

Distributed Real-Time Monitoring Systems for Smart Street Lighting Networks

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ABSTRACT

Inefficient monitoring and limited control in public street lighting systems often lead to increased operational costs and reduced system reliability. However, many existing lighting networks still rely on limited monitoring and control mechanisms, leading to inefficient maintenance and increased operational costs. This study investigates whether a distributed multi-parameter monitoring architecture using low-power wireless communication can improve the reliability and scalability of public street lighting systems compared to conventional centralized approaches. This study proposes a smart street lighting monitoring system based on a distributed monitoring architecture using low-power wireless communication. The system integrates environmental and electrical sensing with real-time scheduling and a wireless monitoring network to support continuous observation and remote operational control of lighting nodes. Experimental evaluation shows that the communication network maintained stable connectivity up to 100 m without packet loss, while supporting reliable data transmission suitable for sensor-based monitoring applications. The system also demonstrated responsive operation and high communication reliability during real-time monitoring. The results demonstrate that the integration of multi-parameter monitoring with mesh-based wireless communication enables reliable real-time data exchange and scalable node-to-node operation in street lighting systems. This approach provides a practical monitoring framework that can be implemented

by urban infrastructure operators to improve maintenance efficiency and reduce operational complexity. The findings highlight the potential of distributed communication architectures to enhance monitoring reliability without reliance on centralized systems. Future work will focus on large-scale deployment and communication optimization in complex urban environments.

Keywords-communication network; IoT (Internet of Things); public street lighting system; real-time monitoring

I. INTRODUCTION

Public Street Lighting (PSL) networks consist of distributed lighting infrastructures that operate continuously to support nighttime visibility and public safety. However, conventional PSL systems remain inefficient due to high energy consumption, limited adaptability to environmental conditions, and costly maintenance [1]. Although the introduction of Light Emitting Diode (LED) lamps and Light Dependent Resistor (LDR)-based automation has reduced power usage and improved reliability, these solutions still require effective monitoring to detect faults, optimize usage, and extend service life [2, 3]. This highlights the urgent need for smart monitoring systems that can ensure both energy efficiency and long-term sustainability of PSL networks.

PSL represents a significant component of urban infrastructure and requires efficient management to ensure reliable operation. Lighting systems can account for a substantial portion of municipal electricity usage, highlighting the importance of efficient monitoring and management strategies. As urban infrastructure continues to expand, the need for scalable and reliable monitoring systems becomes increasingly critical to ensure effective operation and maintenance of distributed lighting networks [4, 5]. In recent years, the Internet of Things (IoT), defined as a network of interconnected devices capable of collecting and exchanging data, has been widely applied to enhance PSL management by integrating sensors, microcontrollers, and communication platforms [6]. These technologies have become an important enabler for intelligent infrastructure management in modern smart city environments. Several studies have demonstrated the benefits of IoT-based systems, such as reduced downtime and improved maintenance efficiency [7]. However, many of these implementations remain limited to single-parameter control, such as monitoring only light intensity or switching schedules. Others lack robust real-time adaptability or rely heavily on centralized architectures, which restrict scalability in large deployments [8]. These limitations suggest that existing systems are not yet fully capable of addressing the operational challenges of modern PSL. This condition highlights the urgent need for monitoring architectures capable of ensuring reliable real-time data exchange and scalable communication between distributed lighting nodes, particularly in rapidly growing urban environments.

Wireless communication technology plays a crucial role in determining the scalability and reliability of PSL systems. Wi-Fi communication provides high data throughput but typically requires higher power consumption and has limited coverage in outdoor environments. LoRa technology enables long-range communication with low power consumption, but its relatively low data rate can limit its effectiveness for frequent real-time monitoring applications. NB-IoT ensures wide coverage and

reliable connections but depends on telecommunication infrastructure, introducing additional operational costs. Zigbee technology has also been widely applied in wireless sensor networks due to its low-power operation and support for mesh networking, although configuration complexity and scalability can become challenging in large network deployments [9]. In comparison, XBee, which is based on the IEEE 802.15.4 standard, provides lower power consumption, easier configuration, and robust mesh networking capabilities suitable for distributed sensor networks [10, 11]. Experimental studies have demonstrated reliable communication performance of XBee modules in wireless sensor network environments. These characteristics make XBee a promising communication solution for mid-range real-time monitoring applications in PSL systems. Furthermore, adaptive street lighting systems have been recognized as an important approach for improving the operational efficiency and scalability of urban lighting infrastructure [12].

