

Review

A Comprehensive Survey of 6G Simulators: Comparison, Integration, and Future Directions

Evgeniya Evgenieva¹, Atanas Vlahov^{1,2}, Antoni Ivanov^{1,*} , Vladimir Poulkov¹  and Agata Manolova¹ 

¹ Faculty of Telecommunications, Technical University of Sofia, bul. Kl. Ohridski 8, 1000 Sofia, Bulgaria; eevgenieva@tu-sofia.bg (E.E.); ici-lab@sofiatech.bg (A.V.); vkp@tu-sofia.bg (V.P.); amanolova@tu-sofia.bg (A.M.)

² Intelligent Communication Infrastructure Laboratory, Sofia Tech Park, 1784 Sofia, Bulgaria

* Correspondence: astivanov@tu-sofia.bg

Abstract

Modern wireless networks are rapidly advancing through research into novel applications that push the boundaries of information and communication systems to satisfy the increasing user demand. To facilitate this process, the development of communication network simulators is necessary due to the high cost and difficulty of real-world testing, with many new simulation tools having emerged in recent years. This paper surveys the latest developments in simulators that support Sixth-Generation (6G) technologies, which aim to surpass the current wireless standards by delivering Artificial Intelligence (AI) empowered networks with ultra-low latency, terabit-per-second data rates, high mobility, and extended reality. Novel features such as Reconfigurable Intelligent Surfaces (RISs), Open Radio Access Network (O-RAN), and Integrated Space–Terrestrial Networks (ISTNs) need to be integrated into the simulation environment. The reviewed simulators and emulators are classified into general-purpose and specialized according to their type of link-level, system-level, and network-level categories. They are then compared based on scalability, computational efficiency, and 6G-specific technological considerations, with specific emphasis on open-source solutions as they are growing in prominence. The study highlights the strengths and limitations of the reviewed simulators, as well as the use cases in which they are applied, offering insights into their suitability for 6G system design. Based on the review, the challenges and future directions for simulators' development are described, aiming to facilitate the accurate and effective modeling of future communication networks.

Keywords: emulators; fifth generation; link-level; network-level; simulators; sixth generation; system-level



Academic Editor: Sotirios K. Goudos

Received: 1 June 2025

Revised: 30 July 2025

Accepted: 18 August 2025

Published: 20 August 2025

Citation: Evgenieva, E.; Vlahov, A.; Ivanov, A.; Poulkov, V.; Manolova, A. A Comprehensive Survey of 6G Simulators: Comparison, Integration, and Future Directions. *Electronics* **2025**, *14*, 3313. <https://doi.org/10.3390/electronics14163313>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Sixth-Generation (6G) wireless networks are set to build upon the advancements introduced by the current standards that provide high throughput and mobility, and low latency. However, as the communication systems become increasingly complex over the next decade, the demands of emerging applications such as ultra-low latency, massive connectivity, and immersive holographic communications and extended reality (XR) will surpass what the Fifth Generation (5G) can deliver [1]. Sixth-Generation wireless networks are designed to meet these challenges, providing superior solutions through enhanced network performance, integration of Artificial Intelligence/Machine Learning (AI/ML), and support for terahertz (THz) communications [2]. Current 5G deployments build upon

the Fourth Generation (4G), achieving end-to-end (E2E) latency of nearly 10 ms, peak data rate of up to 10 Gbps, partial support for AI, autonomous vehicles (AVs) and XR. According to the vision of the International Telecommunication Union (ITU), 6G (also known as International Mobile Telecommunications-2030 technology) reaches peak data rates up to 1 terabit per second. The E2E latency of 1 ms will enable near-instantaneous communication, essential for cutting-edge applications. With a maximum spectral efficiency of 100 bps/Hz, 6G will provide highly efficient utilization of the spectrum, addressing future demands. Mobility support in 6G is expected to reach up to 1000 km/h [3]. These requirements also facilitate the Third-Generation Partnership Project (3GPP) goals of improving the mobility management and energy efficiency of all network operations [4]. For this purpose, there is an increasing effort to incorporate scalable AI methods with small computational cost into their functionalities. Furthermore, 6G will integrate satellite communication fully and use AI extensively, enabling advanced AV capabilities, full XR experiences, and haptic communication. THz communications will be widely supported, as well as intelligent surface architectures to enhance network performance. Other key technologies for 6G are Distributed massive Multiple-Input Multiple-Output (D-MIMO) and Cell-Free (CF) MIMO, addressing challenges in dense deployments and higher frequencies [5]. The New Air Interface will feature innovations like Massive MIMO (M-MIMO), Reconfigurable Intelligent Surfaces (RISs), and Next-Generation Multiple Access (NGMA), enabling improved channel coding and error correction [6,7]. New Networking, including Open Radio Access Networks (O-RANs) and Integrated Space–Terrestrial Networks (ISTNs), will offer resilient and broader connectivity. Integrated Sensing and Communication (ISAC) will enhance the support for applications like AVs and Internet of Things (IoT). AI-driven network management, quantum communication, and security protocols will ensure that 6G operates securely and efficiently.

1.1. Role of Network Simulators in the Development of 6G

As the research on 6G networks progresses, the role of simulators becomes increasingly important due to the inherent complexities and challenges in testing costly real-world prototypes. Network simulators provide a virtual environment where various scenarios and network architectures can be modeled, analyzed, and optimized. Sixth-Generation simulators ensure viable computational complexity by allowing for scalability to simulate networks with millions of connected devices [8]. As the ITU focuses on enhancing current mobile communications, spectrum sharing and utilization, traffic characteristics, and Radio Access Network (RAN) development [3], much effort has been devoted to bringing the virtual environment closer to the realistic scenarios for addressing the 6G requirements. Additionally, high accuracy in simulating the physical layer (PHY) and network protocols is essential, as even small deviations can lead to significant errors in the evaluation of new technologies. Among the emerging tools for communication systems design are the Digital Twins (DTs)—virtual replicas of physical networks. Their simulation is of crucial importance for the creation of these DTs, which assist in the modeling of network behavior, proactive network management, and predictive maintenance under various deployment scenarios. Simulators are significant for research in ISTNs and Unmanned Aerial Vehicle (UAV) communications, as such scenarios are very difficult to implement, and most often the equipment needed is not physically available to the researchers [9].

As the development of 6G is still in its nascent stages, many of the standards and network structures are yet to be fully defined. Unlike 5G, which has established core network components, the precise architecture of 6G remains uncertain. The integration of ML is anticipated to be a key feature, yet the specifics of how it will be embedded within the network functions are still under consideration. Despite this, research must continue to advance our understanding and capabilities. This paper aims to provide a comprehensive survey of available communication network simulators, which can play a critical role in advancing 6G research. Although no single simulator encompasses all the technologies anticipated for 6G, each contributes valuable insights into different aspects of the technology landscape. Simulators like Sionna [10] offer in-depth link-level analysis, while general-purpose tools such as NS-3 (Network Simulator 3) [11] provide broader network-level simulations. Specialized simulators, such as TeraMIMO [12] and WithRAY [13], focus on advanced technologies like M-MIMO and Ray Tracing (RT), respectively. Furthermore, 5G simulators can be extended with tools like Caviar to facilitate the testing of technologies in a 6G context. As 6G aims to achieve specific requirements for reliability, coverage, and throughput [1], naturally, a 6G simulator facilitates the development of algorithms that support one or more of the main 6G enablers, i.e., Millimeter Wave (MMwave), THz, OWC, M-MIMO, RIS, NGMA, AI, ML, ISTN, RIS, and O-RAN (Section 3.1), as most simulation tools are built for specific research topics. The simulators' applicability may be determined based on their agility in implementing algorithms for 6G applications, availability, breadth of documentation, support for relevant technologies, which are noted for throughout this survey.

This paper reviews different types of simulation tools relevant to 6G research, including link-level (LLS), system-level (SLS), and network-level (NLS) simulators, highlighting their unique contributions to various aspects of 6G networks. It then outlines the key technological considerations for evaluating them, including performance metrics such as accuracy, scalability, and computational efficiency, as well as essential functional and non-functional requirements. A comprehensive comparison of several promising 6G simulators is presented, examining their features, strengths, and limitations. Thus, we provide insights into the most suitable tools for different research and development needs. In addition, we give recommendations for selecting appropriate simulators and suggest directions for future research to advance the capabilities of 6G simulation tools, ultimately contributing to the successful deployment of 6G networks.

1.2. Literature Search and Selection Methodology

The goal of this paper is to review simulators applicable to 6G wireless communications, which are classified according to the extent of their capabilities to simulate specific parts of the system. This classification is based on a notable number of relevant papers published in highly influential journals and conferences since 2018. The overall number of papers (out of 141 relevant works) chosen to be included in this survey, after filtering of their contents and topics in regards to relevance and influence, is 69, which shows both the relevance as well as the research potential of 6G simulators. The process of the relevant literature selection for this survey follows the PRISMA protocol [14], and is illustrated in Figure 1.

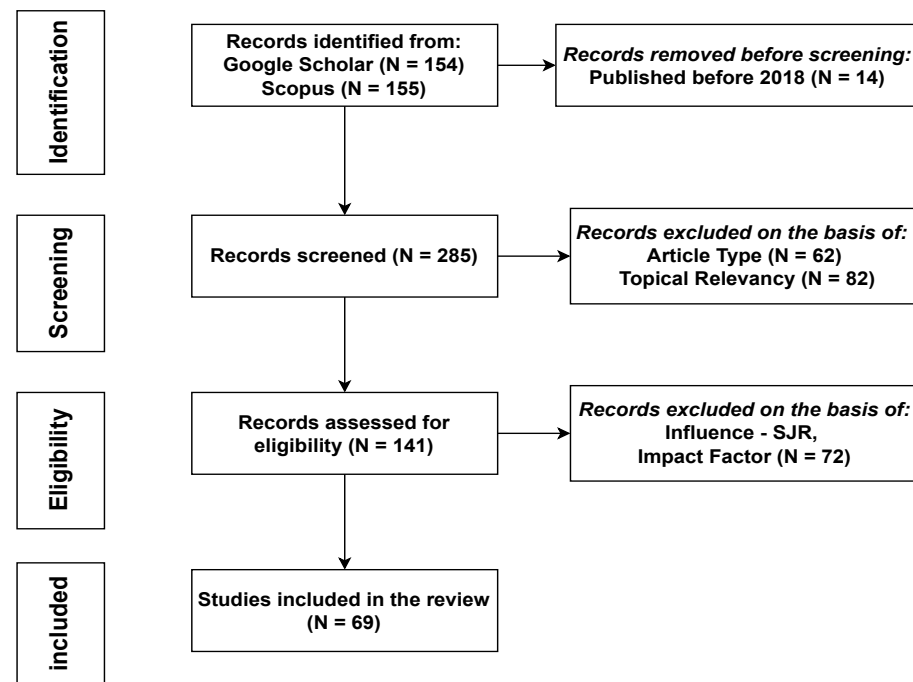


Figure 1. Summary of PRISMA flowchart of the article selection process for this review.

1.3. Contributions

This paper surveys simulators relevant for 6G scenarios in a holistic manner, accounting for all the limitations encountered in several recent related reviews of the topic, and facilitates the future development of 6G simulation tools by providing the following contributions:

- A comprehensive review of simulators relevant for 6G research, categorizing them into general purpose and specialized, according to their type (LLS, SLS, and NLS).
- Comparison of simulators based on key features such as scalability and computational efficiency, along with the technological considerations for 6G, their strengths and limitations, as well as the use cases in which they are applied. Specific emphasis is put on the advantages of open-source simulators.
- Based on the review, the relevant challenges and future directions for the 6G simulators' development are described.

1.4. Structure of the Paper

The rest of this paper is organized as indicated in Figure 2. Section 2 specifies how this survey contributes to the literature by comparing it with several recent relevant reviews on the topic of 6G simulators. Then, Section 3 outlines the basic technological considerations for the application of communication network simulators. Afterwards, Section 4 classifies them according to their type. Section 5 and Section 6 survey the various general-purpose simulators and emulators and specialized simulators, while Section 7 details the relevant simulator extensions. Finally, Section 8 describes the challenges of 6G simulator design, and Section 9 provides the future research directions and concludes this paper.

