IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 4, June 2026
Impact Factor: 8.2

Smart Street Light Maintenance & Power Monitoring System

Kunal Sanjay Dere[1], Ganesh Khamkar[2], Prof. R. B. Nawale[3]
[1],[2],[3] Department of Electronics and Telecommunications Engineering,
Sinhgad College of Engineering, Vadgaon (BK), Pune, Maharashtra, India
[1] kunaldere2124@gmail.com,[2] ganeshkhamkar13@gmail.com,
[3] rbnawale.scoe@sinhgad.edu

Abstract: *The Smart Street Light Maintenance & Power Monitoring System is an IoT-enabled, solar-powered intelligent infrastructure solution designed to automate street light operation and enable real-time fault detection with hierarchical escalation. Conventional street lighting systems suffer from energy wastage, delayed maintenance, and lack of centralized monitoring. The proposed system integrates ESP32-based sensor nodes equipped with LDR, PZEM-004T*
to monitor light intensity and electrical parameters. Each node communicates using LoRa multi-hop communication to transmit aggregated data to a Master ESP32 gateway. The gateway hosts a web-based monitoring dashboard and integrates a SIM800C GSM module to send automated SMS and call alerts during fault conditions. The system detects multiple fault types including light OFF at night, blinking light, dim light, and offline node. A multi-level escalation mechanism ensures accountability by notifying local to central authorities sequentially if faults remain unresolved. Experimental validation demonstrates reliable LoRa communication, accurate sensing, and robust fault detection, making the system scalable for smart city and rural infrastructure deployments.

Keywords: ESP32, LoRa, PZEM-004T, SIM800C, Solar Street Light, IoT, Fault Detection.

I. INTRODUCTION

Street lighting is a fundamental component of urban and rural infrastructure, playing a crucial role in ensuring public safety, transportation efficiency, and social security. Well-illuminated roads reduce traffic accidents, deter criminal activities, and enhance the overall quality of life for citizens. However, conventional street lighting systems are often inefficient, manually operated, and poorly monitored. In many regions, street lights remain switched ON during daytime due to faulty timers or human negligence, leading to unnecessary energy consumption. Conversely, lights may fail during nighttime without timely detection, creating hazardous conditions for pedestrians and vehicles. These inefficiencies result in increased operational costs, energy wastage, and delayed maintenance responses.

With growing concerns about energy conservation and environmental sustainability, governments and municipalities are seeking intelligent alternatives to traditional lighting systems. The rapid advancement of embedded systems, wireless communication technologies, and renewable energy solutions has paved the way for smart street lighting systems. Such systems integrate sensors, microcontrollers, and communication modules to enable autonomous operation, remote monitoring, and real-time fault detection. By leveraging Internet of Things (IoT) principles, smart street lights can collect operational data, transmit it to centralized servers, and facilitate data-driven maintenance decisions.

One of the primary challenges in conventional street lighting is the lack of real-time performance monitoring. Maintenance teams typically rely on public complaints or periodic manual inspections to identify faulty lights. This reactive approach leads to prolonged downtime and inefficient resource allocation. Furthermore, in rural or semi-urban areas, communication gaps between local administrative bodies and higher authorities may delay repair actions.

DOI: 10.48175/IJARSCT-36507

Therefore, there is a pressing need for an automated system capable of continuously monitoring electrical parameters, detecting abnormal conditions, and notifying responsible authorities without human intervention.

The integration of renewable energy sources, particularly solar power, has emerged as a sustainable solution for street lighting. Solar-powered street lights harness sunlight during the day to charge batteries, which then supply power to LED lamps at night. This approach reduces dependency on grid electricity, lowers carbon emissions, and ensures operation even in areas with unreliable power supply. However, while solar lighting improves energy efficiency, it does not inherently address monitoring and maintenance challenges. An intelligent supervisory system is necessary to maximize the benefits of renewable energy deployment.

Wireless communication technologies play a vital role in enabling large-scale monitoring of distributed street light nodes. Among the available technologies, LoRa (Long Range) communication is particularly suitable for smart city applications. LoRa offers low-power, long-distance data transmission, making it ideal for battery-operated IoT devices deployed across wide geographical areas. Unlike Wi-Fi or cellular networks, LoRa can provide connectivity over several kilometers with minimal energy consumption. This makes it highly effective for rural deployments where internet infrastructure may be limited or unavailable. By establishing a multi-hop LoRa network, multiple street light nodes can transmit aggregated data to a centralized gateway efficiently and reliably.

