6G-enabled Digital Twins: Applications, Requirements, and Challenges

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I. INTRODUCTION

Digital Twins (DTs) are rapidly emerging as a core technological enabler for building intelligent, connected, and resilient systems across industries. From modern power systems to future wireless communications, DTs rely on rich, dynamic data exchanges between the physical and virtual worlds. These exchanges must be fast, reliable, and intelligent, where sixth-generation (6G) networks play a transformative role. As shown in Fig. 1, the International Mobile Telecommunications (IMT) 2030 vision sets the stage for 6G, offering advanced capabilities such as Artificial Intelligence (AI)-native design, ultra-reliable low-latency communication, integrated sensing, and pervasive connectivity [1]. These features directly align with and enhance the foundational demands of DTs, including compatibility, scalability, reliability, security, privacy, synchronization, and visualization [2].

This section will explain the critical role of 6G in enabling the full capabilities of DTs. It begins by introducing the concept and communication-centric design of DTs, followed by an overview of the essential technical requirements they must meet. It then highlights how the advanced features of 6G directly support these requirements, positioning 6G as a key enabler for building scalable, responsive, and secure DT systems.

A. Background and definition of Digital Twin

The process of creating a digital duplicate of a real physical system (*"twining"*), product, or service is known as a **DT**. It is typically regarded as a digital model or simulation framework with multiform

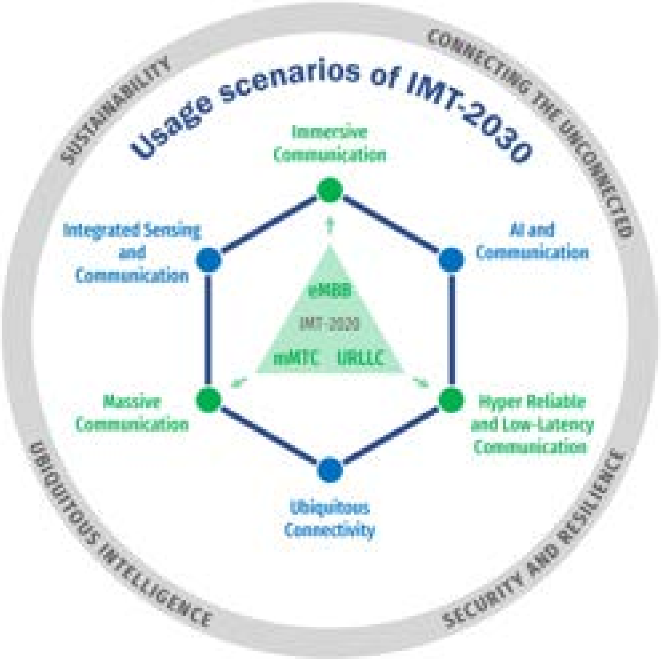

Fig. 1. Usage Scenarios for IMT-2030 [1]

physics and scales, guaranteeing a high degree of realism in replicating the behaviour of a real physical counterpart. The concept of twinning can be dated back to NASA's use of ground-based replicas of its Apollo spacecraft during astronaut missions. They subsequently provided the first official description of a DT, emphasizing interconnected, high-fidelity, and lifetime vehicle systems [3]. The fundamental concept was that the DT would be connected to its physical counterpart for the duration of its existence, allowing these two parts to develop simultaneously [4], [5]. DT can be used to track performance, offering insightful information to improve system performance and anticipate potential problems. By combining historical data, real-time sensor data, and digital models, DT achieves this goal and creates a multitude of advantages such as real-time monitoring and control, predictive maintenance, and sophisticated planning and coordination for a wide range of industry applications [6]. At first, DT was related to the idea of a Cyber-Physical System (CPS) [7]. The key concepts that CPS and DTs have in common include a strong digital-physical link, real-time communication, smooth organizational integration, and broad cooperation. However, the origin, development process, engineering techniques, cyber-physical mapping, and essential functional components of CPS and DTs could be different from each other.

The ability of DT to '*communicate* is one of its main differentiators; in fact, to prevent misunderstandings, additional definitions have been created for *digital model* and *digital shadow* have been created [5]. A digital model replicates a real-world system or item, but there is no two-way communication between them. The DT, on the other hand, communicates data in both directions [8], [9], [10]. For example, in Fig. 2, the visualization of communication links (data flow) for the DT of the wind farm is illustrated and compared with other closely related counterparts (digital model and digital shadow).

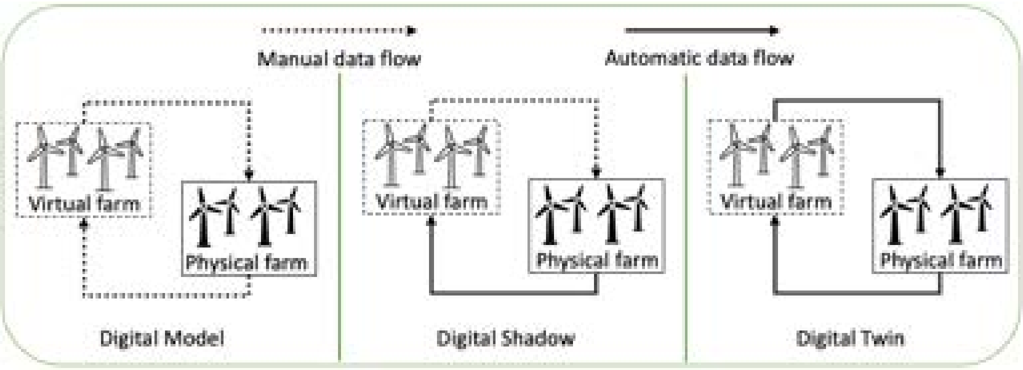

Fig. 2. Communication as a key feature for DT due to twinning

DTs require at least three types of communication [11]: communication between digital and physical twins, communication between multiple DTs in a complex simulated environment, and communication between DTs and domain experts via user interfaces. Tao *et al.* [12] and Qi *et al.* [13] further argue that these communications may not be sufficient to support a wide range of applications. Thus, they proposed a model to include new communication dimensions (services and data). Mathematically, the i^{th} DT model (m_{DT_i}) can be expressed as below.

$$m_{DT_i} = \{p_i, v_j, s_k, d_l, c_{i,j,k,l}\} \tag{1}$$

where p_i represents the i^{th} physical object, v_j denotes the j^{th} virtual DT corresponding to p_i, s_k represents the k^{th} service associated with p_i's application domain, d_l is the associated l^{th} data transferred, and $c_{i,j,k,l}$ represents the connections between the four key components of i^{th} DT model (m_{DT_i}).

The addition of data and services in DTs generates large data volumes from physical twins over time. High-fidelity DTs require high-bandwidth connections like 5G or 6G to handle data collected over extended periods. Multiple DT models, based on different sensor sets, may coexist, even if some are less detailed. Services expand tasks such as assessing system performance, adapting to environmental changes, modifying behavior, and predicting faults. These tasks demand low-latency, highly reliable connections to anticipate safety-critical events and detect potential issues early. A robust, high-quality connection is crucial for accurate and timely data transmission to and from the DT.

B. Key requirements for DTs

A DT must meet several critical requirements to function as a virtual representation of physical assets effectively. These allow for accurate modeling, real-time feedback, monitoring, analysis, and physical systems improvement. The following key elements are essential for the implementation of DTs across different industries and use cases:

- **Real-time communication and connectivity**: Continuous, low-latency communication between the physical and virtual environments is crucial for the DT to operate in real time. Reliable connectivity ensures continuous synchronization between digital replicas and their physical counterparts. This capability will enhance the twin's ability to react to physical system changes in real-time, especially for applications including autonomous vehicles, smart grids, and industrial robotics, where immediate feedback and adjustments are critical.
- **High-fidelity modeling and simulation**: In DTs, physical systems are represented by digital replicas through accurate modeling, including their physical components, behaviors, and interactions. High-fidelity models are critical as they allow for real-time monitoring, predictive analytics, and operational optimization with greater precision and reliability. For instance, modern power systems could leverage high-fidelity electrical and thermal models to help predict how electrical components react to heat generation, dissipation, and environmental factors, ensuring optimal performance, lifespan, and safety.
- **Massive network scalability and heterogeneous integration**: To support the integration of massive internet-of-things networks, DTs are expected to manage heterogeneously connected devices, sensors, and actuators in complex environments where multiple industries and sectors (e.g., energy, health-care, transportation) use interconnected DT systems. These ecosystems require scalable structures to accommodate data throughput and computational resource demands, supporting massive services and applications across various domains.
- **AI and machine learning-driven analytics**: AI and machine learning enabled DTs to offer promising data-driven solutions to support predictive analytics, real-time decision-making, and system self-optimization for future industry applications, including modern power systems, future communications networks, and autonomous vehicles. Massive data generated by sensors, devices, and plants can significantly improve the performance of machine learning-based models. Enabled by the advances in AI cognition, context-aware, and goal-oriented optimization are expected to adapt to alterations in physical systems with optimal resource allocation.