To address the limitations of existing street lighting monitoring systems, this study proposes an IoT-based PSL monitoring system that integrates multiple sensors, a Real-Time Clock (RTC), and an ESP32 microcontroller with XBee wireless communication modules. The proposed system supports real-time monitoring and adaptive control through web and mobile dashboards, allowing users to simultaneously observe illumination levels, electrical parameters, and operational schedules. Unlike earlier approaches, the proposed design emphasizes multi-parameter monitoring, mesh-based communication, and practical scalability designed for scalable deployment in regions where cost efficiency and independence from telecommunication infrastructure are important considerations. By combining these features, the proposed system contributes a reliable, energy-efficient, and sustainable solution for modern street lighting [13].

Several studies have investigated the development of automated public street lighting systems using sensor-based control mechanisms [6, 14]. Early implementations primarily utilized LDR sensors to enable basic illumination control and automatic switching of street lighting systems [15-17]. Although these approaches demonstrated the feasibility of automated lighting control, they typically lacked integration with IoT platforms and therefore did not support real-time monitoring or remote management capabilities [18]. Subsequent studies introduced additional components such as LED lamps and solar energy systems to improve energy efficiency and enable renewable-powered lighting solutions [19, 20]. These systems successfully reduced energy consumption through automated lighting control; however, many of them provided limited monitoring functionality and lacked real-time remote management features.

More recent research has incorporated IoT technologies and additional sensing devices, including Passive Infrared (PIR) sensors and electrical monitoring modules, to enhance system intelligence and enable web-based monitoring interfaces [21, 22]. Although these implementations improved automation and provided basic monitoring capabilities, challenges remain in terms of control optimization, monitoring reliability, and scalability for larger deployments.

These limitations indicate that many existing PSL systems still rely on single-parameter monitoring or centralized architectures, which restrict their ability to support scalable and reliable infrastructure management. Three key research gaps can be identified. First, many existing systems rely on single-parameter monitoring, which limits their ability to capture comprehensive operational conditions. Second, centralized architectures introduce scalability constraints and potential single points of failure. Third, existing communication technologies often fail to balance power consumption, data rate, and reliability for real-time monitoring. To address these challenges, this study proposes a smart PSL monitoring architecture that integrates multiple sensing parameters, real-time clock synchronization, and mesh-based wireless communication using XBee modules. By combining distributed monitoring with low-power wireless communication, the proposed system aims to improve the reliability, scalability, and operational efficiency of modern street lighting networks.

II. PROBLEM STATEMENT AND PRELIMINARIES

Although IoT-based PSL systems have been widely studied, existing solutions still face several important limitations. Prior works have primarily focused on reducing energy consumption through LED and sensor-based automation, yet most implementations were restricted to monitoring a single parameter, such as illumination or switching schedules [23, 24]. Other approaches enabled remote monitoring but lacked the ability to integrate multi-parameter data, including current, voltage, and illumination levels, into a single platform [25]. In addition, many solutions were dependent on centralized architectures, limiting scalability and reliability when deployed in large networks. These limitations reveal a gap in providing a PSL framework that is real-time, multi-parameter, and scalable, while remaining cost-effective for practical use in developing regions.

Another key challenge lies in wireless communication. Wi-Fi delivers high throughput but is power-hungry and unsuitable for outdoor deployment on a large scale. LoRa offers long-distance communication with very low energy consumption, but its data rate is insufficient for real-time monitoring. NB-IoT provides wide coverage and stability but requires licensed spectrum and recurring subscription costs, creating operational dependency on telecom providers. Zigbee, although widely applied in wireless sensor networks, becomes complex and less efficient when extended to large mesh deployments. Therefore, none of these technologies fully satisfy the combined requirements of low power, sufficient throughput, scalability, and independence from telecom infrastructure needed for PSL applications [26, 27].