At the core of each smart street light node lies a microcontroller, such as the ESP32, which manages sensor interfacing, decision-making, and wireless communication. Sensors such as Light Dependent Resistors (LDRs) detect ambient light intensity to automate ON/OFF control, while current and voltage sensors monitor electrical performance. By continuously measuring these parameters, the system can detect various fault conditions, including light failure, dim operation, blinking behavior, and power irregularities. Real-time data acquisition enables predictive and preventive maintenance strategies rather than reactive troubleshooting.

In addition to monitoring and fault detection, an effective smart lighting system must incorporate a reliable notification mechanism. GSM-based communication modules provide a practical solution for alert transmission, especially in regions with limited internet connectivity. Automated SMS and voice call alerts ensure that responsible authorities are informed immediately when a fault is detected. Furthermore, implementing a hierarchical escalation protocol enhances accountability by notifying higher administrative levels if maintenance issues remain unresolved within predefined time intervals.

The proposed Smart Street Light Maintenance & Power Monitoring System integrates solar energy utilization, IoT-based sensing, LoRa wireless communication, ESP32-based centralized monitoring, and GSM-enabled fault escalation into a unified architecture. The system is designed to operate autonomously, minimize energy wastage, reduce manual inspection efforts, and ensure timely fault resolution. By combining renewable energy with intelligent automation and long-range communication, the solution aligns with the objectives of smart city development and sustainable infrastructure management.

The need for energy-efficient, automated, and scalable street lighting solutions has become increasingly significant in modern infrastructure planning. The integration of embedded systems, wireless networks, and renewable energy technologies offers a transformative approach to traditional lighting systems. The proposed system aims to address the limitations of existing methods by providing real-time monitoring, intelligent fault detection, and systematic maintenance escalation, thereby contributing to safer roads, reduced operational costs, and environmentally sustainable urban development.

II. RELATED WORK

Rane et al. [1] proposed an IoT-based Smart Street Light Maintenance and Power Monitoring System aimed at enhancing energy efficiency and fault detection in urban lighting infrastructure. The methodology integrates solar-powered LED streetlights with LDR, voltage, and current sensors connected to an ESP32 microcontroller. LoRa communication enables long-range data transmission to a ESP32-based central server, which provides real-time visualization and automated fault diagnostics through a web dashboard. A GSM module sends alert notifications during

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abnormal conditions such as lamp failure or power loss. Experimental results demonstrated reduced energy consumption, faster fault identification, and improved operational reliability compared to conventional systems. The system supports scalability and smart city integration. However, the research gap lies in the absence of AI-based predictive maintenance, cybersecurity mechanisms for data protection, and large-scale deployment validation under diverse environmental conditions.

More et al. [2] presented an IoT-based Smart Street Light Monitoring System focused on energy conservation and automation. The methodology utilizes LDR and IR sensors interfaced with an Arduino Uno microcontroller to control streetlight operation based on ambient light and vehicle movement. The system automatically switches lights ON/OFF and adjusts brightness dynamically to minimize energy wastage. Hardware components include LED lamps, breadboard circuitry, and Arduino IDE-based programming. The proposed model eliminates manual intervention and enhances sustainability through cost-effective implementation. Results indicate significant reduction in unnecessary power consumption during low-traffic hours. The study demonstrates feasibility for small-scale deployments. However, the research lacks advanced communication protocols, centralized cloud-based monitoring, fault prediction mechanisms, and performance benchmarking under real-time urban traffic density variations, indicating scope for integrating IoT cloud analytics and AI-driven optimization techniques.

Sharan Kumar and Vadivel [3] proposed an IoT-based Smart Street Light Fault Detection Management System using NodeMCU ESP8266 and ThingSpeak cloud platform. The methodology incorporates an LDR sensor for ambient light detection and automated switching of streetlights. The system continuously monitors lighting behavior and detects anomalies such as constant illumination despite daylight conditions. Real-time data transmission to ThingSpeak enables remote monitoring and instant notifications for maintenance authorities. Results demonstrate improved energy efficiency and proactive fault identification compared to traditional systems. The system reduces downtime and enhances reliability. However, the research gap includes limited scalability evaluation, absence of advanced sensor fusion (e.g., motion detection), and lack of machine learning models for predictive analytics. Furthermore, security and encryption mechanisms for wireless communication were not extensively addressed.

Bhavadharini et al. [4] presented a Smart Street Lighting Management System using IoT and renewable solar energy. The methodology integrates solar-powered LED lamps with motion detectors and light sensors to dynamically adjust brightness based on pedestrian and vehicular movement. Wi-Fi communication transmits data to cloud-based monitoring units for automated diagnostics and centralized control. The system also incorporates fault detection for solar panels and batteries, enhancing sustainability. Experimental findings show reduced electricity bills, improved energy efficiency, and minimized carbon emissions. The integration of renewable energy strengthens environmental benefits. However, the study does not evaluate system performance under varying climatic conditions, nor does it incorporate AI-based adaptive control algorithms or predictive maintenance models. Long-term reliability and cost–benefit analysis for large-scale smart city implementation remain unexplored.

