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IoT-Based Public Street Lighting Monitoring and Control System Using LoRa Communication

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ABSTRACT

Public Street Lighting (PSL) systems are important infrastructures that support road safety, reduce criminal activity, and improve public comfort during nighttime conditions. However, conventional PSL systems still experience several limitations, including inefficient energy consumption, delayed maintenance processes, and the absence of real-time monitoring capabilities. This study aims to design and implement an Internet of Things (IoT)-based public street lighting monitoring and control system using LoRa communication technology and the MQTT protocol. The proposed system integrates ESP32 microcontrollers, LoRa E220-900T30D communication modules, Raspberry Pi gateway devices, MQTT brokers, and Node-RED dashboards. The system is also equipped with Light Dependent Resistor (LDR), Passive Infrared Receiver (PIR), and current sensors to support automatic lighting control, motion detection, and abnormal condition monitoring. The research method includes hardware and software design, system integration, and communication performance testing through local networks and internet connections. Experimental results show that the system successfully performs real-time monitoring and remote lighting control. The average transmission delay for node 1 was approximately 15 seconds, while node 2 experienced delays ranging from 21.89 seconds to 36.02 seconds depending on communication conditions and processor workload. The proposed system successfully improves operational monitoring efficiency, supports adaptive lighting control, and reduces energy consumption through dimmer-based lighting adjustment. The developed system can be implemented as an alternative smart city solution for intelligent and efficient public street lighting management.

INTRODUCTION

Public Street Lighting (PSL) is an essential infrastructure that supports transportation safety, public security, and urban mobility during nighttime conditions. Adequate road lighting significantly reduces traffic accidents and criminal activities while increasing the comfort of road users. In urban and rural areas, street lighting systems are continuously developed to support sustainable public infrastructure and smart city implementation.

Despite its importance, conventional PSL systems still face several operational problems. Most existing systems operate continuously at maximum brightness throughout the night without considering environmental conditions or traffic intensity. This operational method causes excessive energy consumption and increases maintenance costs. In addition, the monitoring process is generally conducted manually through field inspections or public reports, causing delays in detecting damaged lamps and abnormal operating conditions.

The rapid development of Internet of Things (IoT) technology provides opportunities to improve the efficiency and intelligence of public street lighting systems (Khan et al., 2022; Wang et al., 2022). IoT enables devices to communicate through internet networks and exchange data in real time for monitoring and automation purposes. Several previous studies have implemented IoT-based PSL systems using ESP32 microcontrollers, wireless communication modules, and web-based monitoring systems.

LoRa technology is widely adopted in IoT systems because it supports long-range wireless communication with low power consumption (Alqahtani et al., 2023; Sharma et al., 2022). Compared to conventional wireless technologies, LoRa provides wider communication coverage and better scalability for distributed monitoring systems. MQTT is also commonly used as a lightweight communication protocol because it supports efficient publish-subscribe communication for IoT applications (Pasha, 2016).

Several previous studies have developed IoT-based PSL systems using LoRa communication and MQTT protocols. However, some limitations remain unresolved, including limited adaptive lighting control, inadequate abnormal condition detection, and restricted communication reliability. In addition, previous systems commonly focused only on lamp activation and monitoring without integrating dimmer-based brightness control and

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comprehensive device monitoring(Taufik et al., 2021; Rahman et al., 2021).

This research proposes an IoT-based public street lighting monitoring and control system using ESP32, LoRa E220-900T30D, Raspberry Pi, MQTT, and Node-RED. The proposed system integrates environmental light sensors, motion detection sensors, current monitoring sensors, and dimmer modules to support adaptive lighting operation and real-time monitoring. The system is expected to improve energy efficiency, simplify monitoring processes, and provide flexible remote management for smart public street lighting systems.

LITERATURE REVIEW

Internet of Things (IoT) technology has become one of the primary solutions for implementing smart city infrastructure (Khan et al., 2022; Wang et al., 2022). IoT enables interconnected devices to exchange information through internet networks for automation, monitoring, and data analysis purposes. The implementation of IoT technology has significantly improved the efficiency, scalability, and flexibility of modern infrastructure systems, including transportation, energy management, environmental monitoring, and intelligent lighting systems. In smart lighting applications, IoT supports remote control, automatic monitoring, and real-time data transmission to improve operational efficiency and simplify maintenance processes. ESP32 is widely used in IoT applications because it integrates wireless communication capabilities, including Wi-Fi and Bluetooth, into a low-cost microcontroller platform (Prasetyo et al., 2022).

