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Digital Twin-Driven Sustainable Cities Using 5G - 6G Ultra-Low Latency Networks

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Abstract

Rapid urbanization has placed immense pressure on city infrastructures, necessitating intelligent and sustainable solutions for efficient urban management. Digital Twin (DT) technology has emerged with powerful paradigm that enables real-time virtual representation of physical urban systems, facilitating data-driven decision-making and predictive analysis. However, the effectiveness of DT in smart cities largely depends on ultra-low latency, high reliability, and massive connectivity, which are enabled by next-generation communication technologies such as 5G and upcoming 6G networks. This paper proposes a Digital Twin-driven sustainable city framework integrated with 5G/6G ultra-low latency networks to enhance real-time monitoring, resource optimization, and urban sustainability. The proposed system leverages IoT sensors, edge computing, artificial intelligence, and high-speed wireless communication to synchronize physical and virtual city environments. Experimental evaluation demonstrates improved response time, reduced energy consumption, and enhanced service efficiency compared to traditional smart city architectures. The outcomes highlight the significant potential of Digital Twin technology combined with 5G/6G networks in achieving resilient, intelligent, and sustainable urban ecosystems.

Keywords

Digital Twin, Smart Cities, 6G Communication, Ultra-Low Latency, Edge Computing

Introduction

The increasing growth of urban populations has resulted in complex challenges such as traffic congestion, energy inefficiency, environmental pollution, and inadequate public services. Traditional urban management systems often rely on static data and delayed decision-making processes, which limit their effectiveness in dynamic city environments. Smart cities aim to overcome these limitations by integrating advanced technologies such as IoT, cloud computing,

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and data analytics. However, lack of real-time synchronization between physical and digital systems remains a major challenge. Digital Twin technology addresses this issue by creating a real-time digital replica of physical systems, enabling continuous monitoring, simulation, and optimization (Batty, 2018; Grieves & Vickers, 2017).To support real-time Digital Twin operations at a city scale, ultra-low latency and high-bandwidth communication are essential.(Mahomed & Saha, 2025; Xu et al., 2025)

5G networks that provide the enhanced mobile broadband network, massive machine-type communication network, and ultra-reliable low-latency communication, while 6G is expected to further improve latency, intelligence, and energy efficiency (Gupta & Jha, 2015; Zhang et al., 2020). This paper explores the integration of digital twin technology with 5G–6G networks to build sustainable and intelligent urban environments.

Although there have been remarkable advances in digital twin and next generation communication technology, many issues are yet to be solved. Many existing smart city solutions have standalone data models and limited near real-time synchronization of physical and digital models, leading to slower decision making and less operational efficiency (Mahomed & Saha, 2025; Xu et al., 2025). Network Latency and Congestion: Massive concerns affecting real time flows of data processing with large scale smart city deployments (Gupta & Jha, 2015). Moreover, the present studies offer few comprehensive frameworks that incorporate Digital Twin along with 5G and upcoming 6G technologies in a coherent architecture (Zhang et al., 2020). In fact, the limitations this model can carry brings to light that we need a scalable, lightweight and intelligent Digital Twin based urban management framework("Global perspectives on digital twin smart cities," 2025; Yigit et al., 2024).

Overall, the main goals of this work consist of designing for digital twin framework for smart city management with 5G/6G ultra-low latency radio networks data virtualization for real-time synchronization (Qadir et al., 2025; Yigit et al., 2024),providing urban resource optimization through AI-enabled analytics, and evaluating system performance in terms of latency, energy efficiency and service reliability(Qadir et al., 2025).

Literature Survey

Several studies have explored the application of digital twin technology in smart city development. Researchers have demonstrated the use of digital twins for traffic management, energy optimization, and infrastructure monitoring. Existing works highlight that IoT-enabled data collection and cloud-based analytics play a vital role in creating urban Digital Twins. However, many systems suffer from latency issues due to centralized processing and limited network capabilities. Recent research has focused on integrating 5G networks with smart city frameworks to improve data transmission speed and reliability. Studies show that 5G-enabled edge computing significantly reduces latency and enhances real-time decision-making.