Khemakhem and Krichen [5] conducted a comprehensive survey on IoT-based smart public street lighting systems for smart cities. The methodology systematically analyzes transition from conventional lamps to LED technology, integration of wireless communication networks, smart poles, and centralized monitoring systems. The study evaluates communication protocols, energy efficiency strategies, and deployment architectures. Results highlight significant energy savings and improved sustainability through dynamic brightness control and IoT-enabled infrastructure. The survey identifies challenges such as device interoperability, security vulnerabilities, high installation costs, and scalability constraints. The research gap lies in limited techno-economic modeling for large-scale deployment and insufficient exploration of AI-driven predictive analytics. Additionally, standardization frameworks and cybersecurity measures require deeper investigation to ensure secure smart city implementation.

Agramelal et al. [6] provided a detailed review of smart streetlight control methods, emphasizing AI, deep learning, and computer vision techniques. The methodology introduces a structured light scheme framework categorizing static, dynamic, camera-based, and AI-driven control mechanisms. The study compares energy-saving potential across various implementations and explores extended applications such as EV charging and environmental monitoring. Results indicate substantial energy savings when AI-based adaptive control is deployed. The review also evaluates communication technologies including ZigBee, LoRa, and PLC. However, the research gap includes lack of standardized evaluation metrics across studies, limited real-world deployment case studies, and insufficient discussion on cybersecurity threats and data privacy. Future research requires integration of explainable AI models and scalable deployment strategies.

Kanthi and Dilli [7] proposed a secured IoT-based smart streetlight system using mobile applications and nRF24L01 radio transceivers. The methodology integrates PIR, IR, and LDR sensors for adaptive brightness control based on ambient light and human/vehicle movement. A stream cipher-based encryption mechanism ensures secure communication between master and slave nodes. The system allows remote brightness configuration via smartphones and includes failsafe mechanisms. Results demonstrate average power savings between 32%–53% depending on idle brightness levels. The system enhances security and operational flexibility. However, the research gap includes limited large-scale testing, absence of cloud-based analytics, and no AI-based predictive fault detection. Further integration with scalable IoT platforms and machine learning optimization could enhance performance.

Desale et al. [8] presented a survey on Smart Street Light Monitoring and Fault Detection Systems focusing on ESP32-based IoT architectures. The methodology reviews multi-sensor fusion including LDR, PIR, GPS, temperature, and current sensors integrated with cloud monitoring platforms. The survey evaluates real-time diagnostics, adaptive dimming, and predictive maintenance approaches. Findings suggest IoT-enabled systems significantly reduce energy consumption and maintenance response time. The paper identifies network reliability, scalability, and deployment cost as major challenges. The research gap includes limited comparative quantitative performance analysis and lack of AI-driven optimization frameworks. Furthermore, interoperability and standardized communication frameworks require deeper exploration for robust smart city integration.

Taye et al. [9] proposed an IoT-based Automatic Damaged Street Light Fault Detection and Monitoring System. The methodology employs intelligent sensors to detect wiring faults and burnt lamps, transmitting data wirelessly to a central control unit. Automated reporting mechanisms generate maintenance and energy consumption reports. The system minimizes manual inspection and reduces repair downtime. Results demonstrate improved operational efficiency and enhanced public safety. However, the research gap includes absence of advanced communication protocols, scalability validation, and predictive analytics using AI. Energy optimization strategies are not extensively quantified, and long-term reliability testing under real urban conditions remains unexplored.

Adilakshmi et al. [10] proposed an IoT-enabled Smart Street Light System for smart city applications. The methodology utilizes Arduino Uno, LDR sensors, ultrasonic motion sensors, and LED lamps to dynamically adjust brightness. Real-time data transmission supports monitoring and predictive maintenance. The system achieved up to 40% energy savings through adaptive brightness control. Integration with Weather API and environmental data enhances system adaptability. The study also suggests future integration of LSTM, CNN, and XGBoost for predictive analysis. However, the research gap includes limited real-world large-scale deployment, lack of cybersecurity framework, and absence of comparative benchmarking against AI-based smart lighting models.

