

ORIGINAL RESEARCH

Open access

Leveraging 5G and Real-Time Digital Twins for Sustainable Smart City Development

Petra Novak^{1*}, Milan Horvat², Jakub Vesely¹, Jana Kralova²

Abstract

The emergence of 5G technology is revolutionizing the development of smart cities by providing unparalleled speed, ultra-low latency, and massive device connectivity. These advancements enable seamless integration of IoT devices, real-time monitoring systems, and innovative urban solutions. This paper investigates the role of 5G in addressing key urban challenges—such as network congestion, energy efficiency, and data security—while emphasizing its transformative potential for advancing smart city architectures. Particular attention is given to integrating 5G with real-time digital twins, which bridge the physical and digital worlds to optimize urban operations, improve resource allocation, and enhance public safety. Despite its promise, 5G deployment faces obstacles including high infrastructure costs, substantial energy consumption, and limited signal coverage. This study reviews current trends, existing implementations, and emerging issues surrounding 5G in smart cities, offering perspectives on its limitations and potential mitigation strategies. It underscores the importance of collaboration among stakeholders to fully unlock 5G's capabilities and develop scalable, secure, and sustainable smart city solutions.

Keywords Smart city, Artificial intelligence, Real-time systems, Wireless networks

*Correspondence:

Petra Novak

petra.novak@cvut.cz

¹ Department of Intelligent Electrical Networks, Faculty of Electrical Engineering, Czech Technical University, Prague, Czech Republic

² Department of Energy Analytics and Digital Systems, Faculty of Informatics, Comenius University, Bratislava, Slovakia

Introduction

As urban areas expand and city populations continue to grow, managing resources, infrastructure, and public services efficiently becomes increasingly complex. To meet these demands, numerous cities are adopting smart solutions powered by advanced technologies intended to enhance urban operations and elevate residents' quality of life [1, 2]. Central to this transformation is 5G technology, which stands out for its exceptional speed, minimal latency, and capacity to connect a vast number of devices simultaneously [3, 4]. These characteristics position 5G as a critical facilitator of instantaneous communication and intelligent processing, offering substantial potential to reshape urban functionality [1-4].

Despite its considerable advantages, implementing smart city initiatives has encountered notable difficulties. Issues such as network overload, unreliable real-time capabilities, and disjointed data architectures can undermine the performance of current systems and obstruct the full achievement of smart city objectives [5, 6]. Additional pressures stemming from urbanization—such as increased energy consumption, cybersecurity risks, and latency demands—further complicate the creation of dependable, scalable solutions. Overcoming these obstacles requires innovative methods that leverage 5G's strengths while effectively mitigating its inherent weaknesses [7, 8].

This paper investigates a promising strategy: integrating 5G technology with real-time digital twins. Digital twins serve as virtual replicas of physical assets and processes, enabling urban planners and administrators to model, observe, and optimize city operations. Enhanced by 5G connectivity, these digital twins deliver continuous data streams and forward-looking analytics, empowering cities to react swiftly and make better-informed long-term decisions [9-12]. The primary aim of this study is to examine how combining 5G with real-time digital twins can strengthen urban planning processes, improve resource utilization, and elevate public safety standards in smart cities.

Although previous research has broadly addressed 5G's contributions to smart cities, this work focuses more specifically on the role of digital twins—an area that remains relatively underexplored. It seeks to demonstrate how 5G's unique attributes can significantly boost the effectiveness of digital twins and, consequently, the overall performance of smart city ecosystems. In addition to highlighting the benefits, the paper also examines critical obstacles that may impede adoption, including technical constraints such as network restrictions and interoperability issues, as well as broader policy and governance considerations. Through a detailed analysis of these issues and the presentation of actionable solutions, this research aims to support the development of smarter, more resilient, and environmentally sustainable urban environments.

Current Trends for 5G in Smart Cities

The integration of 5G technology into city infrastructure marks a critical turning point in the ongoing advancement of smart cities. As urban areas increasingly depend on data-centric systems for managing resources, transportation, and essential services, the ultra-high-speed connectivity and minimal latency delivered by 5G have become indispensable. This section presents an overview of the technical capabilities that render 5G well-suited to smart city settings, followed by practical examples of its current deployment to enhance operational efficiency, public safety, and overall quality of life. It also evaluates the constraints and difficulties associated with 5G adoption in urban environments, including infrastructure requirements, cybersecurity threats, and socioeconomic obstacles. Collectively, these elements provide a comprehensive perspective on the role of 5G in redefining contemporary urban development.

Technological overview

5G technology transforms smart cities by supplying the robust backbone required for complex, highly interconnected ecosystems [11, 12]. When compared to 4G, 5G delivers superior capabilities. It achieves peak data rates of up to 10 Gbps—ten times faster than 4G—enabling seamless support for high-definition video streaming, vehicle-to-everything communication in autonomous driving, and fluid augmented reality (AR) and virtual reality (VR) experiences [13-15]. This dramatic increase in speed significantly reduces download times and response delays, allowing data-intensive urban applications to operate with greater reliability and efficiency [11-14].

A defining attribute of 5G is its ultra-low latency, which can be as little as 1 millisecond. Such near-instantaneous responsiveness is vital for time-critical applications, including autonomous vehicles, remote healthcare procedures, and emergency response systems, where even minor delays can lead to serious consequences [16, 17]. Furthermore, 5G supports an enormous density of connected devices, accommodating up to one million devices per square kilometer [13, 18]. This capacity is especially valuable in smart cities, where vast networks of IoT devices—such as environmental sensors, surveillance cameras, and smart appliances—generate massive data flows that demand reliable, coordinated communication [19, 20].

Figure 1 presents a comparative analysis of performance across successive wireless generations for smart city use cases, clearly demonstrating 5G's superiority in critical metrics [21-27]. The use of a logarithmic scale effectively illustrates the exponential improvements in speed, latency, and device connectivity that 5G brings over earlier standards.

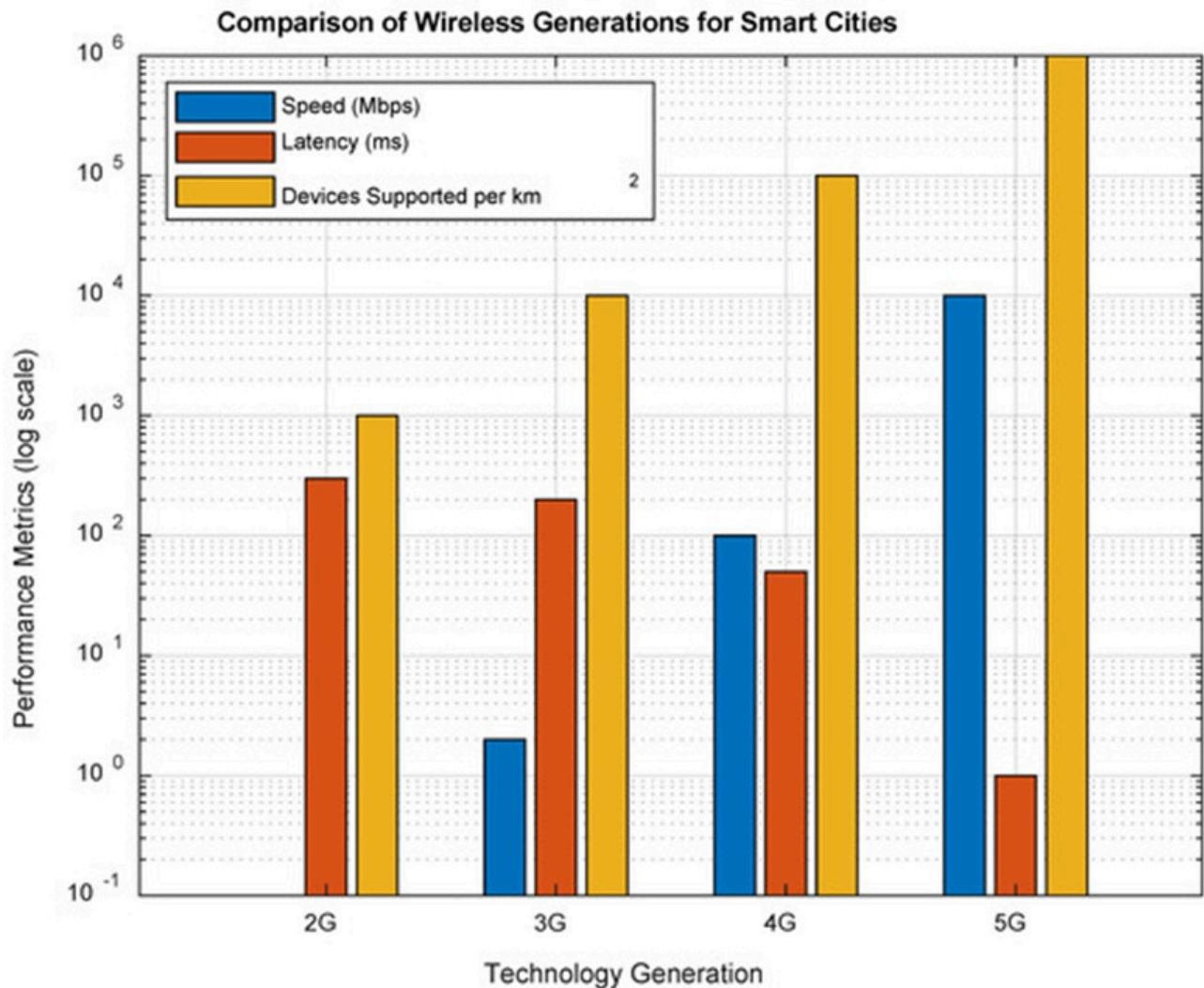


Figure 1. Performance comparison of wireless generations for smart city applications [24, 26, 27].

The enhancements in speed, latency, and device connectivity depicted in **Figure 1** have profound, far-reaching consequences for smart cities. The substantial leap in data transfer rates offered by 5G—up to 10 Gbps—enables the smooth operation of data-intensive applications, including high-definition video streaming, remote surveillance, and instantaneous traffic control [21–24]. This boost in performance underpins essential urban operations, such as autonomous driving, which depend on swift data exchange for safe navigation. It supports the growing adoption of augmented and virtual reality solutions that are proving increasingly valuable in fields like healthcare and education. By drastically reducing download and response times, 5G empowers urban services to address citizens' needs more promptly, resulting in smarter, more agile cities.

The metrics presented in **Figure 1** further demonstrate the transformative advantage of 5G's ultra-low latency for applications that demand immediate responsiveness, such as autonomous vehicles, remote medical procedures, and emergency response operations. The drop from approximately 50 milliseconds in 4G to as little as 1 millisecond in 5G guarantees near-instantaneous action in critical situations, such as adjusting traffic signals or coordinating first responders, where even brief delays can have serious repercussions [21–24]. Equally important, 5G's capacity to support up to one million devices per square kilometer meets the escalating connectivity requirements of densely populated urban settings [25–27]. As the number of IoT devices—from air quality sensors to security cameras—continues to surge, 5G ensures reliable, uninterrupted communication amid the heavy data loads characteristic of smart city environments.

The data visualized in **Figure 1** were derived from projections based on industry benchmarks, technical documentation, and scholarly studies on wireless technologies. The reported values for speed, latency, and device density reflect prevailing trends documented in ITU and 3GPP standards, as well as observed real-world network behavior. Speed figures indicate peak theoretical performance under ideal conditions, while latency measurements represent typical operational delays. Device density statistics underscore progressive improvements in managing network load, particularly through 5G innovations like massive MIMO and network slicing.

Network slicing, a core capability of 5G, adds a powerful dimension of adaptability to smart city networks [28, 29]. By establishing isolated virtual networks tailored to particular use cases or priorities, operators can allocate dedicated resources to mission-critical services—such as public safety and emergency systems—ensuring they receive guaranteed bandwidth and minimal latency [30, 31]. Meanwhile, lower-priority activities, such as leisure streaming or standard environmental sensing, can run on separate slices, optimizing overall resource allocation. This approach maintains consistent high-quality performance across diverse urban domains, from mobility to safety, by shielding essential operations from congestion caused by less time-sensitive traffic [28–31]. Ultimately, 5G network slicing equips smart cities with the flexibility, scalability, and resilience needed to accommodate a wide range of current and future requirements.

Existing applications of 5G in smart cities

The introduction of 5G has significantly enhanced smart cities' capabilities, opening the door to unprecedented levels of connectivity and progress across various domains [9, 32]. Among the most impactful implementations are IoT-based urban monitoring, intelligent transportation systems, and enhanced public safety mechanisms, all of which capitalize on 5G's combination of ultra-low latency, exceptional speed, and massive device support [20, 32]. Before widespread 5G adoption, these systems were constrained by network bottlenecks, restricted device capacity, and delays in real-time information flow [9, 32]. In city-wide IoT deployments, for example, insufficient bandwidth and elevated latency impede rapid data acquisition and processing, reducing the reliability of applications such as waste collection optimization, pollution tracking, and adaptive traffic management. As urban growth and device proliferation intensify, these shortcomings have become more pronounced, resulting in inefficient resource allocation and slower emergency response times. 5G overcomes these barriers by delivering a high-throughput, high-density network with near-instantaneous response times, precisely what real-time smart city functions demand [20, 32].

IoT-driven urban monitoring plays a vital role in enabling smart cities to optimize resource use and improve residents' living conditions. 5G strengthens these IoT ecosystems by supporting vast numbers of devices with minimal latency, allowing continuous, real-time data collection and interpretation across multiple city sectors [18, 20, 30, 31]. Environmental sensors distributed throughout urban spaces, for instance, can continuously measure air quality, noise levels, and water usage, providing actionable intelligence to municipal authorities [33, 34]. Similarly, smart waste management systems employ connected bins that report fill status in real time, enabling optimized routing and reduced collection costs [35, 36]. These examples highlight how 5G empowers evidence-based governance, fostering more sustainable, livable, and efficient urban environments.

However, existing IoT deployments in smart cities encounter several constraints, including network interference, suboptimal data processing, and limited inter-device communication in high-density urban settings [18, 20, 30]. Conventional networks such as 4G often fall short of meeting the rising demand for greater device connectivity and faster data transfer [22–24]. 5G's ability to simultaneously support millions of connected devices while delivering data with near-zero delay markedly enhances the dependability and responsiveness of these IoT ecosystems [34, 35]. By removing bandwidth constraints and enabling true real-time processing, 5G ensures smoother, more effective performance across a wide range of IoT applications—from waste and energy optimization to continuous environmental surveillance.

Figure 2 illustrates the connectivity of IoT devices within a smart city through an urban sensor network. The diagram in **Figure 2** depicts a wireless sensor network (WSN) specifically designed for urban smart-city contexts [32, 33, 36]. These networks comprise interconnected IoT sensor nodes that collaborate to sense, gather, and relay real-time information on

traffic patterns, air quality, energy usage, and structural integrity across diverse urban domains. In smart city environments, such networks are indispensable for delivering adaptive services, promoting efficient resource allocation, and enabling evidence-based municipal decision-making. The structure depicted in **Figure 2** exemplifies the decentralized, self-organizing nature characteristic of WSNs, in which nodes communicate autonomously without relying on a central authority—mirroring the organic integration of IoT devices into city infrastructure. Its graph-based visualization also captures realistic patterns of device interaction, which is vital for both modeling urban connectivity and optimizing network performance.