The ESP32 module also supports flexible integration with sensors, actuators, and communication modules, making it suitable for distributed monitoring and automation systems. In addition, ESP32 provides sufficient processing capability and low power consumption for real-time embedded system applications. LoRa is a Low Power Wide Area Network (LPWAN) communication technology designed for long-distance communication with low power consumption (Sharma et al., 2022; Eldeeb & Alves, 2023). LoRa communication provides wide coverage and is suitable for distributed sensor networks and smart infrastructure systems. Compared to conventional wireless communication technologies, LoRa offers better communication range and lower power requirements, making it highly suitable for smart city applications such as public street lighting systems.

In this research, LoRa E220-900T30D modules are used because they provide higher communication reliability, stronger transmission power, and more flexible communication configuration.MQTT is a lightweight publish-subscribe communication protocol commonly implemented in IoT systems (Sarker et al., 2021). MQTT minimizes communication overhead and enables efficient real-time data transmission between devices, gateways, and monitoring servers. The protocol is widely used because it supports stable communication with relatively low bandwidth usage, which is important for distributed monitoring systems and real-time control applications. Node-RED is a visual programming platform that simplifies IoT system integration through browser-based flow programming. Node-RED also supports dashboard development for real-time visualization and monitoring (Nugroho et al., 2022). The platform enables rapid system integration between sensors, communication protocols, cloud services, and monitoring dashboards without requiring complex programming processes. Therefore, Node-RED is widely adopted in IoT-based monitoring and automation systems.

Several previous studies have implemented smart public street lighting systems using IoT and wireless communication technologies (Yudhi et al., 2024; Taufik et al., 2021). Most previous studies focused on automatic lamp control and basic monitoring functions. However, limited studies integrate adaptive brightness control, current monitoring, abnormal condition detection, and long-range LoRa communication into a single integrated platform. Therefore, this research proposes a more comprehensive IoT-based public street lighting system that combines real-time monitoring, adaptive lighting control, and long-range communication to improve operational efficiency and energy management.

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METHOD

The proposed system consists of node devices and a gateway device connected through LoRa communication. The overall system architecture is shown in Figure 1.

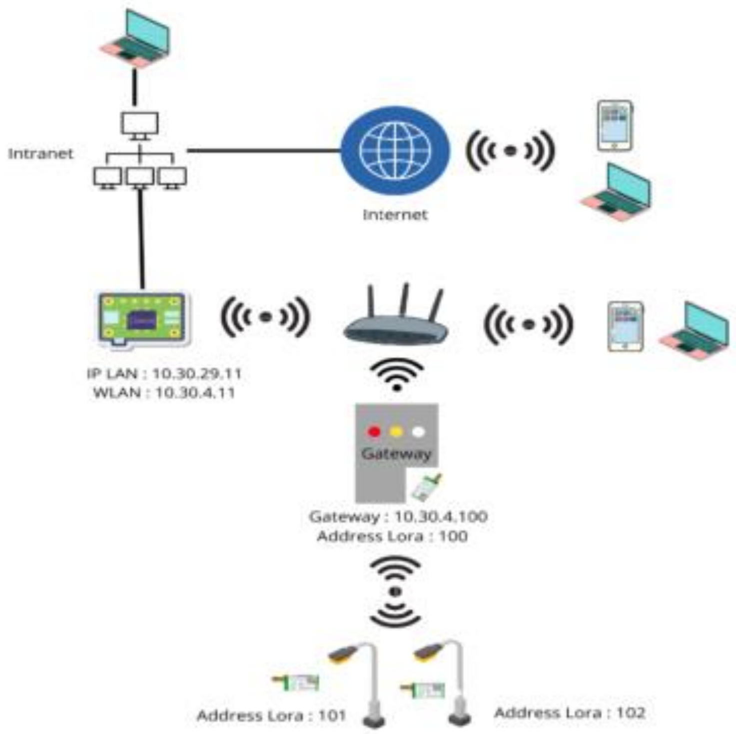

Figure 1. Topology Public Street Lighting

Each node device is installed on a street lighting unit and functions as a data acquisition and lighting control device. The node system integrates ESP32 microcontrollers, LoRa E220-900T30D communication modules, Light Dependent Resistor (LDR) sensors, Passive Infrared Receiver (PIR) sensors, current sensors, relay modules, and AC dimmer modules.

