



Energy-efficient street lighting system based on it and led technology

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Peer Review Information

Submission: 10 Jan 2020
Revision: 25 Feb 2020
Acceptance: 04 Mar 2020

Keywords

Internet of Things, LED street lighting, energy efficiency, adaptive dimming, smart city

Abstract

Street lighting is an essential municipal service, but conventional dusk-to-dawn operation keeps luminaires at full output even when roads are empty, leading to avoidable energy use and maintenance expenditure. This methodology paper presents the design of a low-cost, energy-efficient street lighting system that combines light-emitting diode (LED) luminaires, an ESP32-class Internet of Things (IoT) controller, ambient-light sensing, motion detection, pulse-width-modulation dimming, and MQTT-based remote monitoring. The proposed control strategy uses the light-dependent resistor to identify day/night conditions and a passive infrared sensor to detect road users. At night, the luminaire is maintained at a safe reduced level and increases to full brightness for a configurable interval when movement is detected. Electrical status and operating data are transmitted to a web dashboard for supervision and fault indication. A prototype-level evaluation model of ten 30 W LED luminaires over a 12 h night indicates an estimated consumption of 2.18 kWh, including controller overhead, compared with 3.60 kWh for fixed-output LEDs and 8.40 kWh for 70 W conventional luminaires. This corresponds to approximately 39.3% savings over fixed-output LEDs and 74.0% over the conventional baseline. The design emphasizes inexpensive hardware, local fail-safe operation, scalable IoT communication, and practical deployment in residential streets, campuses, industrial estates, and low-traffic urban roads.

Introduction

Public street lighting supports night-time mobility, pedestrian security, road visibility, and urban activity, yet its energy requirement becomes substantial because large numbers of luminaires operate for many hours every night. Earlier street-lighting installations commonly used high-pressure sodium or other discharge lamps controlled by fixed schedules or centralized switching. Such operation does not respond to real traffic demand and therefore wastes energy during low-occupancy periods. The transition to LEDs provides an important first level of improvement because LEDs offer high luminous efficacy, rapid switching, long service life, and straightforward electronic

dimming. However, replacing the lamp alone does not fully exploit the possible savings; greater reduction is achieved when LED output is adjusted according to ambient light and road activity.

Networked street lighting has consequently become a core smart-city application. Leccese demonstrated that ZigBee-connected sensing and remote supervision can improve the management of public lighting and provide fault information to a control terminal [1]. Magno et al. showed that low-cost wireless sensing, motion detection, and daylight measurements can drive adaptive LED operation while maintaining user requirements [2]. At the infrastructure level,

Shahidehpour et al. described how communications and control can transform streetlights from passive loads into networked assets that support monitoring and additional city services [3]. These studies establish that energy savings depend on three linked elements: efficient LED hardware, context-aware local control, and dependable communication.

The objective of this paper is to develop a practical methodology for an IoT-enabled street lighting node that is inexpensive enough for small-scale deployment but structured for later expansion. The proposed node integrates an ESP32 microcontroller, an ambient-light sensor, a motion sensor, a dimmable LED driver, current/energy feedback, and Wi-Fi communication. The methodology defines the hardware architecture, operating logic, communication layer, evaluation metrics, and a transparent energy model. Unlike approaches that depend entirely on cloud availability, the present design places the essential switching and dimming logic inside each pole controller, while the IoT platform is used for logging, supervision, parameter updates, and maintenance alerts. This arrangement improves resilience while retaining the benefits of connectivity.

Literature Review

Adaptive traffic-responsive lighting has been investigated as an effective method of reducing the operating hours spent at maximum output. Shahzad et al. developed a traffic-adaptive intelligent street-lighting system in which LED luminance is varied with changing traffic volume; their work demonstrated the value of linking sensing information directly to dimming decisions [4]. De Paz et al. proposed an intelligent architecture for centralized public-lighting control in smart cities, highlighting the role of adaptive management and decision support in reducing unnecessary illumination [5]. These approaches are important because they move street lighting from binary ON/OFF operation to continuous or multi-level control.

A second research direction concerns the energy performance of smart lighting in realistic urban settings. Petritoli et al. compared smart-lighting strategies as a basic smart-city building block and evaluated the energy consequences of intelligent operation [6]. Mohandas et al. implemented an artificial-neural-network-based street-lighting system using several sensing inputs and reported reductions in unnecessary utilization and power consumption in a residential case study [7]. Such studies indicate that substantial savings are achievable when the control algorithm combines

environmental and occupancy information rather than relying on only a fixed timer.