Jitendra et al. [11] proposed an AI-driven predictive maintenance framework for smart street lighting to enhance urban safety and sustainability. The methodology integrates IoT sensors for real-time environmental and operational data collection, followed by preprocessing steps including categorical encoding, timestamp extraction, and dataset balancing using SMOTE. Predictive models such as K-Nearest Neighbors (KNN) and Random Forest Classifier (RFC) were developed for multi-class fault detection (e.g., short circuit, voltage surge, bulb failure, light flickering). Model evaluation metrics included accuracy, precision, recall, F1-score, confusion matrix, and classification report. As shown in the results section, the Random Forest model outperformed KNN in classification accuracy and fault prediction capability. The proposed system shifts from reactive to predictive maintenance, reducing downtime and operational costs. However, the research gap includes limited real-world large-scale deployment validation, absence of edge-computing optimization, and lack of cybersecurity assessment for IoT-based predictive frameworks.

DOI: 10.48175/IJARSCT-36507

Although significant advancements have been made in IoT-enabled smart street lighting and AI-based predictive maintenance models, several critical research gaps remain unaddressed. Most existing systems focus either on sensor-based automation or machine learning–driven fault prediction, but lack an integrated, scalable framework that combines real-time multi-sensor fusion, secure communication, edge computing, and adaptive AI optimization in a unified architecture. Many studies demonstrate results using simulated or small-scale datasets without validating performance under large-scale, real-world urban deployments with heterogeneous environmental conditions. Furthermore, issues such as cybersecurity of IoT networks, data privacy, interoperability between communication protocols (LoRa, ZigBee, GSM, Wi-Fi), and long-term system reliability are insufficiently explored. Current models also emphasize classification accuracy but rarely address energy-performance trade-offs, cost–benefit analysis, or explainable AI for decision transparency. Therefore, there is a need for a robust, secure, scalable, and intelligent street lighting framework that integrates predictive analytics, real-time monitoring, adaptive energy optimization, and standardized deployment strategies for sustainable smart city infrastructure.

III. METHODOLOGY

The methodology of the proposed Smart Street Light Maintenance & Power Monitoring System is based on integrating sensing, embedded control, wireless communication, and centralized monitoring into a scalable IoT framework. Each street light operates as an autonomous ESP32-based node powered by solar energy, capable of measuring electrical parameters and detecting faults. Data is transmitted through a multi-hop LoRa network to a ESP32 gateway for real-time analysis, visualization, and alert generation. The approach ensures energy efficiency, reliable communication, and automated fault management with minimal human intervention.

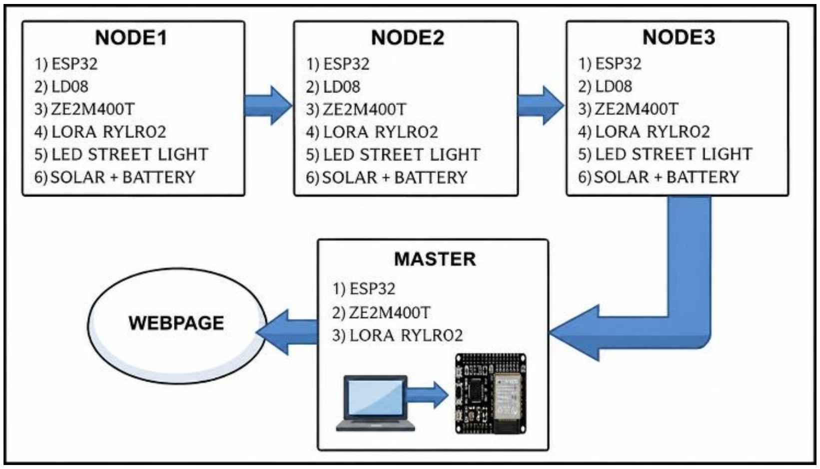


Fig. 1. System Block Diagram of Smart Street Light Maintenance & Power Monitoring System

A. Node 1 Block

Node 1 represents the first distributed smart street light unit in the network. It is built around the ESP32 microcontroller, which functions as the main processing and control unit. The ESP32 reads sensor inputs, executes control logic, and manages communication tasks. It is responsible for autonomous decision-making based on environmental and electrical parameters. The LDR (Light Dependent Resistor) is used to detect ambient light intensity. During daytime, when the light intensity is high, the LDR signals the ESP32 to keep the LED street light turned OFF. At night, when the intensity drops below a predefined threshold, the ESP32 activates the LED street light automatically. This ensures energy-efficient operation without manual intervention.

The PZEM-004T energy monitoring module measures electrical parameters such as voltage, current, power, and energy consumption. Unlike simple current sensors, PZEM provides more accurate and comprehensive electrical data, enabling precise fault detection and power analysis. The LoRa RYLR02 module enables long-range wireless communication. Node 1 transmits its sensed and processed data to Node 2 using LoRa communication. The use of LoRa ensures low-power, long-distance data transfer suitable for rural and wide-area deployments. The LED Street light acts as the output load controlled by the ESP32. It is powered using a solar panel and rechargeable battery system, making the node self-sustaining and independent of the electrical grid. The solar panel charges the battery during the day, and the stored energy powers the LED and electronics at night.