The LDR sensor measures environmental light intensity to determine whether the street lamp should be activated automatically. The PIR sensor detects human or vehicle movement around the lighting area to support adaptive lighting control. The current sensor monitors electrical current conditions and detects abnormal events such as disconnected lamps or damaged cables.

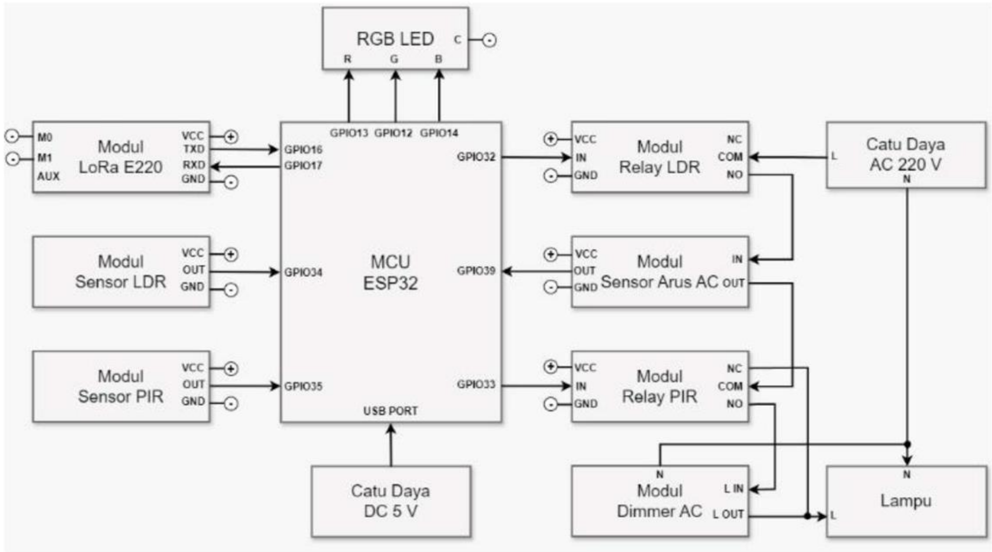

Figure 2. Overall System Architecture

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ESP32 functions as the primary processing unit that collects sensor data, processes information, and transmits data to the gateway through LoRa communication. The relay module controls lamp activation, while the AC dimmer module adjusts lamp brightness according to environmental conditions and user commands.

The gateway system uses Raspberry Pi integrated with a LoRa communication module. The Raspberry Pi functions as a data gateway, MQTT broker, and Node-RED server. MQTT is implemented using a publish-subscribe communication mechanism for efficient real-time communication between nodes and monitoring systems.