To address these challenges, this research adopts XBee wireless modules as the communication backbone. XBee, based on IEEE 802.15.4, combines the benefits of low power consumption, mesh topology support, and simplified configuration, making it a balanced solution for real-time, medium-range PSL deployments. The system is supported by the ESP32 microcontroller, which offers strong processing capability and native connectivity for sensor integration. A Real-Time Clock (RTC) is employed to ensure accurate scheduling of lighting operations, while multi-sensor integration (LDR, voltage, and current sensors) enables simultaneous monitoring of illumination and electrical parameters. Together, these components establish the technical foundation for a PSL monitoring system that is adaptive, reliable, and scalable.

In summary, the research problem can be formulated as follows: how to design and implement a PSL monitoring system that integrates multi-parameter sensing, adaptive RTC-based control, and reliable mesh communication, in order to overcome the limitations of existing IoT-based solutions. The preliminaries described above provide the theoretical and technical basis for the proposed design.

III. MATERIALS AND METHODS

A. System Architecture

The proposed smart PSL system consists of Smart Grid Modules (SGM) connected to a Smart Grid Coordinator (SGC). Each SGM node is equipped with sensors, an RTC, an ESP32 microcontroller, and an XBee module for wireless communication. The SGC collects data from all SGM nodes and transmits it to a monitoring dashboard. The communication is bidirectional: SGM nodes send sensor data to the coordinator, while the dashboard provides remote control commands back to the nodes. Figure 1 provides a block diagram of the system architecture.

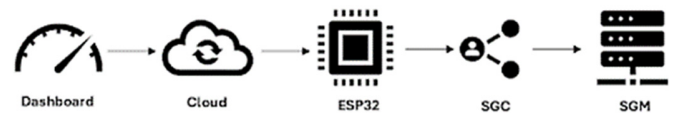


Fig. 1. Architecture of the proposed smart PSL monitoring system, showing SGMs, the SGC, and the monitoring dashboard connected through a mesh-based XBee network for real-time multi-parameter monitoring and control.

Each SGM is designed as an autonomous edge node responsible for local sensing, decision-making, and actuation, integrating multiple sensors, an RTC, and an embedded controller. The SGC serves as a centralized aggregation and coordination unit, collecting multi-parameter data from distributed SGMs via a mesh-based XBee communication network and forwarding the data to the monitoring dashboard. In addition to data acquisition, the SGC enables bidirectional communication by relaying control commands from the dashboard to individual SGMs, thereby supporting real-time monitoring and adaptive control of the lighting infrastructure.

B. Hardware Components

Each SGM node is built around an ESP32 dev module (Espressif ESP32-WROOM-32) with a dual-core 240 MHz processor and integrated wireless connectivity, selected for its dual-core processor, integrated Wi-Fi and Bluetooth, and low-power operation suitable for outdoor IoT applications. Illumination sensing is performed using an LDR GL5528, configured as a voltage divider to detect ambient light intensity. Electrical parameters are monitored using an ACS712-20A current sensor for AC load current measurement and a ZMPT101B voltage sensor module for AC voltage sensing. Time synchronization and scheduling are supported by a DS3231 RTC module, chosen for its high accuracy and temperature-compensated crystal oscillator. Load switching was implemented using a 5 V single-channel relay module, connected to the ESP32 GPIO pins. Wireless communication between SGMs and the SGC was implemented using XBee S2C modules (IEEE 802.15.4, 2.4 GHz) configured in a mesh topology, enabling multi-hop communication. Power for each SGM was supplied from a 220 V AC source and converted to regulated 5 V DC using an isolated AC-DC power supply module.

All hardware components were configured using standard operating parameters to ensure consistent system performance. The ESP32 microcontroller was programmed using Arduino IDE version 2.x, and the XBee S2C modules were configured using XCTU software with mesh networking enabled (API mode). The communication operated at a frequency of 2.4 GHz with default transmission power settings. Sensor calibration was performed before testing to ensure measurement accuracy, particularly for voltage and current sensing modules.