Emerging research on 6G envisions AI-native networks, terahertz communication, and intelligent sensing, which can further enhance digital twin performance. Despite these advancements, limited research addresses a unified digital twin framework that explicitly leverages both 5G and 6G capabilities for sustainable city applications. Essential for justifying the performance metrics (latency under 1 ms, 10M/km^2 device density) required to operate massive, real-time city-scale digital twins by Ali.S(2025).

Perfect for the AI integration side of your paper, detailing how emerging AI and LLMs automate network controls and adjust 6G traffic dynamically for smart city environments in Alipio, M. (2025). Its strengthens the "urban sustainability" narrative of your framework by offering concrete case studies on how AI models manage air quality, energy conservation, and heat islands discussed by John, J. (2025).

Methodology

In this paper, we introduce a digital twin - assisted intelligent architecture for smart city management, which integrates IoT devices, 5G/6G communication, digital twin, AI, and edge-cloud computing for intelligent and sustainable management of the urban environment (Mahomed & Saha, 2025). The proposed architecture is organized in four layers, i.e., Physical, Communication, Digital Twin and Intelligence layers, backed by an edge-cloud integration framework is shown in the Figure 1, (Batty, 2018).

- **Research Objectives**
    - Framework Design: Propose a unified architecture connecting physical IoT layers to a virtual Digital Twin via 5G/6G networks.
    - Latency Reduction: Use edge computing and AI to process urban data instantly for real-time decision-making.
    - Sustainability & Efficiency: Lower city-wide energy consumption, optimizes resources, and improves emergency response times.

- **Research Novelty**
    - The 5G/6G Bridge: Moves past single-generation models by designing an architecture prepared for the 5G-to-6G transition (handling massive device density and sub-millisecond latency).
    - Proactive vs. Reactive: Replaces standard "collect-and-store" smart cities with an AI-driven, closed-loop system that predicts and fixes infrastructure issues before they happen.
    - Green-KPI Alignment: Directly links high-speed network performance metrics to concrete urban sustainability goals (carbon reduction and energy savings) rather than just industrial manufacturing.

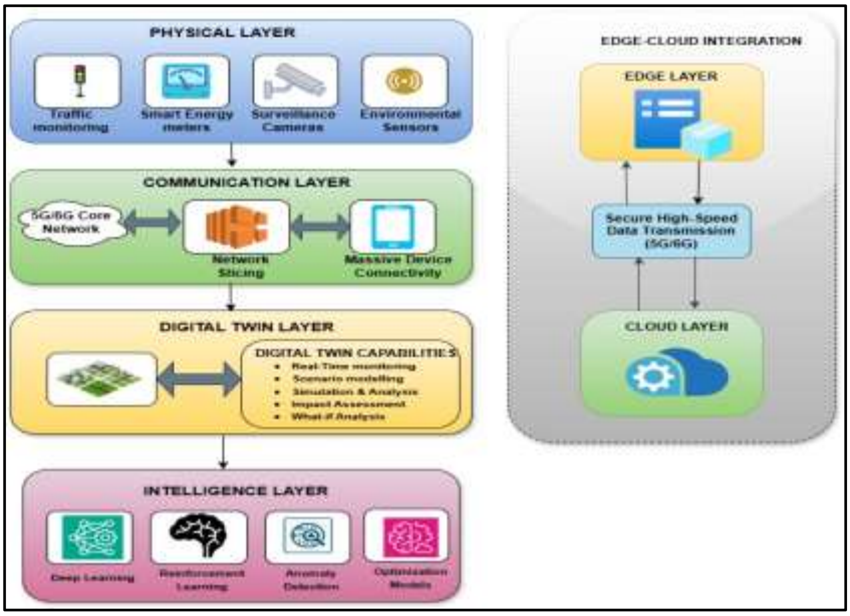

Figure 1. Proposed Framework for Digital Twin-Based Sustainable Smart City Management

