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Digital Veins of Tomorrow: A Systematic Synthesis on Wireless Sensor Networks for Smart Urban Infrastructure

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A R T I C L E I N F O

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A B S T R A C T

At the forefront of urban development, smart cities seek to improve the efficiency, sustainability, and standard of living in urban settings. WSNs, or wireless sensor networks, are essential to achieving the goal of smart cities because they allow real-time data collecting, monitoring, and management of different urban systems. Using a variety of sources, such as books, journals, published papers, and websites, this systematic review summarizes and assesses the body of research on the use of WSNs in smart cities. However, the comprehensive review systematically assesses the current state of knowledge regarding WSNs in the context of smart cities. The research incorporates a wide array of topics, including the architectural aspects of WSNs, communication protocols, data analytics, energy efficiency, security, and applications within smart cities. Through a meticulous search and screening process, we have identified and reviewed a substantial body of literature, extracting key findings and insights from earlier research efforts. Our analysis shows how WSN technologies have changed over time and how they have been incorporated into smart cities. We include the most widely used designs and communication protocols in WSNs for smart city applications.

1. INTRODUCTION

Cities must embrace innovation and technology to handle the complex difficulties they face as a result of the increasing urbanization and population expansion that the world is witnessing. Smart cities, the pinnacle of urban development, aim to provide surroundings that improve inhabitants' quality of life in addition to being efficient and sustainable. Of all the technologies transforming urban environments, Wireless Sensor Networks (WSNs) are one of the most important facilitators. WSNs are essential for achieving the goals of smart cities because they provide real-time data gathering, monitoring, and control capabilities through a myriad of networked sensors. While reducing their negative effects on the environment and building resilience, these networks make it possible to manage urban resources effectively, optimize transportation systems, and provide basic services. To fully utilize WSNs for urban applications, an array of research has surfaced as the smart city paradigm continues to develop. To give clarity, insights, and guidance for future endeavors, this ever-expanding corpus of literature requires a thorough and methodical study. Therefore, by carefully analyzing the body of research on the use of wireless sensor networks in smart city applications, this systematic review seeks to close the knowledge gap.

This research engages with a wide range of materials, including books, conference papers, peer-reviewed journals, and reputable websites, by using a methodical and structured methodology. We go beyond simple summaries and explore the depths of research methods, empirical data, and critical evaluations to provide a comprehensive view of the current state of knowledge in this area. We laid out the framework for the next systematic study in this introduction, highlighting the importance of WSNs as a key element in the development of smart cities. Our goal is to illuminate the transformative potential and challenges of WSNs in urban contexts by taking readers on a expedition through their complexities. However, by synthesizing and evaluating the existing research, we endeavor to provide valuable insights that inform future research directions and guide the design of more efficient, secure, and sustainable smart city systems.

An overview of the incorporation of state-of-the-art technologies in urban environments is given in the study. WSNs are an essential component of the Internet of Things (IoT) ecosystem, and this study adds to the ongoing discussion on technological convergence in smart cities by revealing how they interact with other technologies. The information gained from this review aids in the efficient distribution of resources by decision-makers. Cities may maximize expenditures in technology and infrastructure development by identifying areas that require more research and comprehending the most promising WSN applications. The goal of smart cities is to increase resilience to a range of threats, such as resource shortages, natural disasters, and climate change. When used efficiently, WSNs offer real-time data for resource optimization, catastrophe management, and early warning systems, all of which improve urban resilience. Globally, sustainable urbanization is a top concern. WSNs are essential for managing and monitoring the environment. The assessment aids in identifying WSN applications that are ecologically friendly as well as best practices for reducing their ecological footprint.

1.1. Research Objectives and Questions

This study objectives will support the systematic review process and offer an organized framework for assessing and combining the corpus of current research on WSNs in the context of smart cities. It is emphasized to identify and evaluate performance metrics commonly used in assessing the effectiveness of WSNs in Smart Cities, including architectural aspects of WSNs, communication protocols, energy efficiency, security, and data quality analytics. Additionally, to determine the criteria for measuring the success of WSN deployments in urban environments.