C. Software and Control Algorithm

The control logic was implemented using Arduino IDE, and the Message Queuing Telemetry Transport (MQTT) protocol was used for data exchange between the ESP32 and the monitoring server. The dashboard displays the operational status of each lamp in real time. The core algorithm operates as follows:

- If the RTC indicates nighttime, the ESP32 activates the relay to switch on the light.
- During the day, the system automatically switches off the lights.
- The ESP32 continuously collects data from sensors and transmits it to the dashboard through XBee modules. This ensures both automatic scheduling and continuous monitoring of PSL operations.
- This enables synchronized lighting schedules, continuous multi-parameter monitoring, and remote control of street lighting infrastructure.

D. Range Testing

Range testing was conducted to evaluate the signal quality of XBee modules under outdoor conditions. Measurements were taken at 10, 50, 100, and 150 m distances, with environmental obstacles such as trees and nearby structures present. Communication quality was evaluated using Received

Signal Strength Indicator (RSSI) values, while packet delivery ratio and success rate were used as performance metrics. Each measurement was repeated three times, and the average values were used for analysis.

E. Throughput Testing

Throughput tests were conducted to measure the data transfer rate between SGM nodes and the SGC. The tests involved transmitting packets in kilobyte (kB) units, and throughput was calculated in terms of successful data per second. This evaluation provided insights into the communication reliability and latency of the mesh network under varying distances.

F. Real-Time Monitoring Capability

Real-time monitoring performance was evaluated by measuring the delay between sensor data acquisition at the SGM node and its visualization on the monitoring dashboard. Delay was measured by comparing timestamps recorded during sensor acquisition and dashboard display. The system was designed to maintain a delay of less than 5 s, which is considered sufficient for practical street lighting monitoring applications.

G. Deployment and Validation

The system was deployed on a public roadway with three SGM nodes configured in a mesh network. The system was evaluated for communication stability and real-time monitoring functionality in an outdoor environment with physical obstacles. Testing was limited to a small-scale deployment, and long-term endurance evaluation was not conducted. These results validate feasibility on a limited scale, whereas scalability and energy consumption optimization remain areas for future work.

IV. RESULT

A. Implementation of a Smart Street Lighting System Prototype

The implementation served as a model for an open road lighting framework that utilizes IoT and XBee communication. The equipment involves light sensors, current sensors, voltage sensors, an RTC module, and an ESP32 microcontroller with WiFi and Bluetooth capabilities. For communication, the framework utilizes XBee modules (S2C arrangement) designed in point-to-multipoint mode.

Each light is an SGM. The SGC accepts data from numerous SGMs and transmits them to the server through WiFi or GSM. It also reacts to control commands from the dashboard. The proposed framework can improve efficiency, lighting quality, and offer improved ways for street lighting management. The system was successfully implemented with significant advantages, such as real-time remote control capabilities. As stated in [28], smart systems like this can increase energy savings by up to 80% compared to traditional street lighting systems.

In field implementation, the system was tested by installing it on modified streetlights. Figure 2 shows the device created, which integrates the control module and XBee communication

system with LED lights. With this system, maintenance can be performed more quickly and efficiently without the need for manual inspections directly at the streetlight location.



Fig. 2. Prototype street light using XBee.

This proposed road lighting framework can essentially decrease power utilization while keeping up client comfort and security [29]. In addition, a web-based system was developed, enabling directors to see the status of each light in real-time. The displayed information consolidates voltage, current, lighting level, and light status (energetic, torpid, or falling flat).