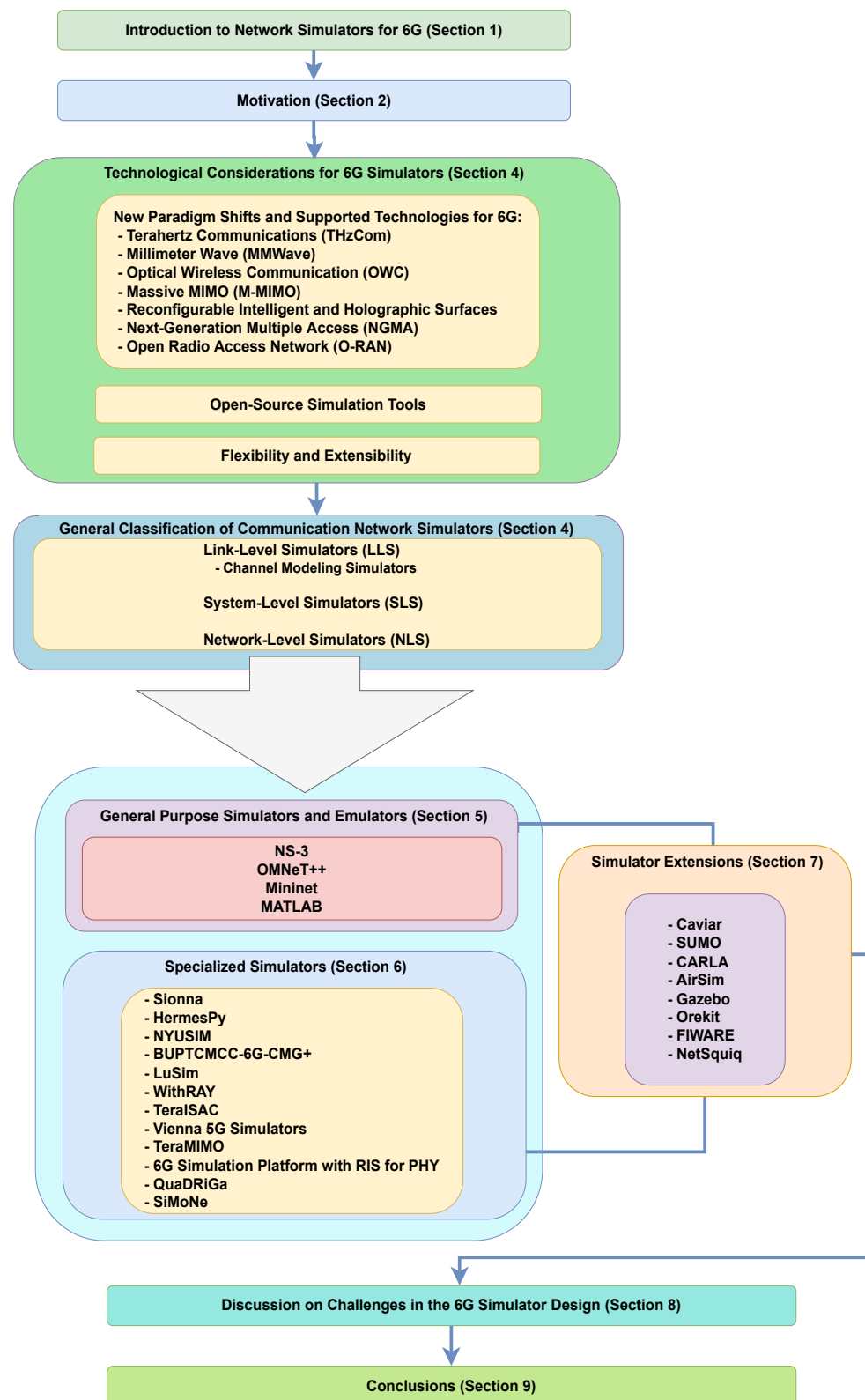


Figure 2. Structure of this paper.

2. Motivation

In recent years, notable research has been carried out on extending current 4G and 5G simulators or introducing new 6G-compatible ones. It is the aim of this paper to survey all types of 6G-relevant simulators and compare them to outline their current development. This section summarizes reviews that are significant for this analysis, and briefly explores

the topics that they are focused on, as well as their limitations, which are outlined in Table 1. Accordingly, the contribution of this article is emphasized. In [15], the authors summarize and compare several simulators for 4G and 5G networks, some of which have remained prominent in the literature. Only the scenarios of cellular and IoT networks are considered. A survey of 5G-compatible simulators is presented in [16]. It focuses on channel modeling for M-MIMO, the requirements for SLS and LLS, and their design challenges and requirements. The authors of [17] review measurement campaigns and the theoretical foundations that were used to model the channels for important 6G technologies such as RIS, ISAC, MIMO, ISTN, and on their basis, have introduced the BUPTCMCCCMG-IMT2023 channel simulator. Additionally, relevant examples for the simulator's usage are presented. The reference [8] surveys 6G simulators with AI-enabled functionalities for cellular scenarios, and focuses on their computational complexity. A review of SLS for 5G cellular networks is made in [18]. An Application Programming Interface (API) is introduced to extend the OMNeT++ tool with end-to-end and full protocol stack simulation capabilities and compatibility with the 3GPP standards. In summary, these surveys offer limited discussion of the development of 6G simulators and 6G technologies within modern simulation tools, thus providing ample motivation for the analysis made in this article.

Table 1. Comparison of relevant surveys on communication networks simulators for 6G.

Survey Paper	Main Topic	Main Contributions	Limitations, Relevant to This Work
Bouras et al. (2020) [15]	Simulators for 4G and 5G cellular networks	Survey and comparison of the features of several general purpose simulators for 4G and 5G.	Limited to use cases for 4G, 5G and IoT.
Gkonis et al. (2020) [16]	Simulators for 5G heterogeneous networks	Survey of LLS and SLS supporting M-MIMO, MMwave and NGMA; Overview of network simulation types; Summary of 5G-compatible simulators.	Limited discussion of 5G simulators.
Zhang et al. (2023) [17]	Channel modeling for 6G	Survey of wireless channel measurement campaigns for RIS, ISAC, MIMO, ISTN; Guidelines for applying the BUPTCMCCCMG-IMT2023 simulator in these scenarios, and practical examples.	Discussion limited to channel simulation.
Manalastas et al. (2023) [8]	Cellular SLS for 6G	Guidelines for development of 6G SLS that support AI; Introducing AI-enabled simulation methodology; Comparing its computational complexity to other simulators.	Discussion limited to 6G simulators for cellular scenarios.
Boeira et al. (2024) [18]	Cellular E2E simulation for 5G	Comparison of the features of 5G-compatible SLS; Calibrating the OMNeT++ simulator using 3GPP standards.	Discussion limited to 5G simulators for cellular scenarios.
This paper	Simulators for 6G	Comprehensive survey and categorization of the various types of the simulators that support 6G technologies and use cases (RIS, ISAC, ISTN, NGMA, M-MIMO, MMwave, THz, OWC, O-RAN); Focus on open-source options; Challenges and perspectives on 6G simulators' future development.	-

3. Technological Considerations for 6G Simulators

3.1. New Paradigm Shifts and Supported Technologies for 6G

Sixth-Generation networks represent a significant departure from previous generations, introducing several paradigm shifts that redefine the goals and capabilities of future communication systems. These new paradigms include global coverage, utilization of all available spectrum, support for a broad range of applications, and enhanced network security. In response to these paradigm shifts, a range of emerging technologies with the potential to meet the diverse and demanding requirements of 6G is being developed. The technologies that are considered crucial for simulators include THz, MMwave, OWC, M-MIMO, RIS, NGMA, AI, ML, ISTN, RIS, and O-RAN. In Section 4, they were divided by the layer on which a given simulator operates. Here in this section, each technology is going to be reviewed in greater detail.

3.1.1. Terahertz Communications (THzCom)

THzCom operating in the ultra-wide frequency band from 0.1 to 10 THz, has the potential to address spectrum scarcity and overcome the capacity limitations of 5G networks [2,19]. This technology is critical for supporting emerging applications that require extremely high data rates, such as holographic telepresence, extended reality, and ultra-high-speed wireless backhaul. Communications in the THz band, particularly for frequencies above 300 GHz, experience unique challenges not encountered in sub-6 GHz and MMwave frequencies. These include severe signal loss due to spreading, high channel sparsity, and molecular absorption loss, which is frequency-dependent. Research on THzCom focuses on areas such as channel measurement, modeling, device technology, and standardization. Despite these advancements, there remains limited research on end-to-end THzCom systems, particularly at the network layer [19]. Research in the THzCom addresses the following main topics: spectrum management, antenna and beamforming design, and the integration with other 6G-enabling technologies.

3.1.2. MMWave Frequency Bands

These bands are comprised of frequencies starting from 24 GHz and extending to 100 GHz. MMwave bands offer a much higher bandwidth compared to lower frequency bands, which results in significantly faster data transfer speeds, making it ideal for densely populated urban areas (such as stadiums, airports, and urban centers) and high-performance applications like AVs, augmented reality, and smart city infrastructure [2]. However, MMwave also presents several challenges with the short range and is easily obstructed by physical barriers such as walls, windows, and foliage, requiring a dense deployment of small cells and repeaters to ensure consistent coverage. To overcome these limitations, next-generation 6G networks are expected to incorporate advanced methods for optimizing MMwave performance, including the integration of sub-THz frequency bands. The use of sophisticated network simulators will play a vital role in modeling these complex environments, enabling researchers and developers to test and optimize MMwave-based solutions before real-world deployment.

3.1.3. Optical Wireless Communication (OWC)

OWC offers an alternative and complementary solution to traditional Radio Frequency (RF) communications [2]. It encompasses a range of technologies, such as Light Fidelity (Li-Fi), Free-Space Optical, Ultra-Violet, and Visible Light Communication (VLC), which utilize optical frequencies in the infrared, visible, and ultraviolet bands for data transmission. These technologies provide high data rates, low power consumption, minimal interference, and unlicensed access to spectrum resources. Current OWC systems are predominantly designed for single-user, point-to-point communication, and there is limited implementation for multi-user environments. Existing research focuses on two main approaches to enhance system capacity: improving optical device performance and optical path design, or using advanced modulation techniques like m-order Quadrature Amplitude Modulation, Orthogonal Frequency Division Multiplexing (OFDM), and Universal Filtered Multi Carrier (UFMC) to optimize spectrum usage.

While OWC offers promising solutions for 6G, it also faces challenges such as sensitivity to ambient light, atmospheric losses, the nonlinearity of light-emitting diodes, and multipath dispersion. These impairments limit the widespread adoption of OWC in Ultra-Reliable Low Latency Communication (URLLC) scenarios, which require extremely low delay and high reliability, such as in telemedicine, autonomous vehicles, and smart grids [20]. However, OWC can still play a vital role in environments where RF communication is constrained, like medical facilities, tunnels, and underwater applications. Given its

non-interference with RF technologies and the license-free nature of the optical spectrum, OWC is expected to coexist with and complement other 6G technologies rather than replace them. It is particularly relevant for niche applications where high data rates, security, and low electromagnetic interference are critical. For example, Li-Fi can be used to implement atto cells for localized indoor coverage and coexistence with RF femto cells, while visible light beacons can facilitate secure and interference-free connections in controlled environments [21].

3.1.4. Massive MIMO (M-MIMO)

M-MIMO utilizes large antenna arrays to enhance spectral and energy efficiency. In 6G, it is poised to enhance wireless localization and sensing for applications in navigation, transportation, and healthcare by offering high accuracy and resolution through its narrow beamwidth capabilities [5]. Challenges such as obstructed Line-of-Sight (LoS) links can affect accuracy, but Intelligent Omni-Surfaces (IOSs) can create additional propagation paths and manipulate signal properties to improve performance. Integrating IOS involves optimizing configurations to balance latency and accuracy, along with managing practical deployment issues. An ultra-massive MIMO operating at THz frequencies (0.1–10 THz) is crucial for achieving 6G's high-capacity communication and ultra-high-resolution sensing [12]. However, these present challenges like high path loss and energy inefficiency. Solutions such as ultra-narrow beamforming with large-scale transceivers (over 1024 antennas) and innovative techniques like RIS, which use numerous small antennas to manage beam characteristics and increase multipath richness, are being explored to address these issues. CF M-MIMO emerges as a promising technology for beyond 5G systems by ensuring uniform service across coverage areas with low-cost access points and joint transmission/reception [2]. This approach, also known as D-MIMO, involves serving each user equipment with multiple access points under favorable channel conditions. The system design incorporates a centralized processing unit linked to access points via fronthaul, with edge clouds adding midhaul transport. Efficient deployment involves cost-effective fronthaul/midhaul technologies like radio stripes and millimeter-wave links, along with energy-saving techniques such as access point switching and resource sharing.

AI plays a crucial role in enhancing M-MIMO systems for Industry 5.0 by improving channel estimation, reducing complexity, and managing interference. AI applications include resource allocation, signal detection, and interference management, which collectively enhance system efficiency and reduce operational costs. Further, near-field MIMO [22] has been established as an important technological enabler for THz and RIS in high-frequency communications as they allow for extremely large-scale antenna arrays. AI-empowered beamforming and precoding are applied to reduce the receiver's computational complexity. This approach improves single- and multi-user capacity, user localization, and wireless power transfer, with its main challenges being the channel estimation, beam misalignment due to the large bandwidths, and hardware designs that support the required processing speed. MATLAB R2013b or later version has been utilized widely for simulating such problems.

3.1.5. Reconfigurable Intelligent and Holographic Surfaces

Holographic antennas and RIS are envisioned to become key technologies for enhancing the performance of wireless communications in 6G networks [2]. These innovative approaches address the limitations of traditional antenna systems, such as phased arrays, which, while effective in M-MIMO, face significant challenges in high-frequency bands, including MMwave and THz. High power consumption, cost, and complexity, especially due to the reliance on power-hungry amplifiers and phase shifters, hinder their scalability.

In response, both RIS and holographic antennas aim to improve signal quality, increase coverage, and reduce energy consumption, all critical factors for 6G networks.

Holographic antennas utilize metasurfaces to steer beams by creating interference patterns between reference waves and object waves. This method of beamforming, while promising, faces limitations due to its static nature, making it less adaptable to dynamic wireless environments. The recent development of Reconfigurable Holographic Surfaces (RHSs) offers a more advanced solution by incorporating tunable metamaterials that allow for real-time control of the radiation pattern [23]. In parallel, RISs are becoming more popular as an energy-efficient solution for improving wireless signal coverage and quality. The combination of RHS and RIS has the potential to create a smart radio environment, where surfaces are no longer passive elements but active participants in optimizing wireless communication [24,25]. While RHS focuses on achieving holographic beamforming through dynamic control of radiation patterns, RIS provides a scalable and low-cost means of improving signal coverage through passive reflection. This synergy between the two technologies is particularly beneficial for 6G networks, which will demand greater flexibility and efficiency to handle the increased data rates and diverse communication environments that will come with the use of higher-frequency bands.