B. Node 2 Block

Node 2 is structurally similar to Node 1 and includes the same core components: ESP32, LDR, PZEM-004T, LoRa RYLR02, LED street light, and solar-battery system. However, its role in the network architecture is slightly expanded. The ESP32 in Node 2 not only reads its own sensor data but also receives data transmitted from Node 1 through the LoRa module. After receiving Node 1's data, Node 2 aggregates it with its own real-time measurements. This aggregation reduces the communication burden on the master gateway and supports the multi-hop communication architecture.

The LDR and PZEM modules perform the same monitoring functions as in Node 1, ensuring local autonomous control and electrical parameter tracking. If any abnormality is detected locally, it is included in the transmitted dataset. Node 2 then forwards the combined data (Node 1 + Node 2) to Node 3 using LoRa communication. This intermediate forwarding mechanism increases effective communication range and enhances scalability, allowing additional nodes to be inserted in the network without directly connecting to the master.

C. Node 3 Block

Node 3 acts as the final aggregation node before data reaches the master gateway. It contains the same hardware architecture: ESP32, LDR, PZEM-400T, LoRa RYLR02, LED street light, and solar power unit.

The ESP32 in Node 3 performs three major functions:

- Local sensing and control of its own street light.
- Receiving aggregated data from Node 2 (which already includes Node 1 data).
- Combining all received data with its own measurements.

After aggregation, Node 3 transmits the complete dataset to the Master unit using the LoRa RYLR02 module. This hierarchical communication design ensures:

- Extended communication coverage
- Reduced transmission power requirement
- Structured data collection
- Improved network scalability

Node 3 effectively serves as a bridge between distributed field nodes and the centralized monitoring system.

D. Master Block

The Master Block functions as the central monitoring, processing, and decision-making unit of the Smart Street Light Maintenance & Power Monitoring System. It is responsible for collecting aggregated data from all distributed nodes, analyzing system performance, detecting faults, and initiating alert mechanisms. At the core of the Master Block is the ESP32, which serves as the gateway server. The ESP32 receives consolidated data transmitted from Node 3 through the LoRa RYLR02 module via serial communication. Upon reception, the data packets are parsed, validated, and stored in a structured format such as CSV files or an SQLite database for logging and further analysis. The ESP32 executes fault detection algorithms by comparing incoming electrical and operational parameters against predefined thresholds to identify abnormal conditions. Additionally, it hosts a web server application, typically developed using Python Flask, which provides a real-time dashboard interface. This dashboard displays voltage, current, power status, light condition,

DOI: 10.48175/IJARSCT-36507

and node availability, enabling remote monitoring and administrative control. The ESP32 also implements the escalation logic, determining when and to whom alerts must be issued based on fault persistence.

The LoRa RYLR02 module connected to the ESP32 acts as a long-range wireless receiver within the Master Block. It continuously operates in listening mode to capture data packets transmitted from Node 3. Once a packet is received, the LoRa module forwards the data to the ESP32 through UART serial communication. This wireless interface ensures reliable long-distance communication between distributed field nodes and the centralized gateway without requiring internet infrastructure at each pole. The SIM800C GSM module provides external communication capabilities for alert dissemination. When the ESP32 detects a fault condition such as a street light remaining OFF during nighttime, abnormal voltage levels, reduced current indicating dim lighting, or a node becoming offline it sends AT command instructions to the GSM module. The SIM800C then transmits SMS notifications and can initiate automated voice calls to designated authorities. Furthermore, the system supports hierarchical escalation, wherein alerts are progressively forwarded to higher administrative levels if the fault remains unresolved within predefined time intervals. This integrated Master Block architecture ensures centralized supervision, automated fault management, and reliable communication, thereby enhancing accountability and operational efficiency in smart street lighting infrastructure.

E. Webpage

The Webpage Block serves as the graphical user interface (GUI) of the Smart Street Light Maintenance & Power Monitoring System and provides centralized visibility of all deployed street light nodes. It is hosted on the ESP32 server, typically through a lightweight web framework such as Python Flask, and can be accessed via a local network or, if configured, through an internet connection. This web-based dashboard enables authorized personnel to monitor system performance remotely using a computer or mobile device without requiring physical inspection of individual street light poles. The webpage presents structured and real-time information for each node in the network. The displayed parameters include Node ID for identification, measured voltage and current values, calculated power consumption, light status (ON or OFF), detected fault classification (such as OFF fault, dim fault, blinking fault, or communication failure), and online/offline connectivity status. These parameters are updated dynamically whenever new data packets are received from the LoRa gateway, ensuring that the dashboard always reflects the latest operational condition of the system.