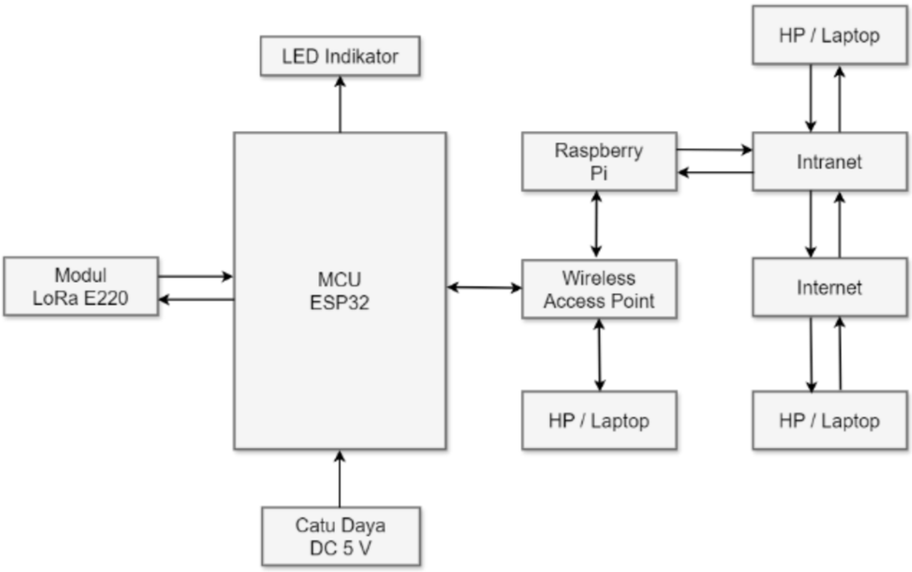

Figure 3. Gateway System Diagram Block

Node-RED is used to develop a web-based dashboard for monitoring sensor values, lamp conditions, communication status, and abnormal events. The dashboard also enables remote lighting control through local area networks and internet connections as shown in figure 4.

The system development process consists of hardware design, software development, system integration, and communication testing. Hardware design includes sensor integration, circuit development, and communication module configuration. Software development includes ESP32 programming using Arduino IDE, MQTT configuration, and Node-RED dashboard implementation.

System testing was conducted to evaluate communication reliability, transmission delay, monitoring performance, and remote control functionality. Data transmission intervals were configured at 10 seconds for node 1 and 20 seconds for node 2.

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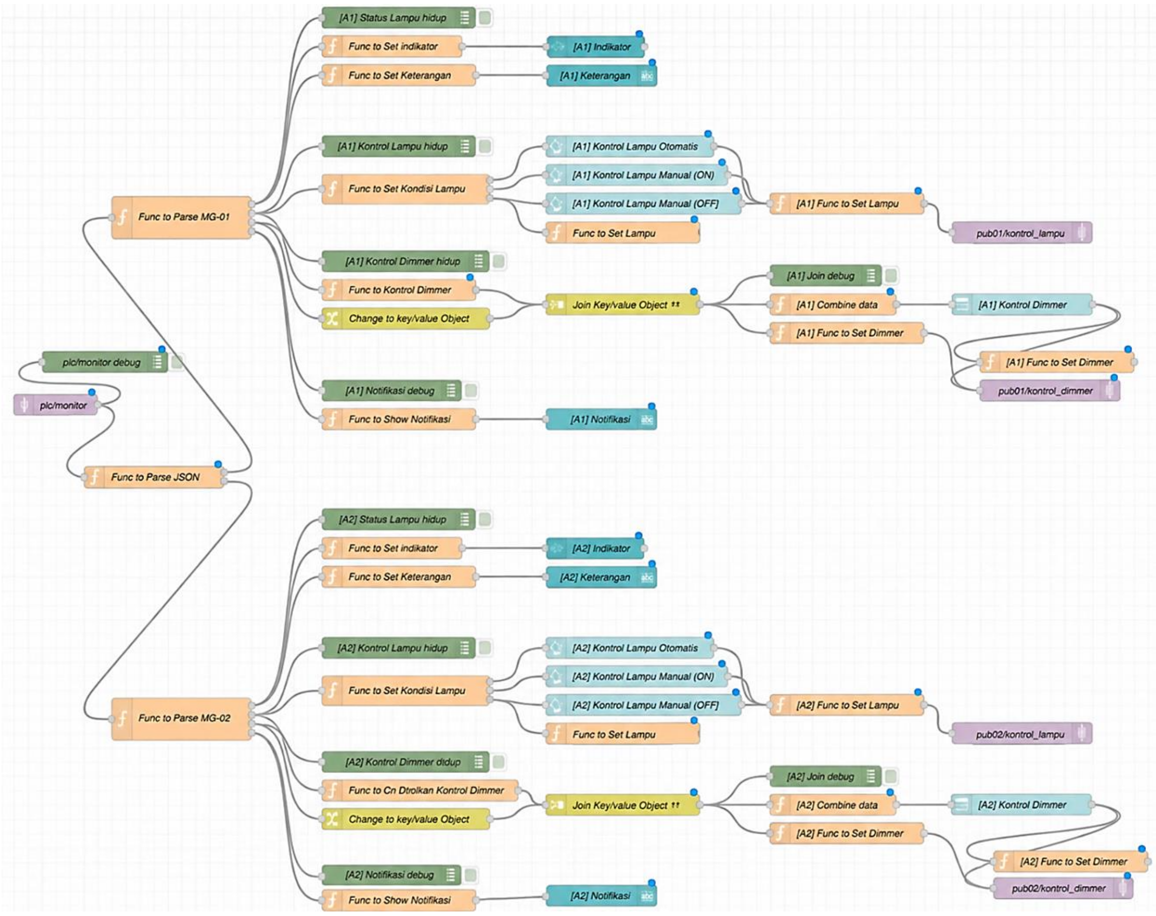