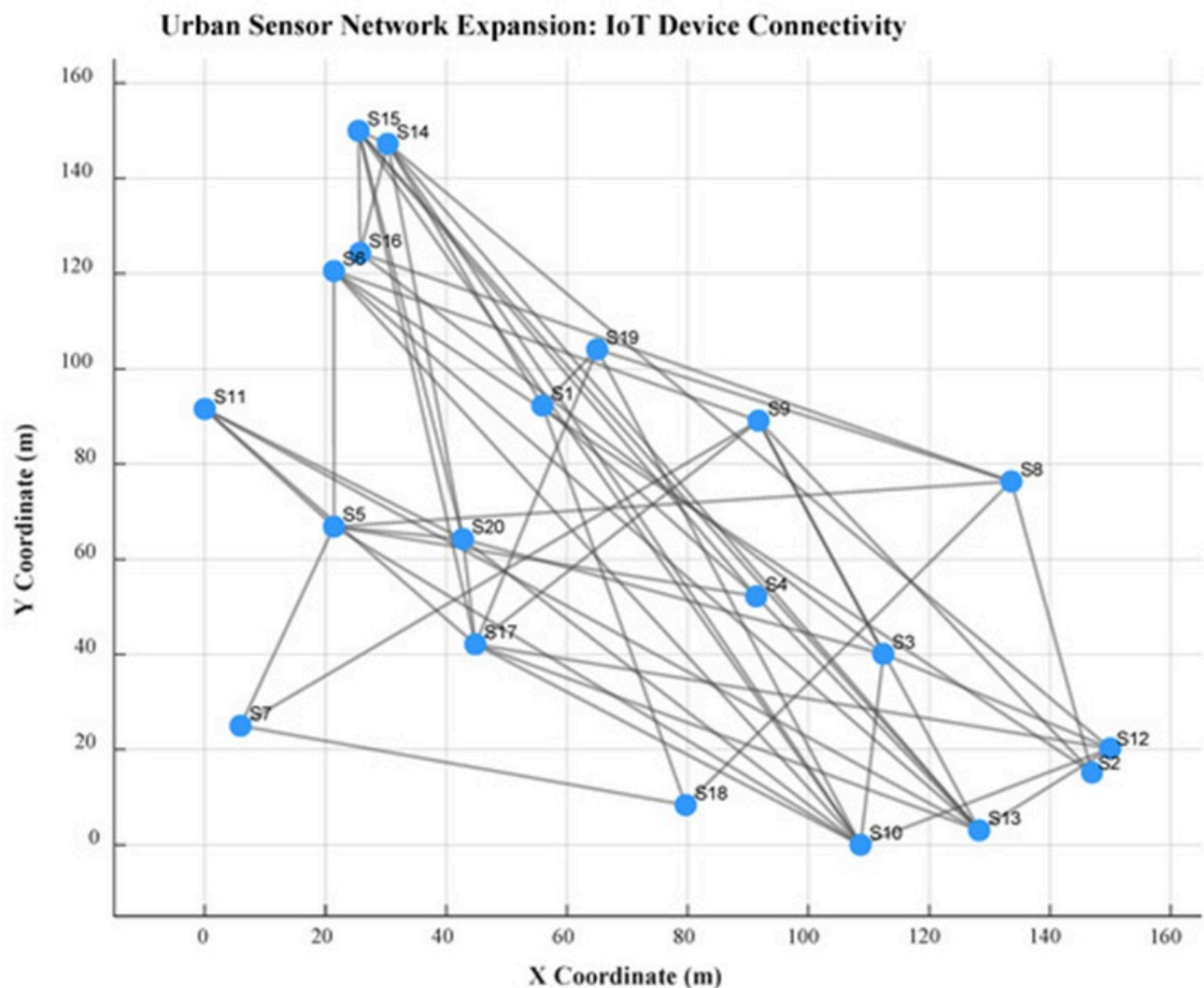


Figure 2. 5G IoT device connectivity: urban sensor network expansion [32, 33, 36].

To model this network, a computational simulation was developed based on a probabilistic graph model that emulates realistic link formation among IoT devices. The network simulation randomly distributed 20 sensor nodes across a defined two-dimensional space, assigning each node distinct X and Y coordinates to represent realistic spatial placement.

Connectivity among the sensors was determined probabilistically, with each pair of nodes having a 30% likelihood of establishing a direct link. This approach accounts for the inherent uncertainties and variability of wireless connections in urban settings, where factors such as physical barriers, signal interference, and limited transmission range influence link reliability. The resulting connectivity information was recorded in an adjacency matrix—a standard mathematical representation indicating direct connections between nodes. This matrix served as the basis for constructing an

undirected graph that visualizes the communication topology. The resulting visualization not only displays the geographic distribution of sensor nodes but also offers clear insight into the self-organizing behavior and real-time interaction capabilities of urban IoT networks. IoT devices within such networks integrate seamlessly to monitor and manage city operations in real time [20, 32, 33]. This connectivity forms the essential backbone of digital twins, enabling accurate virtual replicas of urban infrastructure and processes by providing precise, up-to-the-minute data from physical sensors [32–35]. The widespread adoption of 5G further strengthens this framework through its ultra-low latency and high-bandwidth communication, ensuring swift and reliable data exchange between sensors and processing platforms [33, 35]. Together, the synergy of IoT, digital twins, and 5G drives smarter resource allocation, predictive maintenance, and improved quality of life in urban areas, highlighting their combined role in shaping the next generation of smart cities [32, 33, 35].

Before the introduction of 5G, digital twins and real-time modeling systems often suffered from delays and data discrepancies due to slower network performance and limited communication bandwidth. These issues compromised the precision and immediacy of simulations, hindering effective forecasting of urban patterns and behaviors. 5G's high-speed data transmission capabilities enable seamless aggregation of inputs from diverse IoT sensors into digital twin frameworks, resulting in more precise and up-to-date predictions of city dynamics. Coupled with 5G's ultra-low latency, these timely predictions support near-instantaneous decision-making, ultimately raising the quality of life for urban residents.

Real-time environmental monitoring within smart city infrastructure is depicted in **Figure 3** through a 5G-powered network of interconnected IoT sensors [33, 37–39]. Individual nodes correspond to sensors capturing measurements such as air quality, temperature, or traffic volume [33, 37]. The connecting edges represent robust, low-latency 5G communication links that ensure continuous and reliable data exchange [37–39]. A heatmap overlay emphasizes spatial variations in environmental parameters, enabling dynamic, insight-driven analysis [38, 39]. This visualization aligns closely with digital twin principles by offering a virtual representation of urban spaces, supporting predictive modeling and efficient municipal management [9, 13, 38]. By leveraging 5G, the architecture delivers scalable, trustworthy, and high-throughput data flows, guaranteeing consistent real-time operation across smart city applications [33, 37–39].

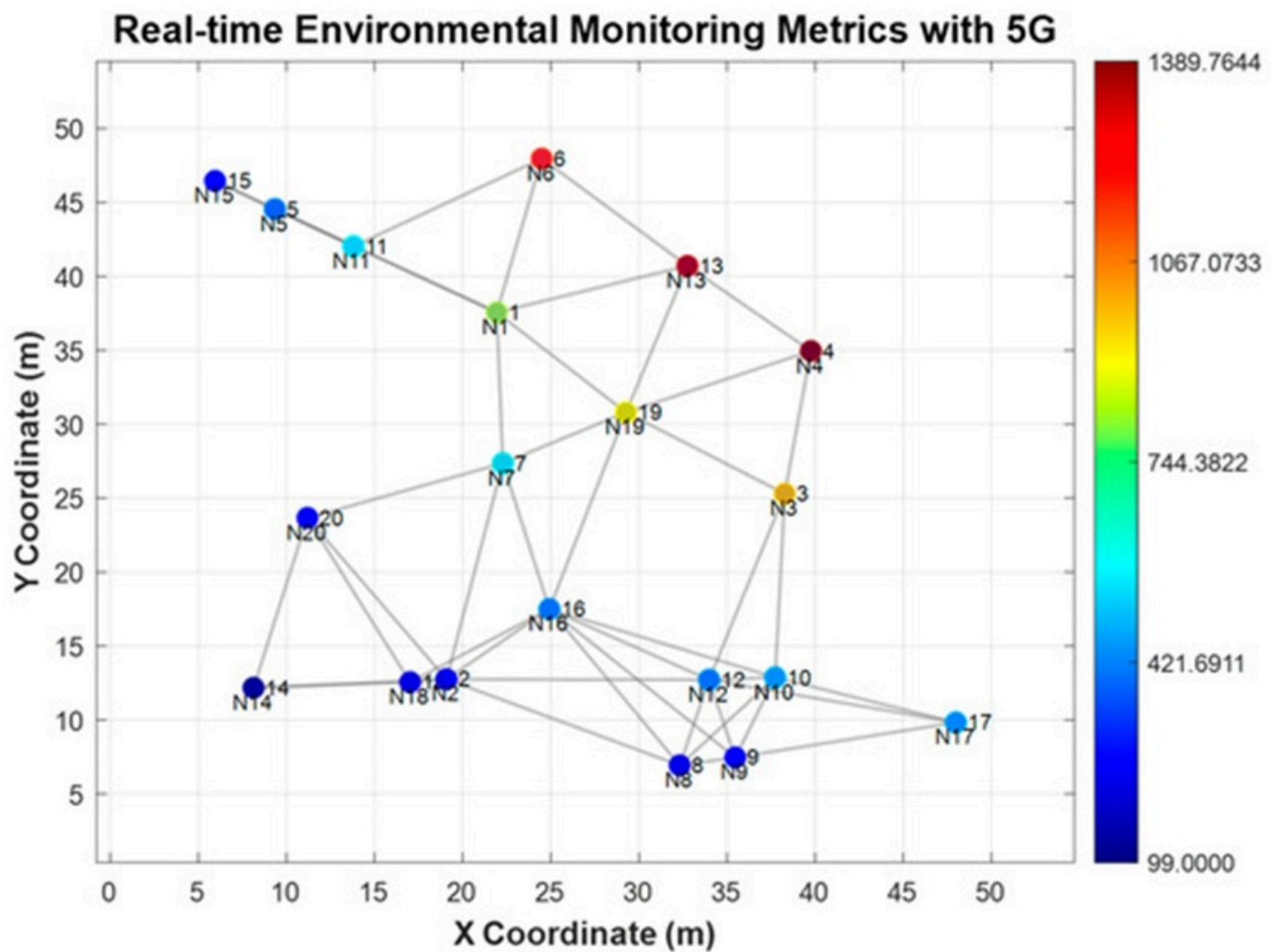


Figure 3. Real-time environmental monitoring metrics with 5G [33, 37-39].

Figure 3 was created using a MATLAB R2024b simulation that emulates the behavior of a 5G-supported wireless sensor network in an urban setting. The model includes 20 IoT sensor nodes randomly positioned within a 50 × 50 unit grid to replicate the irregular placement typical of actual smart city deployments. Node-to-node connections are formed according to a distance-based criterion: any two sensors separated by 15 units or less are linked, reflecting the dependable coverage range characteristic of 5G signals. This rule highlights 5G's ultra-reliable low-latency strengths, especially in high-density city districts. The network topology is represented as an undirected graph derived from an adjacency matrix that records all direct pairwise links and determines the overall layout. The superimposed heatmap is generated from node coordinates and illustrates gradients in environmental variables—such as pollutant concentrations or temperature differences—converting raw positional data into visually accessible, actionable information. Beyond mapping physical node distribution and connectivity, this graphic demonstrates the network's capacity to enable real-time, geographically aware environmental intelligence, a cornerstone of informed smart city governance.

In the past, smart city environmental monitoring initiatives struggled to handle massive datasets from heterogeneous sources, leading to sluggish reporting and delayed responses. Legacy networks frequently proved inadequate to meet the rapid, continuous demands of environmental surveillance, particularly in densely populated areas experiencing high data loads. 5G's proficiency in managing high-volume traffic without introducing delays allows for genuine real-time observation of environmental conditions, empowering cities to react promptly to events such as air pollution surges, traffic bottlenecks, and other pressing urban issues [33, 37, 38]. This capability equips decision-makers with the resources needed for more effective resource stewardship and quicker mitigation of environmental threats.

In the domain of smart transportation, 5G plays a pivotal role in advancing autonomous vehicles and next-generation traffic management solutions [40–42]. The ultra-reliable low-latency communication (URLLC) feature of 5G guarantees instantaneous, dependable exchange of vital data among vehicles, roadside infrastructure, and centralized control platforms [43, 44]. Such robust connectivity is indispensable for boosting road safety and optimizing flow in congested areas [40, 41]. 5G-enabled intelligent traffic systems process live traffic data to adaptively modify signal timings, thereby reducing congestion and enhancing overall system performance [40–42]. Several South African cities—including Cape Town, eThekweni, Tshwane, and Johannesburg—are actively investigating these innovations and the broader transformative impact of 5G on urban environments [45, 46]. These forward-thinking municipalities employ digital tools to increase operational efficiency, conserve resources, and lower carbon emissions, contributing to worldwide sustainability objectives.

Before the emergence of 5G, smart transportation systems faced significant obstacles in processing the enormous volumes of data generated by connected vehicles, intelligent traffic signals, and roadway infrastructure [40–42]. Legacy networks, constrained by lower bandwidth and greater latency, were unable to support instantaneous interactions among these components, resulting in delayed reactions and less reliable traffic forecasting [43, 44]. The deployment of 5G overcomes these shortcomings by enabling seamless, real-time information exchange among autonomous vehicles, traffic control platforms, and supporting infrastructure [42–44]. This advancement markedly improves transportation safety and operational efficiency, leading to reduced congestion, smoother traffic flow, and enhanced overall road safety.

Figure 4 illustrates the substantial contribution of 5G technology to elevating traffic management performance at urban intersections in smart cities [40, 42, 43]. Leveraging ultra-low-latency links and dramatically increased data throughput, 5G facilitates immediate data interchange among connected infrastructure elements, vehicles, and centralized traffic management centers [43, 44]. These improvements enhance the fidelity of digital twins—virtual models of urban traffic environments—by providing continuously updated inputs for accurate simulations, predictive analytics, and informed decision processes [40–42]. The gains in efficiency shown in **Figure 4** underscore 5G's pivotal role in optimizing traffic patterns, alleviating congestion, and promoting environmentally sustainable urban mobility, all of which closely align with broader smart city goals of improving system performance and elevating residents' quality of life.