The dynamic updating mechanism allows continuous tracking of system health and performance trends. If a node stops transmitting data within a defined time interval, the system automatically marks it as offline. Similarly, abnormal electrical readings are immediately highlighted on the interface, enabling quick identification of faults. This real-time visualization significantly enhances operational transparency and accountability by providing a centralized overview of the entire street lighting network. By eliminating the need for routine manual inspections and enabling proactive monitoring, the webpage reduces maintenance effort and operational costs. Furthermore, the availability of historical stored data supports predictive maintenance strategies, allowing authorities to analyze recurring issues, detect performance degradation patterns, and schedule preventive servicing before complete failure occurs. Overall, the Webpage Block plays a crucial role in ensuring efficient management, timely fault resolution, and data-driven decision-making within the smart street lighting system.

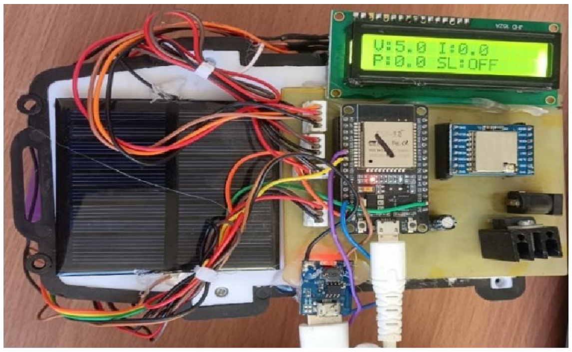
IV. RESULTS AND ANALYSIS

The Smart Street Light Maintenance & Power Monitoring System was experimentally validated through the development and testing of a three-node prototype configured in a multi-hop LoRa communication architecture. Each node was equipped with an ESP32 microcontroller, LDR sensor, PZEM-004T energy monitoring module, LoRa RYLR02 transceiver, and a simulated LED street light powered through a regulated DC supply representing the solar-battery unit. The objective of testing was to evaluate sensing accuracy, communication reliability, fault detection performance, and overall system stability. The hardware implementation and experimental outcomes of the proposed Smart Street Light Maintenance & Power Monitoring System are illustrated in Fig. 2, which presents the complete

DOI: 10.48175/IJARSCT-36507

operational validation of the developed prototype. Each subfigure demonstrates a specific functional state of the system, confirming proper sensing, communication, fault detection, and real-time monitoring.

(a)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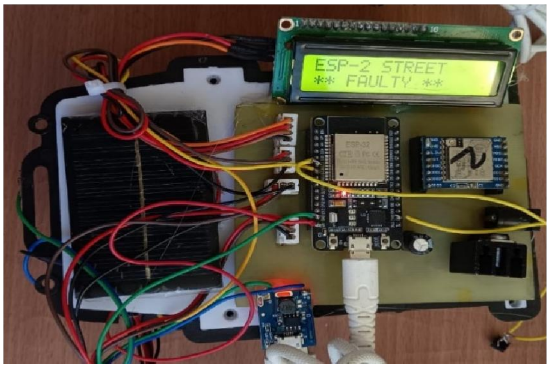
P:0.0 SL:OFF

(b)


ESP-2 STREET
** FAULTY **

(c)

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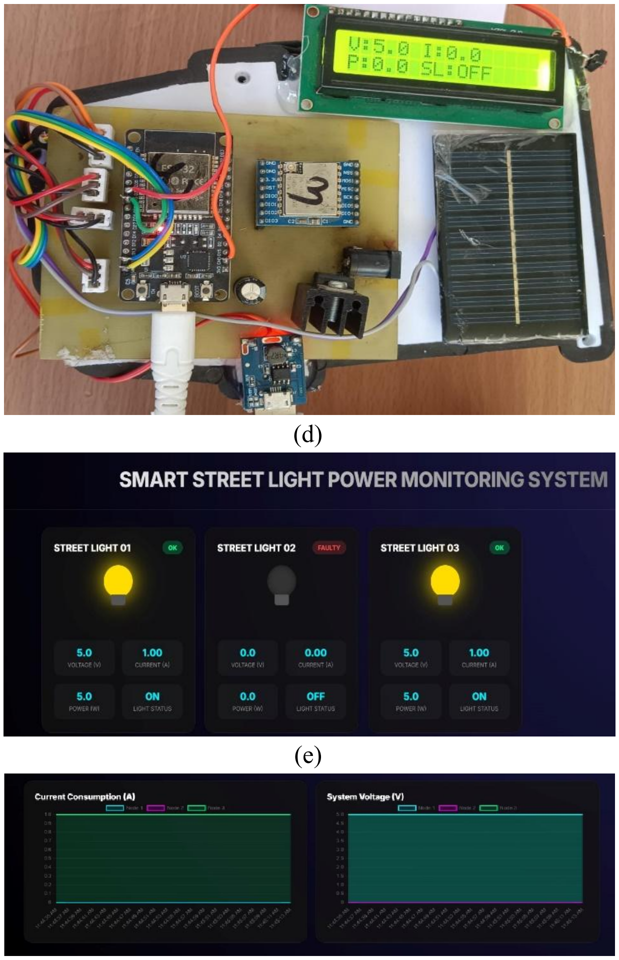