- **Sustainability and energy efficiency**: Sustainability and energy efficiency are essential requirements for DTs because they are critical to optimizing resource use, minimizing environmental impacts, and ensuring long-term operational and financial viability. As DTs continue to advance across various sectors, from manufacturing to energy, particularly with the advent of 6G and AI-driven technologies, their ability to support sustainable development and energy-efficient operations becomes vital for achieving operational success and sustainable development goals.
- **Security, privacy, and trustworthiness**: Security, privacy, and trustworthiness ensure the safe, reliable, and ethical use of DT technology, as it relies on the interconnection of massive users and devices involved with vast data. These requirements protect DTs from cyber threats, safeguard sensitive information, and ensure accurate, reliable system performance. In increasingly connected environments like autonomous vehicles, modern power grids, and 6G networks, these principles are essential to maintain system integrity, protect user data, and build trust in the DT's real-time decision-making capabilities.
- **Immersive interfaces and extended reality (XR)**: Immersive interfaces and XR, including virtual reality (VR), augmented reality (AR), and mixed reality, provide enhanced visualization, real-time interaction, collaborative capabilities, and human-centric control. These technologies enable users to interact with complex systems in an intuitive and immersive manner, leading to better decision-making and improved operational efficiency.
- **Data integration, interoperability and cooperation among heterogeneous DTs:** Fidelity and synchronization rates can vary in DTs and may not always perfectly mirror their physical counterparts. The level of fidelity and synchronization depends on the specific use case and industry requirements. For example, in the healthcare sector, real-time and detailed mirroring is crucial for remote surgery. Since it might mean the difference between life and death, the capability of simulating and acting in real-time is even more crucial in the healthcare industry [8]. The lack of standardized data models or a general DT architecture poses a stringent challenge. A generalised DT design architecture could allow improved interoperability and support managing the diverse environments of varying sizes through the evaluation of existing systems. Data integration includes a process of amalgamating and consolidating data from different sources into a unified and coherent format. This process includes data extraction, transformation, and loading to guarantee compatibility and consistency. Simultaneously, modeling complex phenomena poses stringent challenges; thus, future research must

TABLE I
COMPARISON OF 5G AND 6G [19]

Attributes	5G	6G
Connection density	10^6 devices per km^2	10^7 devices per km^2
Latency	$\approx 1ms$	$\approx 100\mu s$
Data rate	10 Gbps (peak)	1 Tbps (peak)
Energy efficiency	10^3x relative to 4G	10x relative to 5G
Spectrum	3.4 -3.8 GHz	95 GHz - 3 THz
Spectrum efficiency	3-5x relative to 4G	3x relative to 5G
AI support	Partially	Fully
AR/VR support	Partially	Fully
Satellite integration	No	Yes

consider difficulties associated with data integration and modeling these complex occurrences [14], [15], [16].

- **Measurement and performance validation:** Using DTs as “soft sensors” is crucial for extending the measurement range in situations where specific data cannot be directly measured. The lack of accurate measurement of the magnitude and characteristics of benefits is a significant obstacle. More research is needed to understand and measure the benefits of DTs for specific sectors. It is important to examine whether the distribution of simulation data and physically measured data is identical because using simulation data to augment inadequate training data poses a persistent challenge [17].

C. Advancements of 6G and its added value for DT

Fifth Generation New Radio (5G NR) has opened the era of massive machine type communications (mMTC), this enabled the Internet of Everything (IoE), generative AI and several emerging technologies. However, 5G NR is a user-centric network without the extensive intelligence of devices in their design. Therefore, it is evident that there are many new use cases where 5G NR is unable to meet the extremely stringent technical and commercial requirements. For example, use cases such as VR, AR, XR, holographic telepresence, collaborative robots (cobots), telemedicine, etc. are still a challenge for 5G NR. Research and development on the 6G network ecosystem is expected to achieve network connectivity for these novel use cases and address societal needs in the 2030s and beyond [18]. Table I outlines the key milestones of 6G compared to 5G.

1) User and AI-centred networks: In the new 6G era and beyond, there will be user-centered and AI-centered networks in which devices will have learning and computing capabilities. The advancement in AI, the connected end devices or user equipment (UE), and network equipment such as switches and routers have the capability of computing and autonomous AI [20]. Fundamental changes will be made to make 6G an AI-enabled system that is designed to be a new communication system with a comprehensive AI and Communication (AIC) as one of the new usage scenarios in 6G [1], [20]. This would support distributed computing and AI applications with use cases like assisted automated driving, autonomous collaboration between devices for different applications, offloading of heavy computation operations across devices and networks, creation of and prediction with DT, and others that were not exploited in 5G NR systems. AIC would require support of high traffic density, high capacity and data rates, low latency, and high reliability based on the specific use case. This can be easily configured and tested in DT-enabled 6G. This is expected to include capabilities related to the integration of AI and compute functionalities into IMT-2030,, such as data acquisition, preparation and processing from different sources, distributed AI model training, model sharing, and computing resource orchestration and chaining.

2) Ubiquitous connectivity in 6G era: Among the key scenarios in 6G is ubiquitous connectivity aimed at improving global coverage for bridging the digital divide by connecting the unconnected and under-served areas through integration of 6G terrestrial network and Non-Terrestrial Networks (NTN) such as satellites and aerial platforms (e.g., High-Altitude platforms and Unmanned Aerial Vehicles or drones). The integration of 6G and NTN could be quite complex and would require DT and AI to accomplish seamlessly. The essential components to ensure smooth 6G-NTN integration and communication across diverse technologies, systems, and applications are synchronization and interoperability. This will provide unprecedented data rates and hyper-connectivity across heterogeneous networks, devices, and services.

3) Data-driven 6G networks: DT-enabled network management framework and optimization that do not rely heavily on humans, but instead rely on data and AI algorithms are needed to realize the virtualization of users and network devices to achieve resource collaboration and sharing in 6G [20]. The DT can be built using real-time synchronized data from the network and users. Achieving intelligence-driven network management and integration under the emerging paradigm of pervasive intelligence and DT has not been fully exploited in the 5G NR era [20]. The Integrated Sensing and Communication (ISAC) scenario facilitates new applications and services that require sensing capabilities. This makes use of IMT-2030 to offer wide area multi-dimensional sensing that provides spatial information about unconnected objects as well as connected devices and their movements and surroundings. Typical use cases include IMT-2030 assisted navigation, activity detection, and movement tracking, such as posture/gesture recognition, fall detection, vehicle/pedestrian detection, environmental monitoring (e.g., rain/pollution detection), and provision of sensing data/information on surroundings for AI, XR, and DT applications [18]. This usage scenario requires support of high-precision positioning and sensing-related capabilities such as range/velocity/angle estimation, object and presence detection, localization, imaging, and mapping [1].

4) Synchronization and interoperability: The 6G era is distinguished from 5G NR with 3 additional usage scenarios: i) AIC, ii) ISAC, iii) UC. These scenarios require stringent timing accuracy, network synchronization, and the ability to integrate diverse network components and standards. Synchronization is required to make sure that nodes and devices within a network operate simultaneously to reduce errors. While Interoperability makes possible the communication between heterogeneous networks and devices by guaranteeing smooth functionality irrespective of protocols or technologies. Synchronization and interoperability are considered key to achieving the vision of 6G as a consolidated communication ecosystem. These could be first implemented, tested, and validated using a DT-enabled network in the 6G era.

In 6G networks, synchronization is vital in sustaining the operational efficiency of the network nodes, particularly in an ultra-dense and ultra-low latency network environment. 6G is characterized by extensive UEs, actuators, and sensors, as well as hyper-reliable low latency. Precise timing is needed by new applications in 6G, which makes traditional synchronization mechanisms like Precision Time Protocol and Network Time Protocol insufficient. For example, to achieve real-time experience, holographic communication and AR require synchronization in microseconds. Complexity may be added to the synchronization when using distributed architectures such as decentralized Base Stations and edge computing, since devices may not always be connected to the central clock. Therefore, 6G networks will present some challenges, such as device heterogeneity, ultra-low latency requirements, and distributed architectures. These challenges will require advanced solutions in the 6G era that include AI-driven synchronization using machine learning and AI algorithms for prediction and compensation of clock drifts and synchronization errors. This solution can be tested, validated, and optimized using the DT-enabled 6G network [20].