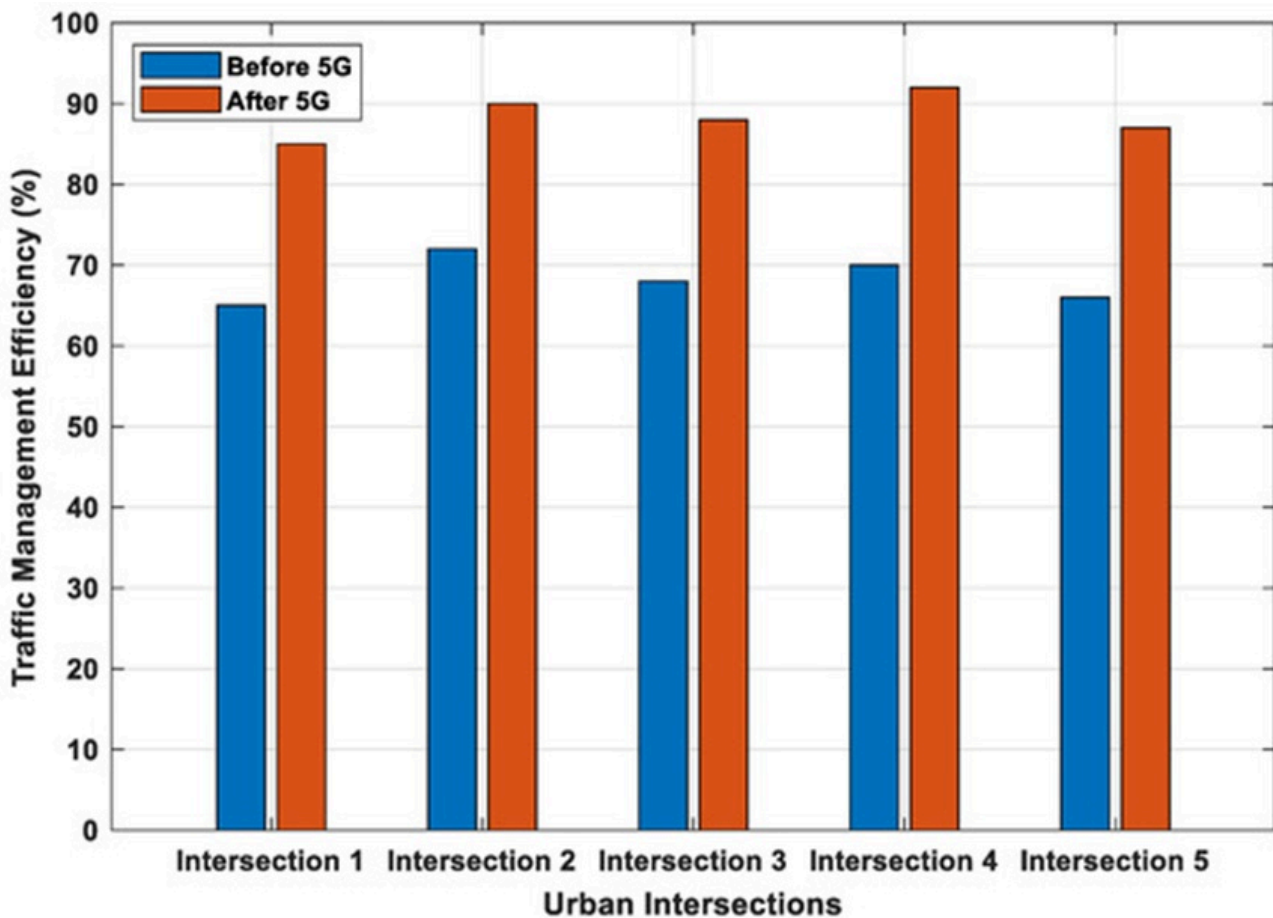


Figure 4. 5G impact on traffic management efficiency [40, 42, 43].

Figure 5 highlights the critical reductions in communication latency among self-driving vehicles that are essential for dependable and effective vehicle-to-vehicle (V2V) interactions in smart city settings [42, 47-49]. **Figure 5** was produced through a MATLAB-based simulation that evaluates latency characteristics across a fleet of autonomous vehicles. In the model, each vehicle receives a distinct identifier, and pairwise communication latencies are captured in a symmetric matrix, with lower values indicating quicker, more responsive links. A heatmap of these latency values provides an intuitive depiction of the distribution of connection quality across the network. This presentation not only emphasizes the imperative for low-latency channels for coordinating autonomous vehicles but also accounts for realistic performance variability driven by environmental and situational factors. By illustrating these disparities, the figure underscores the need for resilient, high-speed, and consistent V2V communication frameworks, especially in complex, ever-changing urban landscapes. The application of a clear professional colormap and appropriately scaled axes improves readability. Overall, **Figure 5** demonstrates how 5G can substantially reduce transmission delays, thereby enabling the secure, synchronized operation of autonomous vehicle ecosystems in smart cities.

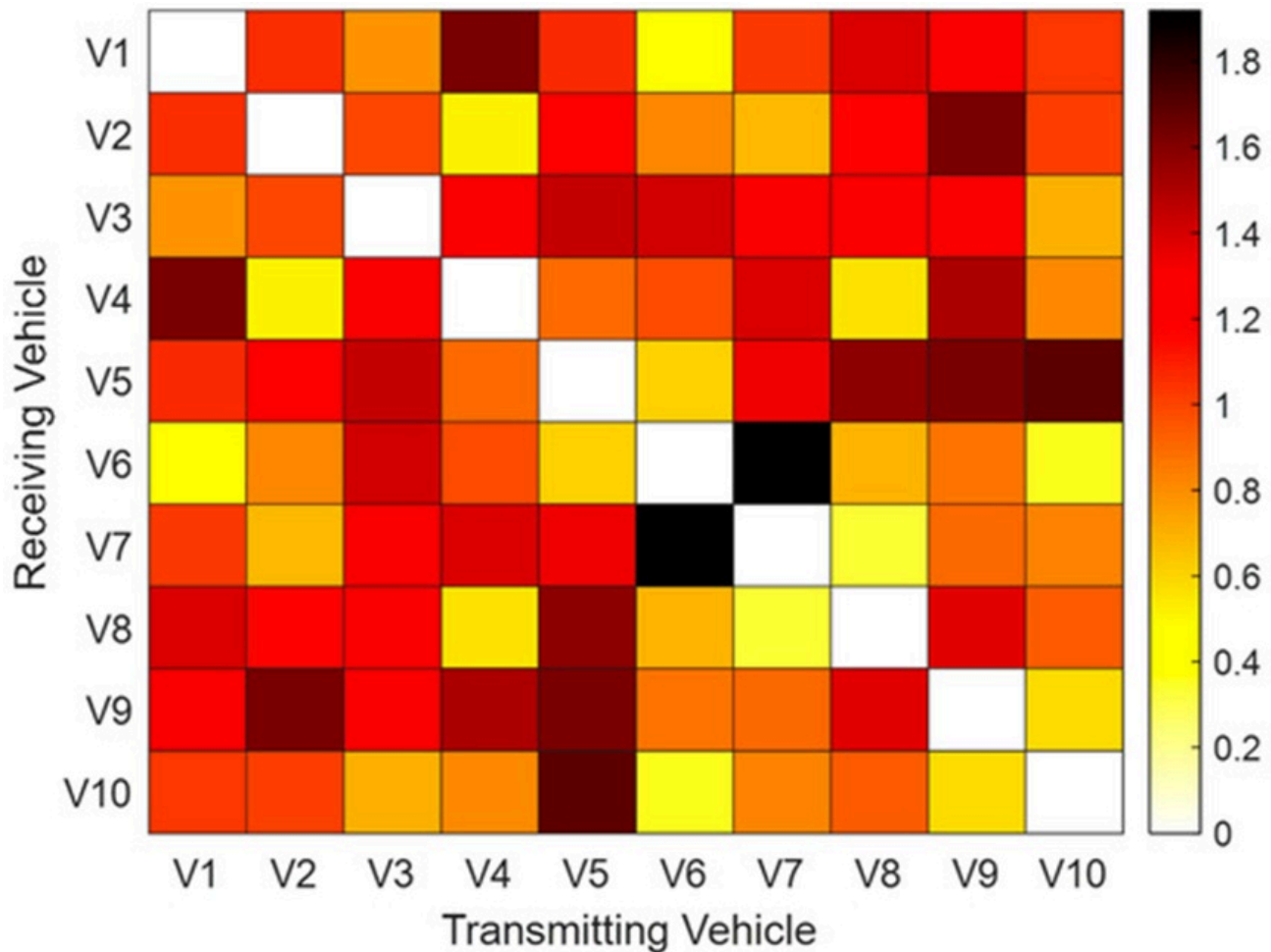


Figure 5. Self-driving vehicle communication latency improvements [42, 47-49].

Through the adoption of 5G, these latency reductions support instantaneous communication required for effective coordination of autonomous vehicles [42, 47, 49]. This capability integrates closely with digital twin methodologies, in which virtual representations of urban elements—including vehicles—continuously incorporate live data streams to refine decision-making processes, optimize traffic management, and enhance overall safety [47, 49]. The figure emphasizes the vital role of advanced communication infrastructure in successfully integrating autonomous mobility solutions into comprehensive smart city architectures.

Public safety frameworks benefit enormously from 5G-supported innovations, which significantly expand their ability to manage crises and mitigate hazards [50, 51]. 5G makes possible the deployment of cutting-edge surveillance platforms featuring AI-powered video analytics capable of detecting irregularities or potential threats in real time [52, 53]. Emergency response teams likewise rely on 5G to maintain robust, dependable communication channels, enabling faster mobilization and more effective coordination in critical incidents [50-52]. Wearable devices for frontline personnel—such as vital sign monitors and real-time location trackers—operate reliably over 5G networks, supplying essential data during operations and rescue efforts [52, 53]. When these components are interconnected, they collectively bolster the security and resilience of urban areas, fostering greater confidence and well-being among the population.

A 5G-supported emergency response communication framework is presented in **Figure 6**, highlighting the fluid interconnection among IoT devices, 5G base stations, and a central command center [20, 51-53]. Dashed lines indicate communication pathways from IoT devices to base stations for continuous real-time data acquisition. Solid lines represent the connections from base stations to the central hub for unified data processing and strategic decision support. To

enhance visual understanding and practical context, the background for **Figure 6** was developed in MATLAB to emulate a believable 5G-enabled emergency communication setting. In this depiction, various IoT devices—representing emergency personnel, first responders, and intelligent sensors—are randomly distributed across a simulated urban area. These devices are computationally linked to the closest 5G base stations, which act as relay points to deliver high-speed, ultra-low-latency data transfer. The base stations subsequently establish dedicated connections to a centralized command hub that collects, processes, and interprets aggregated information. This layout and connectivity pattern accurately mirror the operational dynamics of such networks in actual smart-city emergency scenarios.

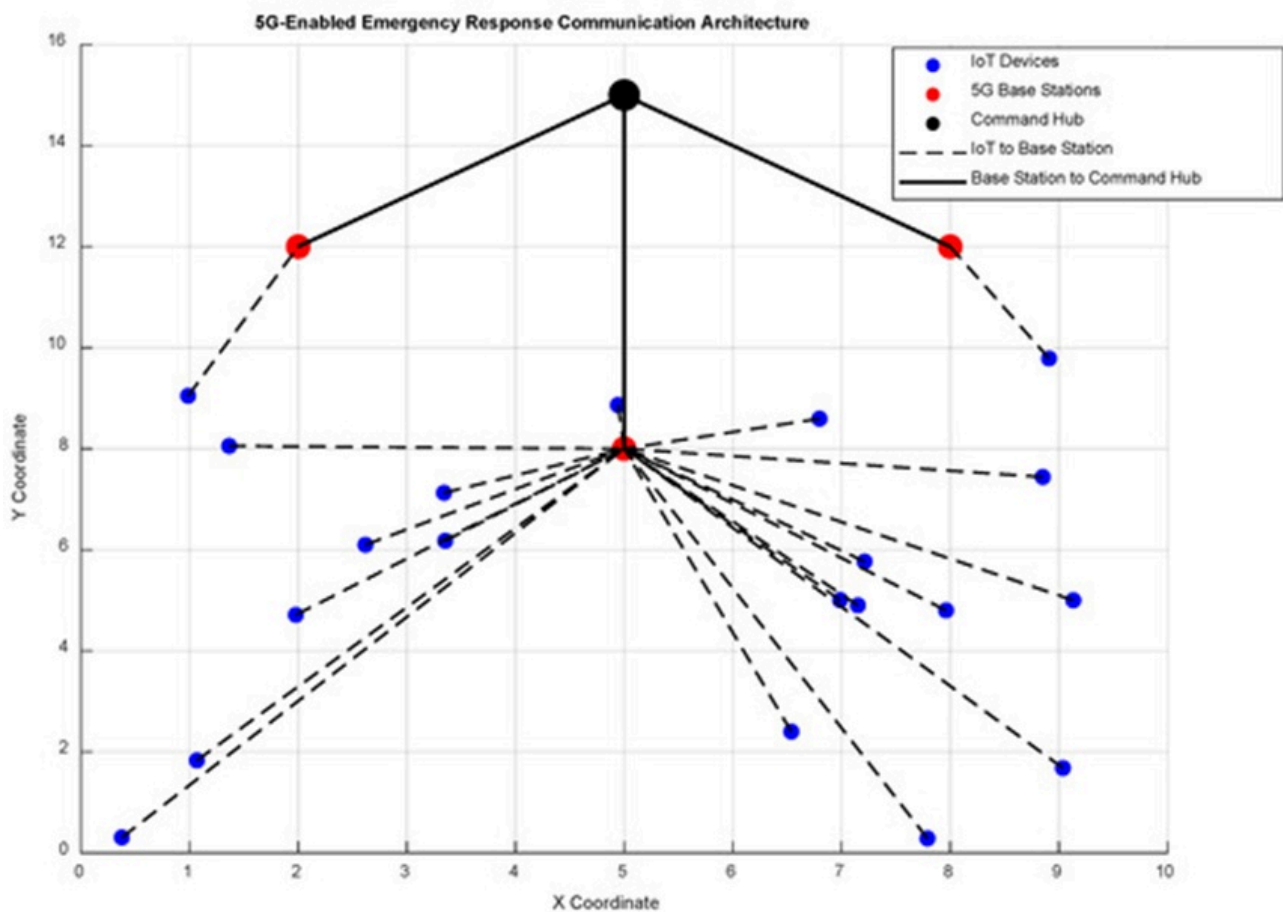


Figure 6. 5G-enabled emergency response communication architecture [20, 51-53].

The color-coded nodes, plotted links, and deliberate positioning of network elements are intended to convey the system's effectiveness and swiftness during crises. By illustrating the coordinated flow from data sensing and transmission to centralized command and control, **Figure 6** emphasizes the framework's capacity to support resilient, expandable emergency management solutions. This design supports the broader goals of smart cities, where digital twins utilize similar infrastructures to perform predictive modeling and streamline emergency operations. The strong synergy between IoT and 5G technologies enhances real-time awareness and accelerates response times, underscoring their critical role in enhancing urban resilience and public safety [20, 51].