Figure 4. Node-RED Monitoring Dashboard

RESULT

System Implementation Results

The proposed IoT-based public street lighting system was successfully implemented using ESP32 microcontrollers, LoRa E220-900T30D communication modules, Raspberry Pi gateways, MQTT protocols, and Node-RED dashboards. The developed system successfully integrated hardware and software components into a real-time monitoring and control platform.

The node devices successfully collected environmental data from the LDR, PIR, and current sensors. The collected data were processed by the ESP32 microcontroller and transmitted to the gateway using LoRa communication. The gateway device successfully received the transmitted data and forwarded them to the Node-RED monitoring dashboard through MQTT communication.

Figure 5. Node Device Hardware Design

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In the process of making boxes for the PJU node system, straw cardboard material is used. This material was chosen because it has a light weight but is still able to provide adequate protection for the electronic components inside. In addition, straw cartons are easy to shape and arrange to fit the space needs of the device. The box is designed as a place to house the developed sensor system, with the placement of the sensors neatly and organized. The dimensions of the box used for the data transmission system are 21 x 14 x 7.5 cm, enough to hold all the necessary components. Figure 5 shows the box, complete with a series of PJU Nodes inside, and shows the arrangement and layout of the components in detail.

Figure 6. Gateway Device Hardware Design

Figure 6 shows a PJU node device specifically designed to support public street lighting systems. The device includes key components such as light fittings, node system boxes, and sturdy support poles. All components are connected using a wiring system designed to integrate the device with other power sources and control systems, ensuring the device operates efficiently and optimally.

Dashboard Monitoring Results

The Node-RED dashboard successfully displayed real-time monitoring information, including lamp conditions, communication status, environmental light intensity, movement detection, and abnormal electrical conditions. The monitoring system could also be accessed through local area networks and internet connections.

The developed dashboard enabled users to remotely control lamp activation and brightness adjustment using dimmer modules. Monitoring information was updated automatically according to sensor readings and communication intervals as shown in figure 7.

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Figure 7. Node-RED Monitoring Dashboard

LDR and PIR Sensor Testing Results

The LDR sensor successfully detected environmental lighting conditions and automatically controlled lamp activation according to surrounding light intensity. During dark conditions, the system activated the street lamps automatically, while during bright conditions, the lamps were turned off.

The PIR sensor also successfully detected movement around the street lighting area. When movement was detected, the system increased lamp brightness to improve visibility and safety conditions around the monitored area.

Table 1. Sensor Functionality Testing Results

Sensor	Function	Result
LDR	Detect environmental light intensity	Successful
PIR	Detect movement around lighting area	Successful
Current Sensor	Detect abnormal current conditions	Successful

LoRa Communication Testing Results

Communication testing was conducted to evaluate data transmission performance between node devices and the gateway using LoRa communication. The programmed transmission interval for node 1 was 10 seconds, while node 2 used a 20-second interval.

Experimental results indicate that node 1 achieved an average transmission delay of approximately 15 seconds. Meanwhile, node 2 experienced transmission delays ranging from 21.89 seconds to 36.02 seconds depending on network conditions and processor workload.

Table 2. Sending data on the dashboard over a LAN network

Sample	Time (s)
Test 1	31.68
Test 2	36.02
Test 3	33.31
Test 4	21.89
Test 5	22.05
Test 6	21.57

Although communication delays exceeded the programmed intervals during several tests, the communication system remained stable and successfully transmitted monitoring data without significant packet loss.