5) Integration of end-to-end semantic awareness: Unlike conventional communication systems that focus on the accurate recovery of transmitted bits or symbols at the receiver, semantic communication introduces a new communication paradigm that emphasizes task effectiveness and system goals beyond data transmission, prioritizing semantic fidelity over bit-level accuracy [21]. This approach aims to reduce the need for redundant information and extract the best performance of the system, which could significantly benefit the DT for efficient resource allocation, synchronization, and interoperability. However, the definition of “best performance” could vary according to specific applications and system requirements. For instance, in the real-time networked control system, the optimal performance may not necessarily involve minimizing the mismatch of states between physical plants and their digital replicas; instead, it could prioritize the freshness of information in the digital replica. Consequently, performance metrics are not limited to the correctness of the information but also the freshness and importance of the information. Enabled by semantic awareness in 6G, new performance metrics, such as age of information, age of incorrect information, and age of loop, can be designed to optimize the system under diverse requirements, leading to more effective resource allocation [22].

Moreover, an end-to-end optimization framework in semantic communication is designed to jointly optimize the transmitter and receiver toward specific transmission goals. This framework is particularly effective in addressing channel distortions such as noise, interference, and fading [23], which are common in dynamic wireless environments. Training the system enables the transmitter to intelligently encode and the receiver to decode information in a way that focuses on preserving the semantic content, even when channel conditions degrade. This joint optimization allows the system to adaptively handle impairments in diverse scenarios, including challenging conditions with high mobility or moving scatterers [24]. For instance, in environments like high altitude platform systems or cooperative ground systems, where users and objects may be in constant motion, the end-to-end framework allows the communication system to dynamically adjust to the rapidly changing channel conditions, ensuring reliable and efficient information transfer even under severe fading or interference. This end-to-end optimization process could be seamlessly integrated with DT applications in industrial automation and control systems, including real-time monitoring, state estimation, and proactive decision-making, thus enabling a goal-oriented joint design of the networked control system.

6) Energy-efficient wireless communication techniques for DT: In traditional wireless communications, signals transmitted through the air experience random scattering, diffraction, and reflections due to environmental obstacles and objects, resulting in an inherently uncontrollable propagation environment [25], [26]. This randomness limits the performance and increases the transmission latency, making it difficult to meet the low latency and reliability requirements of DTs. Typically, mitigating these effects involves deploying numerous antennas and designing complex transceiver schemes [27], which include techniques like coding, modulation, diversity, adaptive rate/power control, and digital beamforming [25]. However, these approaches require sophisticated designs with higher energy consumption and cost while failing to fully address the randomness of wireless channels. Therefore, reconfigurable intelligent surfaces (RISs) and reconfigurable holographic surfaces (RHSs), both cutting-edge metamaterial-based technologies envisioned for 6G networks, are emerging as transformative solutions for creating smart wireless environments [25], [26], [28], [29]. By enabling precise beamforming of signals towards intended destinations, RISs and RHSs significantly improve the transmission latency, received signal strength, and overall performance, which are essential for effective DT communications. While both RISs and RHSs share the advantages of cost-effectiveness, energy efficiency, and the ability to create intelligent propagation environments without the need for complex signal processing, they are designed to fulfill distinct roles. Specifically, RISs are primarily envisioned as advanced replacements for conventional relays, whereas RHSs are set to revolutionize and replace the traditional antenna technologies [25], [26], [28], [29].

Since DTs involve a large number of devices transmitting data, multiple access and multiplexing schemes play a key role in enabling efficient and scalable DT communications. Promising multiple access schemes, such as non-orthogonal multiple access (NOMA) and rate-splitting multiple access (RSMA), which allow devices to share the same resources simultaneously, can be considered key enablers for future DTs [30], [31]. Additionally, the orbital angular momentum (OAM) multiplexing scheme, which leverages the spatial distribution of helical phases, offers additional degrees of freedom by creating new channels for data transmission [32], [33], [34]. This enables multiple devices to share the same resources, including time, frequency, power, and code [32]. As recommended by ITU-R, the OAM multiplexing scheme is particularly advantageous for THz systems [35]. Therefore, these multiple access and multiplexing schemes, i.e., NOMA, RSMA, and OAM, are highly promising for meeting the key requirements of DTs, such as massive connectivity, network scalability, low latency, and energy efficiency, among others.

In order to ensure reliable DT communications, devices such as sensors should be equipped with durable energy sources. Traditional sensors in IoT devices rely on batteries, which have a limited lifespan and require regular maintenance to function properly, thereby limiting the sustainability requirements of DTs [36], [37], [38]. Furthermore, replacing or recharging the batteries of IoT devices, particularly sensors embedded in inaccessible locations, can be extremely challenging [36]. Employing energy harvesting (EH) techniques, which enable devices to harvest energy from pre-existing natural or man-made sources, emerges as a promising solution to address the energy efficiency and sustainability requirements of DTs [37], [38]. However, it is noteworthy that, in some scenarios, the harvested energy might be insufficient to support reliable, low-latency, and long-range communications [36]. In such scenarios, integrating RISs with EH-based devices can help overcome these limitations, making it a promising approach for energy-efficient, sustainable, and reliable DT communications.

7) Physical layer security and ultra-high data rates of DTs: Immersive interfaces and XR, which are essential for enabling an ultra-high data rate DT environment, require a significant amount of bandwidth to ensure high-quality and real-time data transmission. Due to the limited bandwidth available in the existing frequency bands, such as microwave and millimeter-wave bands, the ITU has proposed a shift towards the THz band in future 6G networks [1], [39]. The THz band offers a huge amount of bandwidth, making it a promising solution to support the immersive interfaces and XR [1], [39], requirements of DT systems. In addition, due to the highly directional antennas of THz systems, THz waves exhibit extremely narrow beam-widths, which makes them robust against eavesdropping [40], [41], [42], and thus enhances the physical layer security of DTs. However, in some cases, eavesdroppers may be located in close proximity and have a line-of-sight (LOS) with legitimate communication entities, enabling them to intercept information [41], [42]. Therefore, owing to the beamforming capabilities of RISs and RHSs, signals can be precisely directed towards legitimate DT entities, making it highly challenging for eavesdroppers to intercept the information reliably [41], [42], [43]. Thus, the integration of THz systems with RISs and RHSs emerges as a promising technique to fulfill several key requirements of DTs, such as low latency, sustainability, energy efficiency, ultra-high data rates for immersive interfaces and XR, and improved physical layer security.

II. VISIONS FOR 6G ENABLED DTS AND APPLICATIONS

Industrial automation and control systems are rapidly evolving, driven by the need for efficiency, reliability, and flexibility. The demands of various modern industrial applications are increasingly challenging traditional networked control systems. In this section, the integration of cloud-native networked control systems with DTs and 6G technologies will be introduced. Existing challenges will be identified. Provisional insights on how 6G assisted DTs could enhance various industrial automation and control applications will be given.

A. DTs for wireless communications

In the face of ever-evolving data demands driven by emerging technologies such as autonomous vehicles, smart healthcare, and XR, the landscape of wireless communication is advancing rapidly. The IoE demands mMTC, ultra-reliable low-latency communication (URLLC), and higher data rates, which push beyond the capabilities of existing 5G systems [44], [45]. The evolution towards 6G wireless networks is expected to introduce an integrated approach to communication, sensing, and computing. DT technology offers a transformative way to meet these challenges by linking the physical and digital worlds, simulating real-world wireless networks for optimization and real-time control [44]. Implementing DTs is critical in the context of 6G, which aims to provide seamless connectivity using millimetre wave (mmWave) and THz technologies. DTs will empower wireless networks to adapt, scale, and optimize dynamically in real-time, overcoming physical limitations of new frequency bands, such as signal attenuation and material absorption while maintaining high reliability and low latency [46].

A DT is a virtual representation of a physical object or system, enabling simulations, predictions, and optimization without impacting the live network. In wireless communication, DTs can simulate and optimize network performance before deployment, monitor and troubleshoot networks in real-time, and test new technologies and protocols in a virtual environment [47]. However, this raises the question: Do we truly need DTs for wireless communication? This section explores the pivotal role of DTs in enhancing wireless communication systems, particularly within the context of 6G.