Figure 7 displays the interplay between latency and key performance indicators for AI-based surveillance, including accuracy and bandwidth usage, revealing important trade-offs within 5G networks [51-53]. As latency decreases, both accuracy and bandwidth utilization improve markedly, illustrating 5G's ability to deliver superior real-time performance and resource efficiency [20, 51]. The graph in **Figure 7** was produced in MATLAB as part of an analysis of AI surveillance metrics under varying 5G network parameters. The plotted data points were synthetically defined rather than extracted

from actual field measurements, with the main goal of demonstrating anticipated behavioral patterns in AI systems across different latency levels. The visualized metrics are accuracy (expressed as a %) and bandwidth utilization (expressed as a %), both plotted against latency (in milliseconds). The chosen values follow a trend-oriented model in which accuracy rises as latency increases—possibly reflecting greater processing opportunities—while bandwidth utilization also climbs, likely due to the ability to accommodate larger data volumes under higher latency. These patterns are consistent with recognized dynamics in networked AI environments, where latency frequently governs the balance between processing quality and resource demands. Although not based on empirical observations, the synthetic dataset was carefully crafted to represent realistic system responses, making it suitable for illustrative and conceptual purposes. This method yields a straightforward visualization of performance relationships, aiding a clearer comprehension of how AI surveillance platforms interact with 5G latency characteristics. Real-time AI surveillance applications depend on high accuracy and uninterrupted data flow to accurately represent, track, and anticipate urban processes [51, 52]. The integration of low-latency 5G networks substantially refines these AI capabilities, paving the way for more intelligent and adaptive urban systems. Incorporating 5G into these solutions enables smart cities to achieve higher standards of operational efficiency, environmental sustainability, and overall safety.

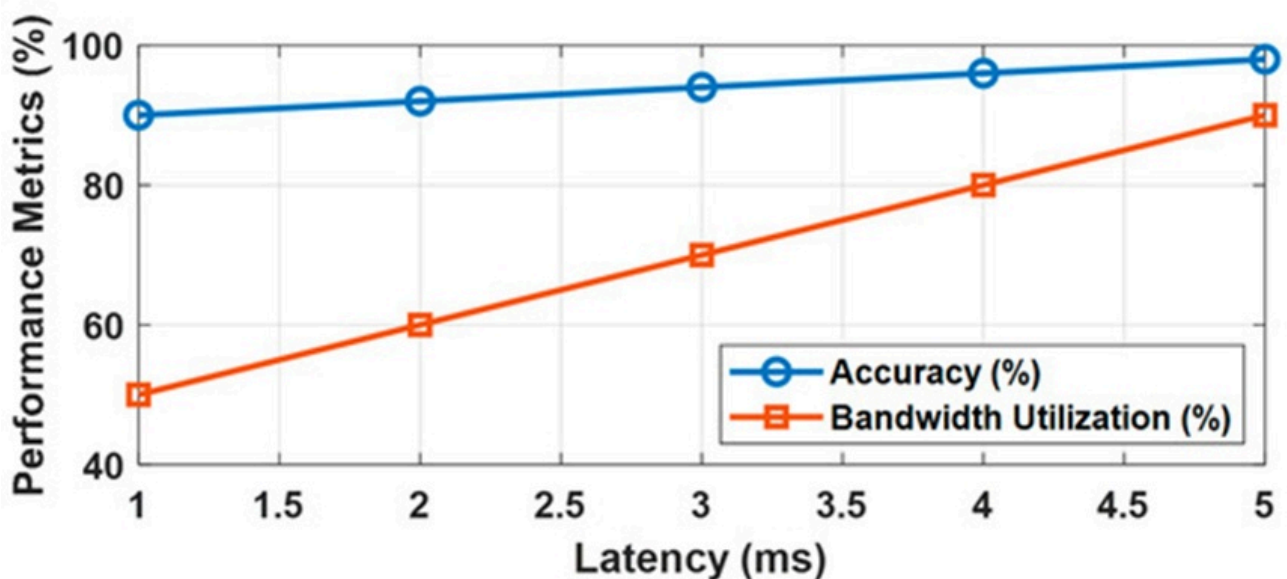


Figure 7. AI surveillance performance metrics with 5G networks.

Limitations of applications of 5G in smart cities

Although 5G technology offers remarkable opportunities to advance smart cities, its practical deployment is hampered by several significant obstacles. One of the primary barriers is the high cost associated with building the required infrastructure [33, 54]. Establishing the dense array of small-cell towers required to transmit 5G's high-frequency signals requires substantial capital investment [54, 55]. These costs extend beyond initial hardware installation to include ongoing maintenance, upgrades, and operational expenses. Such financial demands pose particular difficulties for resource-limited municipalities, especially in developing regions, where funding for 5G initiatives must compete with other pressing urban priorities [33, 54, 55].

Another important limitation is the limited range and coverage of 5G signals. Unlike previous generations, 5G predominantly operates in millimeter-wave bands, which deliver exceptional data rates but suffer from rapid signal attenuation over distance and from penetration issues through obstacles such as buildings, foliage, and other structures [10, 15, 36]. This characteristic creates particular difficulties in densely built urban environments, where dense

construction can block signals and necessitate the deployment of additional base stations to ensure consistent coverage [18, 32, 38]. In practice, achieving reliable, city-wide 5G connectivity often proves both technically demanding and financially burdensome [10, 36].

The energy consumption of 5G networks represents a further notable constraint. The increased density of base stations, combined with the higher power required to process large data volumes, can lead to substantially greater energy consumption than in 4G systems [11, 20, 56]. This conflicts with the sustainability goals central to smart city initiatives, which aim to reduce environmental footprints. Without the adoption of energy-efficient innovations, the widespread rollout of 5G risks exacerbating urban energy challenges [36, 38]. Ongoing research explores solutions such as renewable energy sources and advanced power management techniques, though their broad application remains under development [56, 57].

Data privacy and cybersecurity risks also hinder the widespread adoption of 5G in smart city contexts. The proliferation of connected devices and systems generates enormous quantities of sensitive information [15, 19, 20]. While 5G's ultra-low latency and high throughput support real-time data handling, these same attributes also increase the potential for cyberattacks [13, 14]. Securing such a vast, dynamic network environment demands advanced encryption methods and comprehensive cybersecurity frameworks, both of which are resource-intensive and complex to implement effectively [36, 51].

A lack of interoperability and uniform standards across smart city platforms further impedes the optimal utilization of 5G. Different vendors and providers often rely on proprietary solutions, resulting in compatibility issues [13, 14]. Integrating systems such as intelligent transportation with environmental monitoring may require extensive customization due to incompatible protocols [19, 20]. This fragmentation complicates the realization of cohesive, city-scale smart solutions and limits their potential for expansion and scalability.

Although 5G holds transformative promise for smart cities, the limitations outlined above—and summarized in **Table 1**—present substantial hurdles to its effective rollout. These issues, which include security vulnerabilities, interoperability barriers, and the intricacies of large-scale urban deployment, are examined in greater detail in the following section.

Table 1. Summary of the limitations in 5G deployment for smart cities and proposed mitigations.

Limitation	Description	Implications	Current solutions
High infrastructure costs	5G deployment demands a dense and expensive infrastructure.	Limits expansion in budget-constrained regions.	Shared investment models and phased infrastructure deployment.
	Continuous maintenance is necessary.	Delays the completion of full 5G coverage.	Development of cost-efficient hardware solutions.
Limited coverage	5G signals have a short range and can be easily obstructed.	Requires many base stations for comprehensive city coverage.	Utilization of smart antennas and hybrid network models.
	Maintaining consistent city-wide coverage is challenging.	Leads to reduced network reliability.	AI-based signal optimization techniques.
High energy use	An increase in the number of base stations and data traffic increases energy consumption.	Increases operational costs and environmental impact.	Energy-efficient hardware and integration of renewable energy.
	Conflicts to create green cities.	Affects the sustainability of the network.	Testing of sleep modes and smart grid systems.

Security and privacy risks	The rise of connected devices and real-time data increases vulnerability to cyberattacks.	Poses risks to privacy and security.	Encryption protocols and secure 5G infrastructures.
	Sensitive data requires better safeguarding.	High costs associated with securing infrastructure.	Use of blockchain technology and intrusion detection systems.
Interoperability concerns	Devices and platforms often follow different standards.	Makes system integration difficult.	Adoption of open standards and standardized APIs.
	Vendors often implement proprietary protocols.	Increases the need for customized solutions and limits scalability.	Cross-vendor frameworks are under development.
Regulatory and policy barriers	Local regulations and spectrum policies often limit deployment.	Slows down infrastructure development.	Policy alignment and regulatory reforms are in progress.
	Health concerns may cause public resistance.	It can hinder the installation of necessary base stations.	Awareness campaigns and safety evaluations.
Device readiness	Older devices do not support 5G connectivity.	Upgrading or replacing devices can be expensive.	Introduction of backward-compatible updates.
	There are a few universal standards for devices.	Slows the integration of smart city technologies.	Industry-wide push for standardization.
Digital divide and accessibility	High costs and limited rollout may exclude underprivileged areas.	Exacerbates inequality in access to smart city benefits.	Implementation of subsidies and inclusive policy measures.
	Coverage often prioritizes wealthy or commercial zones.	Worsens the technological accessibility gap.	Adoption of community-led deployment strategies.

Emerging Challenges in Smart City Deployments

Building on the constraints discussed in the preceding section, this part examines the wider emerging obstacles that affect the effective rollout of smart city technologies. While smart city solutions offer groundbreaking approaches to urban governance, their successful and widespread adoption faces multiple hurdles. A primary issue is scalability, particularly in densely populated metropolitan regions where IoT networks connect millions of devices [10, 36, 51]. As the volume of connected devices continues to grow, the underlying network infrastructure often struggles to maintain consistent reliability and minimal latency, leading to congestion that impairs real-time analytical and decision-making processes [32, 33, 35, 36].

Songdo, South Korea, serves as a prominent example of a smart city that has successfully addressed the scalability issues inherent in large-scale IoT deployments [58, 59]. The city integrates millions of interconnected devices, placing considerable demands on network capacity to ensure seamless data exchange and instantaneous operational responses. Songdo's infrastructure is engineered to aggregate and process information from diverse sources—including intelligent buildings, mobility systems, and environmental monitoring stations—through a resilient IoT backbone [58, 59]. A cornerstone of Songdo's strategy to overcome scalability limitations is the adoption of cooperative communication

protocols spanning multiple stakeholder networks [58, 59]. By deploying techniques such as distributed multi-user detection, the city has substantially increased network robustness, reducing congestion and bottlenecks commonly encountered in high-density urban zones. This approach ensures fluid data flow even during peak usage periods. Songdo further employs adaptive load balancing mechanisms that dynamically allocate network resources based on current demand, thereby preserving low latency and high service availability across its IoT ecosystem [58, 59]. These measures strengthen Songdo's ability to accommodate a vast range of devices and services within its smart city framework, demonstrating practical ways to achieve effective scalability in heavily populated urban contexts. Consequently, maintaining reliable connectivity in expansive IoT deployments requires substantial enhancements to the physical infrastructure and strategic resource allocation [33, 35, 36].

The allocation of 5G infrastructure expenditures across major urban sectors in digital-twin-enabled smart cities is illustrated in **Figure 8**. The Residential sector accounts for the largest share at 35%, followed by the commercial sector at 25% and the Transport sector at 15%, underscoring the emphasis on residential connectivity and essential digital services. Smaller proportions are directed toward healthcare (10%), Education (8%), and Public Services (7%), indicating a diversified yet balanced investment strategy aimed at improving overall urban performance and advancing smart city priorities. The figures presented in this visualization are derived from a plausible approximation model rather than verified empirical data, with the intent of highlighting the principal areas of investment focus. For more accurate distributions, validation against current industry analyses and economic assessments would be required. Key influencing variables—such as population density, connectivity requirements, and sector-specific digitalization targets—should be factored in to improve precision [60–62]. Variations are likely to arise from differences in regional urban planning strategies and varying paces of technological uptake. **Figure 8** provides a conceptual overview of how 5G infrastructure investments are distributed across urban sectors within the framework of digital twins and smart cities [33, 60, 63, 64]. Its main purpose is to convey the relative significance of each sector in 5G implementation rather than to provide a precise budgetary breakdown.

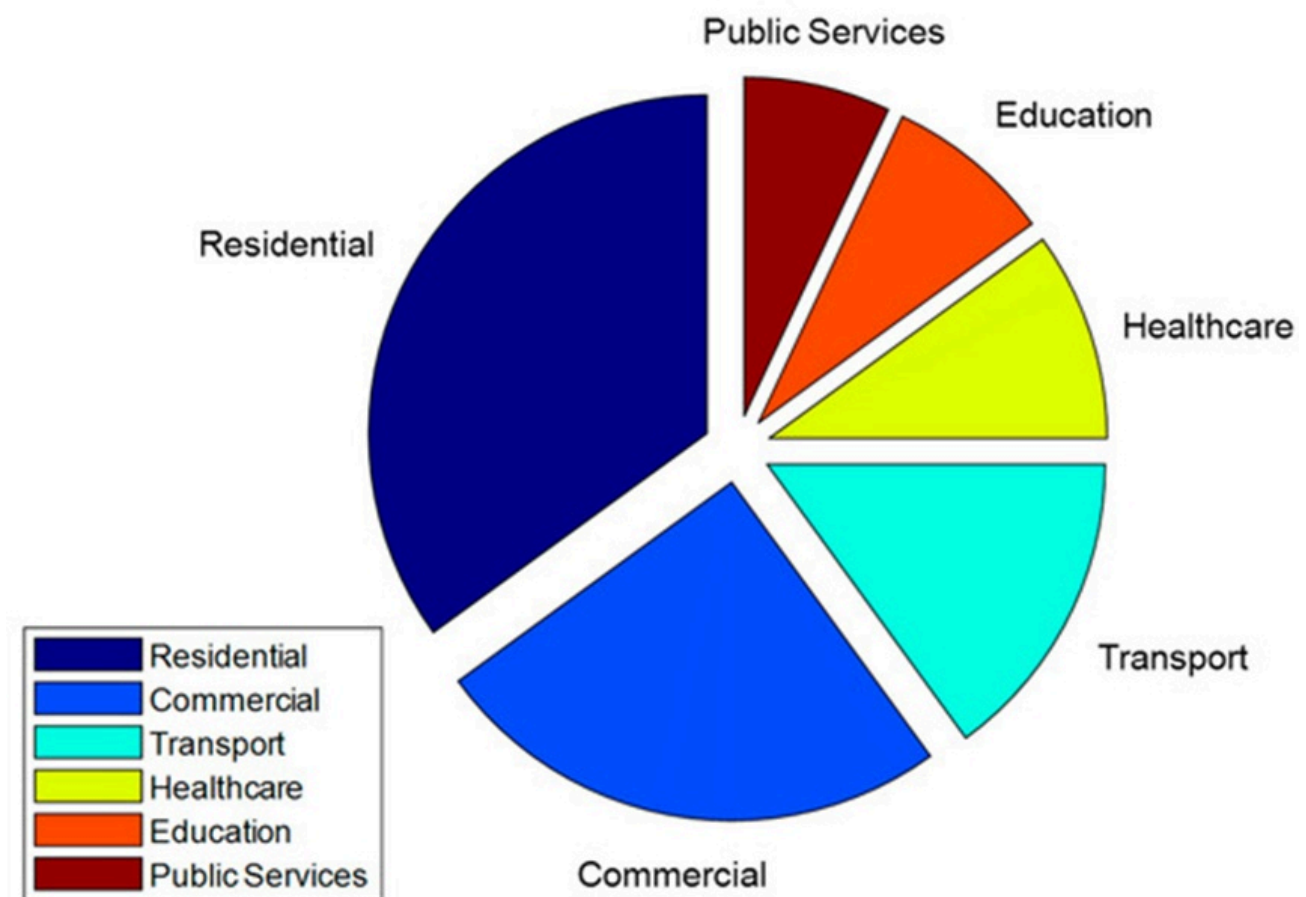


Figure 8. 5G infrastructure cost distribution across urban sectors [33, 60, 63, 64].