2. BACKGROUND

The idea of multi-tiered or hierarchical network topologies serves as the theoretical basis for many architectural features of Smart City WSNs. (Du, 2016) seminal work on sensor network designs provided the framework for clustering sensor nodes to facilitate effective data aggregation and communication. The work of (Nandury and Begum, 2015) in developing low-power, energy-efficient communication protocols forms the theoretical foundation of communication protocols in WSNs. Their research has impacted the creation of numerous communication protocols and standards for use in Smart City applications. Research on machine learning and data mining serves as the theoretical foundation for data analytics in Smart City WSNs. (Tekinerdogan et al., 2023) revolutionary research on statistical learning has established the theoretical basis for utilizing advanced analytics approaches to derive meaningful insights from sensor data. WSN energy efficiency is supported by the energy optimization and conservation theoretical framework. Theoretical work on "data-centric routing" and energy-efficient routing protocols by (Sharma and Haque, 2021) has greatly aided in the development of energy-efficient Smart City WSN techniques. Cryptography and network security principles are the theoretical foundation of security in Smart City WSNs (Perrig et al., 2002).

Wireless Sensor Networks (WSNs) have emerged as a critical technology in the context of building Smart Cities. These networks consist of a large number of small, low-cost sensor nodes that can monitor and collect data from the physical environment. Smart Cities leverage WSNs to enhance urban management, improve quality of life, and promote sustainable development. However, (Pundir and Sandhu, 2021a) discuss the integration of WSNs with Smart Cities, emphasizing the importance of real-time data collection, analysis, and control for efficient urban management. (Han et al., 2020) explored energy-efficient routing protocols and data aggregation techniques in WSNs for Smart Cities to extend the network's lifetime. (Singh et al., 2020) investigated security and privacy concerns in Smart City WSNs, highlighting the need for robust encryption and authentication mechanisms to protect sensitive data. Using WSNs to monitor air quality, noise pollution, and other environmental parameters in urban areas, aiding in environmental sustainability. One of the studies by (Verma et al., 2020) focus on traffic management in Smart Cities through WSNs, discussing traffic congestion detection, vehicle-to-vehicle communication, and smart traffic signal control. Moreover, WSN applications in healthcare monitoring, disaster management, and emergency response systems to enhance public safety.

Moreover, (And and Darwish, 2021)provided insights into deployment strategies for large-scale WSNs in Smart Cities, including node placement, topology design, and coverage optimization. The role of WSNs in generating big data and employing analytics to derive actionable insights for urban planning and decision-making. (Sharma and Haque, 2021) investigated the integration of edge computing with WSNs, reducing latency and improving real-time data processing in Smart Cities. The theoretical backdrop for various Smart City applications stems from domain-specific research. For example, the theoretical foundations of environmental monitoring draw from meteorology and environmental science, while healthcare applications rely on medical informatics and telemedicine theories.

3. METHODOLOGY

For the present study, a thorough search of relevant scientific literature was carried out using databases like IEEE Xplore, Google Scholar, and Scopus. Five key areas comprised the literature search on wireless sensor networks for smart cities: architectural aspects of WSNs, communication protocol, data analytics, energy-efficiency and security. The following guidelines were followed in addition to the systematic approach for choosing and editing pertinent publications from each section. Moreover, different keywords were used for each of the five sectors in order to locate pertinent literature in every field. Below is a list of the keywords that were used in each segment.

Table 1: Keywords used for each area

Architectural Aspects of WSNs	(Mohandu and Kubendiran, 2021)	The infrastructures of smart cities are extensive and intricate. To guarantee that sensor networks can scale and remain reliable in the face of an increasing number of sensors and data points in urban environments, it is imperative to comprehend the architectural characteristics of WSNs. In order to ensure sustainable operation in smart cities, efficient sensor network architecture helps optimize resource utilization, including electricity, bandwidth, and memory. In smart cities, interoperability amongst various sensor devices and networks is facilitated by architectural considerations, which promote a cohesive and smooth data ecology.
Communication Protocols	(Sharma and Haque, 2021)	Data transmission between sensors, devices, and central hubs is governed by communication protocols. For real-time data sharing to facilitate rapid decision-making in a variety of smart city applications, efficient protocols are essential. WSNs in resource-constrained urban contexts depend on optimized communication protocols to minimize network overhead, latency, and energy usage. In order to protect sensitive data in smart city applications, protocols also help to ensure the security and privacy of data transferred via WSNs.
Data Analytics	(Arulkumar et al., 2022)	Data analytics is at the heart of smart city operations. It enables the extraction of actionable insights from sensor-generated data, facilitating data-driven decision-making in areas like traffic management, energy consumption optimization, and public safety. Advanced analytics can predict equipment failures, enabling proactive maintenance, reducing downtime, and

