transformative potential for healthcare. DTs offer the ability to create virtual patient replicas for simulation, diagnosis, and treatment optimization, providing a substantial opportunity to enhance healthcare delivery. However, for practical implementation, several challenges must be addressed, particularly in managing patient mobility. Our work fills a critical gap in existing literature by providing a comprehensive exploration of DT applications in eHealth, identifying associated challenges, and proposing solutions enabled by 6G technologies. Furthermore, we delve into the issue of DT placement and migration at the network edge, considering the mobility of patients. Through a simulation campaign, we gained insights into the dynamics of DT migration, underscoring the need for informed decisions on data transfer strategies. These decisions must account for factors such as data type, transmission frequency, and network conditions to ensure optimal performance.

The potential of 6G to address the challenges of implementing medical DTs presents a compelling opportunity for future research and practical application. With near-zero-latency transmissions, 6G can play a pivotal role in ensuring real-time synchronization between physical and digital twins, especially concerning the mobility of the physical twin. This real-time synchronization ensures that the digital representation remains aligned with the patient's current health status. Additionally, the resource optimization capabilities of 6G can reduce costs, making DT adoption more feasible across various healthcare settings. To advance the practical deployment of medical DTs, future research efforts must focus on developing advanced encryption and authentication mechanisms in 6G to protect patient data integrity and confidentiality. Another important direction is to prioritize real-time synchronization and resource optimization, particularly through network slicing for healthcare and energy-efficient communication for medical devices. These developments are essential for realizing the full potential of medical DTs in improving patient care and optimizing healthcare systems.

REFERENCES

[1] C. De Alwis, A. Kalla, Q.-V. Pham, P. Kumar, K. Dev, W.-J. Hwang, and M. Liyanage, "Survey on 6G frontiers: Trends, applications, requirements, technologies and future research," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 836–886, 2021.

[2] Ericsson. *Making Digital Equality a Reality This Decade*. Accessed: Oct. 2024. [Online]. Available: https://www.ericsson.com/en/about-us/company-facts/ericsson-worldwide/united-states/digital-divide

[3] David Meads. *Cisco: Why Digital Healthcare is the Critical Path Forward*. Accessed: Oct. 2024. [Online]. Available: https://blogs.cisco.com/healthcare/why-digital-healthcare-is-the-critical-path-forward

[4] C. Suraci, S. Pizzi, F. Montori, M. Di Felice, and G. Araniti, "6G to take the digital divide by storm: Key technologies and trends to bridge the gap," *Future Internet*, vol. 14, no. 6, p. 189, Jun. 2022.

[5] K. G. HamlAbadi, M. Vahdati, A. M. Saghiri, and A. Forestiero, "Digital twins in cancer: State-of-the-art and open research," in *Proc. IEEE/ACM Conf. Connected Health: Appl., Syst. Eng. Technol. (CHASE)*, Dec. 2021, pp. 199–204.

[6] S. D. Okegbile, J. Cai, C. Yi, and D. Niyato, "Human digital twin for personalized healthcare: Vision, architecture and future directions," *IEEE Netw.*, vol. 37, no. 2, pp. 262–269, Feb. 2023.

[7] M. Alazab, L. U. Khan, S. Koppu, S. P. Ramu, M. Iyapparaja, P. Boobalan, T. Baker, P. K. R. Maddikunta, T. R. Gadekallu, and A. Aljuhani, "Digital twins for healthcare 4.0–Recent advances, architecture, and open challenges," *IEEE Consum. Electron. Mag.*, vol. 12, no. 6, pp. 29–37, Jun. 2023.

[8] Grandview Res. *Healthcare Digital Twins Market Size, Share & Trends Analysis Report by Type (Process & System Digital Twin, Product Digital Twin), by Application, by End-use, by Region, and Segment Forecasts, 2022–2030*. Accessed: Oct. 2024. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/healthcare-digital-twins-market-report

[9] J. Chen, C. Yi, S. D. Okegbile, J. Cai, and X. Shen, "Networking architecture and key supporting technologies for human digital twin in personalized healthcare: A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 26, no. 1, pp. 706–746, 1st Quart., 2024.

[10] F. Tao, B. Xiao, Q. Qi, J. Cheng, and P. Ji, "Digital twin modeling," *J. Manuf. Syst.*, vol. 64, pp. 372–389, Jul. 2022.

[11] J. Corral-Acero, F. Margara, M. Marciniak, C. Rodero, F. Loncaric, Y. Feng, A. Gilbert, J. F. Fernandes, H. A. Bukhari, and A. Wajdan, "The digital twin to enable the vision of precision cardiology," *Eur. Heart J.*, vol. 41, no. 48, pp. 4556–4564, 2020.