However, despite the promise of RHS and RIS, several challenges remain. One of the most significant needs is the need for accurate channel modeling and estimation, particularly in near-field scenarios and at higher frequencies. Addressing these challenges will require advanced AI and ML methods to optimize beamforming and channel estimation dynamically. The integration of such models into platforms such as Sionna, which already supports RIS, will be crucial in the development of RHS and RIS.

3.1.6. Next-Generation Multiple Access (NGMA)

NGMA incorporates advanced methods for improving network efficiency and capacity. Orthogonal Frequency Division Multiple Access (OFDMA), used in 4G and 5G, assigns distinct physical resources to each user, which effectively mitigates multi-path fading but limits capacity [7]. OFDMA has been enhanced with MIMO to increase spectral efficiency. However, as MIMO dimensions expand, the complexity of MIMO-OFDM adaptation increases, driving the need for AI-driven solutions for efficient MIMO precoding and resource mapping in 6G systems.

Non-Orthogonal Multiple Access (NOMA) offers higher throughput and connection density by allowing multiple users to share the same resources [2]. NOMA uses Successive Interference Cancellation (SIC) to separate users based on power levels, providing better performance compared to traditional Orthogonal Multiple Access, especially in the context of MMwave and other high-frequency bands. NOMA's efficiency is improved when combined with Coordinated Multi-Point, though it introduces higher receiver complexity and potential security concerns.

Future networks will need to handle a massive number of users, so NGMA research is shifting towards modeling channels with growing numbers of users and developing new metrics for these scenarios. The need for low-latency, short-packet transmissions in IoT applications is pushing research on finite block-length coding.

3.1.7. Open Radio Access Network (O-RAN)

The O-RAN is vital for 6G research due to its flexible and open architecture, which supports multi-vendor interoperability and advanced network functionalities [26]. By integrating AI, softwarization, and network slicing, O-RAN enables dynamic and efficient resource management, allowing for more adaptive and scalable operations. For 6G simulators, O-RAN's open framework provides a realistic and comprehensive environment to

model and test the diverse and complex requirements of 6G networks, including various use cases and operational configurations.

3.1.8. Higher Mid-Band Spectrum in Upcoming Communications

Current 3GPP standardization activities are focused on Release 19 with focus on extending the scope of existing communications to enhance their performance, the user experience, and increase their profitability [27,28]. They will provide the foundational basis for 6G, bringing non-terrestrial networks (NTNs) and XR to maturity. Specific emphasis is given to the 7–24 GHz bands termed higher mid-band, bringing the gap between traditional communication spectrum and MMwave. The ongoing 3GPP investigations target sub-band non-overlapping full duplex for concurrent uplink and downlink within the time division duplex frame at the base station side, near-field propagation, and spatial non-stationarity of the channel [29]. Integrating traditional and near-field communication is also being explored. Indoor and urban/rural outdoor environments are considered with the angular (i.e., angle-of-arrival, angle-of-departure, etc.), delay, phase, Doppler shift, and signal's amplitude being the parameters used in evaluating the spectrum allocation and beamforming algorithms.

3.2. Open-Source Simulation Tools

Most of the current research efforts toward 6G have employed open source simulation tools, including simulators, emulators, and simulator extensions. The first two create an environment for evaluating methods or systems of methods that model their operation analytically in a particular environment for a single layer of the communication networks or across layers. Simulator extensions implement a specific communication technology or physical aspect of the simulated scenario, and are often used in combination with multiple extensions and general-purpose or specialized simulators, to model a specific use case such as Vehicle-to-Everything (V2X) communications. Software packages such as NS-3 [30] and OMNeT++ 5.3 (and later versions) [31] are particularly valuable in 6G research due to their adaptability. Given the wide range of emerging technologies and paradigms that 6G encompasses, the ability to customize and modify the simulator's source code is essential. Researchers can experiment with new protocols, design unique network scenarios, and implement innovative algorithms tailored to these specific 6G technologies. For example, simulators can be adapted to model complex propagation environments for THz and MMwave frequencies, optimize resource allocation in M-MIMO and RIS, or test new network architectures like O-RAN or ISTN [32,33]. The community-driven nature of open-source development ensures that these simulators evolve rapidly alongside 6G advancements. Contributions from researchers worldwide help integrate the latest features and capabilities, such as support for AI/ML models for network optimization or new frameworks for evaluating RIS and NGMA technologies [34]. This collaborative approach accelerates innovation and ensures that the simulator can accommodate the latest research challenges and opportunities in 6G. Transparency is another crucial factor, as open-source simulators allow researchers to fully examine and validate the models and algorithms used, ensuring that the simulations accurately reflect the behavior of 6G technologies. This is particularly important when dealing with novel concepts like ISAC or ISTN, where the accuracy of simulation models can significantly impact research outcomes [35].

However, open-source solutions may present some challenges. The lack of dedicated professional support and potential compatibility issues with proprietary systems could limit their applicability in certain environments, especially where integration with existing commercial tools or specific vendor technologies is required. Additionally, varying levels of

documentation quality might require users to have in-depth technical expertise to maximize the benefits of these tools.

3.3. Flexibility and Extensibility

Simulators must be adaptable to a range of network configurations, protocols, and use cases to effectively model the diverse landscape of 6G technologies. Ideally, a flexible simulator should support various 6G advancements—such as THz and MMwave communication—and accommodate different experimental scenarios, from high-speed data transfers to large-scale IoT networks [8]. This flexibility allows the simulator to address a wide range of research objectives and evolving requirements.

Extensibility refers to how easily the simulator can be enhanced or customized [16]. Extensible simulators allow researchers to integrate new features that include advanced AI algorithms and novel communication protocols, or modify existing functionalities. This ability to adapt and expand is essential for keeping pace with emerging technologies and addressing specific research needs.

4. General Classification of Communication Network Simulators

4.1. Link-Level Simulators (LLSs)

LLSs focus on the PHY of communication systems and model the point-to-point communication links between two nodes [36]. These simulators analyze the performance of data transmission in terms of metrics such as Bit Error Rate (BER) and block error rate under varying Signal-to-Interference-plus-Noise Ratio (SINR), which is essential for optimizing modulation schemes, coding techniques, and power control strategies in 6G networks. LLSs simulate the effects of various physical-layer phenomena like fading, interference, noise, and propagation delay on the transmission quality. For instance, in 6G, where communication takes place over higher frequencies (for example, MMwave or THz bands), LLSs must account for specific propagation challenges, including severe path loss, high susceptibility to environmental factors, and reflection or diffraction effects. In addition, they help evaluate the performance of new modulation schemes, such as Orthogonal Time Frequency Space modulation, which is designed for high-mobility scenarios.

The LLSs provide essential inputs to SLS by estimating the BER as a function of the SINR. It determines how different PHY configurations will affect overall network performance. The main demand for these simulators is that they must support a range of technologies, such as THz communication, D-MIMO, and RIS. They are also required to accommodate AI-driven optimization techniques that dynamically adjust transmission parameters to enhance performance.

Channel Modeling Simulators

These LLS specialize in simulating the communication channel's physical characteristics [17]. They are crucial for understanding how signals propagate in different environments, which directly affects communication reliability and performance; this is why they model various propagation phenomena such as path loss, fading, shadowing, multipath effects, and Doppler shifts. They are particularly important for 6G, where communication occurs over MMwave and THz frequency bands as well as in diverse environments (e.g., urban, rural, indoor, and vehicular). Channel Modeling Simulators are used to evaluate the performance of different channel estimation and equalization techniques. They also facilitate the design and optimization of adaptive modulation and coding schemes. These simulators provide crucial information for the link-layer functionalities by generating realistic channel models that reflect the actual propagation conditions in various deployment scenarios such as ultra-dense urban areas, RIS, and high-speed vehicular communications.

4.2. System-Level Simulators (SLSs)

SLSs are designed to evaluate the performance of large-scale cellular networks. Unlike LLSs, which focus on individual communication links, SLSs analyze network-wide performance metrics such as coverage, capacity, throughput, latency, and energy efficiency across various deployment scenarios [37]. SLSs simulate different network configurations, such as the number and placement of base stations, cell density, user mobility patterns, frequency bands for maximizing the coverage capacity while minimizing interference, as well as scheduling policies like diverse traffic types, such as URLLC and enhanced Mobile Broadband in 6G networks. The integration between LLSs and SLSs ensures that network-level simulations reflect actual PHY performance, making those simulators indispensable for designing and optimizing 6G networks that must handle diverse applications with varying Quality of Service (QoS) requirements, such as D-MIMO, ultra-dense networks, or ISTNs. SLSs need to support new network paradigms such as O-RAN, ISAC, and multi-access edge computing, as well as incorporate AI and ML algorithms for dynamic resource allocation, load balancing, and self-optimization.

4.3. Network-Level Simulators (NLSs)

NLSs simulate entire communication networks, encompassing multiple layers and diverse network elements [38]. They are essential for understanding how network protocols (e.g., Transmission Control Protocol or TCP and User Datagram Protocol or UDP) behave under different conditions and how various network components (like routers, switches, and gateways) interact. NLSs model routing algorithms, traffic management techniques, network congestion, load balancing, network security protocols, and quality of service management across large-scale systems, including heterogeneous networks that combine terrestrial, satellite, and aerial components. In the context of 6G research, they optimize the design of complex networks that integrate various types of multiple access for cellular, Wireless Fidelity (Wi-Fi), satellite, and IoT networks.

NLSs integrate with lower-level simulators (LLSs and SLSs) to provide a thorough view of network performance from the PHY up to the application layer. This integration is vital for developing 6G networks that are highly heterogeneous and support seamless connectivity across different network domains. The simulators are required to support next-generation networking paradigms like Software-Defined Networking (SDN), Network Function Virtualization (NFV), and cloud-native network functions. They should also be capable of simulating network slicing, which is critical for providing differentiated services to various applications in 6G.

5. General Purpose Simulators and Emulators

These simulators are designed for a broad range of applications and technologies, not exclusively for 6G but adaptable to various relevant scenarios. They allow researchers to simulate realistic network environments and experiment with various scenarios, which is essential for understanding how AI and ML can be integrated into network functions and how quantum communication can enhance connectivity. Emulators also facilitate the exploration of hybrid networks such as ISTN. Thus, the following emulators will be reviewed to illustrate their importance in advancing simulation capabilities for researching the future 6G networks. A summary of these simulators' features, strengths, weaknesses, and the use cases in which they have been applied, is illustrated in Table 2.

Table 2. Summary of general purpose simulators and emulators.

Simulator	Features	Strengths	Weaknesses	Use Cases and References
NS-3	TeraSim—nanoscale and macroscale THz scenarios, THz directional antenna models; SNS; M-MIMO for THz and MMwave; Dense networks with AI/ML algorithms; Modulation schemes for OWC and VLC;	Open-source; Distributed computing; C++ based emulation; Fast matrix computations and a modular code structure; Comprehensive documentation with a large, active community.	Lack of dedicated support.	ISTN with satellite positioning; VANETs with AI; Predictive QoS; Compatible with O-RAN [11,32–35].
OMNeT++	Routing protocol validation and system performance evaluation; Supports vehicular and wireless body area networks, WSNs and SDNs; Large-scale network simulations.	Open-source; Modular architecture for creating reusable components; Active developer community.	Considerable effort required to learn the custom NED language; Difficult to navigate documentation; Lack of dedicated support.	P2P live streaming; OWC; ISTN; Scalable location-aware content management in VANETs [31,39–42].
Mininet	Network slicing; NFV; Traffic engineering; Network adjustments through AI/ML; Centralized control plane.	Open-source; Supports real-time optimization and orchestration of network resources; Quick and cost-effective deployment through software-based emulation.	Limited hardware emulation; Only partial support for THz, M-MIMO and RIS.	Cellular and vehicular SDNs [40,43–46].
MATLAB	Support for AI models; Adaptive channel estimation; Various modulation techniques.	Native support for software-defined radios (SDRs), ISAC, NTNs, and RIS; 6G exploration library; Active customer support.	Expensive license.	Beamforming; Emergency communications [47,48].

5.1. NS-3 Simulator

The NS-3 is an open-source, discrete-event SLS designed primarily for research and educational purposes [11]. It focuses on network-level simulations and offers a variety of channel propagation models, including antenna characteristics, but has limited configuration options for channel coding and radio-frequency chain models. This simulator has been used for simulating THz communications, including beamforming antenna design and energy harvesting [32]. It also includes an implementation of the 3GPP standards for channel and antenna models in NTN [35]. These standards are 3GPP Technical Report (TR) 38.901 [49] and TR38.821 [50]; the former describes the path loss, atmospheric absorption, shadowing, and fading (with or without LoS) in indoor and outdoor channels, and is widely used in NTN scenarios, while the latter is concerned with the implementation details of various use cases for satellite-ground communications. These data are used for calibrating simulation models so the link-layer and E2E performance may be assessed. NS-3 has also been used to simulate the RAN functionalities of the O-RAN and integrate them with a real-world RAN Intelligent Controller that operates in near real time [33]. This platform, titled NS-O-RAN, enables the development and evaluation of xapps in a realistic environment without the complete O-RAN testbed. NS-3 also supports AI algorithms such as Reinforcement Learning (RL) for predictive quality of service, network management, as well as MMwave and V2X communications [34].