1) Need for DTs in 6G: Deploying higher frequency bands like mmWave and THz introduces complex radio characteristics that present significant challenges. These frequencies are more susceptible to absorption by common materials and experience substantial signal attenuation due to user mobility and environmental obstacles [48]. For instance, the link budget can suffer a power loss of 20 dB or more when obstacles obstruct the line-of-sight (LoS) link, leading to degraded signal quality and unreliable communication conditions critical for time-sensitive applications [49]. These challenges require not only precise beam management but also predictive, data-driven control mechanisms that go beyond traditional static configurations. DTs facilitate this by creating a dynamic digital mirror of the network, enabling continuous optimization and decision-making based on real-time and historical data.

Moreover, the shift towards ultra-dense networks (UDNs) with intelligent beamforming technologies adds complexity. Beamforming, while offering benefits like higher spatial reuse, increased throughput, and minimized interference [50], requires precise beam alignment and management. Achieving this in dynamic environments is challenging due to factors such as device mobility and changes in the radio environment. Additionally, adopting Open Radio Access Network (Open RAN) architectures in 6G networks introduces further challenges. Open RAN promotes interoperability and flexibility by allowing network operators to use equipment from multiple vendors through standardized open interfaces. While this openness accelerates innovation and reduces costs, it also increases the complexity of network integration and management [51]. The heterogeneous nature of Open RAN components can lead to compatibility issues, making it difficult to ensure seamless network performance. Furthermore, open interfaces may introduce security vulnerabilities, necessitating robust measures to safeguard the network. Therefore, to overcome these challenges, future communication systems must embody the following properties:

- **Self-Sustaining Wireless Systems:** Next-generation IoE applications are data-driven, requiring seamless connectivity and dynamic resource allocation. Future 6G networks should use minimal human intervention, leveraging AI and machine learning (ML) techniques for autonomous resource optimization [45].
- **Proactive Operations, Administration, and Maintenance:** Due to their scale and complexity, manually managing UDNs is impractical. Automation through predictive network analytics and advanced AI can optimize communication and computing resources, enhancing operational efficiency [44].
- **Native AI Integration:** AI will be an intrinsic feature of future networks, aiding network management and optimizing physical components. AI-assisted sensing and positioning will enable low-cost, highly accurate beamforming and tracking, significantly impacting air interface design [46].
- **User-Centric Beam Management with Proactive Control:** Beam-based communication is essential for higher frequency bands. Advanced technologies like sensing, AI-driven position estimation, real-time tracking, and proactive handovers are crucial for maintaining seamless connectivity and precise beam alignment [49].
- **Collaborative and Continual Learning:** The dynamic requirements of IoE applications necessitate adaptive learning models. Traditional learning techniques are inadequate for the complex wireless environments of 6G networks. Collaborative intelligence and continuous learning models can address these complexities, providing robust solutions in dynamic conditions.

2) DT - A catalyst for wireless network evolution: DT technology, originally adopted in industries like manufacturing for modeling complex systems, is now emerging as a pivotal tool in wireless communication. In this context, a DT is a virtual wireless network model that mirrors its physical counterpart in real-time. The DT framework leverages real-time sensory data, including network traffic patterns, user mobility, and environmental factors, to generate insights that can proactively adjust network parameters, such as

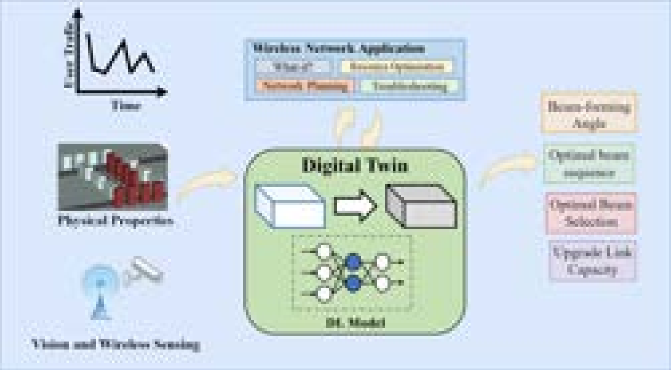

Fig. 3. Generalised architecture of wireless DT for 6G communication.

beam angles, power levels, and handovers. This enables adaptive, predictive, and highly efficient network management, which is critical for 6G use cases like autonomous vehicles and XR [52]. However, it is very difficult to model the entire wireless communication system with a single DT. Therefore, the wireless communication system can be divided into multiple manageable twin objects to serve dynamic applications and services for efficient modelling. By partitioning the wireless system into smaller, manageable DT objects, each representing a subsystem like base stations, mobile devices, or user clusters, the overall system becomes highly scalable and adaptable. This modular approach allows for localized optimizations, enabling fine-grained control of network resources and reducing the computational load on any single DT instance.

Moreover, it is essential to categorize the wireless DT and identify the entities and objects based on which a wireless DT will be created to serve a specific purpose. The generalised architecture of wireless DT is presented in Fig. 3, representing a single twin object. The essential component of this architecture is DT, which represents the physical network by taking the multi-modal data and physical properties of the system and providing output-related network configurations. In this context, achieving accurate and efficient beam alignment is one of the main challenges for future wireless communication [49]. This requires a high degree of coordination between the different antenna elements and can be affected by factors such as the movement of devices and changes in the radio environment. Additionally, beamforming can be computationally intensive and challenging for devices with limited processing power.

In wireless communication systems, DTs can be categorized based on their role in modeling, optimizing, and managing various aspects of the wireless network. Below are potential categories that can be used to classify the DTs in wireless communication systems:

a) Infrastructure-level DTs: **Base Stations**: DT for base stations enables the detailed modelling of key physical and operational parameters, including antenna arrays, coverage areas, and environmental variables influencing signal propagation (e.g., building obstructions, weather conditions). By creating a virtual counterpart for each base station, network operators can perform real-time simulations to optimize beamforming techniques, enhance coverage, and dynamically adjust load balancing strategies to accommodate varying user densities. This modelling ensures robust performance even in ultra-dense network environments, characteristic of 6G systems [44], [52]. **Core Network Elements**: DT of core network components, such as mobility management entities (MMEs), serving gateways (SGWs), and packet data network gateways (PGWs), allow for the simulation and prediction of network bottlenecks and potential failures. These simulations enable proactive management by optimizing data routing paths to minimize latency and prevent congestion during peak loads. By mirroring the performance of core network elements, operators can enhance throughput and ensure seamless end-to-end connectivity in response to fluctuating traffic demands, particularly for mission-critical applications [46]. **Edge Nodes**: In the context of 6G networks, edge computing is critical in reducing latency for time-sensitive applications such as autonomous driving, remote surgery, and immersive XR. DT of edge nodes facilitates network functions' virtualization, including content caching and data processing, ensuring minimal delays by dynamically managing resources close to the user. Through these simulations, network operators can optimize the deployment and configuration of edge nodes, delivering high-quality services with ultra-low latency while reducing the backhaul burden on the core network [52].

b) UE-level DTs: DTs for UEs are vital for optimizing the performance and efficiency of mobile and connected devices in 6G networks. For mobile devices such as smartphones and wearables, DTs simulate connectivity, mobility, and power consumption, enabling real-time optimization of power-saving mechanisms and seamless handovers, ensuring extended battery life and uninterrupted connectivity, even in high-speed environments [44]. For IoT devices, DTs manage the energy consumption and data transmission of low-power devices, such as sensors, by optimizing resource allocation for mMTC, enhancing energy efficiency while supporting large-scale IoT deployments [53]. In vehicle-to-everything (V2X) communication, DTs model interactions between vehicles and network infrastructure, optimizing signal quality and reducing latency to ensure reliable, low-latency communication essential for autonomous vehicles, even in dynamic and challenging environments [53], [54].

c) Network-level DTs: Network-Level DTs are essential for managing the dynamic and complex environments of 6G networks, offering real-time insights into network performance and optimization. One key functionality is resource allocation, where DTs can simulate the distribution of wireless resources, such as spectrum, power, and bandwidth, across diverse users and applications [55]. This ensures efficient utilization, particularly in ultra-dense network scenarios, optimizing overall network capacity.