Dashboard Communication Testing Results

The MQTT communication mechanism successfully transmitted monitoring data from the gateway to the Node-RED dashboard through Local Area Network (LAN), Wireless Local Area Network (WLAN), and internet connections. Real-time monitoring data could be displayed properly without major communication interruptions.

The monitoring dashboard successfully displayed communication status and sensor readings during all communication scenarios.

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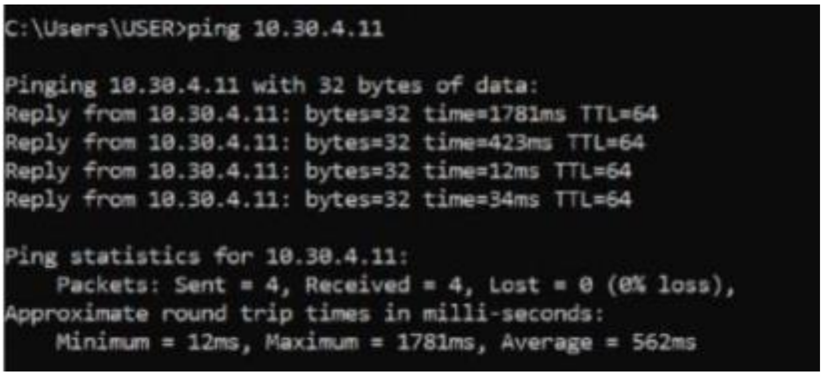

Figure 8. WLAN communication testing

Dimmer Control Testing Results

The AC dimmer module successfully controlled lamp brightness according to sensor input and user commands from the monitoring dashboard. The brightness adjustment mechanism enabled adaptive lighting operation and contributed to energy-saving performance.

The dimmer system successfully reduced lamp brightness during low activity conditions while maintaining adequate illumination when movement was detected.

Table 3. Average Data Transmission Performance

Parameter	Node 1	Node 2	Status
Programmed Transmission Interval	10 s	20 s	Configured
Average Transmission Delay	15 s	21.89–36.02 s	Measured
Communication Status	Successful	Successful	Stable
Monitoring Platform	Node-RED	Node-RED	Active

Based on Table 3, the LoRa communication system successfully transmitted monitoring data from both node devices to the gateway. Node 1 was configured with a transmission interval of 10 seconds and achieved an average transmission delay of approximately 15 seconds. Meanwhile, Node 2 was configured with a 20-second interval and experienced transmission delays ranging from 21.89 seconds to 36.02 seconds. Despite the delay variations, the communication system remained stable, and all monitoring data were successfully displayed on the Node-RED monitoring platform.

Table 4. Dashboard Communication Testing Results

Communication Network	Monitoring Status	Result
LAN	Real-time monitoring	Successful
WLAN	Real-time monitoring	Successful
Internet	Real-time monitoring	Successful

Table 4 shows that the monitoring system successfully operated through multiple communication networks, including LAN, WLAN, and internet connections. In all testing scenarios, the Node-RED dashboard was able to display monitoring data in real time without significant communication interruptions. These results indicate that the proposed IoT-based public street lighting system supports flexible and stable remote monitoring across different network infrastructures.

Table 5 Dimmer Control Functionality Results

Function	Result
Lamp ON/OFF control	Successful
Brightness adjustment	Successful
Remote control from dashboard	Successful
Adaptive lighting operation	Successful

Table 5 indicates that the implemented dimmer control system successfully performed all lighting control functions. The system was able to turn the lamps ON and OFF, adjust brightness levels, and execute remote control commands through the Node-RED dashboard. In addition, the adaptive lighting mechanism operated properly by automatically adjusting lamp brightness according to environmental conditions and detected activity around the street lighting area.

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DISCUSSION

The experimental results demonstrate that the proposed IoT-based public street lighting system successfully performs monitoring and remote control operations using LoRa communication technology. The integration of ESP32, LoRa E220-900T30D, Raspberry Pi, MQTT, and Node-RED enables efficient real-time communication between node devices and monitoring servers. The developed system successfully supports automatic lighting operation, abnormal condition detection, and remote management through web-based dashboards.