Smart city systems, especially those reliant on 5G networks, demand considerable electrical power to run base stations, edge computing nodes, and end-user devices [36, 55]. With growing emphasis on environmental sustainability, achieving energy-efficient network performance has become a critical priority [38, 51]. Research shows that, despite delivering superior speeds and greater capacity, 5G deployment is associated with notably higher energy consumption compared to previous wireless generations [36, 54, 55].

Dubai, located in the United Arab Emirates, has taken a leading role in embedding sustainable practices within its 5G network architecture, directly confronting the substantial energy consumption associated with these next-generation systems [65, 66]. As 5G networks expand to deliver faster data rates and more reliable connectivity, the resulting surge in power requirements becomes a pressing issue [36, 54, 55]. In response, Dubai has proactively integrated renewable energy sources—particularly solar power—into its 5G operations [65, 66]. The city has implemented arrangements in which solar panels supply electricity to a large number of 5G base stations and edge computing units, significantly reducing the network's overall carbon emissions [65, 66]. This integration not only reduces the ecological impact of 5G deployment but also promotes more sustainable, resource-efficient network performance. Dubai has further explored adaptive energy management systems that adjust power usage in response to fluctuating network loads, achieving notable reductions in consumption during periods of lower demand [65, 66]. These measures align closely with Dubai's overarching vision of ranking among the world's most sustainable urban centers while preserving the superior connectivity levels required for a fully functional smart city [65, 66]. The city's approach to energy-conscious 5G rollout offers a valuable model for other municipalities seeking to balance technological advancement with environmental responsibility.

Solutions such as dynamic power allocation and the incorporation of renewable energy sources continue to be researched and refined. Yet, they require further development and wider implementation to reach full maturity [19, 51, 54]. **Figure 9** compares the energy consumption profiles of 4G and 5G network deployments across different sectors in urban digital-twin smart cities. Although 5G provides markedly improved data throughput and connectivity, its power usage exceeds that of 4G in residential, commercial, industrial, and public domains [10, 28, 57, 67]. This disparity stems primarily from the denser infrastructure required by 5G, including more base stations and edge computing resources [57, 67]. These findings highlight the urgent need for energy-optimized strategies—such as intelligent power management and the adoption of renewable energy—to address the sustainability drawbacks inherent in 5G networks.

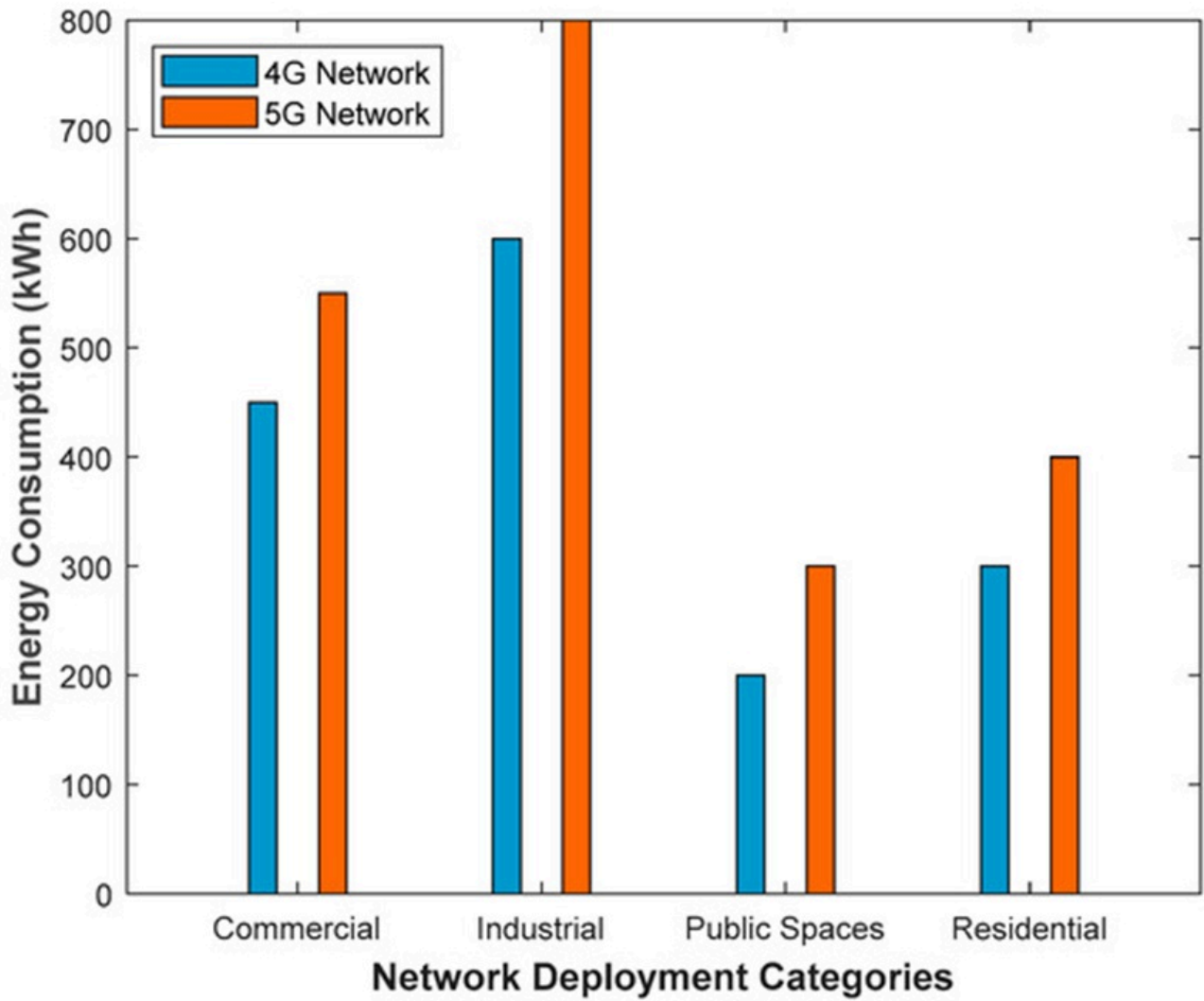


Figure 9. Energy consumption comparison: 4G vs. 5G network deployment [10, 28, 57, 67].

Data privacy and cybersecurity represent major hurdles in the functioning of smart cities [37, 51]. The extensive rollout of sensors and data-intensive applications generates vast quantities of sensitive information, encompassing personal details, behavioral patterns, and environmental readings. Ensuring the secure collection, storage, and handling of this data is essential to maintaining public confidence [19, 36]. However, documented cyberattacks targeting IoT endpoints and critical urban systems have exposed vulnerabilities in current protections [19, 36, 37]. Establishing robust encryption protocols, secure authentication mechanisms, and comprehensive threat detection frameworks is indispensable for mitigating these dangers [36, 37].

Economic and societal barriers further complicate the advancement of smart city initiatives. Implementing 5G-enabled smart solutions entails significant upfront capital expenditure on infrastructure, which can be prohibitive for municipalities in less developed regions. The digital divide exacerbates existing disparities, as lower-income populations may have limited or no access to the benefits of smart city innovations. Policymakers and urban planners must therefore prioritize inclusive approaches that ensure equitable participation and help narrow social gaps. By adopting scalable, energy-efficient technologies, strengthening cybersecurity measures, and enhancing system interoperability, smart cities can effectively navigate these obstacles and unlock their full transformative potential.

Integrating 5G with Real-Time Digital Twins

The core idea behind digital twins is to create a living, virtual counterpart of a physical entity that maintains ongoing alignment between the virtual model and its real-world counterpart [9–11]. Digital twins are constructed from continuous streams of data gathered from sensors, IoT endpoints, and other inputs, enabling them to accurately reflect current physical states in near-instantaneous time [36, 68]. By applying sophisticated analytics, modeling techniques, and artificial intelligence, digital twins deliver deep visibility into operational dynamics, forecast upcoming conditions, and support performance optimization. This approach has gained widespread use across diverse sectors—including manufacturing, healthcare, and city planning—where it strengthens strategic decision-making, boosts operational effectiveness, and reduces potential risks [10, 11].

Applying real-time digital twins within smart cities centers on virtual models of physical urban assets that have emerged as powerful tools for managing complex environments [9, 10]. These virtual constructs deliver a live, up-to-the-minute view of city components, empowering planners and decision-makers to evaluate system performance, anticipate issues, and test hypothetical scenarios to guide evidence-based actions [9, 67]. For example, a digital twin of a municipal water supply network might track live metrics such as pressure levels, usage rates, and signs of leaks. Upon detecting a pressure drop in a specific zone, the system can notify personnel of potential leaks and suggest proactive repairs, thereby reducing service interruptions and controlling costs.

The effectiveness of digital twins depends heavily on their ability to ingest and analyze massive quantities of live data. This is precisely where 5G becomes indispensable, providing the high-speed, ultra-low-latency, and reliable connectivity required to sustain seamless real-time digital twin operations [10, 37, 62]. In practical terms, 5G enables rapid data transfer from IoT components (such as sensors and actuators) to the digital twin platform—essential for time-sensitive use cases such as automated traffic oversight, immediate emergency response, and smart grid stabilization. For instance, 5G-powered intelligent traffic solutions can dynamically regulate signals based on prevailing conditions and sensor feedback, substantially easing peak-hour congestion and shortening commute times.

The 5G network framework supporting real-time digital twin systems is outlined in **Figure 10**, detailing the primary elements and their linkages. At the heart of this structure is the Core Network (blue), which serves as the principal coordinator, overseeing data flows and interfacing with the Radio Access Network (RAN) (green) to enable wireless connectivity [10, 60, 63]. The Core Network handles vital tasks, including user authentication, security protocols, mobility tracking, and efficient data forwarding, thereby ensuring smooth interoperability among various digital twin services and connected endpoints.

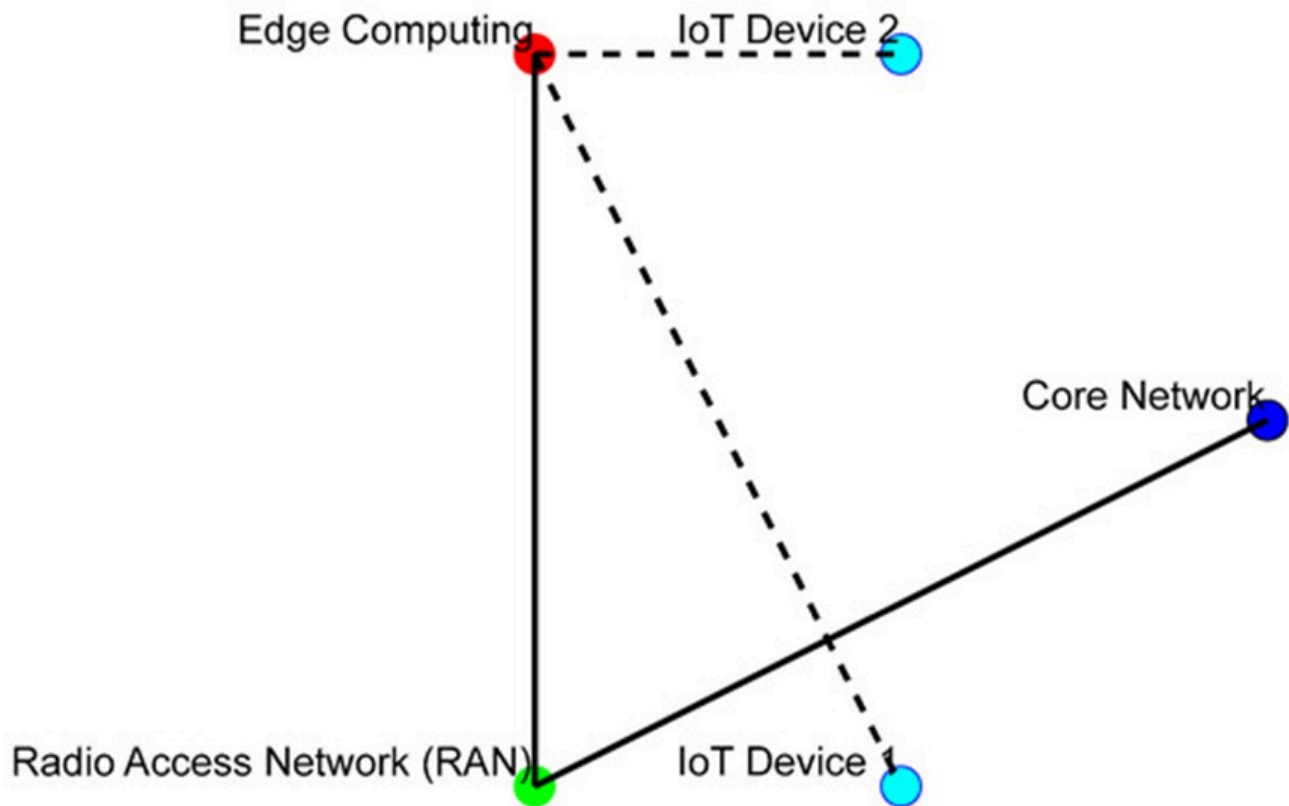


Figure 10. 5G network architecture for real-time digital twin infrastructure [9, 10, 67].

A critical element in this design is Edge Computing (red), deployed in proximity to IoT devices (cyan) to perform immediate data processing with drastically reduced latency. In contrast to conventional centralized cloud models that route all information to distant servers, edge computing executes computations nearer to the data source, minimizing transmission delays. This approach dramatically enhances responsiveness, rendering real-time digital twins exceptionally suitable for scenarios requiring split-second decisions—such as autonomous traffic regulation, crisis intervention, and intelligent energy distribution [10, 37, 60, 63].

Consider a live traffic management application: roadway-embedded sensors and traffic light units continuously capture information on vehicle volumes, pedestrian activity, and ambient conditions. Processing occurs at the edge, where AI-driven logic can promptly reconfigure signals to favor emergency vehicles and maximize roadway capacity, thereby alleviating bottlenecks [9, 10, 37]. In a similar vein, for disaster preparedness, edge computing enables rapid flood detection by analyzing real-time water sensor readings and issuing timely warnings to authorities, helping prevent extensive damage.

The network linkages illustrated in Figure 10 are differentiated by solid and dashed lines to denote distinct categories of data interaction. Solid lines indicate stable, direct pathways connecting the Core Network, RAN, and Edge Computing layers, underscoring the dependable backbone of 5G that supports high-throughput, ultra-low-latency traffic. Dashed lines illustrate the continuous, bidirectional real-time data streams flowing between Edge Computing nodes and IoT devices. This bidirectional capability is indispensable for systems that depend on ongoing feedback mechanisms, such as predictive equipment maintenance in intelligent manufacturing facilities or live urban air-quality surveillance.