5.2. OMNeT++

OMNeT++ is an open-source, component-based discrete event simulation tool tailored for academic research [31]. It is not a network simulator in itself but rather a versatile simulation framework that supports a wide range of applications. The simulator effectively models various networks, including Mobile Ad-hoc Networks, Wireless Sensor Networks (WSNs), and Vehicular Ad-hoc Networks (VANETs). Due to its extensibility, OMNeT++ has the possibility to simulate emerging technologies, such as THz, MMwave, RIS, ISTN, and ISAC. The authors of [39] have utilized OMNeT++ to measure the throughput in the

transport layer of vehicular nodes simulated through SUMO [40]. This research focuses on selecting the nodes with the most reliable measurements, i.e., those with the least variance in their throughput. In [41], a 5G network that provides service to remotely operated vehicles is explored. The procedures over all communication layers are simulated, while the vehicular physics are realized in the CARLA simulator extension [42].

5.3. Mininet

Mininet is a lightweight, open-source network emulator widely used for creating realistic virtual networks by running real kernel, switch, and application code on a single machine, whether it is a virtual machine, cloud environment, or native hardware [43]. It supports the development and experimentation of SDN systems using protocols such as OpenFlow and P4, enabling researchers to explore and test new network designs and functionalities. Some applications of this emulator are hereby described. The authors of [44] mitigate the effect of link fabrication attacks on the SDN controller. Through additional authentication, link discovery delays in dense networks are reduced. In [45], Mininet emulates the SDN's nodes and their traffic for the implementation of a graph convolutional RL method for user queuing and load balancing to improve the throughput and E2E delay. In addition, SDN emulation has been used for traffic management between trains and vehicular nodes to facilitate spectrum coexistence in the 2.4 and 5 GHz bands [46]. The vehicles' movements and physics are simulated using the simulator extension SUMO [40].

5.4. MATLAB

MATLAB's 6G simulation capabilities offer a comprehensive platform for designing, testing, and deploying next-generation wireless communication systems [51]. With an extensive array of toolboxes such as the Communications Toolbox, Radar Toolbox, 5G Toolbox, and Phased Array System Toolbox, MATLAB provides a flexible and well-rounded environment for tackling the key technological challenges of 6G. From AI-driven network optimization to NTN, RIS, and enhanced data rates, MATLAB supports end-to-end workflows in signal processing, deep learning (DL), waveform design, and system validation through computer simulation or research equipment such as SDRs. It facilitates simulation and experimentation in joint communications and sensing, higher frequency communications, and PHY design, making it an essential tool for researchers and developers exploring the frontiers of 6G technology. Near-field communications for large-scale MIMO in THz and RIS have been evaluated extensively using this simulator. The authors of [47] design an adaptive phase precoding for RIS with time delay that compensates for the beam misalignment resulting from the wideband (>1 GHz) channels in THz communications. Channel estimation for near-field MIMO in the higher mid-bands is also investigated, with specific focus on the channel model's degrees of freedom, beam tracking, and beam training that adapt to the variation in both distances and angles between the transmitting and receiving antennas [48]. The analysis is facilitated by prior information about the signal scattering obtained through RT, also implemented in MATLAB.

6. Specialized Simulators

These simulators are specifically designed for 6G or certain cutting-edge technologies such as THz communication, channel modeling, or particular 6G scenarios. The features, strengths, and weaknesses of the specialized LLS and SLS, as well as the use cases that they have been applied to, are summarized in Table 3.

Table 3. Summary of specialized LLS and SLS.

Simulator	Features	Strengths	Weaknesses	Use Cases and References
Sionna	Support for GPUs, M-MIMO, RIS, AI/ML; O-RAN, MMwave and THz;	Open-source; High-level APIs for faster development; RT, scene management, and radio materials information for accurate channel modeling; Support for panel arrays, directional antennas, and phased arrays; Extensive documentation.	Partial support for OWC; Limited efficiency on systems without NVIDIA GPUs.	Channel prediction; Synchronization in IoT; DTs; RIS [52–54].
NYUSIM	Support for THz, M-MIMO, MMwave, RIS, beamforming and various waveforms; Geometry-based channel modeling.	Open-source; Modular and scalable architecture; Dynamic human blockage and shadowing loss model; Outdoor-to-indoor penetration loss model	Difficult to learn and master.	Urban and rural cellular and MMwave networks [55].
BUPTCMG-6G	Support for THz, M-MIMO, MMwave, RIS, ISAC; GBSM.	Free to access; Graphical interface; Antenna measurements; RT and stochastic techniques for accurate channel modeling; Simulates both near-field and far-field effects, and integrates spatially non-stationary channel characteristics; Highly customizable.	Limited documentation; Not open-source.	Urban and rural/indoor and outdoor cellular and MMwave networks; ISTN; satellite-to-ground, air-to-ground, and air-to-air communications [17,56,57].
LuSim	Support for AI/ML, M-MIMO; Geometry-based channel modeling.	Open-source; RT and stochastic techniques for accurate channel modeling.	Not accessible at present; Limited documentation.	Indoor and outdoor cellular networks; wireless power transfer [58].
HermesPy	Support for ISAC, M-MIMO, MMwave; Simulation of waveform generation, forward error correction codes, channel modeling.	Open-source; Active community; Support for SDRs.	Support for AI/ML is not currently documented; Not appropriate for real-time simulations.	Smart cities; Dense cellular networks; antenna evaluation [59–61].
WiThRay	Modeling of Electromagnetic (EM) propagation capturing reflection, diffraction, and scattering; Support for RIS, MIMO, beamforming; Simulation of fast-fading, high-mobility environments with Doppler shifts.	Open-source; Time-domain and frequency-domain analyses; Decreased computational complexity.	Limited documentation.	Indoor and outdoor cellular networks [13,62,62].
TeraISAC	Support for ISAC, M-MIMO, MMwave; Simulation of waveform generation for 5G and beyond.	Free to access; Support for ultra-high bandwidth and advanced waveforms and the configuration of waveform numerologies such as subcarrier spacing.	Lack of duplex communications, angle estimation capabilities and wideband effects in THz; Supports only MATLAB.	THz Backhaul; High-resolution sensing [63].

Table 3. Cont.

Simulator	Features	Strengths	Weaknesses	Use Cases and References
Vienna 5G	Includes SLS and LLS; Traffic engineering; Zero Forcing equalization; Support for MIMO, NOMA, both uplink and downlink, channel estimation, user scheduling and association; Simulation of waveform generation for 5G and beyond.	Support for doubly fading, time and frequency selective, tap-delay, and spatial channel models; RT; High flexibility and customization; Mobility modeling.	Limited free academic license; Requires MATLAB; High computational cost.	Urban, rural, indoor cellular networks; V2X [36,64].
TeraMIMO	Support for MIMO, THz, beamforming; Simulation of waveform generation for THz.	Open-source; Support for various time, frequency and space related wireless channel parameters; Molecular absorption models and spherical wave propagation models; GUI.	Support for only PHY; Requires MATLAB.	Urban outdoor, indoor cellular and AV networks [12].
6G-Sim-RIS	Modeling of EM propagation for large RIS arrays, capturing reflection, diffraction, and scattering.	Open-source; Flexibility for modeling various RIS setups.	Limited documentation and community support.	RSI for V2X and PHY security [65].
QuaDRiGa	Geometry-based channel modeling for RIS, M-MIMO, MMwave; Clustered-delay-line model; Rayleigh fading; Large-scale path loss.	Free to access; 3D stochastic channel model; Large range of supported frequencies; Support for GNU Octave and GPUs.	Substantial effort to learn.	Indoor/outdoor RIS-aided networks [66].
SiMoNe	Includes SLS and LLS for cellular networks planning. Support for THz; PHY implementations	Realistic 3D channel model with fading and Phase Noise; Large-scale simulations; Modular architecture.	Closed-source; Limited Availability.	Urban, rural, and high-speed mobility scenarios; V2X; User localization [67].

6.1. Sionna

Sionna is a powerful open-source library built on TensorFlow and designed for simulating the PHY of wireless and optical communication systems [10]. Developed by NVIDIA, it facilitates rapid prototyping of complex communication system architectures by using modular building blocks provided as Keras layers. These layers are differentiable, allowing gradients to be backpropagated through the entire system, which is crucial for system optimization and machine learning applications, including the integration of neural networks.

Sionna supports acceleration with NVIDIA graphical processing units (GPUs), which significantly speed up simulations, enabling interactive exploration of communication systems in environments like Jupyter notebooks or cloud platforms, for example, Google Colab. The library is tailored for 5G and 6G research, supporting multi-user MIMO link-level simulations, 5G-compliant coding schemes such as low-density parity-check and Polar codes, 3GPP channel models, OFDM, channel estimation, equalization, and soft-demapping. Additional components include convolutional and Turbo codes, the split-step Fourier method for fiber-optic channel simulation, and various filters and windows for single-carrier waveform analysis. Each module is designed to be independently tested, understood, and modified, supported by comprehensive documentation and references. RT datasets created using Sionna for both indoor and outdoor environments, are applied in applications like channel impulse responses prediction in three-dimensional (3D) [52], real-world 5G coverage maps verification [53], localization of objects through visual sensing and communication signals [68], and RIS in cellular base stations [54].

6.2. NYUSIM

NYUSIM is an open-source wireless channel simulator developed by New York University (NYU) WIRELESS, designed to model the propagation characteristics of radio waves over a frequency range from 500 MHz to 150 GHz [55]. This makes it a critical tool for exploring wireless channels in the sub-THz spectrum, particularly for 6G. The simulator supports various environments, including urban microcell, urban macrocell, rural macrocell, indoor hotspot, and indoor factory scenarios, all grounded in real-world radio propagation measurements. The empirical foundation on data collected by NYU WIRELESS ensures that the channel models NYUSIM produces are realistic and applicable to actual deployment conditions. Though implemented in MATLAB, NYUSIM can be integrated into a wide range of simulation environments, including LLS, SLS, and NLS, making it versatile for different stages of wireless network research and development. With customizable parameters like carrier frequency, bandwidth, and antenna configuration, NYUSIM provides detailed and flexible modeling capabilities, supporting both academic and industrial research in advancing communication technologies.

6.3. BUPTCMG-6G

BUPTCMCCMG-IMT2023, also termed BUPTCMCC-6G-CMG+ or BUPTCMG-6G, is a 6G link-level channel simulator developed for research and experimentation in next-generation wireless communication systems [17,56]. It is built upon the prominent 3D Geometry-Based Stochastic Model (GBSM) methodology, which is a widely recognized approach for modeling wireless channels with high spatial resolution and accuracy. This methodology allows for the simulation of complex channel characteristics by incorporating 3D geometries and stochastic processes to capture the effects of scattering, reflection, diffraction, and other propagation phenomena that occur in realistic environments.

BUPTCMG-6G supports the simulation of a wide range of potential 6G technologies, including those that are still in development or exploration stages. It offers a versatile platform for evaluating the performance of new algorithms and protocols under various channel conditions, from sub-6 GHz frequencies to MMwave and THz bands, which are critical for future 6G communications. By accurately simulating the behavior of wireless channels at these frequencies, BUPTCMG-6G provides researchers with the ability to analyze and optimize M-MIMO, ultra-dense networks, RIS, and advanced modulation schemes. This simulator has been utilized to implement a multi-static ISAC that integrates both sensing for UAV localization and the channel parameters [57]. The algorithm considers cellular base stations that perform the ISAC functions.

6.4. LuSim

LuSim is a state-of-the-art LLS developed for detailed and realistic wireless propagation simulations in various environments, ranging from urban landscapes to indoor settings [58]. Leveraging the Unity game engine, LuSim efficiently handles complex ray-casting tasks, utilizing GPU capabilities to meet the growing needs of researchers and engineers. The simulator fully supports CF network scenarios, accommodating large numbers of antennas and enabling studies on dynamic resource allocation.

With a flexible architecture, LuSim allows for external configuration through json or yaml files, offering adaptability for large-scale studies and sensitivity analyses. This modularity, combined with the simulator's cross-layer capabilities, enables seamless integration between physical and application layers, facilitating applications like resource orchestration and data synthesis. LuSim's design ensures that it serves as a crucial tool for exploring, developing, and deploying CF-based 6G networks.

6.5. *HermesPy*

HermesPy (also referred to as Hermes) is an open-source, Python-based framework designed for simulating and evaluating algorithms in current and next-generation wireless systems [59]. It bridges the gap between communication and sensing simulations by providing a flexible and extensible architecture for a wide range of link-level wireless scenarios. With its support for SDR devices, HermesPy can be used for both theoretical simulations and real-world measurement campaigns. This simulator has been employed for evaluating aperture-coupled antennae for ISAC signals in the 6 GHz range [60]. In a similar manner, the performance of a radar sensing antenna for the MMwave is assessed in [61] by using an SDR controlled by HermesPy.

6.6. *WithRAY*

WiThRay is a specialized RT-based simulator designed for modeling EM wave propagation in 3D environments [13]. It accurately simulates real-world factors like reflection, diffraction, and scattering that impact signal quality, offering crucial insights into signal strength, data rates, and coverage. WiThRay goes beyond traditional simulators by generating detailed channel data in both time-domain (multi-tap channels) and frequency-domain (subcarrier channels) formats. This allows for versatile testing of a wide range of wireless systems, making WiThRay a valuable resource for researchers in the development of 6G communication systems. An example of applying this simulator is the work in [62], which obtains the channels between the nodes in a cellular network [62]. The authors use the resulting dataset in an RL-based method for semantic communications.