In handover management, DTs model user mobility patterns and real-time radio conditions, enabling seamless handover between base stations or network slices. This reduces service interruptions and maintains consistent connectivity, crucial for mobile and mission-critical applications [52]. Additionally, DTs play a critical role in network slicing, simulating the creation and management of virtual network segments tailored to specific use cases, such as IoT or enhanced mobile broadband (eMBB). These slices are optimized for resource allocation and provide isolated, customized service delivery for each use case, ensuring high-performance and reliability across diverse network demands.

d) Environment-level DTs: Environment-Level DTs enable the simulation of signal propagation and network behaviour across diverse geographic landscapes, ensuring optimized connectivity tailored to specific environments. In urban environments, where high building density and device interference can significantly affect signal quality, DTs model the impact of skyscrapers, traffic, and other obstacles on signal propagation [56]. These simulations guide the optimal placement of base stations, small cells, and relay nodes, ensuring seamless connectivity and minimal interference in densely populated areas. For indoor environments, DTs account for the complexities of signal behaviour within buildings, including the effects of walls, furniture, and human movement on wireless performance. By simulating these conditions, DTs help network operators optimize indoor coverage in smart buildings, shopping malls, and large venues, ensuring reliable signal quality and efficient use of wireless resources. Additionally, in rural and remote areas, DTs simulate the unique challenges of long-distance signal propagation, such as increased signal attenuation and sparse infrastructure [44], [56]. These models aid in strategically placing macro base stations or satellite links, maximising coverage and ensuring connectivity in areas where network infrastructure is limited or difficult to deploy.

e) Application-level DTs: Application-level DTs play a critical role in optimizing wireless networks for specific, high-demand use cases in 6G environments, ensuring that the unique requirements of each application are met with precision. For instance, in the case of autonomous vehicles, DTs are essential in managing vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2X) communications [56]. By creating real-time virtual replicas of vehicular communication networks, DTs can predict potential signal disruptions caused by high mobility or environmental obstacles, optimizing connectivity and handover processes. Additionally, another example could be XR applications, including AR and VR, demand ultra-low latency and high bandwidth to ensure seamless, real-time interaction. A DT for XR creates a virtual network model, simulating the bandwidth requirements and latency-sensitive nature of XR experiences. By predicting latency bottlenecks and dynamically adjusting network parameters such as resource allocation and traffic prioritization, DTs ensure uninterrupted, high-quality immersive experiences for users.

B. Modern power systems

The conventional power system, based on centralized generation and uni-directional energy flow, has been the foundation of electrical energy distribution for years. However, the demand for a resilient and sustainable power system has become evident due to the depletion of conventional energy sources, climate change, and the rising need for electricity, which has driven the advancement of intelligent distribution systems that include the concept of smart grids, microgrids, and virtual power plants. Modern power systems incorporate intelligent management techniques, communication systems, and advanced technologies to optimize the functioning of power systems [57]. They allow for bi-directional power flow, real-time monitoring, and enhanced control, improving the sustainability, reliability, and efficiency of the energy distribution system. Through the use of technologies like energy management systems, grid automation, demand response programs, distributed energy resources, and smart metering infrastructure, the modern power system enables the integration of non-conventional energy sources, such as wind and solar [58]. Also, it enhances energy infrastructure resilience by providing real-time observation and detection of faults in the power system with automatic system restoration abilities, ensuring a reliable energy supply even during disruptions [59]. Furthermore, modern power systems enhance grid flexibility and demand management by encouraging consumers to modify their energy consumption patterns [60]. It allows grid operators to balance energy demand and supply, prevent overloads, and delay expensive infrastructure upgrades, ultimately leading to a more stable and efficient power system.

Although modern power systems have advanced in accommodating distributed energy resources, they continue to encounter the following challenges and limitations due to the increasing operational complexity.

- The growing inclusion of distributed energy resources, such as electric vehicles, batteries, wind turbines, and rooftop solar modules, in distribution systems presents flexibility and scalability issues for energy management systems [61]. Initially designed for the centralized grid, these systems may struggle to adapt to the decentralized and dynamic characteristics of distributed energy resources. Consequently, the full potential benefits of these resources may remain unrealized.

- Conventional grid management systems lack real-time information, complicating the monitoring and response to dynamic grid variations [62]. This limitation impedes the efficient management of intermittency and uncertainty in renewable energy generation, often leading grid operators to adopt conservative strategies that can result in the sub-optimal utilization of renewable resources.
- The enhanced connectivity and digitization of modern power systems also present cybersecurity risks [63]. As modern power systems depend on interconnected smart appliances and communication infrastructures, they become susceptible to cyberattacks. Safeguarding the power system against such threats is crucial for maintaining its resilience and reliability.
- Effective grid management necessitates smooth data exchange and communication among diverse components such as energy sources, storage units, and appliances. However, current communication protocols and architectures may be insufficient for managing the substantial data volumes produced by modern power systems, potentially leading to suboptimal decision-making, data loss, and communication delays [64].

To overcome these limitations and challenges, the 6G wireless communication protocol presents a promising solution. 6G networks are anticipated to substantially improve reliability, latency, capacity, and speed [65]. Advancements in 6G will enable faster, more secure communication between power system components, supporting efficient data exchange, real-time monitoring, and rapid decision-making. 6G technology, with its capacity for supporting large-scale machine-type communications, is well-suited to managing the vast amounts of data produced by modern power systems. Furthermore, the ultra-reliable and low-latency communication features of 6G networks will enhance the control and coordination of distributed energy resources, thereby optimizing grid balance and the use of renewable energy sources. Moreover, the enhanced cybersecurity capabilities of 6G networks will help reduce risks and maintain the resilience and integrity of energy management systems. A basic structure of a 6G-assisted modern power system is shown in Fig. 4 with a focus on its features and advantages.

The objective of 6G networks is to deliver exceptional reliability, ultra-low latency, high availability, and support for a vast number of devices concurrently. The architecture of 6G networks is still developing, but several critical technologies are anticipated to define the future of wireless connectivity. These technologies

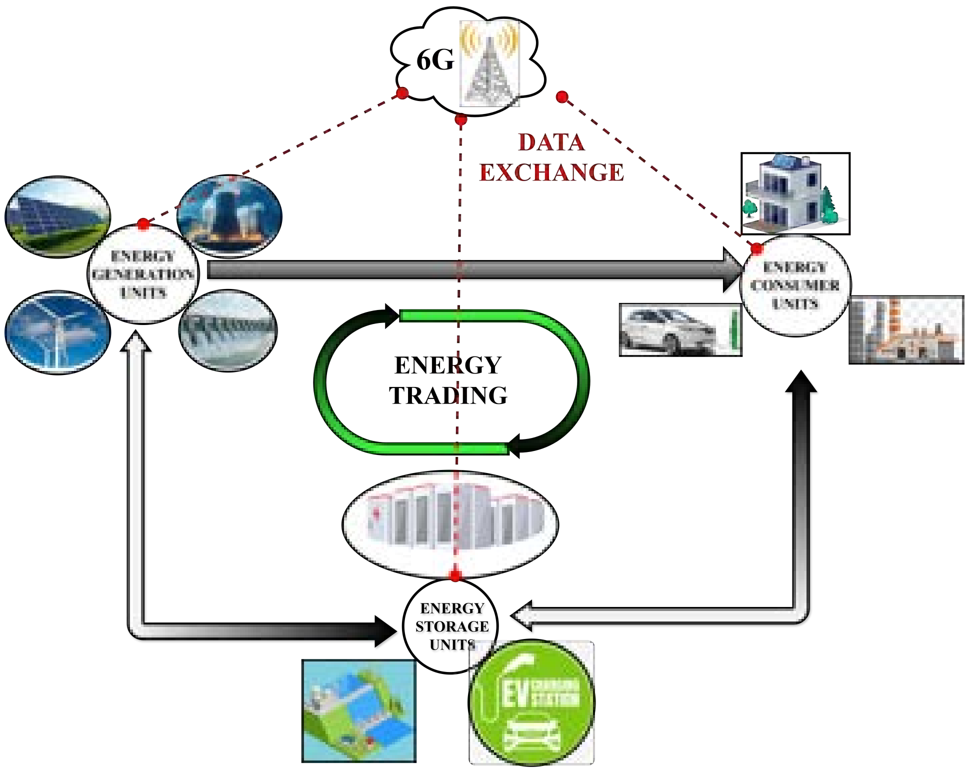

Fig. 4. Schematic structure of 6G-assisted modern power systems.

include the concept of DTs, blockchain technology, advanced authentication approach, intrusion detection and prevention systems, multi-layered security strategies, network slicing, and secure communication protocols. With the vision to improve resilience and cybersecurity in the modern power system, the concepts of DT add the following advantages:

- **Real-time fault and anomaly detection:** A key benefit of DT is its capacity to facilitate predictive fault detection and maintenance within the grid. By examining data from the DT, operators can anticipate potential concerns, irregularities, or failures in the grid before they affect the physical system [66]. This proactive strategy helps avert disruptions, minimize grid downtime, and optimize maintenance plans, thereby enhancing operational efficiency and grid reliability.
- **Energy planning and operational scheduling:** DT enables the application of optimization algorithms and advanced analytics to the virtual model of the grid. Utilizing AI and machine learning, the DT can model various scenarios, conduct predictive analyses, and enhance grid operations. It includes grid resiliency planning, energy management optimization, and demand response in virtual power plants and microgrids [67], [68]. Insights from the DT can support decision-making and facilitate more effective and efficient energy management strategies.