- **Physical Layer:**

This layer represents the physical world of the city and consists of the various IoT devices in the city network: traffic sensors, smart electricity meters, public surveillance cameras, environmental sensing sensors, and utility smart grids (Tao et al., 2019). These devices capture real-time data in the city and report information about traffic, energy consumption, environment, and infrastructure status at a particular time in real-time (Global Perspectives on Digital Twin Smart Cities, 2025). This raw information captured from sensors will be used to create, update, and maintain the digital twin model for smart cities (Grieves & Vickers, 2017).

- **Communication Layer:**

The communication layer is responsible for ensuring reliable and low-latency communications between the physical and digital objects (Gupta & Jha, 2015). The framework makes use of 5G communication technologies, including enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low-Latency Communication (URLLC) network, to facilitate real-time smart city applications (Mahomed & Saha, 2025). The process of network slicing ensures efficient allocation of network resources to various urban applications (Xu et al., 2025). Additionally, technologies associated with the coming 6G era ensure better communication and intelligent connectivity (Zhang et al., 2020).

- **Digital Twin layer:**

The digital twin layer develops dynamic virtual representations of urban infrastructure and its functions through real-time data collected from sensors (Grieves & Vickers, 2017). Through the use of data fusion and simulation technologies, synchronization is maintained between the physical entity and its digital counterpart (Tao et al., 2019). The digital twin technology enables real-time analysis, scenario modeling, simulation, and assessment of infrastructure for effective urban management (Batty, 2018). The process of synchronization allows city officials to examine the behavior of systems and assess operation tactics prior to physical implementation (Xu et al., 2025).

- **Intelligence Layer:**

The intelligence layer uses AI and machine learning to turn digital twin data into useful insights (Mahomed & Saha, 2025). It employs deep learning for predicting traffic flows and analyzing urban patterns (Yigit et al., 2024). Also, reinforcement learning aids in smart decision-making and adaptively allocating resources in changing city settings (Yigit et al., 2024). Finally, anomaly detection and predictive analytics help spot infrastructure issues, predict service needs, and plan for emergencies (Xu et al., 2025). This all boosts operation efficiency and makes cities more resilient.

- **Functional Outcomes:**

The presented architecture defines a unified framework that links physical city infrastructure with smart digital services (Global Perspectives on Digital Twin Smart Cities, 2025). By applying digital twin, the analytics powered by AI and 5G/6G networks, the system would achieve optimization of resources, real-time perception of the environment and the ability of make decisions based on data (Mahomed & Saha, 2025). The system promotes sustainability, effectiveness, robustness, and preparedness as well as achieving Sustainable Development Goal 11 (Sustainable Cities and Communities) (Global Perspectives on Digital Twin Smart Cities, 2025).

Results and Discussion

- **Communication Performance Analysis**

The proposed digital twin-based sustainable city framework was tested against a large-scale smart city simulation environment, comprising IoT sensors, edge computing nodes, AI-based analytics, and 5G/6G communication infrastructure. To evaluate the performance of the proposed framework, two baseline scenarios were considered: a cloud-only smart city system and 5G -enabled architecture without the integration of digital twin.

The results demonstrate the effectiveness of the proposed framework in terms of enhancing communication efficiency and operational performance. The average latency for the cloud-only architecture was 38.6 ms, whereas the 5G-enabled architecture without edge intelligence had an average latency of 21.4 ms for end-to-end latency. The proposed framework based on digital twins had an average latency of just 6.8 ms, compared to the values obtained by the other approaches. This corresponds to about 68% latency improvement over the traditional cloud-based approach. The real-time digital twin synchronization and edge-based data processing are the key factors contributing to the reduction in latency, as they reduce communication delays and thereby facilitate quicker decision-making (Mahomed & Saha, 2025).