The literature also emphasizes scalability, communications, and maintenance. Mahoor et al. reviewed smart streetlight architectures and classified their control strategies, communication networks, smart-city functions, and cybersecurity concerns [8]. Yang et al. presented a high-efficiency smart street-light management implementation with real-time data transmission, configuration, authentication, and web-based management, illustrating the need for a structured data layer when large numbers of poles are connected [9]. In parallel, Gagliardi et al. developed a low-cost adaptive street-lighting architecture in which lighting poles participate in an IoT network and automatically change brightness according to detected vehicles and pedestrians [10]. Their work is particularly relevant to the present study because it combines low-cost hardware with adaptive operation and networking.

A 2020 case study of Nagpur Smart City further demonstrated the practical significance of combining LEDs, sensors, and IoT supervision. Prasad reported substantial monthly energy reduction after outdated luminaires were replaced and motion-responsive smart lighting was introduced [11]. Taken together, the studies from 2013-2020 support a design philosophy based on efficient LEDs, distributed sensing, local dimming intelligence, remote supervision, and incremental deployment. The remaining methodological need is a simple academic prototype that clearly separates safety-critical local control from non-critical cloud functions and quantifies the energy effect of each operating state. The system developed below addresses this need.

Methodology

1. System Architecture and Hardware Selection

The proposed system is organized as a pole-level sensing and actuation node connected to an IoT supervision layer. Each node contains an ESP32 controller, an LDR voltage-divider circuit for ambient-light measurement, a PIR sensor for movement detection, a PWM-capable LED driver interface, and a low-cost energy/current sensing module. The ESP32 was selected because it combines microcontroller resources and Wi-Fi connectivity on one board, reducing external components. For a laboratory prototype, a 30 W dimmable LED luminaire represents the streetlight load. In a field installation, the same logic can drive a certified constant-current

dimnable LED streetlight driver through an isolated 0-10 V, PWM, or DALI interface depending on the luminaire.

Table 1. Proposed prototype components and design role

Component	Typical specification	Primary function	Illustrative cost (INR)
ESP32 development board	Wi-Fi, ADC, PWM	Local logic and IoT communication	450
LDR + resistor network	Analog ambient-light input	Day/night decision and light compensation	30
PIR motion sensor	3-7 m adjustable detection	Vehicle/pedestrian presence trigger	120
PWM/isolated LED interface	Logic-to-driver control	30-100% dimming command	250
Energy/current sensor	Voltage/current/power feedback	Consumption logging and fault indication	450
30 W LED luminaire	Dimmable LED load	High-efficiency road illumination	900
Power supply, enclosure, protection	5 V control supply + fuse/MOV	Safe prototype operation	500

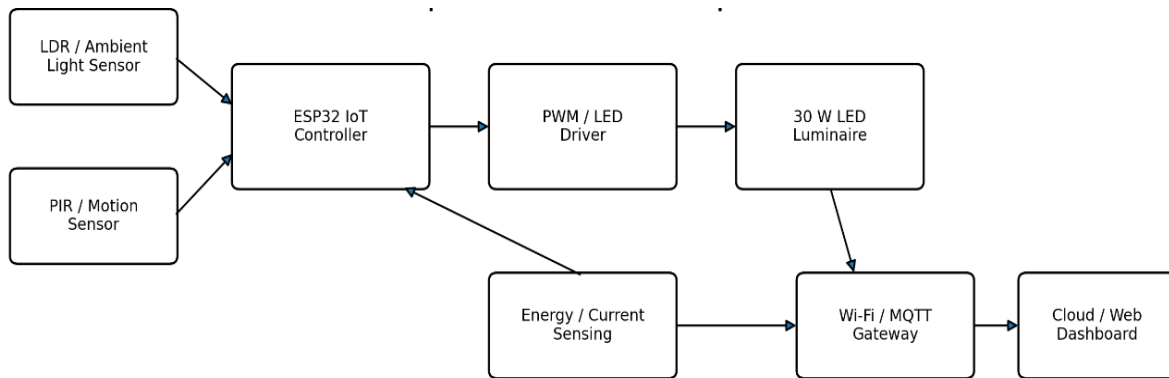


Figure 1. Functional architecture of the proposed IoT-enabled adaptive LED street-lighting node.