- **Training and testing model:** The DT offers a secure and controlled environment for simulating and assessing various grid management strategies, response plans, and emergency scenarios. It supports grid operators and technicians in advancing their skills, validating new technologies, and improving grid resilience.
- **Cybersecurity:** By consistently monitoring the DT, operators can identify and address potential cyber threats and vulnerabilities in real-time [69]. The DT can serve as a controlled model for testing security patches and simulating cyber attacks, thereby enabling operators to enhance the physical grid's security proactively.

Incorporating DT technology and 6G into modern power systems offers a range of significant benefits. It strengthens transparency, trust, and data security by offering an immutable and decentralized platform for the verification and protection of information.

C. Autonomous ground systems and vehicles

The incorporation of DT technology into intelligent vehicles for the purposes of monitoring, simulation, and sustaining the vehicular operations over its lifespan has been extensively examined in prior research [70], [71], [72]. Additionally, DT is prevalently employed in the automotive industry to facilitate the testing and certification processes of vehicles prior to their deployment on public roads. This integration allows DT to augment several vehicular facets, including design, traffic optimization, autonomous driving tests, and the upkeep of critical infrastructure [73]. Prior to vehicle assembly, engineers and manufacturers employ AI to evaluate the vehicle and utilize simulation models to forecast potential malfunctions, defects, and deterioration. Through these methodologies, DTs can mitigate unforeseen expenditures by obviating the necessity for maintenance and road testing.

The automotive sector is experiencing significant transformations due to advancements in digitized technologies, which are reshaping the trajectory of Autonomous Vehicles (AVs). Consequently, there will be a marked increase in data processing within AV platforms and the supporting IoT infrastructure. In AVs, driving tasks may be partially or entirely automated with minimal driver intervention, adhering to varying levels of autonomy as defined by the Society of Automotive Engineers (SAE). Level 0-1 denotes the absence of automation, wherein the driver maintains comprehensive control over fundamental vehicle functions, including steering, braking, and propulsion. At Level 2, the manufacturer automates certain functions, permitting the driver to maintain overarching control and assure safe operation. Level 3 involves the integration of at least two key functions that collaborate to assist the driver, enabling engagement in other activities. Level 4 permits limited self-driving capabilities, allowing the driver to relinquish control of safety-critical functions, especially concerning environmental and traffic conditions. At Level 5, the vehicle achieves complete self-driving abilities, executing all driving tasks and continuously monitoring road conditions throughout the journey. The vehicle does require driver-provided input for destination and navigation parameters. Once instructions are delivered, the autonomous vehicle can operate independently, with automated systems ensuring the vehicle's operational safety [74], [75].

AVs integrate connectivity and automation with the aim of minimizing driver error and enhancing the efficiency of transportation, ultimately striving to achieve a safer road ecosystem. The characteristic ability of AVs to exchange data in real-time with other vehicles, infrastructure, and external sources is facilitated by advanced communication technologies. This capability permits the synchronization of vehicle movements, such as merging and the formation of vehicle platoons. Figure 5 illustrates a typical Connected and Autonomous Vehicle (CAV) scenario, wherein multiple vehicles communicate and sense data from their surroundings to accomplish broader objectives.

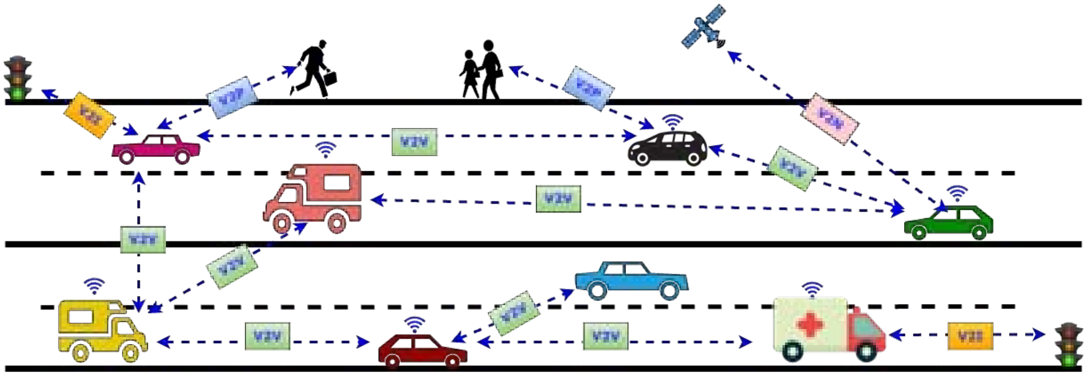

Fig. 5. CAV Exemplar Scenario

The realization of a CAV scenario in practical applications necessitates overcoming several significant challenges. Chiefly, as highlighted by *safety and comfort*, it is imperative that there is a high level of precision in perception and response times, measured in milliseconds. As a result, it is crucial to enhance path planning and adopt adaptive traffic management systems to optimize road efficiency [76]. The architectural framework of an Autonomous Vehicle (AV) is divided into five distinct domains as outlined by perception, localization, planning, control, and system management. Domain *Perception* involves the employment of onboard sensors such as light detection and ranging (LIDAR), cameras, and radio detection and ranging systems to sense and interpret the environment in real time. Domain *Localisation* deploys various methodologies to determine the vehicle's precise positioning. Domain *Planning* pertains to the decision-making processes and action execution within the self-driving platform, contingent upon its capability for environmental perception and localization. Domain *control system* is accountable for executing a range of actions, including braking, acceleration, and steering. Finally, Domain *System management* encompasses the monitoring and logging of system activities, the detection of faults, and the provision of a human-machine interface for advanced driver assistance systems (ADASs). DTs offer a practical virtual setting for the evaluation of ADASs, while automated driving systems constitute valuable benchmarks for conducting autonomous driving tests [77], [78]. The automotive industry is currently incorporating DTs, encompassing four stages of data exchange, as indicated by

- During the initial stage, AVs gather data about manufacturing, driver perception, and external systems.
- The operational driving phase involves acquiring sensor data from various operational properties and environmental factors.
- In the analytics phase, the DT utilises collected data to make informed decisions.
- The reporting phase suggests enhancing driving protocols, which engineers can manage. Stakeholders are provided with manually created reports for further examination.

The adoption of DT-based automatic driving tests can result in significant time and cost savings. It facilitates repeated testing under identical road conditions, thereby diminishing the number of parameters in the actual vehicle dynamics model and significantly enhancing the accuracy of the test results. Operating within a virtual environment aids in the prevention of accidents under real traffic conditions and minimizes material losses, thereby reducing business costs. Consequently, the utilization of DTs in autonomous driving introduces new possibilities for automobile production and performance evaluation. As discussed in the aforementioned proposals [76], [79], [80], DTs play a pivotal role in advancing the development and deployment of CAV-enabling technologies. Some of these roles are summarized below

- **Comprehensive Testing and Validation:** DTs realise a virtual replica of physical CAVs, allowing comprehensive testing and validation without any additional risks and costs associated with real-world experiments. Comprehensive testing and validation plays a crucial role for CAVs, given their complex nature and strict safety requirements.
- **Real-time Monitoring and Predictive Maintenance:** DTs enable continuous monitoring of vehicle systems and processes, helping to identify potential malfunctions much before before they actually occur. Thereafter, the predictive maintenance feature ensures increased reliability and safety for CAVs.

- **Performance Optimization:** DTs enable developers to to simulate and analyse various configurations, un-seen driving scenario's and varied driving strategies, leading to improved vehicle operations, characterized by increased efficiency and effectiveness.
- **Enhanced Development and Innovation:** DTs provides flexible platform for experimenting with new technologies and concepts such as explainable models, thereby expediting the advancement of functionalities and thereafter there ensuring seamless integration into the vehicles.
- **Regulatory Compliance and Certification:** DTs help demonstrate adherence to regulatory standards by providing comprehensive simulations and evaluations that can be used as an evidence during certification and validation processes.
- **Enhanced User Experience:** Manufacturers can use DTs to simulate user interactions with CAVs, improving the interface and ensuring a smooth and intuitive user experience.