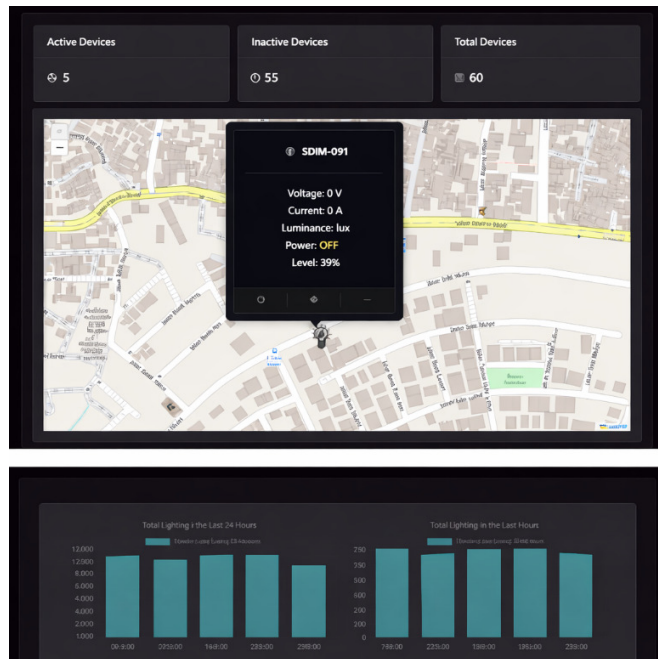


Fig. 3. Smart street lighting monitoring website interface.

The operational status of each lamp is also shown, enabling managers to easily determine whether the lamp is functioning properly or experiencing problems. With this system, maintenance processes can be carried out more quickly and effectively without the need for manual on-site inspections at the street lamp location. In [30], energy, cost efficiency, and lower power consumption were confirmed compared to before using the smart system.

B. XBee Signal Range Testing

The testing process began with assessing the communication range of the XBee module, which aimed to

understand how well the light nodes could connect to the street lighting system. A Radio Range Test was used to assess signal strength and communication stability between XBee modules. The testing was conducted on Sidomukti Street with several distance scenarios to find the optimal system performance.

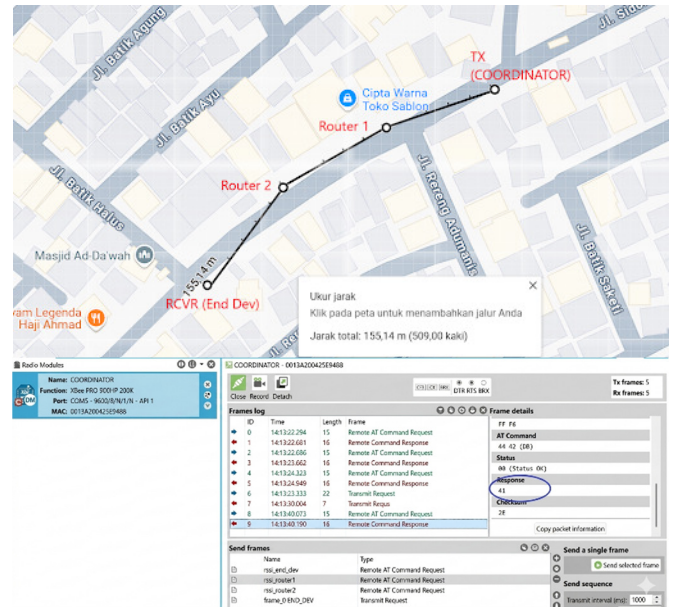


Fig. 4. Communication range testing.

Wireless communication range testing was conducted in an outdoor area. Testing involved steadily expanding the distance by 50 m until it reached 155.14 m between the transmitter and the collector. The normal RSSI values measured at both hubs were roughly -48 dBm at 50 m, -59 dBm at 75 m, and -68 dBm at 100 m. This demonstrates an adequately steady connection, maintaining association quality between XBee hubs. At a distance of 100 m, all data packets sent during the testing were successfully received by the remote node, recording a 100% success rate with no packet loss. This indicates that the XBee communication system is highly reliable in outdoor situations. However, at a distance of 150 m, the success rate only reached 40-50% due to interference from the densely populated residential environment. This indicates that as the distance increases, the signal weakens.