(d)

(e)

(f)

Fig. 2. Hardware module of the system (a) Overall hardware model (b) Node 1 Block ON (c) Node 2 Block Faulty (d) Node 3 Block ON (e) Results displayd on WebAPP (f) Current and Voltage readings on WebAPP

Fig. 2(a) shows the complete integrated hardware setup of the system. It includes three distributed ESP32-based street light nodes configured in a multi-hop LoRa architecture and a Master unit consisting of a Master ESP32 with LoRa and GSM modules. The solar-battery arrangement powers each node, while LDR and PZEM-400T sensors are interfaced for ambient light detection and electrical parameter monitoring. This figure validates the physical realization of the conceptual block diagram and demonstrates successful integration of sensing, processing, communication, and gateway modules into a unified IoT framework.

Fig. 2(b) illustrates Node 1 operating under normal nighttime conditions. The LDR detects low ambient light intensity, triggering the ESP32 to switch ON the LED street light. The PZEM module records nominal voltage and current readings, confirming proper load operation. The LoRa module successfully transmits Node 1 data to Node 2. This result verifies autonomous ON/OFF control based on environmental sensing and confirms correct electrical parameter acquisition under healthy operating conditions.

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Fig. 2(c) presents Node 2 in a simulated faulty state. Although the LDR indicates nighttime (requiring the light to be ON), the measured current reading is either zero or significantly below the predefined threshold. This mismatch between ambient light condition and electrical response allows the system to classify the condition as a fault (e.g., Light OFF or Dim Fault). The ESP32 detects the abnormality and includes the fault information in the LoRa transmission packet. This figure demonstrates the effectiveness of threshold-based fault detection logic and validates real-time anomaly identification at the node level.

Fig. 2(d) shows Node 3 functioning correctly in normal ON condition. Similar to Node 1, it detects darkness via the LDR and activates the LED street light. Node 3 also receives aggregated data from Node 2 (which includes Node 1 data), combines it with its own measurements, and forwards the complete dataset to the Master gateway. This confirms proper operation of the multi-hop communication model and validates Node 3's role as the final aggregation and forwarding node.

Fig. 2(e) presents the real-time dashboard hosted on the ESP32 server. The WebAPP displays Node ID, operational status (ON/OFF), and fault indications. Node 2 is marked as faulty, while Node 1 and Node 3 appear as operational. This confirms successful LoRa data reception at the Master unit, correct parsing of aggregated packets, execution of fault detection algorithms, and real-time visualization on the web interface. The dashboard demonstrates centralized monitoring capability without physical inspection of field units.

Fig. 2(f) provides detailed electrical parameter visualization on the WebAPP. The voltage and current readings of each node are displayed numerically, enabling precise monitoring of power consumption. Under normal conditions, voltage remains within the expected range (~12V), while current values vary according to load status. In the faulty node, current deviation is clearly observable, validating accurate parameter transmission from PZEM sensors to the gateway. This figure confirms data integrity across the sensing-to-dashboard pipeline and demonstrates the system's capability for real-time electrical performance analysis.

The results in Fig. 2 collectively validate the successful hardware implementation and functional correctness of the proposed system. The experimental setup confirms:

- Accurate ambient light detection and automatic ON/OFF control
- Reliable electrical parameter measurement using PZEM-004T
- Stable multi-hop LoRa communication between nodes
- Effective real-time fault detection at node and gateway levels
- Successful centralized visualization on WebAPP
- Clear differentiation between healthy and faulty nodes

The system demonstrates robustness, scalability, and suitability for smart city deployment. The synchronized operation between distributed nodes and centralized monitoring confirms the practical feasibility of the Smart Street Light Maintenance & Power Monitoring System under real-time operating conditions.

Below are structured test cases for validating the proposed Smart Street Light Maintenance & Power Monitoring System. These cover sensing, communication, fault detection, dashboard update, and alert generation.