The discussion elucidates that AVs are fundamentally reliant on real-time perception, localization, planning, decision-making, and actuation. However, to achieve this in real-world CAV settings, low latency, high bandwidth, and dependable vehicle-to-everything (V2X) communication are requisite. Current systems exhibit limitations in simulating complex traffic environments in real-time, thereby constraining AV safety and learning capabilities. Presently, 5G-enabled AV systems still contend with edge/cloud latency, restricted multi-agent simulation, and network congestion. Nonetheless, DTs afford the capability to simulate and predict vehicular behavior in real-time, proving beneficial for training, testing, and live operations. Concurrently, emerging 6G technology can furnish scalable, distributed, and real-time synchronization of physical and virtual environments. In conclusion, 6G-enabled DTs for CAVs can offer multifaceted advantages:

- Sub-millisecond latency for decision feedback.
- Significant improvements in hazard/obstacle detection accuracy through real-time DT simulation.
- Scalable multi-agent coordination within shared DT environments.
- A 6G edge-cloud continuum for ultra-low-latency data exchange.
- Expedited AV model validation cycles prior to road testing.
- AI/ML models trained in high-fidelity DT environments.
- A continuous synchronization loop between physical AVs and their DTs.

Thus, 6G is poised to be a foundational enabler for secure Level 4/5 autonomy. AVs will function as both data producers and consumers within the 6G-DT ecosystem. Future urban landscapes may host urban-scale

DTs, consistently updated by fleets of 6G-enabled AVs.

III. CHALLENGES AND KEY ENABLERS

In this section, challenges and key enablers for the 6G-enabled DTs will be discussed in terms of managing the growing volume of data and increasing complexity of models, ensuring data safety and security, and managing seamless inter-twin and intra-twin communications.

A. *Connectivity*

The realization of DTs technology and its applications are intrinsically linked to robust and efficient connectivity. Accurate and real-time DTs demand seamless communication between physical assets and their virtual counterparts, requiring the transmission of vast amounts of data with minimal latency. This subsection discusses the connectivity challenges inherent in developing DTs and explores the enabling technologies that address these obstacles.

1) Challenges:

- **High data volume and velocity**: DTs necessitate real-time data streams from many sensors and devices, generating massive amounts of data that must be transmitted promptly. Bandwidth limitations and network congestion can impede data throughput, leading to outdated or incomplete digital representations [45].
- **Ultra-low latency requirements**: Synchronization between the physical system and its DT demands minimal latency. Applications like autonomous vehicles and XR require end-to-end latencies in the order of milliseconds, posing significant challenges in achieving ultra-reliable low-latency communication (URLLC) over wireless networks [44].
- **Network reliability and availability**: Continuous operation of DTs depends on highly reliable networks. Issues such as signal fading, interference, and hardware failures can disrupt data exchange, compromising the DT's accuracy and effectiveness.
- **Scalability in ultra-dense networks**: The proliferation of connected devices in 6G networks leads to ultra-dense environments. Managing interference, ensuring quality of service (QoS), and efficiently allocating resources become increasingly complex as the number of devices and DT instances grows.
- **Security and privacy**: Transmitting sensitive operational data over wireless networks introduces risks of eavesdropping, tampering, and cyberattacks. Ensuring data integrity, confidentiality, and authentication is critical to protect both the physical system and its DT [46].

2) *Key enabling technologies:*

- **Advanced wireless communication technologies**: The advent of 6G promises enhanced bandwidth, lower latency, and improved reliability through technologies like terahertz (THz) communication and intelligent reflecting surfaces. These advancements facilitate high-speed data transmission essential for real-time DT synchronization [49]. Massive Multiple-Input Multiple-Output systems increase network capacity and spectral efficiency. Beamforming techniques direct signals toward intended receivers, reducing interference and enhancing signal quality, which is crucial for handling high data volumes [50].
- **Edge computing and fog networking:** Processing data at the network edge reduces latency and alleviates bandwidth demands on the core network. Edge computing enables real-time analytics and decision-making for DTs, enhancing responsiveness and reducing reliance on centralized cloud resources.
- **Network slicing and virtualization**: Network slicing allows the creation of virtual network segments tailored to specific DT requirements, providing dedicated resources and optimized configurations. Technologies like Software-Defined Networking and Network Functions Virtualization enable dynamic resource allocation and flexible network management [51].
- **Artificial intelligence and machine learning**: AI and ML algorithms optimize network performance by predicting traffic patterns and dynamically adjusting resources. AI-driven self-organizing networks can automate network configuration and healing, enhancing reliability and efficiency for DT communications [45].
- **Blockchain and distributed ledger technologies**: Blockchain offers a secure framework for data exchange between DT components, ensuring data integrity and authentication. Its decentralized nature enhances security by eliminating single points of failure and enabling transparent, tamper-proof transactions.

B. Scalability in 6G-enabled DTs

The scalability of resources is essential in a 6G-enabled DT environment to handle the unprecedented volume and complexity of data collected, transmitted, and processed in real time. 6G's promises of ultra-low latency, high-speed connectivity, and massive device integration introduce substantial demands on data throughput and computational resources. The corresponding DT environments must evolve to support vast volumes of real-time, heterogeneous data and computational workloads. This section outlines the primary scalability challenges in DT systems and proposes enabling technologies and frameworks to overcome them.

1) Challenges:

- **High data throughput and real-time processing:** The vast volume of sensor and telemetry data generated in DT environments demands ultra-fast processing. Ensuring low-latency and high-accuracy simulations in real time requires scalable and responsive data pipelines.
- **Dynamic workload adaptation:** DT systems often experience fluctuating workloads due to variations in user demand, event triggers, or system scale. Managing these changes efficiently requires dynamic resource allocation across computing layers.
- **Computational and energy trade-offs:** Achieving high computational performance while minimizing energy consumption is a persistent challenge. As DT environments scale, balancing these requirements becomes increasingly complex.
- **Vertical and horizontal resource scalability:** To support a wide range of DT applications, infrastructure must scale both vertically (enhancing the capability of existing nodes) and horizontally (adding new nodes or clusters).

2) Key enablers: To address the above challenges, a real-time and resilient data processing framework is illustrated in Fig. 6. This framework integrates distributed computing and orchestration mechanisms to enable scalable DT operations.

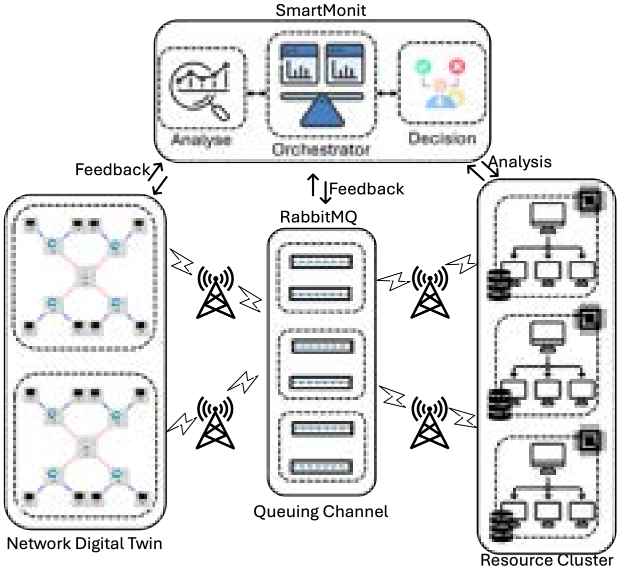

Fig. 6. Real-time Data Processing Framework

The components of the framework are discussed below:

- **Hadoop:** An open-source framework called Hadoop manages and processes enormous amounts of data in distributed computing environments. It works by distributing the data processing and storing among several machines, enabling fault-tolerant and scalable data processing. The MapReduce programming technique is used for processing, and the Hadoop Distributed File System (HDFS) is used for storing in the Hadoop architecture. While MapReduce analyses these blocks in parallel to increase efficiency and speed, HDFS divides massive datasets into smaller blocks and replicates them across multiple nodes. This decentralised methodology guarantees that Hadoop can efficiently handle petabytes of data and recover from failures with minimal disturbance [81].
- **Spark:** Apache Spark, a powerful open-source unified analytics engine, focuses on large-scale data processing. It is excellent at quickly processing large amounts of data in memory and can handle various tasks, including batch processing, interactive queries, streaming data, and machine learning. Resilient distributed datasets (RDDs), which enable effective data processing by distributing data over a cluster of servers, are the foundation of Spark's design. Spark is a flexible technology used for a wide range of big data applications because of its libraries for machine learning, SQL querying, and streaming data [82].
- **RabbitMQ:** RabbitMQ leverages the Advanced Message Queuing Protocol to facilitate communication across various distributed system components. Queues are used to organise and transport communications between producers, or applications that send messages, and consumers, or applications that receive messages. RabbitMQ can manage complex routing scenarios, guarantee dependable delivery, and support multiple message patterns, including publish/subscribe and point-to-point. Message acknowledgment, resilient queues, and transaction support to ensure message consistency and integrity are some of its strong points [83].