The proposed XBee-based smart street lighting system can provide reliable communication up to 100 m with 100% packet delivery success, while performance degrades at 150 m due to environmental interference. This finding is consistent with [31], which reported that throughput stability in wireless sensor networks based on IEEE 802.15.4 remains consistent under moderate distances but decreases as the number of hops increases. Our results extend these observations by validating that even at medium-range distances, XBee can sustain packet integrity and low latency, which is critical for real-time monitoring of public infrastructure. Compared to previous IoT-based street lighting systems that primarily relied on Wi-Fi or LoRa [21, 22], the proposed approach demonstrates a more balanced trade-off between range, power consumption, and

D. Dashboard Functionality Testing

This test was conducted to determine and ensure that all dashboard features are functioning properly. This testing stage was conducted by examining all the features of the system.

In addition to the above test results, a questionnaire was distributed to various users to evaluate their understanding, perceived benefits, and suggestions about the PSL dashboard system. 85% of users agreed that the dashboard was easy to

use, indicating that its design was intuitive and user-friendly, while 73% were satisfied with their experience using the dashboard. Most respondents stated that they understood the dashboard's functions and that it supported their work activities, particularly in managing and monitoring streetlights in real-time, detecting disruptions, and viewing energy usage statistics. The real-time monitoring feature was considered the most beneficial.

TABLE I. DASHBOARD FUNCTIONALITY

Test scenarios	Action	Expected results	Test Results	Conclusion
Log in to the dashboard	Enter the Website URL	Home screen view	Home screen view	Appropriate
Viewing the lights in realtime monitoring	Zoom in the maps (Specific locations)	Can view the light on the real-time monitoring.	Can see the light on the real-time monitoring.	Appropriate
Realtime notification and monitoring value	Clicking the refresh button	Can see the notification and light monitoring status.	Can see the notification and light monitoring status.	Appropriate
Viewing history	Clicking the history button at the top navigation	Can see history and graphic over the last 24 hours.	Can see history and graphic over the last 24 hours	Appropriate
Viewing and managing the devices	Clicking the devices button and manage device availability.	Display the list of devices and manage add or remove devices.	Display the list of devices and manage add or remove devices	Appropriate

The user evaluation of the dashboard further highlights the practicality of the system, with 85% of respondents rating it easy to use. This result is comparable to the usability scores reported in [19], which presented a solar-powered smart street lighting system with web-based monitoring but noted limitations in interface intuitiveness. The positive user feedback indicates that the dashboard design enhances operational efficiency by simplifying remote monitoring and fault detection.

In terms of generalizability, while the current deployment was limited to three nodes in a small-scale test environment, the mesh topology of XBee provides scalability potential for wider urban applications. Previous large-scale smart lighting deployments [30] demonstrated significant energy savings when real-time control was implemented. The proposed architecture may be particularly beneficial in urban infrastructure environments where telecom-independent communication solutions are required.

However, this study acknowledges limitations: (i) large-scale validation across hundreds of nodes is still required, (ii) long-term endurance and environmental resilience (rain, temperature, interference) were not tested, and (iii) energy savings were inferred rather than measured directly. Addressing these aspects in future work will strengthen the evidence base and enhance the transferability of the system to larger smart city deployments.

In summary, the proposed XBee-based system demonstrates (a) reliable medium-range wireless communication for real-time monitoring, (b) integration of multi-parameter sensing with RTC scheduling, and (c) a user-friendly dashboard that supports practical adoption. These features collectively advance the state of smart street lighting systems beyond single-parameter or centralized solutions, positioning the system as a scalable and sustainable option for modern public lighting infrastructures. The proposed system also supports adaptive lighting operation through real-time monitoring and scheduling, which can contribute to reducing

unnecessary illumination and improving energy efficiency. This capability is aligned with emerging lighting regulations that emphasize minimizing energy waste and environmental impact.

V. DISCUSSION

The experimental results demonstrate that the proposed PSL monitoring system can support reliable real-time monitoring and communication among distributed lighting nodes. Range testing shows that the XBee-based mesh communication network maintains stable connectivity within the tested distances, while throughput measurements confirm that the network can transmit multi-parameter sensor data required for monitoring illumination levels as well as electrical parameters such as voltage and current. These results indicate that the proposed architecture is suitable for medium-range monitoring of PSL infrastructure.