The implementation of LDR and PIR sensors contributes significantly to energy-saving operation. The LDR sensor enables automatic lamp activation according to environmental light intensity, while the PIR sensor allows adaptive lighting operation based on movement detection around the street lighting area. This mechanism reduces unnecessary energy consumption during low traffic conditions and improves operational efficiency compared to conventional public street lighting systems that operate continuously at maximum brightness(Zhou et al., 2021).

The use of the LoRa E220-900T30D module provides advantages in communication range and transmission stability(Sharma et al., 2022). Compared to several previous studies that used standard LoRa modules or integrated ESP32-LoRa boards, the proposed system offers stronger transmission capability and more flexible communication configuration. The system also supports real-time communication over relatively long distances while maintaining low power consumption.

The communication testing results indicate that the average transmission delay for node 1 was approximately 15 seconds, while node 2 experienced delays ranging from 21.89 seconds to 36.02 seconds. These delays were influenced by processor workload, communication scheduling, LoRa transmission overhead, and network conditions. Although the measured delay exceeded the programmed transmission intervals, the communication system remained stable and successfully delivered monitoring data without significant packet loss.

The Node-RED dashboard successfully visualized monitoring information, including lamp conditions, sensor values, communication status, and abnormal events. This capability improves maintenance efficiency because system administrators can monitor lighting infrastructure remotely without conducting direct field inspections. The MQTT protocol also enabled lightweight and efficient communication between devices and the monitoring platform(Sarker et al., 2021). Compared to previous studies, the proposed system provides more comprehensive functionality through the integration of dimmer-based brightness control, abnormal condition monitoring, and adaptive lighting mechanisms in a single platform. The addition of current sensors also improves fault detection capability, especially for disconnected lamps and damaged electrical lines.

Despite the successful implementation, several limitations remain in this study. The testing process was conducted using a limited number of node devices and within relatively controlled environmental conditions. Communication performance under large-scale deployment scenarios and severe environmental interference conditions was not extensively evaluated.

Future studies should focus on evaluating large-scale deployments with more node devices and longer communication distances. Additional improvements can include cloud-based data storage, artificial intelligence integration for predictive maintenance, and machine learning-based energy optimization systems.

CONCLUSION

This research successfully designed and implemented an IoT-based public street lighting monitoring and control system using LoRa communication technology and MQTT protocols. The developed system integrates ESP32 microcontrollers, LoRa E220-900T30D communication modules, Raspberry Pi gateways, Node-RED dashboards, and multiple sensors to support intelligent lighting operation and real-time monitoring.

The proposed system successfully performs automatic lamp activation, motion detection, abnormal condition monitoring, remote communication, and dimmer-based brightness adjustment. The implementation of LDR and PIR sensors enables adaptive lighting control according to environmental conditions and user activity, thereby supporting energy-efficient operation.

Communication testing results show that monitoring data can be transmitted successfully between nodes and gateways using LoRa communication. The average transmission delay for node 1 was approximately 15 seconds, while node 2 experienced delays between 21.89 seconds and 36.02 seconds depending on communication conditions and processing workload. Although transmission delays varied during testing, the system maintained stable communication performance without significant data transmission failures.

The implementation of MQTT and Node-RED successfully provided flexible real-time monitoring through local networks and internet connections. The developed dashboard also simplified system management and enabled remote monitoring of lamp conditions, sensor values, and abnormal operating conditions.

Overall, the developed system improves monitoring efficiency, reduces maintenance complexity, supports energy-saving operation, and provides practical implementation opportunities for smart city public street lighting infrastructure. Future research should focus on improving communication scalability, evaluating large-scale deployment performance, and integrating intelligent analytics for predictive maintenance and energy optimization applications.

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The proposed system successfully performs automatic lamp activation, motion detection, abnormal condition monitoring, remote communication, and dimmer-based brightness adjustment. Communication testing results show that monitoring data can be transmitted successfully between nodes and gateways using LoRa communication.

The implementation of MQTT and Node-RED also enables flexible monitoring through local area networks and internet connections. The developed system improves monitoring efficiency, reduces maintenance complexity, and supports energy-saving operation for intelligent public street lighting infrastructure.

Future research should focus on improving communication scalability, evaluating large-scale deployment performance, and integrating artificial intelligence for predictive maintenance and smart energy optimization.

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