6.7. *TeraISAC*

TeraISAC is a recently developed ISAC LLS for THz bands, written in MATLAB [63]. The simulator is designed to model and evaluate communication systems in the THz range (140 GHz and 300 GHz) with a focus on the convergence of communication and sensing. It supports multiple air-interface waveforms, which are considered promising modulation schemes for future 6G THz ISAC systems. The simulator is based on the latest 5G standardization, making it relevant for next-generation wireless communications. However, it is currently limited by its fixed frame structure and a lack of angle estimation capabilities, restricting its applicability in more advanced scenarios.

6.8. *Vienna 5G Simulators*

The Vienna 5G Simulator includes both link-level and system-level simulations. The LLS is designed to evaluate the PHY performance of wireless networks through Monte Carlo simulations, enabling the assessment of a wide range of 5G and beyond technologies [36,64]. This simulator offers a high level of flexibility, allowing users to individually configure the simulation parameters for each node in a given scenario. It supports both frequency division duplex and time division duplex frame structures, making it applicable for a variety of use cases. By simulating both uplink and downlink data channels and incorporating advanced features like RIS, the simulator is a powerful tool for studying the complex behavior of modern wireless networks.

The Vienna 5G SLS offers extensive functionality aimed at modeling large-scale wireless networks. It supports the simulation of multiple base stations (macro, pico, or femto cells) and user types (vehicular, pedestrian, and indoor) within the same environment. Users can define the number of antennas, transmit power, and positioning of both base stations and users, enabling complex scenarios. Blockages and buildings can also be modeled, with support for layouts such as Manhattan grid, predefined settings, or Open Street Maps (OSM)-based models. Supporting various link properties such as LoS and NLoS conditions,

path loss, scheduling, and cell association, the simulator provides detailed insights into key performance metrics, such as SINR and user throughput. Its modular design allows for high customization, making it suitable for various deployment scenarios, including urban, suburban, and indoor environments.

6.9. TeraMIMO

TeraMIMO is a MATLAB-based simulator designed specifically for THz communication systems [12]. Unlike many existing solutions, which focus on broader frequency ranges, TeraMIMO simulates the PHY for THz band communications. Its unique focus on 3D geometry of signal propagation makes it a valuable tool for exploring the challenges and peculiarities of THz signal behavior, including molecular absorption and beamforming. While it is primarily a PHY LLS, it can be extended to support system-level simulations. TeraMIMO provides a comprehensive 3D end-to-end THz channel model that addresses unique challenges such as misalignment, spherical wave propagation, phase uncertainties in phase shifters, and beam splitting. It supports multiple propagation scenarios, including LoS, Non-Line-of-Sight (NLoS), and LoS-dominant and NLoS-assisted communications, offering a flexible environment for simulating various THz conditions. The simulator generates detailed channel statistics, including coherence time, coherence bandwidth, maximum Doppler shift, and time delay spread, making it suitable for precise modeling of THz channels. Additionally, TeraMIMO handles frequency-selective THz channels across a range of communication distances, from nano communications to short-range indoor/outdoor scenarios and even long-range LoS links reaching hundreds of meters. To support hybrid beamforming, it adopts an array-of-subarrays antenna structure, which accounts for spatial sparsity. Different channel domains are supported, including the delay domain and frequency domain for time-invariant channels, and the time-delay and time-frequency domains for Time-Variant (TV) channels. Moreover, TeraMIMO offers both an approximate planar wave model and an accurate spherical wave model, which consider the curvature of transmitted wavefronts, crucial for near-field propagation. Finally, its efficient GUI enables the simulation of multiple channel profiles, making it an accessible and powerful tool for researchers working on THz communications.

6.10. Sixth-Generation Simulation Platform with RIS Support for PHY (6G-Sim-RIS)

The simulator developed by Papadopolus et al. [65] is a small-scale, open-source platform designed to model PHY EM coupling and signal propagation between RIS pairs. It allows users to customize the physical layer, starting with a basic unit cell and scaling up to simulate multiple, large RIS arrays. The platform primarily focuses on RIS interactions, generating verifiable stochastic models for simulating multi-RIS deployments. The platform provides tools for deriving accurate wireless channel models validated through realistic physics simulations for RIS. These models enable a variety of application domains, such as V2X communications in AVs and cybersecurity defense mechanisms in PHY. 6G-Sim-RIS has a great potential for extensions regarding refining the stochastic and macroscopic channel models, support for SDN, and multi-layer network analysis.

6.11. QuaDRiGa

QuaDRiGa is primarily designed as a system-level channel simulator rather than a LLS [66]. Its focus is on modeling the radio propagation channel, particularly for mobile networks, including aspects like spatial consistency, MIMO, and TV channel behavior over large areas and multiple links, which are important for an SLS. QuaDRiGa constructs a 3D stochastic channel model that considers the channel temporal dynamics and a simulation platform developed at Fraunhofer Heinrich-Hertz-Institut that models MIMO channels for a variety of wireless networks, including indoor, outdoor, and satellite environments.

The simulator operates across a wide frequency range of 0.45–100 GHz, focusing on the propagation of EM waves through scatterers. This platform is particularly valuable for modeling RIS as it incorporates a range of statistical distributions extracted from real-world measurements to model the channel behavior accurately over time, capturing essential parameters such as delay, angles of departure, and arrival. With its capability to simulate realistic channel conditions, QuaDRiGa has been adopted for evaluating various 3GPP proposals and specifications, making it a trusted tool for assessing the performance of advanced wireless communication systems.

6.12. SiMoNe

The Simulator for Mobile Networks (SiMoNe) is a software framework designed to provide realistic radio network simulations across multiple generations of mobile systems, including 5G, as well as V2X communication using the IEEE (Institute of Electrical and Electronics Engineers) 802.11p standard and high-speed radio links using the IEEE 802.15.3d standard [67]. SiMoNe integrates both link-level and system-level simulation capabilities, making it versatile for evaluating a wide range of wireless communication scenarios. It is used for network planning and simulation across various real-world conditions. SiMoNe's ability to simulate detailed channel characteristics and large-scale networks provides a comprehensive tool for studying mobile network performance.

SiMoNe's LLS is designed for frequencies up to THz, incorporating fading models such as Rayleigh, Rician, and RT. It also includes support for single carrier waveforms and various channel coding schemes, providing detailed channel representation. Notably, it accounts for oscillator Phase Noise, which is often overlooked in other simulators, delivering more realistic interference and signal degradation simulations. For system-level simulations, SiMoNe supports large-scale network modeling, capable of simulating thousands of base stations and users under time-varying conditions. The system-level simulator incorporates various mobility models and deterministic 3D propagation models, enabling the evaluation of scenarios that include real data transmissions and dynamic user behavior. It provides tools for analyzing performance in dense urban areas, rural environments, and high-speed mobility situations.

7. Simulator Extensions

The transition to 6G is marked by the integration of various advanced technologies that enhance network performance and resilience. Hybrid networks, which combine terrestrial and satellite communications, are crucial for expanding coverage and ensuring robust connectivity. Furthermore, the synergy between traditional and quantum communications enhances security measures, with Quantum Key Distribution (QKD) playing a significant role. In this context, DTs are essential for simulating and optimizing network operations, allowing real-time analysis and monitoring. Robotics and V2X are pivotal in 6G, supporting AVs and smart city initiatives. To address these advancements, the following simulators are introduced as extensions to the simulation tools for communication problems. They simulate specific environments and objects such as AVs, robots, satellites, etc., and generate datasets which can then be used by communications-specific simulators to design the desired algorithms. Examples of such datasets are the BUPTCMCC-6G-DataAI+ [69] and WAIR-D (Wireless AI Research Dataset) [70], DeepSense 6G [71] and DeepVerse 6G [72]. They focus on channel modeling and beamforming for MIMO and MMwave, considering different antenna configurations, delay, and path loss for each transmission in both uplink and downlink for various transmitter and receiver configurations (WAIR-D) as well as Doppler phase shifts, moving users, THz and RIS (BUPTCMCC-6G-DataAI+). They are usually generated through high-fidelity RT simulators (such as Sionna, BUPTCMG-6G+,

or Remcom Inc. Wireless InSite) as synthetic data samples, which supplement real-world measurements to increase the accuracy of DT models. For this purpose, DeepSense 6G and DeepVerse 6G, comprised of real-world and simulated RF, LiDAR, radar, visual, and weather data, have been used for beam management and localization in MMwave communications. The beamforming efficiency was notably improved through transfer learning of the synthetic-data trained ML method using only a small number of measured samples [73]. A summary of the features, strengths, weaknesses, and the use cases that the simulator extensions have been applied in is illustrated in Table 4.

Table 4. Summary of simulator extensions.

Simulator Extension	Features	Compatible Simulators	Strengths	Weaknesses	Use Cases and References
Caviar	Design of 3D terrestrial and aerial networks; Ray tracing; DT.	NS-3; Sionna; AirSim; SUMO.	Open source; modular architecture; simulation of environment.	Limited documentation; computationally intensive.	UAV and V2X [74,75].
SUMO	Simulation of traffic management; vehicular route optimization.	OMNeT++; Caviar; CARLA.	Open source; realistic urban environment modeling.	Non-trivial to learn; limited documentation.	V2X; ISAC [40,76–80].
CARLA	Simulation of autonomous vehicles; support for various sensors.	SUMO; Sionna.	Open source; modular architecture; realistic urban environment modeling.	Computationally intensive.	V2X; vehicle platoons [42,78,81].
AirSim	Design of 3D terrestrial and aerial networks; RL and DL support.	MATLAB; Caviar.	Open source; extensive documentation; realistic urban environment modeling.	Limited number of nodes; simplistic models; computationally intensive.	High-speed V2X and UAV; ISAC [79,82].
Gazebo	Design of 3D autonomous robotic systems; support for various sensors.	NS-3; MATLAB.	Open source; extensive documentation.	Requires effort to learn the simulation description format; computationally intensive.	IoT in indoor and outdoor; ISAC; SLAM [83–85].
Orekit	High-precision modeling of space flight dynamics and space events detection.	-	Open source; extensive documentation; active community; supports both Java and Python.	Non-standalone; setup and usage are non-intuitive for novice users.	Satellite communications [86].
FIWARE	Design of scalable DTs; supports integration of AI methods.	MATLAB.	Open source; extensive documentation; not vendor-locked.	High computational requirements.	IoT for smart cities and agriculture [87,88].
NetSquid	Modeling of physical devices for quantum computations; supports control plane protocols.	-	Scalable; free; written in Python; modular architecture.	Limited documentation.	Quantum communication via optical fiber [89,90].

7.1. CAVIAR

CAVIAR is an open-source Python package designed for co-simulation, enhancing 6G network research [74]. It consists of three primary modules: “3D”, which includes a mobility simulator for 3D computer-generated imagery; “Communications”, which models various communication systems, including MMwave and fiber-based fronthaul; and an “AI/ML” module for integrating AI and ML into simulations. Each module operates independently, allowing for flexibility in simulating complex scenarios across different domains, thereby facilitating comprehensive evaluations of emerging technologies in the context of 6G. An example of this extension’s usage is for creating an RL framework for training an agent (MMwave base station) to learn the scheduling and MIMO beam selection to improve the network throughput [75]. The scenario of a 3D urban environment with moving ground and UAV-based nodes is simulated using AirSim.

7.2. Gazebo

Gazebo is primarily a 3D robotics simulator that excels in modeling real-world physical environments for testing and developing robotic systems [83]. It is not purposefully designed for wireless communication or 6G network simulation, but can be integrated with network simulators like NS-3 or OMNeT++ to simulate communication scenarios, including 6G environments. This simulator extension is valuable in the broader context of combining physical simulations with network simulations, such as evaluating robotic performance as well as Simultaneous Localization And Mapping (SLAM) in environments where communication infrastructure is critical (e.g., IoT and edge computing). It has been utilized as a building block of a DT for trajectory tracking of multiple UAVs [84]. The UAVs' movement is simulated in Gazebo, with the results being input into the tracking method implemented in NS-3, which updates their flight path. By communicating with each other, the UAVs provide their data to the federated learning-based tracking and adjust their movement, with or without a dedicated aerial edge server (base station) operating in close proximity to the other aerial nodes.

7.3. SUMO

SUMO is a versatile open-source traffic simulation tool that excels in modeling complex urban mobility scenarios, making it a leading two-dimensional microscopic simulator for testing AVs [40,76,77]. Its capabilities in V2X communications are crucial for exploring how 6G can enhance intelligent transport systems and optimize traffic management. SUMO supports multimodal traffic simulation and allows the import of maps, such as OSM. Through its socket-based communication interface termed TraCI, SUMO enables real-time interaction with AV dynamics, facilitating the evaluation of various Operational Design Domains essential for identifying edge cases in AV algorithms. While SUMO provides advantages such as realistic car-following models, it also has limitations, including the predetermined behavior of background vehicles, which can reduce real-world variability. Additionally, the steep learning curve associated with its setup may challenge integration into AV testing pipelines. Despite these hurdles, SUMO remains a vital tool for simulating urban scenarios in the context of advancing 6G networks, where cutting-edge communication technologies will be integral to developing connected transport systems. In methods for ISAC, this extension has been used for the generation of vehicular movement and the physics of the road environments, based on which reflectivity of the vehicles is studied [80]. Thus, radar-sensing contributes to a more realistic channel estimation for improved V2V communication. SUMO may also be applied for simulating UAVs, together with vehicular nodes in an urban environment recreated in AirSim. The authors of [79] combine these tools to evaluate a 3D ISAC system based on sensing of the azimuth angle from the OFDM reference signals.