[12] A. Balasubramanyam, R. Ramesh, R. Sudheer, and P. B. Honnavalli, "Revolutionizing healthcare: A review unveiling the transformative power of digital twins," *IEEE Access*, vol. 12, pp. 69652–69676, 2024.

[13] M. A. Uusitalo, P. Rugeland, M. R. Boldi, E. C. Strinati, P. Demestichas, M. Ericson, G. P. Fettweis, M. C. Filippou, A. Gati, M.-H. Hamon, M. Hoffmann, M. Latva-Aho, A. Pärssinen, B. Richerzhagen, H. Schotten, T. Svensson, G. Wikström, H. Wymeersch, V. Ziegler, and Y. Zou, "6G vision, value, use cases and technologies from European 6G flagship project Hexa-X," *IEEE Access*, vol. 9, pp. 160004–160020, 2021.

[14] S. Yrjola, P. Ahokangas, M. Matinmikko-Blue, R. Jurva, V. Kant, P. Karppinen, M. Kinnula, H. Koumaras, M. Rantakokko, V. Ziegler, A. Thakur, and H.-J. Zepernick, "White paper on business of 6G," 2020, *arXiv:2005.06400*.

[15] M. Ericson, M. Condoluci, P. Rugeland, S. Wänstedt, M. S. H. Abad, O. Haliloglu, M. Saimler, and L. Feltrin, "6G architectural trends and enablers," in *Proc. IEEE 4th 5G World Forum (5GWF)*, Oct. 2021, pp. 406–411.

[16] O. Chukhno, N. Chukhno, G. Araniti, C. Campolo, A. Iera, and A. Molinaro, "Placement of social digital twins at the edge for beyond 5G IoT networks," *IEEE Internet Things J.*, vol. 9, no. 23, pp. 23927–23940, Dec. 2022.

[17] M. Vaezi, K. Noroozi, T. D. Todd, D. Zhao, and G. Karakostas, "Digital twin placement for minimum application request delay with data age targets," *IEEE Internet Things J.*, vol. 10, no. 13, pp. 11547–11557, Mar. 2023.

[18] Y. Zhou, Y. Fu, Z. Shi, K. Hung, T. Q. S. Quek, and Y. Zhang, "Sustainable placement with cost minimization in wireless digital twin networks," *IEEE Trans. Veh. Technol.*, vol. 74, no. 1, pp. 1064–1077, Jan. 2025.

[19] Y. Zhang, H. Zhang, Y. Lu, W. Sun, L. Wei, Y. Zhang, and B. Wang, "Adaptive digital twin placement and transfer in wireless computing power network," *IEEE Internet Things J.*, vol. 11, no. 6, pp. 10924–10936, Jun. 2023.

[20] L. U. Khan, Z. Han, W. Saad, E. Hossain, M. Guizani, and C. S. Hong, "Digital twin of wireless systems: Overview, taxonomy, challenges, and opportunities," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 4, pp. 2230–2254, 4th Quart., 2022.

[21] E. Bozkaya, "Digital twin-assisted and mobility-aware service migration in mobile edge computing," *Comput. Netw.*, vol. 231, Jul. 2023, Art. no. 109798.

[22] O. Hashash, C. Chaccour, W. Saad, K. Sakaguchi, and T. Yu, "Towards a decentralized metaverse: Synchronized orchestration of digital twins and sub-metaverses," 2022, *arXiv:2211.14686*.

[23] M. Mashaly, "Connecting the twins: A review on digital twin technology & its networking requirements," *Proc. Comput. Sci.*, vol. 184, pp. 299–305, Mar. 2021.

[24] Y. Wang, Z. Su, S. Guo, M. Dai, T. H. Luan, and Y. Liu, "A survey on digital twins: Architecture, enabling technologies, security and privacy, and future prospects," *IEEE Internet Things J.*, vol. 10, no. 17, pp. 14965–14987, Sep. 2023.

[25] F. Tang, X. Chen, T. K. Rodrigues, M. Zhao, and N. Kato, "Survey on digital twin edge networks (DITEN) toward 6G," *IEEE Open J. Commun. Soc.*, vol. 3, pp. 1360–1381, 2022.

[26] L. Tang, L. Wang, D. Fang, and Q. Chen, "Dynamic slice resource management and information synchronization strategy in IoV based on digital twin," *IEEE Trans. Intell. Transp. Syst.*, vol. 26, no. 5, pp. 6635–6650, May 2025.

[27] Y. Zhang, L. Wang, and W. Liang, "Deep reinforcement learning for mobility-aware digital twin migrations in edge computing," *IEEE Trans. Services Comput.*, vol. 18, no. 2, pp. 704–717, Apr. 2025.