This 5G-supported framework enables effective real-time data handling and computation—essential prerequisites for the seamless performance of digital twins. By capitalizing on the core strengths of 5G, namely ultra-reliable low-latency communication (URLLC), massive machine-type communication (mMTC), and enhanced mobile broadband (eMBB),

smart cities gain the capacity to deploy and expand real-time digital twin solutions with exceptional precision and immediacy [9, 10, 37, 62, 67].

Ultra-reliable low-latency communication (URLLC) guarantees near-instantaneous data delivery for digital twin applications that cannot tolerate delays, including autonomous traffic coordination, telesurgery, and factory automation [9, 62, 67]. In connected vehicle ecosystems, for instance, even minor latency variations in exchanges between vehicles and traffic control platforms can profoundly affect safety outcomes and the effectiveness of traffic regulation.

Massive machine-type communication (mMTC) accommodates the concurrent connection of billions of IoT endpoints—ranging from intelligent sensors and security cameras to environmental detectors and structural health monitors [9, 67]. Within a smart city context, this capacity supports comprehensive, multi-source data acquisition, allowing digital twins to perform thorough real-time assessments of urban conditions, detect irregularities, and refine operational processes across the city.

Enhanced mobile broadband (eMBB) supplies the high-speed, high-capacity links needed for digital twins to manage, render, and interpret intricate datasets, detailed 3D representations, and high-resolution simulations without interruption [62, 67]. This feature proves particularly valuable in applications such as virtual urban design, augmented reality interfaces, and remote infrastructure oversight, empowering planners and decision-makers to simulate future scenarios, evaluate disaster impacts, and arrive at well-informed conclusions efficiently.

By combining these three foundational 5G attributes, smart cities can seamlessly interconnect, supervise, and orchestrate large-scale digital twin environments. This integration promotes anticipatory governance, optimized resource allocation, and greater overall resilience across critical sectors, including mobility, energy systems, public safety, and environmental stewardship [62, 67].

Among the most effective strategies for building 5G-enabled digital twin frameworks is network slicing, which partitions the 5G Core Network into tailored virtual sub-networks optimized for specific purposes. High-performance, low-latency slices can be dedicated to autonomous vehicle fleets, delivering precise real-time positioning and improved safety by eliminating communication lag [62, 67, 69, 70]. Massive IoT-oriented slices can support extensive sensor arrays embedded in public infrastructure, continuously monitoring structural stability, atmospheric quality, and water distribution to enhance municipal oversight [67, 69, 70]. Dedicated high-security slices can be reserved for governmental operations and emergency services, ensuring reliable connectivity even under extreme conditions [62, 67, 70].

A particularly compelling application of this architecture lies in smart energy grids, where digital twins of electricity distribution systems monitor voltage fluctuations, load patterns, and asset performance in real time [40, 47, 62, 71]. When paired with 5G and edge computing, utilities can identify line anomalies, forecast maintenance requirements, and dynamically balance energy flows, resulting in greater operational efficiency and minimized service interruptions. For instance, upon detecting early indicators of transformer degradation, the digital twin can trigger proactive servicing, thereby averting costly blackouts and preserving a stable, trustworthy power supply for end users.

The 5G network architecture designed for real-time digital twin infrastructure forms the essential backbone of next-generation smart city ecosystems, enabling superior efficiency, adaptability, and robustness in urban development and administration [9, 10, 37, 62, 67]. Through the convergence of ultra-fast wireless connectivity, localized edge processing, and advanced analytics, digital twins maintain active, bidirectional synchronization with their physical counterparts, driving evidence-based decision-making across multiple fields such as transportation, healthcare delivery, energy management, and urban security.

A primary benefit of combining 5G with digital twins is their ability to support large-scale IoT environments characterized by dense connectivity and instantaneous data handling [37, 67]. Contemporary smart cities depend on extensive networks of interconnected sensors, surveillance cameras, self-driving vehicles, and intelligent energy grids that

continuously generate and share information. The ultra-reliable and low-latency properties of 5G ensure that digital twins receive precise, up-to-the-moment updates, thereby strengthening their ability to model, forecast, and refine urban operations with greater effectiveness [10, 55, 71]. For example, digital twins of traffic networks supported by 5G can continuously evaluate inputs from intersection sensors, onboard vehicle data, and pedestrian detection points to adjust signal phases, redirect flows, and avert gridlock in real time [40, 47, 62, 71].

In addition to mobility management, 5G enables edge computing, shifting computational workloads away from centralized servers to minimize delays and accelerate response times for essential municipal services. This decentralized model proves particularly valuable in time-critical domains such as emergency response, where edge-supported digital twins of critical infrastructure can swiftly detect hazards, allocate resources optimally, and activate automated countermeasures in mere seconds [10, 71]. A notably impactful application appears in municipal water supply management. A live digital twin of an urban water network can track pressure variations, detect contamination indicators, and identify leaks, pinpointing irregularities that signal potential pipe failures or quality issues. When linked to automated valves and controls, these digital twins enable rapid isolation of compromised sections, redirection of supply routes, and prompt deployment of repair teams, thereby limiting service interruptions and conserving water resources [62, 67].

The substantial decrease in latency provided by edge computing relative to conventional cloud-based methods is demonstrated in **Figure 11** within the framework of urban digital twins for smart cities. As illustrated, edge computing (blue line) consistently achieves lower latency values across successive time intervals, thereby boosting the speed and reliability of real-time data analysis. This latency improvement is fundamental to elevating the agility and overall efficacy of smart city systems, supporting quicker judgments and more effective governance of urban environments [44, 69, 70].

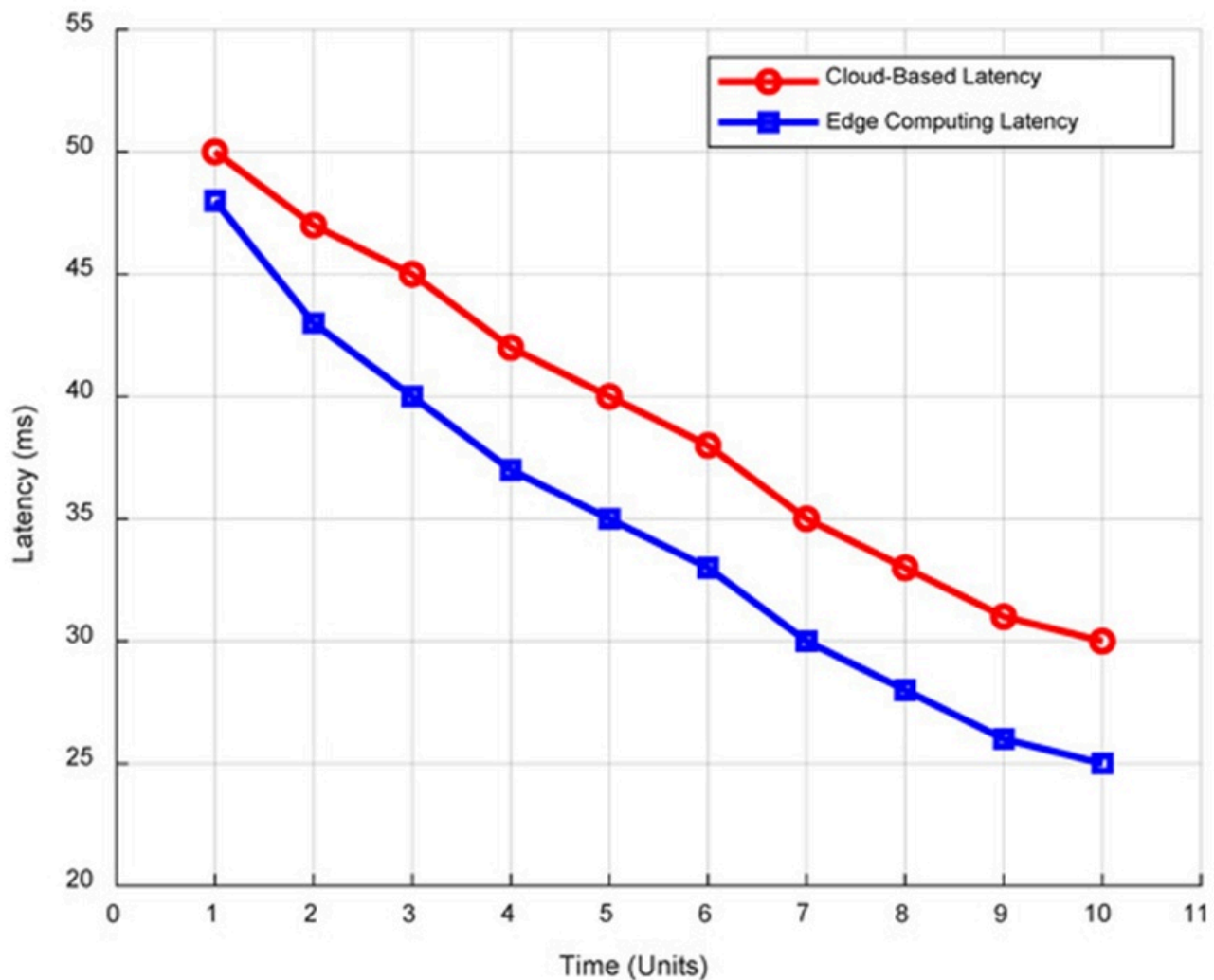


Figure 11. Edge computing latency reduction in urban digital twins [44, 69, 70].

A further promising domain is the maintenance and predictive assessment of physical infrastructure. Leveraging 5G-integrated digital twins, cities can perform ongoing surveillance of roadways, bridges, and buildings [9, 10]. Through pattern recognition in sensor-derived data, the digital twin can anticipate potential breakdowns, schedule preventive interventions, and prevent costly damage or catastrophic events [62, 67]. This predictive functionality not only extends the service life of assets but also enhances resident safety and reduces cumulative maintenance expenditures [36, 37, 55, 71].

Despite the considerable promise it holds, the broad adoption of 5G-supported digital twins faces substantial technical and practical challenges. Establishing the necessary high-performance processing capabilities, secure connectivity frameworks, and compatible digital twin platforms requires considerable financial commitment [69, 70, 71]. Given that real-time digital twins process sensitive civic and individual data, implementing stringent cybersecurity defenses, advanced encryption standards, and adherence to privacy legislation becomes imperative. Successfully navigating these obstacles is vital to fully harnessing the capabilities of digital twins and advancing toward the realization of autonomous, self-optimizing urban systems [69, 70]. Through the harmonious integration of 5G and digital twins, smart cities stand poised to transform urban administration by delivering superior efficiency, environmental sustainability, and elevated living standards for vast numbers of city dwellers.

Technological and Policy Recommendations

The successful rollout of 5G within smart cities demands a well-coordinated combination of technological innovation and supportive policy frameworks. A range of targeted actions must be prioritized to ensure the secure, efficient, and environmentally responsible integration of 5G into urban settings. By proactively tackling core issues—including infrastructure funding, system interoperability, energy optimization, cybersecurity defenses, data protection, and multi-stakeholder coordination—municipalities can fully capitalize on 5G's advantages while effectively managing associated risks.

One of the most pressing obstacles to 5G adoption is the substantial capital required to build its supporting infrastructure. In contrast to earlier wireless standards, 5G relies on a closely spaced grid of small cells, extensive fiber backhaul, and sophisticated transport links to achieve its promised ultra-low latency and blazing data rates [10, 29, 51]. These elements require significant expenditures from both government and commercial entities. In the absence of sufficient funding, 5G availability will likely remain confined to densely populated city centers, widening the digital divide and denying rural and marginalized populations access to vital smart city functionalities [36, 71].

To overcome this barrier, public authorities should introduce policies that promote colocation and sharing of infrastructure among operators, thereby lowering individual costs and hastening network expansion. Economic incentives—including tax reductions, grants, and collaborative public–private financing models—can play a decisive role in mobilizing capital for 5G projects. At the same time, regulatory processes should be simplified and accelerated to expedite permitting for small-cell installations in metropolitan zones, eliminating administrative bottlenecks that frequently postpone progress.

Achieving seamless interoperability between 5G and legacy communication systems is fundamental to delivering uninterrupted connectivity throughout diverse smart city services. Without uniform standards, integrating 5G with established platforms such as 4G LTE, Wi-Fi, and IoT architectures can lead to operational inefficiencies, higher costs, and inconsistent performance [13, 14]. The development and enforcement of international and domestic interoperability standards are therefore essential to create unified smart city environments in which heterogeneous technologies interact reliably and efficiently [32, 38].

Establishing a clear communication protocol standardization roadmap is indispensable for ensuring interoperability across intricate digital infrastructures, especially in the context of smart cities and urban digital twins [68, 72, 73]. Such a roadmap enables stakeholders to methodically pinpoint deficiencies in current standards, conduct rigorous testing and protocol refinement, and roll out adaptable solutions that support ongoing technological evolution [68, 72, 73]. This structured process encourages uniformity, mitigates fragmentation, and strengthens partnerships among equipment manufacturers, regulators, and solution providers, ultimately contributing to a more coherent and high-performing urban digital ecosystem.

The Communication Protocol Standardization Roadmap shown in **Figure 12** offers a conceptual model outlining a potential timeline for advancing communication protocol standardization in urban digital twin environments. Developed from established research findings and broader industry forecasts in smart city and telecommunications domains—rather than specific measured data—this illustrative roadmap identifies four progressive stages: Exploration (2024), focused on recognizing deficiencies in prevailing standards; Pilot (2026), centered on designing and validating prototype implementations; Implementation (2028), involving the widespread adoption of harmonized protocols throughout smart city operations; and Optimization (2030), dedicated to continuous refinement and expansion to accommodate future innovations [68, 72, 73]. Each stage is carefully sequenced to achieve pivotal objectives, including enhanced stakeholder alignment, rigorous scalability evaluation, and robust interoperability assurance, thereby guiding the field toward a dependable, standardized communication foundation [68, 73].