7.4. CARLA

CARLA is an open-source simulation platform designed for developing, training, and validating autonomous driving systems [42]. It features realistic urban environments and a range of digital assets for comprehensive testing. With customizable sensor suites and environmental conditions, CARLA is essential for evaluating the impact of 6G on autonomous navigation and safety. The platform supports scalability through a multi-client architecture, enabling simultaneous control of multiple actors. Its flexible API allows for extensive manipulation of simulation elements, including traffic dynamics and weather. It has been so far applied to V2X communications to generate the physics of the vehicular nodes, while the wireless channel is estimated using RT in Sionna [81]. The dataset is applied together with LiDAR data to predict blockages of the LoS, as well as optimize

the beam direction and antenna position of the MMwave base stations to improve their coverage. In addition, the authors of [78] integrate CARLA with SUMO to simulate the traffic and its control, and implement vehicle platoons.

7.5. AirSim

AirSim is an open-source simulation platform developed by Microsoft Research, designed for testing and validating autonomous vehicles and aerial systems [82]. Built on the Unreal Engine, AirSim provides a rich environment for simulating various scenarios involving drones and cars, enabling researchers to experiment with DL and RL. It supports both software-in-the-loop and hardware-in-the-loop simulations, allowing for realistic modeling of vehicle dynamics and environmental interactions. As 6G networks are set to enhance communication and connectivity for autonomous vehicles, AirSim's advanced simulation features will play a crucial role in evaluating how these vehicles can leverage the high-speed, low-latency communication.

7.6. Orekit

Orekit is an open-source space dynamics library in Java, recognized for its precise components for flight dynamics applications [86]. It provides essential elements for orbit modeling, attitude dynamics, and algorithms for propagation and pointing. With both Java and Python APIs, Orekit facilitates integration into diverse research environments. In the context of 6G research, Orekit is pivotal for simulating non-terrestrial networks. Its capabilities enable researchers to model satellite orbits and analyze communication dynamics, enhancing the study of how 6G networks can leverage space-based systems for improved connectivity and coverage.

7.7. FIWARE

FIWARE is an open-source platform that plays a key role in advancing DT frameworks, enabling the creation of digital replicas of physical systems, particularly for smart city infrastructures and IoT-based farming [87,88]. In the context of 6G research, FIWARE facilitates the modeling and simulation of complex network systems, allowing researchers to analyze performance, predict issues, and optimize configurations. By utilizing FIWARE's Smart Data Models and modular component architecture, researchers can integrate diverse data sources and extract valuable insights from the IoT infrastructure of cities. This scalability and interoperability make FIWARE well-suited for large-scale applications, ensuring seamless interaction with various domains, including 6G network simulations. FIWARE's adaptability extends beyond smart cities, with its eXtended DT concept integrating Building Information Modeling, XR, and AI to enhance sustainability and operational efficiency in smart buildings. These principles can be applied to 6G research to simulate and optimize complex communication networks, driving technological advancements and improving network performance in real-time scenarios.

7.8. NetSquid

NetSquid is a specialized quantum network simulation tool developed at QuTech for modeling scalable quantum networks and modular quantum computing architectures [89]. It excels in accurately simulating the effects of time on quantum systems, which is essential for mitigating qubit degradation in scalable designs. The simulator's modular architecture allows for detailed physical modeling of components, enabling users to assemble them like Lego blocks to create complex simulations of large-scale systems. This flexibility is particularly beneficial for applications such as QKD, quantum repeaters, and entanglement-based networking, all of which are relevant for security in 6G. NetSquid supports various quantum state representations, including ket vectors, stabilizers, and density matrix states.

Optimized with C and Cython for performance, it features an asynchronous framework for programming quantum network protocols and classical control planes, along with a user-friendly Python interface for simulating network hardware. This combination of features makes NetSquid a valuable tool for advancing research in secure communication for future 6G applications.

8. Discussion on Challenges in the 6G Simulator Design

On the basis of this review, the following challenges for future development are identified:

- **Technological coverage**—One of the primary limitations of current 6G simulators lies in their narrow technology coverage. Most of these simulators support only one to three 6G technologies, and this limitation highlights the potential value of collaboration between simulators operating at the same or different levels (e.g., LLS, SLS) to achieve more complete and realistic simulations. A serious advantage of modern simulators is the open-source distribution of most of them. Because of this, developers and researchers have a solid basis for the integration of multiple tools into unified packages that can simulate the 6G network's subsystems. With the proliferation of simulators and emulators for various 6G technologies, as described in this survey, there is the question of which are the most adequate for a specific research task. Often in scientific investigation, the objective is improving on the state-of-the-art in a narrow topic, such as channel estimation, user localization, or frequency allocation. Then, simple open-source tools may be used without the need for substantial modifications. On the other hand, in industrial research and commercial deployment, these simulators and emulators would increase efficiency and reduce costs. Nevertheless, due to their independent development, they lack unified interoperability, which will lead to added complexity to the goal of designing reliable systems and devices [91]. Furthermore, designing dense terrestrial networks and ISTNs significantly increases the computational cost of the design process [92].
- **Realistic design**—In communication system design, there are considerations of agility and reliability with regard to the real-world impairments and limitations. Describing these analytically is both difficult and often computationally nonviable for implementation. In reality, assumptions for the devices' appropriate operational conditions are made, so the design only approximates the environment. Thus, determining whether its physical influences are realistic enough is an open question, largely depending on the design's viability for a particular application. One way of determining the simulation/emulation's effectiveness is by comparing its output with real-world measurements through specialized equipment such as software-defined radios and spectrum analyzers [17,55]). Such experiments, however, involve expensive equipment that may not be easy to obtain, and in this case, reasonable assumptions may be taken from the literature and relevant specialized LLS and SLS based on RT, as it obtains the closest approximations. Some, such as Sionna [10] perform the RT computations on GPUs, significantly increasing the simulation's speed.
- **Computational complexity**—as mentioned above, designing algorithms and networks for the 6G requirements is likely to be very computationally intensive. Even the availability of GPUs may not be viable, as the necessary power to simulate large-scale dense networks may be prohibitive. Alternatives may be found in analog signal processing [93] or quantum computing [89,90], with the former allowing for a significant increase in both the simulations' speed and their energy efficiency, while the latter provides faster transmission and better security. However, modeling algorithms and systems for wireless communications using these two technologies are

still open research areas with limited contributions. Despite the considerable potential of analog processing, a fundamental challenge is its inherent inaccuracy caused by noise, component-based variations, and temporal drift [94]. When traditional algorithms designed for digital arithmetic are run on analog hardware, their numerical precision can decrease substantially, which would lead to a critical performance degradation in simulating dense networks, and some applications, such as adaptive channel estimation, are difficult to achieve in real-world implementations [95]. In the case of quantum computing, specialized simulators are now applied for the design and modeling of wireless systems with the goal to improve their resilience to eavesdropping and state of polarization distortion in use cases such as smart factories and UAV-assisted communications [91].

- **Limited technological support**—Of the currently supported 6G concepts, there is a lack of maturity, as these use cases and environments are only partially implemented in modern simulation tools. Emerging technologies such as ISTN often appear as separate link simulations for satellite and terrestrial communications rather than as a fully implemented SLS. Similarly, OWC, despite its potential to support satellite and remote communication for 6G, is among the rarest technologies to be implemented in the current simulators. One example of a specialized simulator, OptiSystem, offers the opportunity to not only enhance OWC testing but also better support ISTN scenarios. Simulators are generally limited to frequency ranges below 100 GHz, which does not comprehensively capture the whole potential of the THz bands. Additionally, some technologies, such as M-MIMO, do not yet support the “massive” scale expected for 6G deployment, leading to less realistic simulations. AI and ML support in simulators can enable intelligent network management and optimization, yet currently, this capability is only partially implemented in some of them. While there is ML-based customization for scenario testing, few simulators provide a fully integrated solution. This gap indicates another area where future development or targeted extensions could enhance 6G research capabilities. The integration of multiple technologies for simulation of holistic 6G use cases via Network DTs is currently under investigation [91]. This concept builds on individual simulation tools to create virtual models of the interoperability of the RAN, core, and transport networks for large-scale deployments.

9. Conclusions

There are still significant gaps and uncertainties in 6G research. A critical consideration is the absence of a standardized, universally agreed-upon 6G core network architecture, which limits the development of precise network functions. As a result, fully dedicated 6G emulators are still far from maturity. Involving emulators, such as Mininet and experimental test-beds like Colosseum [96], suggest potential testing methods for network management, security protocols, and edge computing functionalities, although in limited capacity until a standardized 6G framework becomes available.

At present, the most accessible simulators operate at the link level, with strong support for technologies such as THz, RIS, M-MIMO, MMwave, and ISAC, though there is comparatively less coverage of ISTN, OWC, and NGMA. AI and ML also remain critical, as these technologies offer opportunities for autonomous, adaptive network behaviors. Among the current options, Sionna and NS-3 stand out due to their large communities, comprehensive documentation, demonstrated use cases, and versatile sets of features. Future directions for development include the combination and common integration of different simulators, which could offer broader simulation scenarios across different 6G use cases, bridging some of the limitations in current platforms while advancing the field toward the eventual goal of a comprehensive 6G simulation toolkit.

Author Contributions: Conceptualization, E.E. and A.V.; methodology, E.E. and A.V.; writing—original draft preparation, E.E., A.V. and A.I.; writing—review and editing, V.P. and A.M.; verification, A.I., V.P. and A.M.; supervision, A.M. and V.P.; project administration, A.M.; funding acquisition, V.P. and A.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the European Union-Next Generation EU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No BG-RRP-2.004-0005: “Improving the research capacity and quality to achieve international recognition and resilience of TU-Sofia” (IDEAS) and performed with the support of the Intelligent Communication Infrastructures Laboratory at the “Research and Development and Innovation Consortium”, Sofia, Bulgaria.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: During the preparation of this manuscript, the authors used GPT-4o and Gemini 2.5 Flash and Pro for the purposes of refining some parts of the abstract and introduction, LaTeX formatting of the tables and generating some entries in the list of references and the list of abbreviations. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3D	Three-dimensional
3GPP	Thrid-Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
6G	Sixth-generation
AI	Artificial Intelligence
AI/ML	Artificial Intelligence/Machine Learning
API	Application Programming Interface
AirSim	AirSim
AVs	Autonomous Vehicles
BER	Bit Error Rate
CF	Cell-Free
Colab	Colaboratory
D-MIMO	Distributed Massive Multiple-Input Multiple-Output
DL	Deep Learning
DTs	Digital Twins
E2E	End-to-End
EM	Electromagnetic
GBSM	Geometry-Based Stochastic Model
GPU	Graphical Processing Unit
IOS	Intelligent Omni-Surfaces
ISAC	Integrated Sensing and Communication
ISTN	Integrated Space–Terrestrial Networks
ISTNs	Integrated Space–Terrestrial Networks
ITU	International Telecommunication Union
Li-Fi	Light Fidelity
LLS	Link-Level Simulator
LoS	Line-of-Sight
LuSim	LuSim
M-MIMO	Massive MIMO

MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
Microsoft Research	Microsoft Research
mmwave	Millimeter-Wave
NFV	Network Function Virtualization
NGMA	Next-Generation Multiple Access
NLoS	Non-Line-of-Sight
NLS	Network-Level Simulator
NOMA	Non-Orthogonal Multiple Access
NS-3	Network Simulator 3
NTNs	Non-Terrestrial Networks
NVIDIA	NVIDIA
NYU	New York University
O-RAN	Open Radio Access Network
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OMNeT++	OMNeT++
OSM	Open Street Maps
OWC	Optical Wireless Communication
PHY	Physical Layer
QKD	Quantum Key Distribution
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
RHS	Reconfigurable Holographic Surfaces
RIS	Reconfigurable Intelligent Surfaces
RL	Reinforcement Learning
RT	Ray Tracing
SDR	Software-defined Radio
SDRs	Software-defined Radios
SDN	Software-Defined Networking
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference-plus-Noise Ratio
SLS	System-Level Simulator
TCP	Transmission Control Protocol
THz	Terahertz
THzCom	Terahertz Communications
TR	Technical Report
TV	Time-Variant
UAV	Unmanned Aerial Vehicle
UDP	User Datagram Protocol
UFMC	Universal Filtered Multi Carrier
Unreal Engine	Unreal Engine
URLLC	Ultra-Reliable Low Latency Communication
V2X	Vehicle-to-Everything
VANET	Vehicular Ad-hoc Network
VLC	Visible Light Communication
Wi-Fi	Wireless Fidelity
WSN	Wireless Sensor Network
XR	Extended Reality