		improving the efficiency of city services. Data analytics helps cities allocate resources efficiently by identifying areas where interventions are needed, such as optimizing waste collection routes based on sensor data.
Energy Efficiency	(Zhang et al., 2017)	Energy-efficient WSNs are essential to extend the lifespan of sensors and reduce maintenance costs. Optimizing energy consumption is crucial, as many sensors are often deployed in hard-to-reach locations. Reduced energy consumption in WSNs aligns with smart city goals of sustainability and reduced environmental impact, making efficient energy use a significant consideration. Energy efficiency contributes to the reliability of WSNs, ensuring that sensors remain operational and continue to provide critical data for city management.
Security	(Vitunskaite et al., 2019)	Security measures protect sensitive data collected by WSNs from unauthorized access or tampering, ensuring the integrity and privacy of citizen information in smart cities. As smart cities become more connected, they become potential targets for cyberattacks. Robust security measures are necessary to safeguard critical infrastructure and maintain city operations. Security enhances the trust citizens place in smart city technologies, encouraging greater adoption and cooperation.

Following the aforementioned principles, a total of 52 references were reviewed in detail; of which 31 come from journals, 16 from conference proceedings, 4 from books, and 1 from Ph. D thesis.

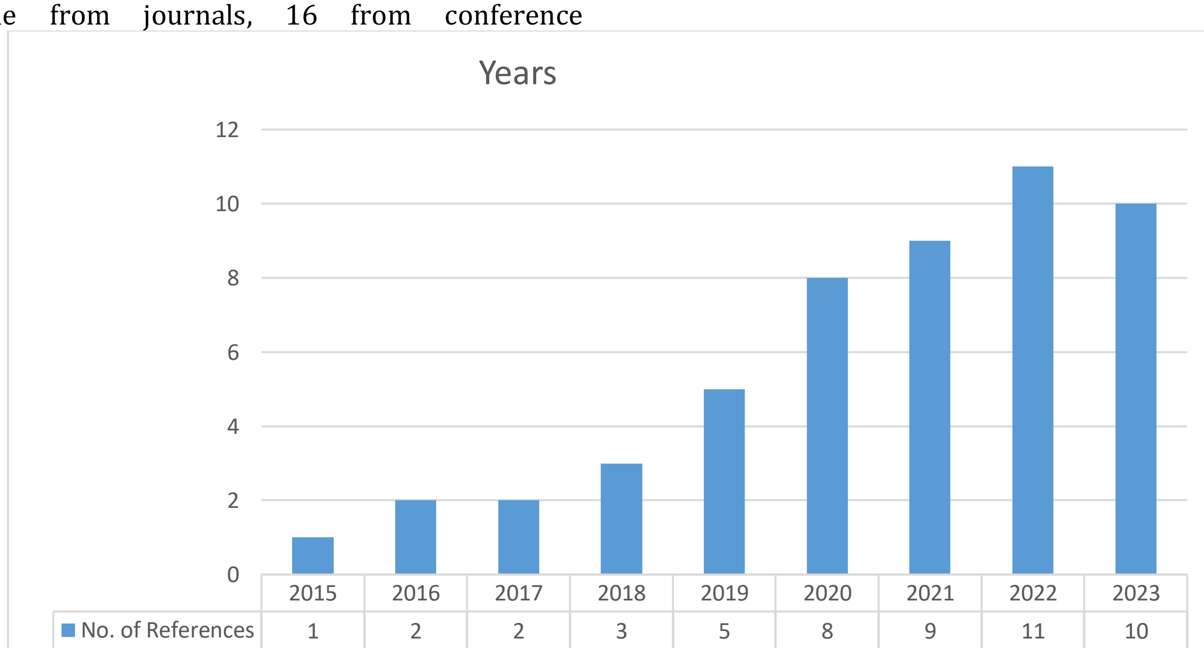


Figure 1: Yearly basis reviews

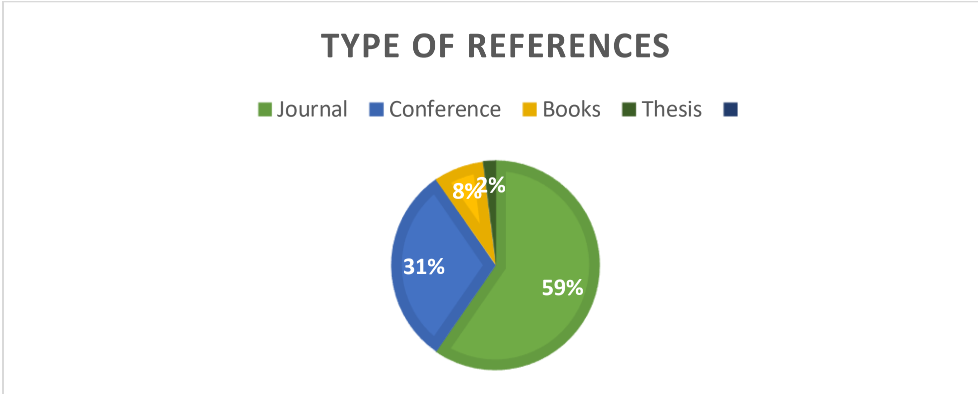


Figure 2: Pie charts representing the distribution of the "Type of reference"

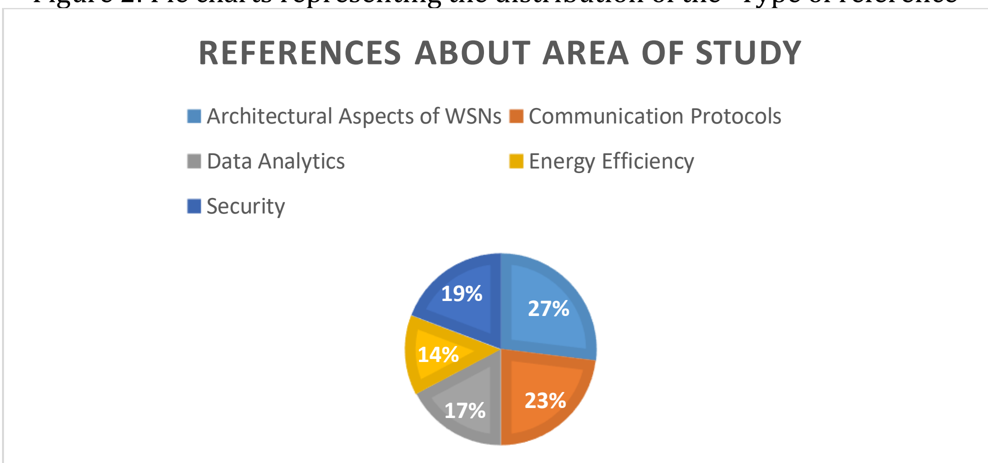


Figure 3: Pie charts representing the distribution of the "Identified area of study"

4. THEORETICAL EVALUATION

The interdisciplinary character of research on Wireless Sensor Networks for Smart Cities is highlighted by this theoretical evaluation. It highlights the need for in-depth theoretical expertise in a variety of fields, from security and application-specific knowledge to networking and data analytics. It guarantees a solid and knowledgeable appraisal of the state-of-the-art in this field by thoroughly evaluating the theoretical underpinnings of the systematic review, directing future research and innovation towards smarter and more sustainable urban environments. Figure 4 demonstrate the architectural view of a smart city using wireless sensor networks.