Compared to previous IoT-based PSL implementations, many existing systems focus mainly on automated switching or illumination-based control using LDR sensors and microcontroller platforms [4, 5]. Although these approaches demonstrate basic automation capability, they often lack integrated monitoring of electrical parameters, which limits their ability to support predictive maintenance and operational diagnostics [6]. Other studies have incorporated IoT connectivity and web-based monitoring platforms to improve system visibility and maintenance efficiency [11, 21]. However, many of these implementations rely on single-parameter sensing or centralized communication architectures, which may limit scalability and operational flexibility in larger lighting networks [22]. In contrast, the proposed system integrates multiple sensing parameters, including illumination, current, and voltage measurements, within a unified monitoring platform, enabling more comprehensive monitoring. In addition, the use of mesh-based wireless communication improves network resilience by allowing multi-hop data transmission, which is more suitable for distributed infrastructures compared to centralized approaches. This

difference explains the improved communication stability observed in the experimental results, particularly for medium-range deployment scenarios.

From an operational perspective, efficient monitoring and low-power wireless communication can contribute to more optimized energy usage in street lighting infrastructure. By enabling continuous observation of electrical parameters and lighting conditions, the proposed system supports improved operational management and maintenance strategies. In this context, energy efficiency refers to optimized operational energy usage and efficient communication within the monitoring network rather than the sustainability of primary energy sources or renewable energy generation. Nevertheless, several limitations of this study should be acknowledged. The experimental validation was conducted using a small-scale deployment consisting of three monitoring nodes under specific environmental conditions. Although the results obtained demonstrate stable communication performance in the tested environment, larger deployments may introduce additional challenges such as signal interference, network congestion, or physical obstacles that may affect communication reliability. Therefore, these results should be interpreted as feasibility validation rather than a comprehensive evaluation of large-scale infrastructure deployment.

Future research should investigate large-scale deployment scenarios and evaluate the communication performance of the proposed architecture under more diverse environmental conditions. Advanced analytical approaches, including simulation models and digital twin technologies, may provide additional insights for predicting system behavior and assessing techno-economic feasibility before real-world implementation. Further studies are also required to analyze long-distance communication performance and optimize energy consumption in smart street lighting networks.

Overall, the proposed system provides a practical framework for integrating multi-parameter monitoring with mesh-based communication in PSL systems. It demonstrates that a distributed architecture can achieve reliable real-time communication and scalability without reliance on telecommunication infrastructure. This enables improved fault detection, more efficient maintenance, and enhanced operational visibility. From a performance perspective, the system achieves 100% packet delivery up to 100 m, throughput of 1.96–2.38 Kbps, and communication delay below 5 s, indicating reliable support for real-time monitoring. Although energy savings were not directly quantified, continuous monitoring and anomaly detection can contribute to more efficient system operation and reduced maintenance overhead.

VI. CONCLUSIONS

This study demonstrates that a distributed monitoring architecture, integrating multi-parameter sensing with mesh-based XBee wireless communication, can provide a reliable framework for managing PSL networks. The proposed system enables stable bidirectional communication between lighting nodes and the control center, supporting real-time monitoring and operational control of the street lighting infrastructure. Experimental validation indicates that the communication

network maintained stable connectivity up to 100 m without packet loss, while supporting a data transmission rate of approximately 2.38 Kbps, which is sufficient for sensor-based monitoring applications. The integration of environmental and electrical sensors with real-time scheduling enables responsive system operation with sub-second response time and high communication reliability. In addition, the centralized dashboard simplifies the monitoring and maintenance processes, improving operational efficiency.

The results suggest that the proposed IoT-based monitoring architecture, which integrates multi-parameter sensing with mesh-based wireless communication, can improve monitoring capability and operational efficiency in distributed street lighting systems. The proposed approach has potential as a scalable monitoring solution for smart street lighting infrastructure and may support the development of practical IoT-based monitoring architectures for urban infrastructure management.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing interests that could have influenced the results of this study.

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DATA AVAILABILITY

This study did not use any datasets. The data collected are available from the corresponding author upon reasonable request.

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