References

1. Chowdhury, M.Z.; Shahjalal, M.; Ahmed, S.; Jang, Y.M. 6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions. *IEEE Open J. Commun. Soc.* **2020**, *1*, 957–975. [\[CrossRef\]](#)
2. Jiang, W.; Luo, F.L. *6G Key Technologies: A Comprehensive Guide*; Wiley-IEEE Press: Hoboken, NJ, USA, 2022. [\[CrossRef\]](#)
3. ITU-R Working Party 5D. Framework and overall objectives of the future development of IMT for 2030 and beyond, 2023. Presented at the ITU-D SG2 Q3/2 Workshop on 5G Cybersecurity, Geneva, Switzerland, 26 September 2023.
4. 3GPP. Summary for RAN Rel-18 package. Technical Report RP-213468, 3GPP. Presented at 3GPP RAN#94-e, December 2021. 2021. Available online: https://www.3gpp.org/ftp/tsg_ran/TSG_RAN/TSGR_94e/Docs/RP-213469.zip (accessed on 30 July 2025).
5. Huo, Y.; Lin, X.; Di, B.; Zhang, H.; Hernando, F.J.L.; Tan, A.S.; Mumtaz, S.; Demir, Ö.T.; Chen-Hu, K. Technology Trends for Massive MIMO towards 6G. *Sensors* **2023**, *23*, 6062. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Zhao, J. A survey of intelligent reflecting surfaces (IRSs): Towards 6G wireless communication networks. *arXiv* **2019**, arXiv:1907.04789. [\[CrossRef\]](#)
7. Liu, Y.; Zhang, S.; Mu, X.; Ding, Z.; Schober, R.; Al-Dhahir, N.; Hossain, E.; Shen, X. Evolution of NOMA toward next generation multiple access (NGMA) for 6G. *IEEE J. Sel. Areas Commun.* **2022**, *40*, 1037–1071. [\[CrossRef\]](#)
8. Manalastas, M.; bin Farooq, M.U.; Zaidi, S.M.A.; Imran, A. Toward the development of 6g system level simulators: Addressing the computational complexity challenge. *IEEE Wirel. Commun.* **2023**, *30*, 160–168. [\[CrossRef\]](#)
9. Ammar, S.; Lau, C.P.; Shihada, B. An in-depth survey on virtualization technologies in 6g integrated terrestrial and non-terrestrial networks. *IEEE Open J. Commun. Soc.* **2024**, *5*, 3690–3734. [\[CrossRef\]](#)
10. Hoydis, J.; Ait Aoudia, F.; Cammerer, S.; Nimier-David, M.; Binder, N.; Marcus, G.; Keller, A. Sionna RT: Differentiable ray tracing for radio propagation modeling. In Proceedings of the 2023 IEEE Globecom Workshops (GC Wkshps), Kuala Lumpur, Malaysia, 4–8 December, 2023; pp. 317–321.
11. Campanile, L.; Griboaud, M.; Iacono, M.; Marulli, F.; Mastroianni, M. Computer network simulation with ns-3: A systematic literature review. *Electronics* **2020**, *9*, 272. [\[CrossRef\]](#)
12. Tarboush, S.; Sameddeen, H.; Chen, H.; Loukil, M.H.; Jemaa, H.; Alouini, M.S.; Al-Naffouri, T.Y. TeraMIMO: A channel simulator for wideband ultra-massive MIMO terahertz communications. *IEEE Trans. Veh. Technol.* **2021**, *70*, 12325–12341. [\[CrossRef\]](#)
13. Choi, H.; Oh, J.; Chung, J.; Alexandropoulos, G.C.; Choi, J. WiThRay: A versatile ray-tracing simulator for smart wireless environments. *IEEE Access* **2023**, *11*, 56822–56845. [\[CrossRef\]](#)
14. Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; Shamseer, L.; Tetzlaff, J.M.; Akl, E.A.; Brennan, S.E.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ* **2021**, 372. [\[CrossRef\]](#)
15. Bouras, C.; Gkamas, A.; Diles, G.; Andreas, Z. A comparative study of 4G and 5G network simulators. *Int. J. Adv. Netw. Serv.* **2020**, *13*, 11–20.
16. Gkonis, P.K.; Trakadas, P.T.; Kaklamani, D.I. A comprehensive study on simulation techniques for 5g networks: State of the art results, analysis, and future challenges. *Electronics* **2020**, *9*, 468. [\[CrossRef\]](#)
17. Zhang, J.; Lin, J.; Tang, P.; Zhang, Y.; Xu, H.; Gao, T.; Miao, H.; Chai, Z.; Zhou, Z.; Li, Y.; et al. Channel measurement, modeling, and simulation for 6G: A survey and tutorial. *arXiv* **2023**, arXiv:2305.16616.
18. Boeira, C.; Hasan, A.; Papry, K.; Ju, Y.; Zhu, Z.; Haque, I. A calibrated and automated simulator for innovations in 5g. *arXiv* **2024**, arXiv:2404.10643. [\[CrossRef\]](#)
19. Shafie, A.; Yang, N.; Han, C.; Jornet, J.M.; Juntti, M.; Kürner, T. Terahertz Communications for 6G and Beyond Wireless Networks: Challenges, Key Advancements, and Opportunities. *IEEE Netw.* **2022**, *36*, 94–101. [\[CrossRef\]](#)
20. Arai, S.; Kinoshita, M.; Yamazato, T. Optical wireless communication: A candidate 6G technology? *IEICE Trans. Fundam. Electron. Commun. Comput. Sci.* **2021**, *104*, 227–234. [\[CrossRef\]](#)
21. Zhang, R.; Cui, Y.; Claussen, H.; Haas, H.; Hanzo, L. Anticipatory association for indoor visible light communications: Light, follow me! *IEEE Trans. Wirel. Commun.* **2018**, *17*, 2499–2510. [\[CrossRef\]](#)
22. Cui, M.; Wu, Z.; Lu, Y.; Wei, X.; Dai, L. Near-field MIMO communications for 6G: Fundamentals, challenges, potentials, and future directions. *IEEE Commun. Mag.* **2022**, *61*, 40–46. [\[CrossRef\]](#)
23. Deng, R.; Zhang, Y.; Zhang, H.; Di, B.; Zhang, H.; Song, L. Reconfigurable holographic surface: A new paradigm to implement holographic radio. *IEEE Veh. Technol. Mag.* **2023**, *18*, 20–28. [\[CrossRef\]](#)
24. Zhu, J.; Gu, Z.; Ma, Q.; Dai, L.; Cui, T.J. Holography inspired self-controlled reconfigurable intelligent surface. *arXiv* **2024**, arXiv:2403.16062. [\[CrossRef\]](#)
25. Aboumahmoud, I.; Hossain, E.; Mezghani, A. Resource Management in RIS-Assisted Rate Splitting Multiple Access for Next Generation (xG) Wireless Communications: Models, State-of-the-Art, and Future Directions. *IEEE Commun. Surv. Tutor.* **2024**, *27*, 1618–1655. [\[CrossRef\]](#)

26. Polese, M.; Bonati, L.; D'oro, S.; Basagni, S.; Melodia, T. Understanding O-RAN: Architecture, interfaces, algorithms, security, and research challenges. *IEEE Commun. Surv. Tutor.* **2023**, *25*, 1376–1411. [\[CrossRef\]](#)
27. 3GPP. *Summary for RAN Rel-19 Package: RAN1/2/3-led*; Technical Report RP-232745; 3GPP: Sophia Antipolis, France, 2023.
28. 3GPP. *RAN Chair's Summary of Rel-19 Workshop*; Technical Report RWS230488; 3GPP: Sophia Antipolis, France, 2023.
29. 3GPP. Study Report on 7–24 GHz Channel Model for NR. Technical Report RP-234018, 3GPP. Draft Document from TSG-RAN Working Group 1 (RAN1) 117th Meeting Inbox. 2024. Available online: [https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_117/Inbox/drafts/9.8\(FS_NR_7_24GHz_CHmod\)/RP-240xxx%20SR%207-24%20channel%20model.docx](https://www.3gpp.org/ftp/tsg_ran/WG1_RL1/TSGR1_117/Inbox/drafts/9.8(FS_NR_7_24GHz_CHmod)/RP-240xxx%20SR%207-24%20channel%20model.docx) (accessed on 30 July 2025).
30. Pagin, M.; Lagén, S.; Bojovic, B.; Polese, M.; Zorzi, M. Improving the Efficiency of MIMO Simulations in ns-3. In Proceedings of the 2023 Workshop on ns-3, Washington, DC, USA, 28–29 June 2023; pp. 1–9.
31. Varga, A. A practical introduction to the OMNeT++ simulation framework. In *Recent Advances in Network Simulation: The OMNeT++ Environment and Its Ecosystem*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 3–51.
32. Hossain, Z.; Xia, Q.; Jornet, J.M. TeraSim: An ns-3 extension to simulate terahertz-band communication networks. *Softw. Impacts* **2019**, *1*, 100004. [\[CrossRef\]](#)
33. Lacava, A.; Bordin, M.; Polese, M.; Sivaraj, R.; Zugno, T.; Cuomo, F.; Melodia, T. ns-o-ran: Simulating o-ran 5g systems in ns-3. In Proceedings of the 2023 Workshop on ns-3, Washington, DC, USA, 28–29 June 2023; pp. 35–44.
34. Drago, M.; Zugno, T.; Mason, F.; Giordani, M.; Boban, M.; Zorzi, M. Artificial intelligence in vehicular wireless networks: A case study using ns-3. In Proceedings of the 2022 Workshop on ns-3, Virtual Event, 20–23 June 2022; pp. 112–119.
35. Sandri, M.; Pagin, M.; Giordani, M.; Zorzi, M. Implementation of a channel model for non-terrestrial networks in ns-3. In Proceedings of the 2023 Workshop on ns-3, Washington, DC, USA, 28–29 June 2023; pp. 28–34.
36. Pratschner, S.; Tahir, B.; Marijanovic, L.; Mussbah, M.; Kirev, K.; Nissel, R.; Schwarz, S.; Rupp, M. Versatile Mobile Communications Simulation: The Vienna 5G Link Level Simulator. *EURASIP J. Wirel. Commun. Netw.* **2018**, *2018*, 226. [\[CrossRef\]](#)
37. Jia, X.; Liu, P.; Qi, W.; Liu, S.; Huang, Y.; Zheng, W.; Pan, M.; You, X. Link-level simulator for 5G localization. *IEEE Trans. Wirel. Commun.* **2023**, *22*, 5198–5213. [\[CrossRef\]](#)
38. Ghosh, S.; Busari, S.A.; Dagiuklas, T.; Iqbal, M.; Mumtaz, R.; González, J.; Stavrou, S.; Kanaris, L. SDN-Sim: Integrating a system-level simulator with a software defined network. *IEEE Commun. Stand. Mag.* **2020**, *4*, 18–25. [\[CrossRef\]](#)
39. Hu, W.; Ohsita, Y.; Shimonishi, H. Digital Twin-Enhanced Framework for TCP Throughput Map Construction in Dynamic IoV. In Proceedings of the 2025 28th Conference on Innovation in Clouds, Internet and Networks (ICIN), Paris, France, 11–14 March, 2025; pp. 156–160.
40. Shamim Akhter, M.; Ahsan, N.; Quaderi, S.; Al Forhad, M.; Sumit, S.; Rahman, M. A SUMO based simulation framework for intelligent traffic management system. *J. Traffic Logist. Eng.* **2020**, *8*, 1–5. [\[CrossRef\]](#)
41. Cislighi, V.; Quadri, C.; Mancuso, V.; Marsan, M.A. Simulation of tele-operated driving over 5g using carla and omnet++. In Proceedings of the 2023 IEEE Vehicular Networking Conference (VNC), Istanbul, Türkiye, 26–28 April 2023; pp. 81–88.
42. Malik, S.; Khan, M.A.; El-Sayed, H. Carla: Car learning to act—An inside out. *Procedia Comput. Sci.* **2022**, *198*, 742–749. [\[CrossRef\]](#)
43. Hasan, M.; Dahshan, H.; Abdelwanees, E.; Elmoghazy, A. SDN mininet emulator benchmarking and result analysis. In Proceedings of the 2020 2nd Novel Intelligent and Leading Emerging Sciences Conference (NILES), Giza, Egypt, 24–26 October 2020; pp. 355–360.
44. Joseph, K.; Eyobu, O.S.; Kasyoka, P.; Oyana, T.J. A link fabrication attack mitigation approach (LiFAMA) for software defined networks. *Electronics* **2022**, *11*, 1581. [\[CrossRef\]](#)
45. Fawaz, H.; Houidi, O.; Zeghlache, D.; Lesca, J.; Quang, P.T.A.; Leguay, J.; Medagliani, P. Graph convolutional reinforcement learning for load balancing and smart queuing. In Proceedings of the 2023 IFIP Networking Conference (IFIP Networking), Barcelona, Spain, 12–15 June 2023; pp. 1–9.
46. Singh, R.; Soler, J.; Sylla, T.; Mendiboure, L.; Berbineau, M. Coexistence of railway and road services by sharing telecommunication infrastructure using sdn-based slicing: A tutorial. *Network* **2022**, *2*, 670–706. [\[CrossRef\]](#)
47. Su, R.; Dai, L.; Ng, D.W.K. Wideband precoding for RIS-aided THz communications. *IEEE Trans. Commun.* **2023**, *71*, 3592–3604. [\[CrossRef\]](#)
48. Kosasih, A.; Demir, Ö.T.; Kolomvakis, N.; Björnson, E. Spatial Frequencies and Degrees of Freedom: Their roles in near-field communications. *IEEE Signal Process. Mag.* **2025**, *42*, 33–44. [\[CrossRef\]](#)
49. 3GPP. Study on Channel Model for Frequencies from 0.5 to 100 GHz V16.1.0. Technical Report TR 38.901, 3GPP. 2020. Available online: https://www.3gpp.org/ftp/Specs/archive/38_series/38.901/ (accessed on 30 July 2025).
50. 3GPP. Solutions for NR to Support Non-Terrestrial Networks (NTN). Technical Report TR 38.821, 3GPP Technical Specification Group Radio Access Network. 2019. Available online: https://www.3gpp.org/ftp/Specs/archive/38_series/38.821/ (accessed on 30 July 2025).
51. MathWorks. 6G Exploration Library. 2024. Available online: <https://www.mathworks.com/help/5g/6g-exploration-library.html> (accessed on 21 May 2025).