Communication Protocol Standardization Roadmap in Urban Digital Twins

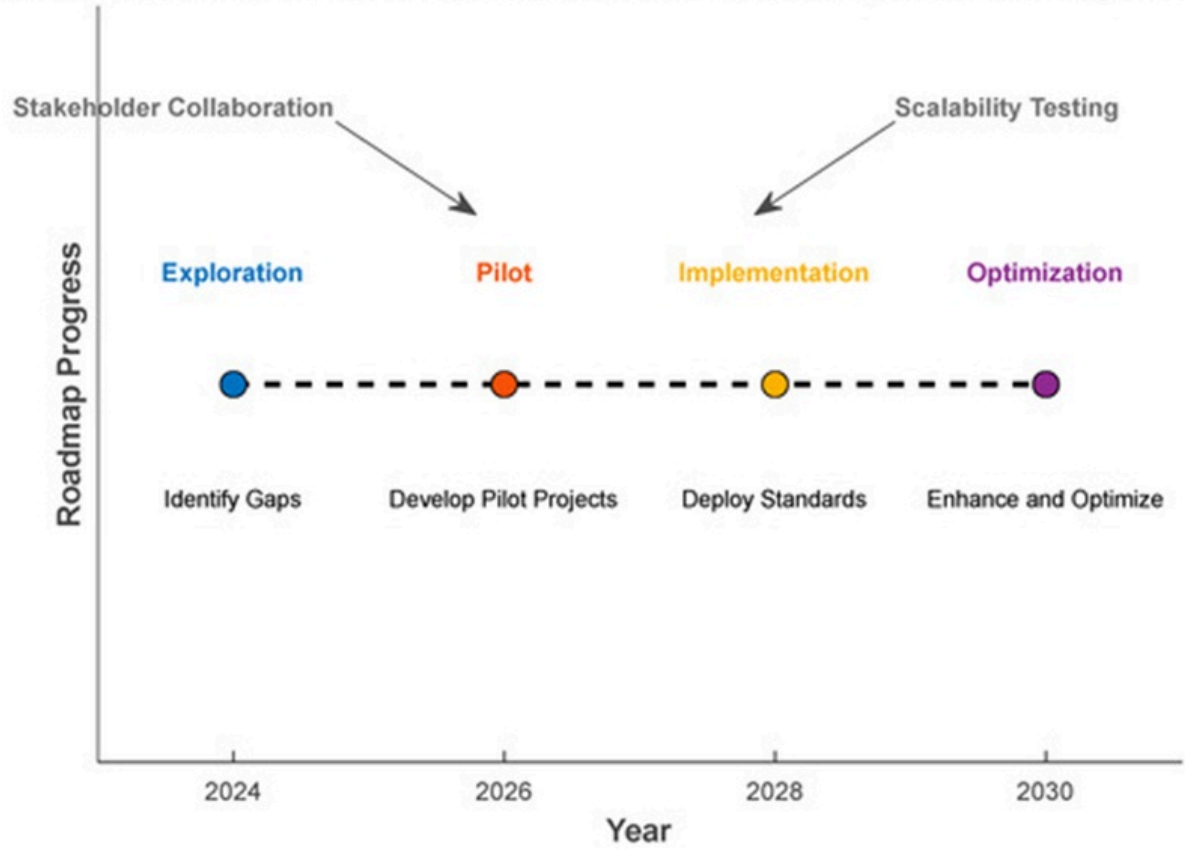


Figure 12. Communication protocol standardization roadmap [68, 72, 73].

The elevated power demands of 5G networks represent a serious concern for municipalities committed to sustainability targets [10, 34, 51]. Compared with prior generations, 5G requires a denser array of base stations operating at higher frequencies, resulting in markedly higher electricity consumption. To counteract the ecological footprint of large-scale 5G expansion, smart cities must prioritize incorporating energy-conscious technologies into their network designs.

A practical strategy involves powering 5G base stations with renewable sources—such as solar photovoltaic arrays and wind turbines—to decrease reliance on conventional fossil-fuel-based electricity. Improvements in hardware efficiency, including adaptive power-management features that scale consumption according to instantaneous traffic levels, can further optimize energy use [36, 38]. Additionally, deploying AI-driven network orchestration enables predictive algorithms to anticipate demand patterns and dynamically adjust resource allocation, thereby eliminating wasteful power consumption. By consistently applying these measures, cities can align 5G development with global environmental commitments, substantially cutting greenhouse gas emissions without compromising connectivity performance.

The vast connectivity provided by 5G heightens vulnerability to cyber threats that could jeopardize vital urban infrastructure. Malicious attacks targeting 5G networks have the potential to interrupt essential services—including transportation networks, medical facilities, and power distribution systems—resulting in profound social and economic repercussions [33, 60]. As smart cities grow ever more reliant on densely interconnected devices, the adoption of strong cybersecurity architectures becomes imperative to protect confidential information and maintain operational continuity [3, 30].

An effective cybersecurity architecture for 5G environments combines multiple layers, such as firewalls, continuous threat monitoring, and comprehensive end-to-end encryption. Cutting-edge encryption methods—including those resistant to

quantum-computing attacks—shield data against emerging threats, while AI-powered anomaly-detection tools actively identify and neutralize intrusions [36, 51]. In addition to technical safeguards, rigorous regulatory guidelines, and periodic security audits, these measures help enforce adherence to industry-leading standards. Educational campaigns aimed at the public further reinforce protection by encouraging safe online behavior among citizens and organizations.

The integrated structure of cybersecurity risk-reduction approaches for 5G networks in urban digital twin smart cities is shown in **Figure 13**. Central elements—such as 5G towers, data centers, IoT endpoints, and municipal command centers—form interconnected nodes fortified by layered security protocols [11, 74, 75]. Dashed lines denote protected communication channels, highlighting the critical role of strong encryption and ongoing surveillance. Annotations call attention to specific defenses, including firewalls, intrusion detection mechanisms, and data encryption practices, all designed to counter network weaknesses [76, 77]. The diagram emphasizes the pivotal position of 5G infrastructure in supporting fluid data exchange and centralized oversight within urban digital twins, while illustrating the multi-tiered protective strategies required to secure sensitive information and preserve resilience against cyber risks [75-77].

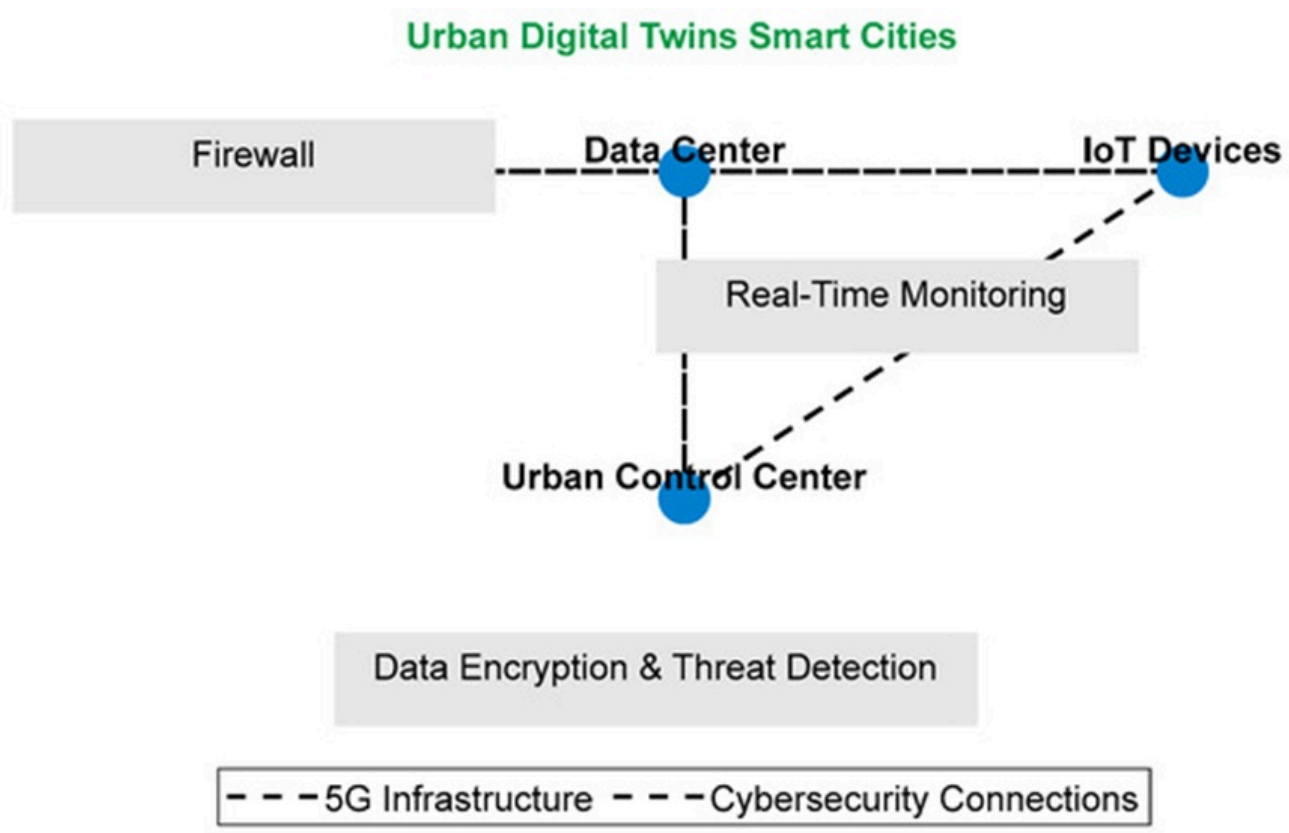


Figure 13. Cybersecurity risk mitigation strategies in 5G networks [11, 74-76].

The rapid expansion of 5G networks in smart cities, which generate enormous volumes of personal and functional data, intensifies worries about privacy protection and the responsible handling of information [51, 77]. In the absence of well-defined rules, risks arise from unchecked data gathering, inappropriate use, and possible infringements on personal privacy.

To mitigate these issues, lawmakers must develop thorough data governance policies that clearly outline the processes for collecting, storing, and applying data across smart city platforms [11, 75]. Such regulations should mandate techniques such as data anonymization to preserve individual privacy while still enabling valuable analytics for urban planning [75, 77]. Residents deserve meaningful authority over their information, supported by mechanisms such as informed consent requirements and the option to participate in data-sharing programs.

Ethical principles must also guide deployment, ensuring that 5G-driven smart city tools reflect broader societal norms [11, 75, 77]. This involves scrutinizing and correcting biases embedded in AI-based decision engines, and maintaining openness about the algorithmic treatment of urban datasets. By enacting robust privacy legislation, municipalities can foster greater public confidence in smart city programs and facilitate broader acceptance of 5G-supported innovations.

Achieving widespread and effective 5G integration in smart cities hinges on close cooperation among governmental bodies, industry participants, and academic researchers. Public–private partnerships (PPPs) play a vital role in overcoming funding and technical obstacles, enabling faster, more cost-effective network expansion [10, 68]. Governments can stimulate PPP formation by introducing performance-linked incentive structures that allow private entities to fund infrastructure in return for sustained operational advantages. Collaborative research programs uniting universities and companies can spur breakthroughs, yielding innovative 5G solutions customized to city-specific demands. Multi-party agreements can encourage shared infrastructure use, enabling several operators to leverage common physical assets, thereby eliminating duplication and reducing rollout costs [68, 75, 77]. Cultivating a collaborative environment accelerates the shift to 5G while ensuring that technological progress delivers equitable benefits to all parties.

By systematically addressing essential technological and regulatory priorities, smart cities can harness the full transformative power of 5G to improve daily living, increase operational performance, and advance environmental sustainability. Coordinated efforts in infrastructure development, standardization initiatives, energy optimization, cybersecurity protection, privacy safeguards, and cross-sector alliances must converge to establish an equitable and resilient urban framework anchored in 5G capabilities. Striking the right equilibrium between forward-thinking innovation and thoughtful governance will enable cities to mature into truly intelligent spaces that offer inclusive, high-quality digital experiences to their inhabitants.

Conclusion

In summary, this study has highlighted the critical role of 5G technology in enabling the real-time fusion of digital twins within smart city environments. Digital twins, empowered by 5G's exceptional speed and minimal latency, deliver a superior platform for continuous urban observation, forward-looking analytics, and streamlined decision processes. By synchronizing virtual representations with physical city assets, local authorities can achieve more precise resource allocation, strengthen emergency preparedness, and improve the quality of public services. However, successful adoption requires overcoming barriers related to data compatibility, cybersecurity, and power consumption. Ongoing improvements in 5G deployment, combined with unified standards for digital twin implementation, will remain crucial to fully unlocking this technology's transformative impact on urban evolution.

Compared to prevailing smart city solutions, the proposed combination of 5G and digital twins offers a far more agile and extensible approach to city administration. Conventional smart city setups often rely on disjointed IoT configurations and sluggish, centralized cloud-based processing, which constrain their adaptability and responsiveness. By contrast, the 5G-supported digital twin framework enables almost immediate data alignment and modeling, facilitating real-time oversight, proactive maintenance, and swift governance responses. This represents a fundamental transition from reactive to forward-thinking urban stewardship. The proposed framework places strong emphasis on seamless interoperability and holistic system cohesion—areas where many current implementations struggle due to isolated components and inconsistent protocols. Consequently, this approach not only capitalizes on the advantages of established smart city tools but also overcomes their primary shortcomings through superior connectivity and accurate virtual mirroring.

In addition to digital twin synergy, 5G technology brings unmatched potential to accelerate smart city progress. Its capacity to accommodate expansive IoT networks, deliver instantaneous interactions, and power edge computing drives breakthroughs in urban facilities, citizen safety, and advanced mobility solutions. Pairing 5G with forward-looking innovations such as digital twins cultivates more flexible, responsive city systems. The real-time analytics and scenario

modeling enabled by 5G networks empower municipalities to proactively manage assets, anticipate structural vulnerabilities, and fine-tune essential operations.

While these benefits are substantial, expanding and sustaining 5G networks pose notable challenges, particularly in energy efficiency, security, and safeguarding personal information. As urban areas increasingly adopt these systems, resolving such issues becomes paramount to ensuring environmentally sound, inclusive smart city development. More robust regulatory structures are required to guide the responsible use of data and oversee the accelerated expansion of 5G-based offerings.

Looking ahead, research efforts should investigate the convergence of 5G with next-generation tools such as artificial intelligence (AI) and machine learning (ML) to further strengthen smart city decision intelligence. The creation of comprehensive benchmarks and protocols covering data protection, network defense, and inter-industry cooperation will be indispensable for the effective rollout of 5G-driven urban environments. As these innovations continue to mature, additional investigations into the social and economic ramifications of 5G implementation will also be essential to guarantee equitable distribution of benefits and to avoid deepening digital inequalities across urban populations.

Acknowledgements

None

Conflict of interest

None

Financial support

None

Ethics statement

None

Received: 04 Apr 2023

Revised: 16 May 2023

Accepted: 06 Jul 2023

Published online: 20 September 2023

Rights and permissions

Open Access The author(s) retain copyright. This article is licensed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. It may be shared and adapted for non-commercial purposes with appropriate attribution, an indication of changes, and distribution of adaptations under the same license. Third-party material may be subject to separate terms identified in its credit line. View the license at <https://creativecommons.org/licenses/by-nc-sa/4.0/>.

References

Trindade EP, Hinnig MPF, da Costa EM, Marques JS, Bastos RC, Yigitcanlar T. Sustainable development of smart cities: A systematic review of the literature. *J Open Innov Technol Mark Complex*. 2017;3:1–14.

Stratigea A, Papadopoulou C-A, Panagiotopoulou M. Tools and technologies for planning the development of smart cities. *J Urban Technol*. 2015;22:43–62.

Korczak J, Kijewska K. Smart logistics in the development of smart cities. *Transp Res Procedia*. 2019;39:201–11.

Stratigea A. The concept of smart cities. Towards community development? *Netcom Réseaux Commun Territ*. 2012;26:375–88.

Islam S, Atallah ZA, Budati AK, Hasan MK, Kolandaisamy R, Nurhizam S. Mobile networks toward 5G/6G: Network architecture, opportunities and challenges in smart city. *IEEE Open J Commun Soc*. 2024;1.

Mishra P, Thakur P, Singh G. Sustainable smart city to Society 5.0: state-of-the-art and research challenges. *SAIEE Afr Res J*. 2022;113:152–64.