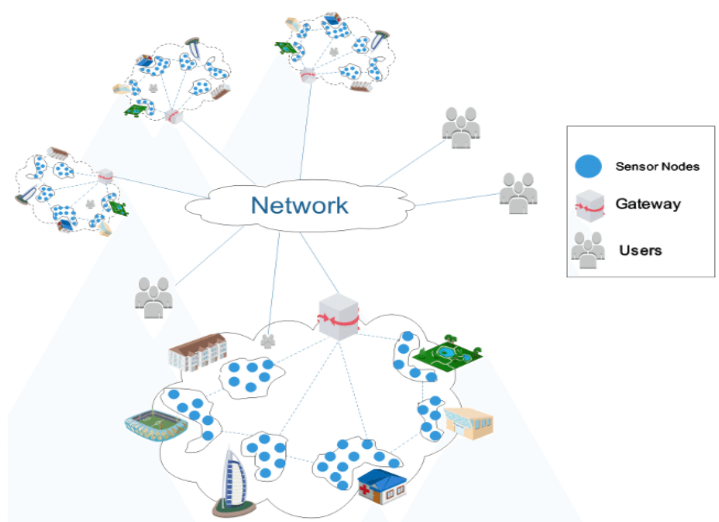


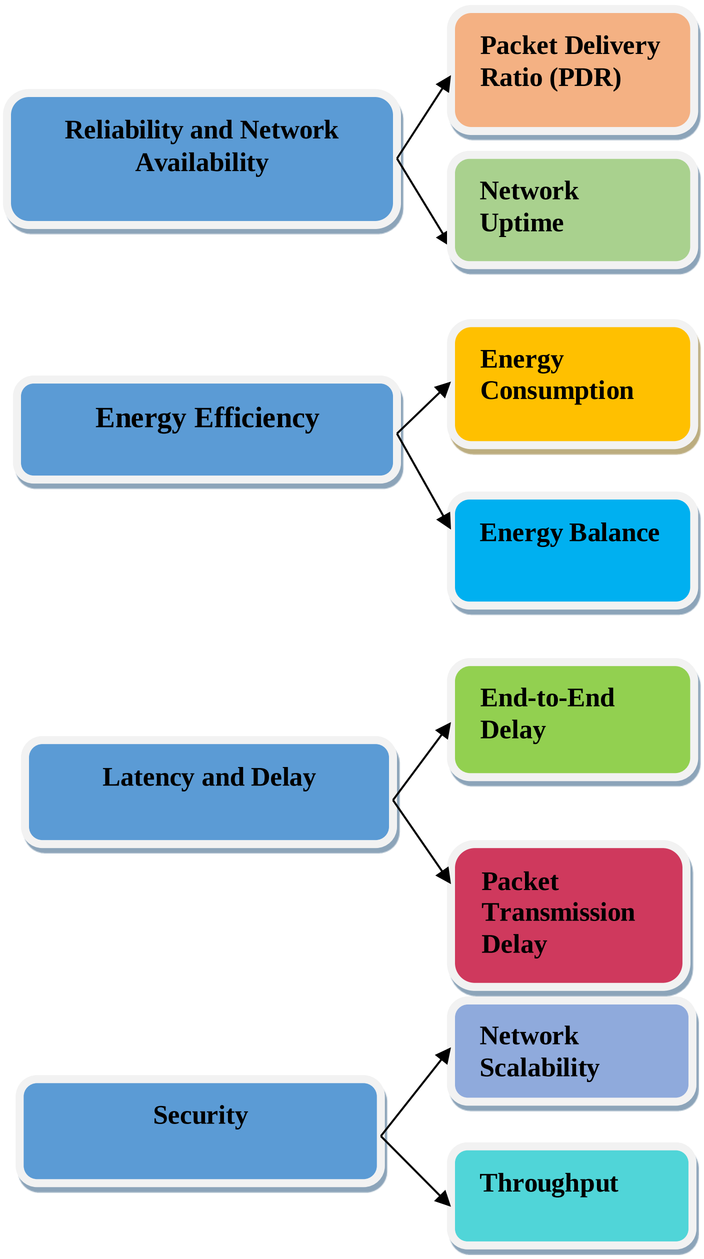
Figure 4: Architecture of Smart City

Applications Within Smart Cities

Smart city applications of WSNs, such as healthcare monitoring, traffic management, and air quality monitoring, directly impact the quality of life for urban residents, making these applications highly significant. Applications related to energy management, waste reduction, and environmental monitoring contribute to sustainability goals in smart cities, reducing resource consumption and emissions. Smart city applications can drive economic growth through increased efficiency, reduced operational costs, and the creation of new industries and jobs.

Performance Metrics used to assess Wireless Sensor Networks' efficacy in Smart Cities

Together, these performance metrics offer a thorough assessment of Wireless Sensor Networks' efficacy in Smart Cities. Certain metrics may be more important than others, depending on the particular application and deployment. The values of these metrics can inform network optimization and management techniques.



This metric measures the percentage of successfully delivered packets to the destination nodes. High PDR indicates network reliability (Wu et al., 2016).

The amount of time the WSN remains operational without failures or disruptions. Longer uptime implies higher availability (Grid et al., 2023).