[28] Y. Wang and X. Zhao, "A digital twin dynamic migration method for industrial mobile robots," *Robot. Comput.-Integr. Manuf.*, vol. 92, Apr. 2025, Art. no. 102864.

[29] O. Chukhno, N. Chukhno, G. Araniti, C. Campolo, A. Iera, and A. Molinaro, "Learning-powered migration of social digital twins at the network edge," *Comput. Commun.*, vols. 226–227, Oct. 2024, Art. no. 107918.

[30] G. Thakur, P. Kumar, Deepika, S. Jangirala, A. K. Das, and Y. Park, "An effective privacy-preserving blockchain-assisted security protocol for cloud-based digital twin environment," *IEEE Access*, vol. 11, pp. 26877–26892, 2023.

[31] C. Alcaraz, I. H. Meskini, and J. Lopez, "Digital twin communities: An approach for secure DT data sharing," *Int. J. Inf. Secur.*, vol. 24, no. 1, pp. 1–19, Feb. 2025.

[32] *SmartM2M; Digital Twins Communication Requirements*, document ETSI TS 103 845 V1.1.1, ETSI, Feb. 2024.

[33] *SmartM2M; SAREF: Digital Twins Opportunities for the Ontology Context*, document ETSI TR 103 827 V1.1.1, ETSI, Sep. 2023.

[34] *Study on Channel Model for Frequencies From 0.5 to 100 GHz (Release 17)*, document TR 38.901 V17.0.0, 3GPP, Mar. 2022.

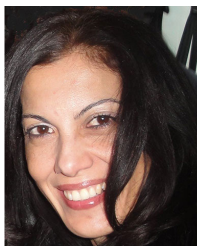
[35] O. Chukhno, G. Singh, C. Campolo, A. Molinaro, and C. F. Chiasserini, "Machine learning performance at the edge: When to offload an inference task," in *Proc. 2nd Workshop Networked Sens. Syst. Sustain. Soc.*, Oct. 2023, pp. 180–186.

[36] C. Campolo, A. Iera, A. Molinaro, and G. Ruggeri, "MEC support for 5G-V2X use cases through Docker containers," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2019, pp. 1–6.

CHIARA SURACI (Member, IEEE) received the M.Sc. degree in telecommunications engineering and the Ph.D. degree in information engineering from the University Mediterranea of Reggio Calabria, Italy, in 2018 and 2022, respectively. She is currently an Assistant Professor with the DIIES Department, University Mediterranea of Reggio Calabria. Her current research topics include 5G/6G networks, device-to-device (D2D) communications, network security, virtualization technologies, and eHealth services.

OLGA CHUKHNO received the B.Sc. degree in business informatics and the M.Sc. degree in fundamental informatics and information technologies from the Peoples' Friendship University of Russia (RUDN University), Russia, in 2017 and 2019, respectively, and the double Ph.D. degree from Tampere University, Finland, and the Mediterranea University of Reggio Calabria, Italy, in 2022. She was a MSCA Fellow with Tampere University and Mediterranea University of Reggio Calabria. She is currently an Assistant Professor with Tampere University and Mediterranea University of Reggio Calabria. Her main research interests include wireless communications and mathematical modeling.

GABRIEL-MIRO MUNTEAN (Fellow, IEEE) is currently a Professor with the School of Electronic Engineering, Dublin City University (DCU), Ireland. He coordinated the EU project NEWTON and led the DCU research teams in the EU projects HEAT and TRACTION. He is an Associate Editor of IEEE Transactions on Broadcasting, the Multimedia Communications Area Editor of IEEE Communications Surveys and Tutorials, and a reviewer of important international journals, conferences, and funding agencies.



ANTONELLA MOLINARO (Senior Member, IEEE) received the degree in computer engineering from the University of Calabria, in 1991, the master's degree in information technology from the CEFRIEL/Polytechnic of Milano, in 1992, and the Ph.D. degree in multimedia technologies and communications systems, in 1996. She is currently a Full Professor of telecommunications with the University Mediterranea of Reggio Calabria, Italy, and University of Paris Saclay, France. Her research mainly focuses on wireless and mobile networking, vehicular networks, and future internet.

GIUSEPPE ARANITI (Senior Member, IEEE) received the Laurea degree and the Ph.D. degree in electronic engineering from the University Mediterranea of Reggio Calabria, Italy, in 2000 and 2004, respectively. He is currently an Associate Professor of telecommunications with the University Mediterranea of Reggio Calabria. His major area of research is on 5G/6G networks and it includes personal communications, enhanced wireless and satellite systems, traffic and radio resource management, multicast and broadcast services, device-to-device (D2D), and machine-type communications (M2M/MTC).