52. Cao, G.; Gradoni, G.; Peng, Z. Photon Splatting: A Physics-Guided Neural Surrogate for Real-Time Wireless Channel Prediction. *arXiv* **2025**, arXiv:2507.04595.
53. Ltaief, F.; Lozenguez, G.; Savard, A.; Fabresse, L. Toward Robot-based Validation of Simulated 5G Coverage Maps in an Industrial Context. *HAL* **2025**, preprint.
54. Beyraghi, S.; Interdonato, G.; Geraci, G.; Buzzzi, S.; Lozano, A. Evaluating the Performance of Reconfigurable Intelligent Base Stations through Ray Tracing. *arXiv* **2025**, arXiv:2507.08611. [[CrossRef](#)]
55. Poddar, H.; Ju, S.; Shakya, D.; Rappaport, T.S. A tutorial on NYUSIM: Sub-terahertz and millimeter-wave channel simulator for 5G, 6G, and beyond. *IEEE Commun. Surv. Tutor.* **2023**, *26*, 824–857. [[CrossRef](#)]
56. Zhao, C.; Zhang, J.; Zhang, Y.; Tian, L.; Wang, H.; Jiang, H.; Liu, Y.; Chen, W.; Jiang, T.; Liu, G. BUPTCMCC-6G-CMG+: A GBSSM-based ISAC standard channel model generator. *Sci. China Inf. Sci.* **2025**, *68*, 1–15. [[CrossRef](#)]
57. Huang, Y.; Yang, J.; Xia, S.; Wen, C.K.; Jin, S. Learned Off-Grid Imager for Low-Altitude Economy with Cooperative ISAC Network. *arXiv* **2025**, arXiv:2506.07799.
58. Tärneberg, W.; Fedorov, A.; Callebaut, G.; Van der Perre, L.; Fitzgerald, E. Towards Practical Cell-Free 6G Network Deployments: An Open-Source End-to-End Ray Tracing Simulator. In Proceedings of the 2023 57th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 29 October–1 November 2023; pp. 1000–1005.
59. Adler, J.; Kronauer, T.; Barreto, A.N. Hermespy: An open-source link-level evaluator for 6g. *IEEE Access* **2022**, *10*, 120256–120273. [[CrossRef](#)]
60. Ramzan, M.; Adler, J.; Kamal, S.; Matthe, M.; Sen, P. Indoor ISAC Demonstrator with Aperture Coupled Antennas (ACA) at Wi-Fi Band for 6G Applications. In Proceedings of the 2025 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Poznan, Poland, 3–6 June 2025; pp. 247–251.
61. George, S.; Sen, P.; Umar, M.; Matthé, M.; Adler, J.; Ramzan, M.; Carta, C. Over-the-air 26GHz Receiver Hardware-Software Evaluation towards Joint Communication and Radar Sensing. In Proceedings of the 2024 54th European Microwave Conference (EuMC), Paris, France, 23–27 September 2024; pp. 509–512.
62. Kim, Y.; Seo, S.; Park, J.; Bennis, M.; Kim, S.L.; Choi, J. Knowledge distillation from language-oriented to emergent communication for multi-agent remote control. In Proceedings of the ICC 2024-IEEE International Conference on Communications, Denver, CO, USA, 9–13 June 2024; pp. 2962–2967.
63. Han, C.; Wu, Y.; Chen, Z.; Chen, Y.; Wang, G. THz ISAC: A physical-layer perspective of terahertz integrated sensing and communication. *IEEE Commun. Mag.* **2024**, *62*, 102–108. [[CrossRef](#)]
64. Müller, M.K.; Ademaj, F.; Dittrich, T.; Fastenbauer, A.; Elbal, B.R.; Nabavi, A.; Nagel, L.; Schwarz, S.; Rupp, M. Flexible multi-node simulation of cellular mobile communications: The Vienna 5G System Level Simulator. *Eurasip J. Wirel. Commun. Netw.* **2018**, *2018*, 227. [[CrossRef](#)]
65. Papadopoulos, A.; Lalas, A.; Votis, K.; Tyrovolas, D.; Karagiannidis, G.; Ioannidis, S.; Liaskos, C. An open platform for simulating the physical layer of 6g communication systems with multiple intelligent surfaces. In Proceedings of the 2022 18th International Conference on Network and Service Management (CNSM), Thessaloniki, Greece, 31 October–1 November 2022; pp. 359–363.
66. Jaeckel, S.; Turay, N.; Raschkowski, L.; Thiele, L.; Vuoltoniemi, R.; Sonkki, M.; Hovinen, V.; Burkhardt, F.; Karunakaran, P.; Heyn, T. Industrial indoor measurements from 2 to 6 GHz for the 3GPP-NR and QuaDRiGa channel model. In Proceedings of the 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), Honolulu, HI, USA, 22–25 September 2019; pp. 1–7.
67. Eckhardt, J.M.; Herold, C.; Jung, B.K.; Dreyer, N.; Kürner, T. Modular link level simulator for the physical layer of beyond 5G wireless communication systems. *Radio Sci.* **2022**, *57*, 1–15. [[CrossRef](#)]
68. Amatare, S.; Singh, G.; Kharel, A.; Roy, D. Real-time localization of objects using radio frequency propagation in digital twin. In Proceedings of the MILCOM 2024-2024 IEEE Military Communications Conference (MILCOM), Washington, DC, USA, 28 October–1 November 2024; pp. 653–654.
69. Yu, L.; Zhang, J.; Fu, M.; Wang, Q. BUPTCMCC-6G-DataAI+: A generative channel dataset for 6G AI air interface research. *arXiv* **2024**, arXiv:2410.10839. [[CrossRef](#)]
70. Huangfu, Y.; Wang, J.; Dai, S.; Li, R.; Wang, J.; Huang, C.; Zhang, Z. Wair-d: Wireless ai research dataset. *arXiv* **2022**, arXiv:2212.02159. [[CrossRef](#)]
71. Alkhateeb, A.; Charan, G.; Osman, T.; Hredzak, A.; Morais, J.; Demirhan, U.; Srinivas, N. DeepSense 6G: A large-scale real-world multi-modal sensing and communication dataset. *IEEE Commun. Mag.* **2023**, *61*, 122–128. [[CrossRef](#)]
72. Demirhan, U.; Taha, A.; Alkhateeb, A. DeepVerse 6G. *IEEE Dataport* **2022**. [[CrossRef](#)]
73. Alkhateeb, A.; Jiang, S.; Charan, G. Real-time digital twins: Vision and research directions for 6G and beyond. *IEEE Commun. Mag.* **2023**, *61*, 128–134. [[CrossRef](#)]
74. Borges, J.; Bastos, F.; Correa, I.; Batista, P.; Klautau, A. CAVIAR: Co-simulation of 6G Communications, 3D Scenarios and AI for Digital Twins. *IEEE Internet Things J.* **2024**, *11*, 31287–31300. [[CrossRef](#)]

75. Borges, J.P.T.; De Oliveira, A.P.; Bastos, F.H.B.E.; Suzuki, D.T.N.D.N.; Junior, E.S.D.O.; Bezerra, L.M.; Nahum, C.V.; dos Santos Batista, P.; Júnior, A.B.D.R.K. Reinforcement learning for scheduling and MIMO beam selection using Caviar simulations. In Proceedings of the 2021 ITU Kaleidoscope: Connecting Physical and Virtual Worlds (ITU K), Virtual Event, 6–10 December 2021; pp. 1–7.
76. Gillgallon, R.; Almutairi, R.; Bergami, G.; Morgan, G. SimulatorOrchestrator: A 6G-Ready Simulator for the Cell-Free/Osmotic Infrastructure. *Sensors* **2025**, *25*, 1591. [\[CrossRef\]](#)
77. Lopez, P.A.; Behrisch, M.; Bieker-Walz, L.; Erdmann, J.; Flötteröd, Y.P.; Hilbrich, R.; Lücken, L.; Rummel, J.; Wagner, P.; Wießner, E. Microscopic traffic simulation using sumo. In Proceedings of the 2018 21st International Conference on Intelligent Transportation Systems (ITSC), Maui, HI, USA, 4–7 November 2018; pp. 2575–2582.
78. Xu, R.; Guo, Y.; Han, X.; Xia, X.; Xiang, H.; Ma, J. OpenCDA: An Open Cooperative Driving Automation Framework Integrated with Co-Simulation. *arXiv* **2021**, arXiv:2107.06260. <http://arxiv.org/abs/2107.06260>.
79. Yang, Z.; Gao, S.; Cheng, X.; Yang, L. Synesthesia of Machines (SoM)-Enhanced Sub-THz ISAC Transmission for Air-Ground Network. *arXiv* **2025**, arXiv:2506.12831.
80. Khan, A.U.; Mint, S.J.; Shah, S.N.H.; Schneider, C.; Robert, J. Exploring the Impact of Bistatic Target Reflectivity in ISAC-Enabled V2V Setup Across Diverse Geometrical Road Layouts. *IEEE Open J. Veh. Technol.* **2025**, *6*, 948–968. [\[CrossRef\]](#)
81. Gharsallah, G.; Kaddoum, G. MVX-ViT: Multimodal collaborative perception for 6G V2X network management decisions using vision transformer. *IEEE Open J. Commun. Soc.* **2024**, *5*, 5619–5634. [\[CrossRef\]](#)
82. Turco, L.; Zhao, J.; Xu, Y.; Tsourdos, A. A study on co-simulation digital twin with MATLAB and AirSim for future advanced air mobility. In Proceedings of the 2024 IEEE Aerospace Conference, Big Sky, MT, USA, 2–9 March 2024; pp. 1–18.
83. Wang, W. Robot Autonomous Avoidance System Based on Reinforcement Learning in 6G Network Scenarios. *Wirel. Pers. Commun.* **2024**, *2024*, 1–15. [\[CrossRef\]](#)
84. Zhou, L.; Leng, S.; Wang, Q. A federated digital twin framework for uavs-based mobile scenarios. *IEEE Trans. Mob. Comput.* **2023**, *23*, 7377–7393. [\[CrossRef\]](#)
85. Nithya, M.; Rashmi, M. Gazebo-ROS-Simulink framework for hover control and trajectory tracking of crazyflie 2.0. In Proceedings of the TENCON 2019-2019 IEEE Region 10 Conference (TENCON), Kochi, India, 17–20 October 2019; pp. 649–653.
86. Criscola, F.; Singla, A.; Ponce, E.; Calveras, A.; Ruiz-De-Azua, J.A.; Canales, D. Development of a Simulator for Coverage Planning of a 6G/IOT Constellation. In Proceedings of the 33rd AAS/AIAA Conference Pend, Charlotte, NC, USA, 7–11 August 2022; pp. 1–19.
87. Kolehmainen, K.; Pirazzi, M.; Soininen, J.P.; Backman, J. Simulation Based Performance Evaluation of FIWARE IoT Platform for Smart Agriculture. In Proceedings of the IoTBDS, Prague, Czech Republic, 21–23 April 2023; pp. 73–81.
88. Muñoz, M.; Guzmán, J.L.; Sánchez-Molina, J.A.; Rodríguez, F.; Torres, M.; Berenguel, M. A new IoT-based platform for greenhouse crop production. *IEEE Internet Things J.* **2020**, *9*, 6325–6334. [\[CrossRef\]](#)
89. Coopmans, T.; Kneijens, R.; Dahlberg, A.; Maier, D.; Nijsten, L.; de Oliveira Filho, J.; Papendrecht, M.; Rabbie, J.; Rozpedek, F.; Skrzypczyk, M.; et al. Netsquid, a network simulator for quantum information using discrete events. *Commun. Phys.* **2021**, *4*, 164. [\[CrossRef\]](#)
90. Avis, G.; Ferreira da Silva, F.; Coopmans, T.; Dahlberg, A.; Jirovská, H.; Maier, D.; Rabbie, J.; Torres-Knoop, A.; Wehner, S. Requirements for a processing-node quantum repeater on a real-world fiber grid. *Npj Quantum Inf.* **2023**, *9*, 100. [\[CrossRef\]](#)
91. Tran, D.H.; Waheed, N.; Saputra, Y.M.; Lin, X.; Nguyen, C.T.; Abdu, T.S.; Vo, V.N.; Pham, V.Q.; Alsenwi, M.; Adam, A.B.M.; et al. Network Digital Twin for 6G and Beyond: An End-to-End View Across Multi-Domain Network Ecosystems. *arXiv* **2025**, arXiv:2506.01609. [\[CrossRef\]](#)
92. Pegurri, R.; Linsalata, F.; Moro, E.; Hoydis, J.; Spagnolini, U. Toward digital network twins: Integrating sionna RT in ns-3 for 6G Multi-RAT networks simulations. *arXiv* **2024**, arXiv:2501.00372.
93. Dakic, K.; Al Homssi, B.; Al-Hourani, A. Spiking-unet: Spiking neural networks for spectrum occupancy monitoring. In Proceedings of the 2024 IEEE Wireless Communications and Networking Conference (WCNC), Dubai, United Arab Emirates, 21–24 April 2024; pp. 1–6.
94. Nandakumar, S.; Le Gallo, M.; Boybat, I.; Rajendran, B.; Sebastian, A.; Eleftheriou, E. A phase-change memory model for neuromorphic computing. *J. Appl. Phys.* **2018**, *124*, 152135. [\[CrossRef\]](#)
95. Gupta, A.; Dizdar, O.; Chen, Y.; Wang, S. SpikingRx: From neural to spiking receiver. *arXiv* **2024**, arXiv:2409.05610. [\[CrossRef\]](#)
96. Melodia, T.; Basagni, S.; Chowdhury, K.R.; Gosain, A.; Polese, M.; Johari, P.; Bonati, L. Colosseum, the world's largest wireless network emulator. In Proceedings of the 27th Annual International Conference on Mobile Computing and Networking, New Orleans, LA, USA, 25–29 October 2021; pp. 860–861.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.