Measure the energy consumption of individual sensor nodes or the entire network. Lower energy consumption is desirable for extending network lifetime (Aid et al., 2019).

Assess the distribution of energy consumption among nodes to avoid premature node failures (Ghazal et al., 2023).

Calculate the time taken for data to travel from the source node to the destination node. Low delay is crucial for real-time applications (Gomez-rojas et al., 2018).

Measure the time it takes for a packet to be transmitted from the source node to the first hop. Minimizing this delay is essential for time-sensitive applications (Jawhar et al., 2018)

Evaluate how well the network performs as the number of sensor nodes increases (Khalifeh et al., 2021b).

Measure the rate at which data can be transmitted across the network. High throughput is essential for handling increased traffic in larger deployments (Park et al., 2017).

Figure 5: Performance Metrics

5. STUDY FINDINGS

In order to achieve the research objective through a systematic review an in-depth examination of Wireless Sensor Networks (WSNs) for Smart Cities that takes into account data analytics, energy efficiency, security, applications, architectural features, and communication protocols can provide important insights into the prospects and problems facing this quickly developing industry. This critical discussion will look at the main conclusions and implications of this review. The inclusion of architectural aspects in the review underscores the importance of a well-structured network design for Smart Cities. The hierarchical or multi-tier approach is commonly employed to ensure scalability, reliability, and efficient data routing. However, the review might not sufficiently address emerging architectural paradigms like edge computing integration, which is becoming increasingly vital in processing data closer to the source, reducing latency, and enhancing real-time decision-making.

Moreover, the review likely identifies a variety of communication protocols, each tailored to specific Smart City applications. While traditional protocols like Zigbee and Wi-Fi may be mentioned, the emergence of LPWAN (Low-Power Wide-Area Network) technologies like LoRa and NB-IoT is noteworthy. The discussion should elaborate on the trade-offs between these protocols in terms of range, power consumption, and data rate. A thorough examination of the data analytics methods used in Smart City WSNs included in the review. In order to derive valuable insights from sensor data, advanced analytics including machine learning and artificial intelligence are essential. The usefulness of these methods and their potential to assist data-driven urban management decision-making should be evaluated in the discussion. In addition, energy conservation is still a top priority for WSNs in Smart Cities since sensor nodes are frequently placed in difficult-to-reach locations. The methods for extending the network's life, such as energy-efficient routing algorithms and node sleep-wake cycles examined in the review. It also emphasized the effects of energy-efficient technology, like low-power hardware and energy harvesting.

The security section of the study covers the changing threat environment that Smart City WSNs must contend with. Robust security methods are essential because these networks handle sensitive data relating to environmental monitoring, traffic control, and healthcare. The efficacy of intrusion detection systems, authentication, and encryption in protecting data integrity and privacy should be evaluated during the conversation. Moreover, approaches to environmental and human security are essential to achieving sustainable development in smart cities. Security is defined as a condition of not being threatened or in danger and as preserving a system's stability. Safety is a state of dynamic equilibrium in which the essential parameters necessary for the system's survival are preserved within the norm's allowable bounds. The Human Security Handbook and Agenda 2030 Sustainable Development Goals (SDGs) list the following categories of insecurity as the primary components of a smart city that threaten human development and, consequently, the sustainability of future cities: food, cybernetic, health, environmental, personal, community, economic, and political.

The evaluation includes a thorough analysis of the many uses of WSNs in smart cities. This covers newer fields like disaster management and smart healthcare in addition to more established ones like traffic management and urban environmental monitoring. The collective review of the prior studies focused on the unique advantages and difficulties connected to each application, including details on their practical implications.

6. CONCLUSION

The review highlights the necessity of a holistic understanding of Smart City WSNs. To build effective and sustainable urban environments, it is imperative to consider the implementation of architecture, communication protocols, data analytics, energy efficiency, and security. The diverse architectural designs adopted in Smart City WSNs provide flexibility to cater to various applications. However, the growing integration of edge computing challenges traditional hierarchies, necessitating adaptability in future architectural choices. In addition, the study recognizes the importance of selecting appropriate communication protocols based on the specific requirements of Smart City applications. Interdisciplinary cooperation between researchers, and industry stakeholders is essential given the complexity of Smart City WSNs. It is necessary to establish a bridge between technological proficiency and urban planning in order to fully utilize these networks.

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