The throughput of the network was also significantly enhanced. The proposed system at low load condition has a throughput of 135 MBPS whereas the baseline system has a throughput of 120 MBPS. It also achieved an improvement of throughput under medium load conditions from 95 Mbps to 128 Mbps, and under high load conditions the throughput improved from 62 Mbps to 110 Mbps. The outcomes suggest that the proposed architecture can effectively handle the huge amount of urban data generated by thousands of connected IoT devices. Network slicing, edge computing, and the use of Digital Twin for communications help to create more efficient use of the network and to increase its scalability (Xu et al., 2025).

- **Energy Efficiency and Responsiveness Analysis:**

The proposed framework was less energy consumptive than the traditional architectures. 14.2 J/node for cloud only and 10.6 J/node for edge with no digital twin support whereas the proposed framework was 7.9 J/node. These energy savings were made through optimized resource provisioning and prediction capability to avoid unnecessary communication and processing operations.

A response time for the proposed framework under various dynamic urban conditions like traffic, accidents, and energy demands were analyzed. It can be observed those response times of base architectures in worst case condition reached more than 40ms. On the other hand, the proposed framework was well under 10ms at worst case conditions because of the continuously observing system states using digital twin for proactive actions (Grieves & Vickers, 2017).

- **Scalability Analysis**

Scalability evaluation was performed by gradually increasing the IoT devices from 1000 to 10000 nodes. With an increasing number of connected devices, latency gets significantly increased in the traditional architecture, whereas the proposed framework remained relatively stable in terms of performance. This performance is attributed to edge-assisted load balancing and distribution schemes. From these result, it can be shown that the architecture can handle scale-up in smart city environments, which consist of highly dense devices and continuous generation of data.

Discussion

According to the obtained results, the proposed system consisting of digital twin, edge computing, and 5G/6G network shows a significant improvement in the performance of smart city systems. The significant end-to-end latency reduction can be attributed to the real-time synchronization of physical entities and digital representations that allows the processing and analysis of data and effective decision-making in the shortest possible time frame. These results concur with Mahomed & Saha (2025), who showed digital twin-supported communication, supports real time urban services.

The increases seen in network throughput add to the effectiveness of the presented system by efficiently handling a vast amount of data from myriad IoT devices while upholding stable network performance. Similarly, Xu et al. (2025) noticed similar improvement gains by integrating communication and sensing networks for digital twin driven smart city applications. This decrease in energy consumption is representative of how predictive analytics and intelligent resource management may minimize communication and computation that may not be necessary. This increase in responsiveness under dynamic urban conditions implies that the constant monitoring and simulation provided by digital twin allows for intelligent urban planning and immediate response.

The main innovation of the framework is that it offers an integrated application of IoT sensing, digital twin synchronization, AI, edge computing, and 5G-6G communication into a holistic multi-layer architecture. Traditional cloud-based smart city systems usually consist of real-time virtual city modeling coupled with AI decision-making, and distributed computing power-although the latter does not provide a dynamic virtual city model like the current solution.

Conclusion

A digital twin-based smart city sustainable management framework utilizing IoT devices, 5G/6G networks, artificial intelligence, and edge-cloud computing was designed and proposed in this paper. The multi-layer architecture is well-designed to collect real-time data, synchronize the digital twin in real-time, predict future events, and make an adaptive decision. Based on the experimental analysis, the proposed framework greatly outperformed traditional smart city architectures in terms of communication efficiency, energy-saving efficiency, system responsiveness, and scalability. Combined with digital twin, edge processing, and next- generation network, it can efficiently utilize system resources and support smart city operation in real-time. In this research, the main contribution is to integrate all digital twin, AI, edge computing, and 5G-6G as one system for sustainable smart city management and to achieve scalability and future-proofing. The proposed architecture will be the backbone to enable smart services and sustainable development. The future research would focus on the real implementation of this framework, as well as further introducing advanced AI-native 6G to strengthen system intelligence.

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