To achieve real-time orchestration and resource adaptation, the end-to-end workflow is as below:

- **Data generation and transmission:** The DT continuously generates data representing the operational statuses, performance metrics, and circumstances of the physical counterpart in real time. This information is sent to RabbitMQ, which manages message routing and queuing to guarantee dependable delivery.
- **Data forwarding and processing:** RabbitMQ receives this data and uses it for message routing and

queuing to guarantee timely delivery. Hadoop uses MapReduce to process data in batches and HDFS to manage distributed storage. Spark performs in-memory data processing to accelerate computations, utilizing RDDs and DataFrames for efficient data manipulation and analysis.

- **Monitoring and orchestration:** Hadoop, Spark, RabbitMQ, and the entire system are all under the orchestrator's control. It gathers performance measurements and real-time logs, including CPU, RAM, disc I/O, network throughput, and RabbitMQ queue data.
- **Analysis and dynamic scaling:** The orchestrator analyzes the collected log details of the resources to assess their performance and identify resource utilization patterns. After this analysis, the orchestrator dynamically scale-up or scale-down the resources configured in the cluster. This helps to handle the increased load and scaling down during low demand to save resources.
- **Resource optimization and energy efficiency:** The scale-up and scale-down characteristics of the cluster nodes ensure that computational resources are optimally used, preventing both over-provisioning and under-utilization, resulting in an energy-efficient framework.

C. Enhancing security for DT technologies

The increasing adoption of DG technologies across critical domains, such as manufacturing, healthcare, energy, and smart cities, raises pressing concerns about cybersecurity. As DTs integrate real-time data from physical assets, networked systems, and distributed platforms, the attack surface grows significantly. Ensuring secure, resilient, and trustworthy DT operations is vital for maintaining system integrity, user trust, and operational continuity. This section presents key security challenges and identifies enabling technologies and practices to mitigate them.

1) Challenges:

- **Data integrity and authenticity:** DTs rely on real-time data streams from the physical world to make accurate predictions and decisions. Any compromise in the data integrity—such as tampering with sensor data—can lead to faulty analytics, misguided operations, or, in severe cases, physical damage. Ensuring the authenticity of the data collected and processed by the DT is critical to avoid manipulation and falsified inputs.
- **Data privacy and confidentiality:** DTs often collect sensitive data related to operational systems, intellectual property, or even personal information in healthcare applications. Unauthorized access to this data can lead to privacy violations, intellectual property theft, and industrial espionage.

Proper access control, encryption, and secure data storage mechanisms are essential to protect the confidentiality of data.

- **Cyber-physical security:** The interconnected nature of DTs means that a breach in the digital layer can have direct consequences on the physical system it represents. In critical infrastructures like energy grids or transportation systems, malicious actors could exploit vulnerabilities in the DT to disrupt physical operations, resulting in equipment failures, service interruptions, or even safety hazards.
- **Network and communication security:** DTs rely on secure communication channels between the physical system, the twin, and associated analytical platforms. Attacks on these communication protocols, such as man-in-the-middle attacks, can intercept or alter the data in transit. Secure communication protocols, encryption, and integrity checks are crucial for maintaining the integrity of the data exchanged between entities.
- **System availability and resilience:** In many industries, DTs are mission-critical systems, meaning any downtime can lead to significant financial and operational consequences. Distributed Denial of Service attacks, ransomware, and other cyber threats could target the availability of DTs, disrupting services and operations. Building resilience through redundancy and robust incident response plans is vital.
- **Interoperability and integration risks:** DTs are often integrated into broader Industrial Internet of Things ecosystems, interacting with various legacy systems, cloud platforms, and third-party services. Each point of integration introduces new potential vulnerabilities. Secure integration practices, robust API management, and monitoring are necessary to ensure that vulnerabilities are not introduced into the system during integration.

2) Key enablers:

- **End-to-end encryption:** Encryption of data at rest and in transit is fundamental to maintaining confidentiality and protecting data integrity. Encrypting sensor data, communication between the DT and its physical counterpart, and storage in the cloud can mitigate the risk of unauthorized access or tampering.
- **Zero trust architecture:** Implementing a zero-trust security model ensures that no entity inside or outside the network perimeter is trusted by default. Access to the DT and its components should be restricted based on identity verification, least privilege principles, and continuous monitoring of all entities interacting with the system.

- **Strong authentication and access control:** Multi-factor authentication and role-based access control ensure that only authorized users can interact with the DT. Access rights should be assigned based on the principle of least privilege, and sensitive actions within the system should require elevated access permissions.
- **Secure data provenance and auditing:** Data provenance systems should track the origin, history, and modifications made to the data flowing into the DT. This allows for real-time verification of data authenticity and helps identify potential tampering or unauthorized changes. Continuous auditing and logging of system activities can provide early detection of suspicious behavior.
- **AI-driven threat detection and response:** Given the complexity and real-time nature of DTs, traditional security monitoring tools may not be sufficient. AI and machine learning-based security tools can provide enhanced threat detection capabilities by identifying anomalous patterns and behaviors in the system. These systems can trigger automated incident responses to contain potential threats before they cause significant damage.
- **Resilience and redundancy:** Ensuring the availability and reliability of DT systems is critical for operations, particularly in sectors like manufacturing or energy. Redundancy in the form of backup systems, real-time failover mechanisms, and geographically distributed DTs can mitigate the risk of outages or failures.
- **Regular security audits and penetration testing:** Given the evolving nature of cyber threats, DT systems should undergo regular security audits and penetration testing to identify and remediate vulnerabilities. Security patches and updates must be applied promptly to minimize the risk of exploitation.
- **Adherence to security standards and frameworks:** Aligning with established cybersecurity standards, such as the NIST Cybersecurity Framework, ISO/IEC 27001 for information security management, and IEC 62443 for industrial control systems, helps ensure comprehensive risk management and system hardening. These frameworks provide structured approaches to governance, monitoring, incident response, and continuous improvement, reinforcing the overall security posture of DT systems.

IV. CONCLUSION

The integration of 6G technologies with DTs represents a transformative advancement in building intelligent and interconnected ecosystems. By providing robust support for real-time data exchange, enhanced interoperability, and seamless integration of end-to-end systems, 6G enables DTs to unlock their full potential across diverse domains, including modern power systems, autonomous transportation, and next-generation wireless networks. This white paper has comprehensively addressed the essential elements of 6G-assisted DTs. It begins by identifying the key requirements for DTs, such as synchronization, scalability, and data integrity. The added value of 6G for DTs has been explored through its contributions to advanced synchronization and interoperability, energy-efficient wireless communications, and enhanced physical layer security. Furthermore, the paper highlights the visions and promising applications of 6G-enabled DTs, emphasizing their transformative role in modern power systems, autonomous driving, and future wireless communication systems.

Recognizing the path to realization, this white paper also outlines the key challenges facing 6G-assisted DT deployment. These include issues related to inter-twin and intra-twin connectivity, managing data and resource scalability, and addressing complex security concerns. To address these barriers, key enablers have been identified, such as advancements in distributed intelligence, scalable framework designs, and innovative security mechanisms. These enablers provide a roadmap for overcoming challenges and fostering future research directions.

Looking ahead, several promising avenues of research and innovation are expected to shape the future of 6G-enabled DT ecosystems:

- **Connectivity and architecture:** Future DT networks will benefit from semantic and goal-oriented communication paradigms that enable context-aware information exchange. Integration with non-terrestrial networks (e.g., satellites and aerial platforms) and ISAC technologies will support ubiquitous and resilient DT deployment.
- **Scalability and resource optimization:** Continued work is needed on decentralized orchestration and federated edge intelligence to reduce system bottlenecks and improve elasticity. Energy-efficient workload distribution and green computing models will play a key role in sustainability.
- **Security and trust:** With increasing cybersecurity threats, DT systems must evolve toward quantum-resistant cryptographic frameworks and leverage blockchain-based provenance tracking. Federated learning techniques will also enable collaborative model development without compromising privacy.
- **Application-oriented advances:** In power systems, DTs will support grid optimization and real-time fault detection. In autonomous driving, ensuring seamless vehicle-to-infrastructure communication and high-fidelity synchronization will be critical. In wireless communication, DTs will be used to

simulate, monitor, and adapt network conditions for optimal performance.

In summary, the convergence of 6G and DT technologies offers a path to smarter, more adaptive, and more resilient digital ecosystems. By addressing current limitations and advancing research across connectivity, scalability, security, and real-world applications, 6G-enabled DTs can become a foundational element of the connected, intelligent future.

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