Gür G, Kalla A, De Alwis C, Pham Q-V, Ngo K-H, Liyanage M, et al. Integration of ICN and MEC in 5G and beyond networks: mutual benefits, use cases, challenges, standardization, and future research. *IEEE Open J Commun Soc*. 2022;3:1382–412.

Hofmann F, Wurster S, Ron E, Böhmecke-Schwafert M. The immutability concept of blockchains and benefits of early standardization. In: *Proceedings of the 2017 ITU Kaleidoscope: Challenges for a Data-Driven Society (ITU K)*. Nanjing, China; 2017. p. 1–8.

Ferré-Bigorra J, Casals M, Gangolells M. The adoption of urban digital twins. *Cities*. 2022;131:103905.

Al-Sehrawy R, Kumar B, Watson R. The pluralism of digital twins for urban management: bridging theory and practice. *J Urban Manag*. 2023;12:16–32.

Rodrigo MS, Rivera D, Moreno JI, Álvarez-Campana M, López DR. Digital twins for 5G networks: A modeling and deployment methodology. *IEEE Access*. 2023;11:38112–26.

Nguyen HX, Trestian R, To D, Tatipamula M. Digital twin for 5G and beyond. *IEEE Commun Mag*. 2021;59:10–5.

Erunkulu OO, Zungeru AM, Lebekwe CK, Mosalaosi M, Chuma JM. 5G mobile communication applications: a survey and comparison of use cases. *IEEE Access*. 2021;9:97251–95.

Navarro-Ortiz J, Romero-Diaz P, Sendra S, Ameigeiras P, Ramos-Munoz JJ, Lopez-Soler JM. A survey on 5G usage scenarios and traffic models. *IEEE Commun Surv Tutor*. 2020;22:905–29.

Jabagi N, Park A, Kietzmann J. The 5G revolution: expectations versus reality. *IT Prof*. 2020;22:8–15.

Loghini D, Cai S, Chen G, Dinh TTA, Fan F, Lin Q, et al. The disruptions of 5G on data-driven technologies and applications. *IEEE Trans Knowl Data Eng*. 2020;32:1179–98.

Yang Y, Hua K. Emerging technologies for 5G-enabled vehicular networks. *IEEE Access*. 2019;7:181117–41.

Tang Y, Dananjayan S, Hou C, Guo Q, Luo S, He Y. A survey on the 5G network and its impact on agriculture: challenges and opportunities. *Comput Electron Agric*. 2021;180:105895.

Gharaibeh A, Salahuddin MA, Hussini SJ, Khreishah A, Khalil I, Guizani M, et al. Smart cities: A survey on data management, security, and enabling technologies. *IEEE Commun Surv Tutor*. 2017;19:2456–501.

Akpakwu GA, Silva BJ, Hancke GP, Abu-Mahfouz AM. A survey on 5G networks for the Internet of Things: Communication technologies and challenges. *IEEE Access*. 2017;6:3619–47.

3GPP TR 38.913, Study on Scenarios and Requirements for Next Generation Access Technologies. 3rd Generation Partnership Project. 14 March 2017. https://www.3gpp.org/ftp/Specs/archive/38_series/38.913/ (accessed on 23 December 2024).

ITU-R M.2083-0, IMT Vision—Framework for Future IMT for 2020 and Beyond. ITU (International Telecommunication Union). 2015. <https://www.itu.int/pub/R-REP-M.2083-2015> (accessed on 24 December 2024).

Ericsson. Ericsson Mobility Report. June 2023. <https://www.ericsson.com/en/reports-and-papers/mobility-report> (accessed on 25 December 2024).

Qualcomm. Qualcomm 5G Latency Analysis: A Technical Overview. 2020. <https://www.qualcomm.com/research/5g> (accessed on 28 December 2024).

3GPP TR 22.891, Feasibility Study on New Services and Markets Technology Enablers for 5G. 14 September 2016. https://www.3gpp.org/ftp/Specs/archive/22_series/22.891/ (accessed on 28 December 2024).

Cisco. Cisco Annual Internet Report (2023–2028). March 2023. <https://www.cisco.com/c/en/us/solutions/executive-perspectives/annual-internet-report/index.html> (accessed on 28 December 2024).

GSMA. 5G and IoT: The Path to 1 Million Devices per Square Kilometer. GSMA Intelligence Report. July 2022. <https://www.gsma.com/futurenetworks/> (accessed on 2 January 2025).

Foukas X, Patounas G, Elmokashfi A, Marina MK. Network slicing in 5G: survey and challenges. *IEEE Commun Mag*. 2017;55:94–100.

Li X, Samaka M, Chan HA, Bhamare D, Gupta L, Guo C, et al. Network slicing for 5G: Challenges and opportunities. *IEEE Internet Comput*. 2017;21:20–7.

Wijethilaka S, Liyanage M. Survey on network slicing for Internet of Things realization in 5G networks. *IEEE Commun Surv Tutor*. 2021;23:957–94.

Ravindran R, Chakraborti A, Amin SO, Azgin A. 5G-ICN: delivering ICN services over 5G using network slicing. *IEEE Commun Mag*. 2017;55:101–7.

Yang C, Liang P, Fu L, Cui G, Huang F, Teng F, et al. Using 5G in smart cities: a systematic mapping study. *Intell Syst Appl*. 2022;14:200065.

Shehab MJ, Kassem I, Kutty AA, Kucukvar M, Onat N, Khattab T. 5G networks towards smart and sustainable cities: a review of recent developments, applications and future perspectives. *IEEE Access*. 2021;10:2987–3006.

Santos J, Leroux P, Wauters T, Volckaert B, De Turck F. Anomaly detection for smart city applications over 5G low power wide area networks. In: *Proceedings of the 2018 IEEE/IFIP Network Operations and Management Symposium (NOMS)*. Taipei, Taiwan; 2018. p. 1–9.

Dua A, Dutta A, Zaman N, Kumar N. Blockchain-based E-waste management in 5G smart communities. In: *Proceedings of the IEEE INFOCOM 2020—IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*. Toronto, ON, Canada; 2020. p. 195–200.

Banda L, Mzyece M, Mekuria F. 5G-IoT and sustainability: smart city use case. In: *Proceedings of the 2024 IEEE 100th Vehicular Technology Conference (VTC2024-Fall)*. Washington, DC, USA; 2024. p. 1–5.

Lv Z, Hu B, Lv H. Infrastructure monitoring and operation for smart cities based on IoT system. *IEEE Trans Ind Inform*. 2019;16:1957–62.

Bacco M, Delmastro F, Ferro E, Gotta A. Environmental monitoring for smart cities. *IEEE Sens J*. 2017;17:7767–74.

Segura-Garcia J, Calero JMA, Pastor-Aparicio A, Marco-Alaez R, Felici-Castell S, Wang Q. 5G IoT system for real-time psycho-acoustic soundscape monitoring in smart cities with dynamic computational offloading to the edge. *IEEE Internet Things J*. 2021;8:12467–75.

Elassy M, Al-Hattab M, Takruri M, Badawi S. Intelligent transportation systems for sustainable smart cities. *Transp Eng*. 2024;16:100252.

Mamun MI, Rahman A, Khaleque MA, Mridha MF, Hamid MA. Healthcare monitoring system inside self-driving smart car in 5G cellular network. In: *Proceedings of the 2019 IEEE 17th International Conference on Industrial Informatics (INDIN)*. Helsinki, Finland; 2019;1:1515–20.

Hakak S, Gadekallu TR, Maddikunta PKR, Ramu SP, Parimala M, De Alwis C, et al. Autonomous vehicles in 5G and beyond: a survey. *Veh Commun*. 2023;39:100551.

Khorov E, Krasilov A, Selnitskiy I, Akyildiz IF. A framework to maximize the capacity of 5G systems for ultra-reliable low-latency communications. *IEEE Trans Mob Comput*. 2020;20:2111–23.

Sutton GJ, Zeng J, Liu RP, Ni W, Nguyen DN, Jayawickrama BA, et al. Enabling technologies for ultra-reliable and low latency communications: from PHY and MAC layer perspectives. *IEEE Commun Surv Tutor*. 2019;21:2488–524.

Holmes CK. South Africa's readiness of the smart built environment towards 2035. Nelson Mandela University, Faculty of Business and Economic Sciences, Gqeberha, South Africa; 2019.

Duca F, Mutua A, Tetley-Brown L, Karuri-Sebina G, Backhouse J. Smart cities governance in the Southern African Development Community (SADC) region: A systematic review of the literature. *Res Sq*. 2024.

Aoki S, Rajkumar R. Dynamic intersections and self-driving vehicles. In: *Proceedings of the 2018 ACM/IEEE 9th International Conference on Cyber-Physical Systems (ICCPs)*. Porto, Portugal; 2018. p. 320–30.

Panwar S. Breaking the millisecond barrier: robots and self-driving cars will need completely reengineered networks. *IEEE Spectr*. 2020;57:44–9.

Ndikumana A, Tran NH, Kim KT, Hong CS. Deep learning based caching for self-driving cars in multi-access edge computing. *IEEE Trans Intell Transp Syst*. 2020;22:2862–77.

Ramu SP, Boopalan P, Pham QV, Maddikunta PKR, Huynh-The T, Alazab M, et al. Federated learning enabled digital twins for smart cities: concepts, recent advances, and future directions. *Sustain Cities Soc*. 2022;79:103663.

Ali K, Nguyen HX, Vien QT, Shah P, Raza M, Paranthaman VV, et al. Review and implementation of resilient public safety networks: 5G, IoT, and emerging technologies. *IEEE Netw*. 2021;35:18–25.

Sheraz M, Chuah TC, Lee YL, Alam MM, Al-Habashna AA, Han Z. A comprehensive survey on revolutionizing connectivity through artificial intelligence-enabled digital twin network in 6G. *IEEE Access*. 2024;12:49184–215.

Wang S, Qureshi MA, Miralles-Pechuán L, Huynh-The T, Gadekallu TR, Liyanage M. Explainable AI for 6G use cases: technical aspects and research challenges. *IEEE Open J Commun Soc*. 2024;5:2490–540.

Banerjee A, Costa B, Forkan ARM, Kang Y-B, Marti F, McCarthy C, et al. 5G enabled smart cities: a real-world evaluation and analysis of 5G using a pilot smart city application. *Internet Things*. 2024;28:101326.

Agiwal M, Roy A, Saxena N. Next generation 5G wireless networks: a comprehensive survey. *IEEE Commun Surv Tutor*. 2016;18:1617–55.

Wu Q, Li GY, Chen W, Ng DWK, Schober R. An overview of sustainable green 5G networks. *IEEE Wirel Commun*. 2017;24:72–80.

Williams L, Sovacool BK, Foxon TJ. The energy use implications of 5G: reviewing whole network operational energy, embodied energy, and indirect effects. *Renew Sustain Energy Rev.* 2022;157:112033.

Carrera B, Peyrard S, Kim K. Meta-regression framework for energy consumption prediction in a smart city: a case study of Songdo in South Korea. *Sustain Cities Soc.* 2021;72:103025.

Raman R, Kumar V, Sanjay C, Rabadiya D, Patre S, Meenakshi R. Optimizing power consumption for business networks through cooperative communication in mixed wireless environments. In: *Proceedings of the 2024 International Conference on Knowledge Engineering and Communication Systems (ICKECS)*. Chikkaballapur, India; 2024;1:1–5.

Kuru K, Ansell D. TCitySmartF: A comprehensive systematic framework for transforming cities into smart cities. *IEEE Access.* 2020;8:18615–44.

Neirotti P, De Marco A, Cagliano AC, Mangano G, Scorrano F. Current trends in smart city initiatives: some stylised facts. *Cities.* 2014;38:25–36.

Jalali R, El-Khatib K, McGregor C. Smart city architecture for community level services through the internet of things. In: *Proceedings of the 2015 18th International Conference on Intelligence in Next Generation Networks*. Paris, France; 2015. p. 108–13.

Vetrivel S, Vidhyapriya P, Arun V. Evaluating the economic impact of 5G-6G implementations across diverse industry sectors. In: *5G/6G Advancements in Communication Technologies for Agile Management*. IGI Global Scientific Publishing; Hershey, PA, USA; 2025. p. 83–116.

Kokkinis D, Ioannou N, Katsianis D, Varoutas D. A techno-economic modeling approach to 6G network deployment: exploring costs and use case feasibility. *IEEE Access.* 2025;13:35597–608.

Riadh A-D. Dubai, the sustainable, smart city. *Renew Energy Environ Sustain.* 2022;7:3.

Ye N, Miao S, Pan J, Xiang Y, Mumtaz S. Dancing with chains: spaceborne distributed multi-user detection under inter-satellite link constraints. *IEEE J Sel Top Signal Process.* 2025;1–16.

Mylonas G, Kalogeras A, Kalogeras G, Anagnostopoulos C, Alexakos C, Muñoz L. Digital twins from smart manufacturing to smart cities: a survey. *IEEE Access.* 2021;9:143222–49.

Ahmadi H, Nag A, Khar Z, Sayrafian K, Rahardja S. Networked twins and twins of networks: An overview on the relationship between digital twins and 6G. *IEEE Commun Stand Mag.* 2021;5:154–60.

Zhou Z, Jia Z, Liao H, Lu W, Mumtaz S, Guizani M, et al. Secure and latency-aware digital twin assisted resource scheduling for 5G edge computing-empowered distribution grids. *IEEE Trans Ind Inform.* 2021;18:4933–43.

Sun W, Zhang H, Wang R, Zhang Y. Reducing offloading latency for digital twin edge networks in 6G. *IEEE Trans Veh Technol.* 2020;69:12240–51.

Tao F, Zhang H, Liu A, Nee AYC. Digital twin in industry: state-of-the-art. *IEEE Trans Ind Inform.* 2018;15:2405–15.

Ma S, Flanigan KA, Bergés M. State-of-the-art review and synthesis: a requirement-based roadmap for standardized predictive maintenance automation using digital twin technologies. *Adv Eng Inform.* 2024;62:102800.

Hribernik K, Cabri G, Mandreoli F, Mentzas G. Autonomous, context-aware, adaptive digital twins—state of the art and roadmap. *Comput Ind.* 2021;133:103508.

Karamchandani A, Sanz M, Burgaleta Á, De La Cal L, Mozo A, Moreno JI, et al. Design of an AI-driven Network Digital Twin for advanced 5G-6G network management. In Proceedings of the NOMS 2024—2024 IEEE Network Operations and Management Symposium, Seoul, Republic of Korea, 2024. p. 1–7.

Rebecchi F, Pastor A, Mozo A, Lombardo C, Bruschi R, Aliferis I, et al. A digital twin for the 5G era: The SPIDER cyber range. In: Proceedings of the 2022 IEEE 23rd International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM). Belfast, UK; 2022. p. 567–72.

Mohan JP, Sugunaraj N, Ranganathan P. Cyber security threats for 5G networks. In: Proceedings of the 2022 IEEE International Conference on Electro Information Technology (eIT). Mankato, MN, USA; 2022. p. 446–54.

Maksimović M, Jokić S, Bošković MČ. Digital twins and 5G: unlocking the potential in the energy sector. In: Proceedings of the 2024 23rd International Symposium INFOTEH-JAHORINA (INFOTEH). East Sarajevo, Bosnia and Herzegovina; 2024. p. 1–6.