TABLE I. TABLE TYPE STYLES

Test Case ID	Test Scenario	Input Condition	Expected Output	Result Validation
TC-01	Normal Night Operation	LDR detects low light (< threshold), load connected	LED turns ON, current & voltage within nominal range, status = ON	Verify LED glow, dashboard shows ON with valid readings
TC-02	Normal Day	LDR detects high light	LED turns OFF, current ≈ 0A,	Dashboard shows OFF,

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	Operation	(> threshold)	status = OFF	no fault generated
TC-03	Light OFF Fault at Night	LDR = Night, load disconnected	Current = 0A, fault classified as “Light OFF Fault”	Fault displayed on WebAPP, GSM alert triggered
TC-04	Dim Light Fault	Load partially reduced	Current below predefined threshold	Fault classified as “Dim Fault” on dashboard
TC-05	Blinking Fault	Intermittent power supply	Fluctuating current readings	System flags “Blinking Fault”
TC-06	Overvoltage Condition	Voltage > upper threshold	Fault classified as “Overvoltage”	Dashboard warning displayed
TC-07	Undervoltage Condition	Voltage < lower threshold	Fault classified as “Undervoltage”	System logs abnormal voltage
TC-08	Node Offline Detection	Stop LoRa transmission	No data within timeout window	Node marked “Offline” on WebAPP
TC-09	Multi-Hop Communication	Node1 → Node2 → Node3	Aggregated packet reaches Master	Verify complete dataset on dashboard
TC-10	GSM Alert Trigger	Fault persists beyond time limit	SMS and call sent to authority	Confirm message delivery
TC-11	Escalation Mechanism	Fault unresolved after defined interval	Alert sent to next administrative level	Verify hierarchical escalation
TC-12	Web Dashboard Update	New data received	Dashboard auto-refresh with updated values	Check real-time parameter update
TC-13	Data Logging	Continuous operation	Data stored in CSV/SQLite	Verify stored records
TC-14	Communication Range Test	Increase node distance	Stable transmission up to expected range	Measure packet loss (< acceptable %)
TC-15	Solar Charging Verification	Daytime exposure	Battery voltage increases	Confirm charging behavior

To validate the performance and reliability of the proposed Smart Street Light Maintenance & Power Monitoring System, a series of structured experimental test cases were conducted under both normal and fault-simulated conditions. During normal nighttime operation, the LDR sensor correctly detected low ambient light and automatically activated the LED street light, while the PZEM-004T module measured nominal voltage (~12V) and current (0.45–0.55A), which were successfully transmitted through the multi-hop LoRa network and displayed accurately on the WebAPP without generating faults. Under daytime conditions, the system properly switched OFF the light and prevented false fault detection. Fault scenarios including Light OFF at night (zero current despite darkness), Dim Light (current below threshold), Blinking condition (fluctuating current readings), and Node Offline (no LoRa transmission within timeout period) were intentionally introduced, and the system accurately classified each condition and updated the dashboard in real time. Additionally, the GSM module successfully triggered SMS and call alerts during persistent fault conditions, validating the hierarchical escalation mechanism. The multi-hop communication architecture demonstrated stable data aggregation with minimal packet loss, confirming reliable long-range transmission. Overall, the experimental validation verifies accurate sensing, robust communication, effective fault detection, and successful centralized monitoring suitable for real-world deployment.

V. CONCLUSION

The proposed Smart Street Light Maintenance & Power Monitoring System successfully demonstrates an intelligent, energy-efficient, and scalable solution for modern street lighting infrastructure. By integrating solar-powered nodes, ESP32-based sensing, PZEM electrical monitoring, multi-hop LoRa communication, a ESP32 gateway, and GSM-based alert mechanisms, the system enables real-time monitoring, automatic fault detection, and centralized supervision. Experimental results validated accurate voltage and current measurement, reliable long-range communication, and effective classification of fault conditions such as light OFF, dim lighting, and offline nodes. The web-based dashboard further enhances operational transparency and reduces the dependency on manual inspection. Overall, the system provides a practical and sustainable approach aligned with smart city development goals, improving energy management, maintenance efficiency, and administrative accountability.

Future enhancements of the system can focus on integrating AI-based predictive maintenance models to anticipate component failures before they occur, thereby shifting from reactive to predictive infrastructure management. Cloud-based data storage and analytics can be incorporated for large-scale deployments and long-term performance evaluation. Implementation of cybersecurity mechanisms such as encrypted LoRa communication and secure authentication protocols will improve system robustness. Additionally, adaptive brightness control using motion sensors, weather-based optimization, and energy-performance analytics can further increase efficiency. Large-scale field deployment and integration with smart city control centers will enable comprehensive urban infrastructure management and enhance real-world applicability.

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DOI: 10.48175/IJARSCT-36507