Figure 1 shows the main signal path. Sensor values are sampled locally and the controller determines the required brightness. The LED driver receives a PWM command, while the energy sensor returns electrical status. Wi-Fi is used to publish time-stamped measurements and node status to an MQTT broker. A lightweight dashboard can display lamp state, motion count, measured power, communication health, and accumulated energy. Because the lighting decision is executed locally, a temporary network outage does not switch the streetlight off; the node continues operating using the last valid local parameters.

2. Control Algorithm

The control sequence is based on three illumination states. During daylight, the LDR threshold keeps the LED OFF. After the ambient-light level falls below the night threshold for a debounce period, the node enters NIGHT-DIM

mode at 35% rated output. Detection of movement changes the state to NIGHT-FULL at 100% output for 30 s. Each additional detection restarts the full-brightness timer so that a moving road user remains inside an illuminated corridor. When the timer expires, the controller gradually returns to 35% output instead of switching abruptly. A minimum dim level is retained to preserve basic road visibility and to avoid frequent complete switching. If either the LDR or PIR sensor reports an implausible value, a fail-safe schedule maintains the luminaire at 60%-night output and raises a diagnostic flag on the dashboard.

The algorithm can be expressed by the following rule set: if ambient light is above the daylight threshold, duty cycle $D = 0$; if ambient light is below the night threshold and motion is absent, $D = 0.35$; if motion is present, $D = 1.00$. The electrical power of a dimmed LED is approximated as $P(t) = P_{\text{rated}} \times D(t) + P_{\text{node}}$,

where P_{node} represents controller and sensing overhead. Nightly energy is calculated as $E = \sum P_i \Delta t_i$. Energy saving relative to a reference system is $\eta = [(E_{\text{ref}} - E_{\text{proposed}})/E_{\text{ref}}] \times 100\%$. These equations allow the control profile to be evaluated without assuming that every dimming level produces exactly the same luminous efficacy; final field commissioning should therefore verify illuminance with a lux meter and confirm compliance with applicable road-lighting requirements.

3. IoT Communication and Data Management

MQTT is used because it publish/subscribe model is lightweight and suitable for distributed embedded nodes. Each pole publishes a compact message containing node identifier, timestamp, LDR value, motion state, PWM level, voltage, current, instantaneous power, energy counter, and fault code. The broker forwards these values to a dashboard and time-series database. Control messages are limited to non-safety-critical parameters such as dim level, motion hold time, reporting interval, and maintenance reset. Authentication credentials are stored per node and communications should be protected by TLS in field use. The dashboard never becomes the only control path; local firmware continues the configured lighting schedule if communication fails, consistent with the reliability concerns identified in the smart-streetlight literature [8], [9].

4. Experimental / Analytical Evaluation Procedure

The methodology evaluates three equivalent ten-lamp scenarios over a 12 h night: (A) conventional 70 W luminaires operating

continuously, (B) 30 W LED luminaires operating continuously, and (C) the proposed 30 W IoT-LED system. For Scenario C, the representative low-to-medium traffic profile contains 4 h equivalent operation at 100% brightness and 8 h at 35% brightness. Controller overhead is assumed as 1.2 W per node during the night. Energy is calculated directly from rated power and operating duration. A bench prototype should additionally be tested for 50 repeated motion events, day/night threshold transitions, loss and restoration of Wi-Fi, and current-sensor fault detection. The response time from motion detection to full brightness is targeted below 0.5 s, while MQTT telemetry is transmitted every 30 s to avoid unnecessary network traffic.

Results

The analytical prototype evaluation indicates that replacing conventional 70 W lamps with fixed 30 W LEDs reduces nightly energy from 8.40 kWh to 3.60 kWh for ten luminaires, a 57.1% reduction. Adaptive IoT operation reduces the LED lighting energy further to 2.04 kWh. Adding 0.144 kWh of controller and sensing overhead gives a total of 2.184 kWh per night. The proposed configuration therefore provides an estimated 39.3% saving compared with fixed-output LEDs and 74.0% compared with the conventional baseline. The magnitude is consistent with the direction of earlier experimental and field evidence showing that adaptive sensing and intelligent control add savings beyond the basic LED retrofit [2], [4], [7], [10], [11].

Table 2. Energy-performance comparison for the defined 10-lamp test profile

Scenario	Rated lamp power	Operating profile	Lighting energy/night	Node overhead	Total energy/night
A. Conventional	70 W $\times$ 10	100% for 12 h	8.400 kWh	0	8.400 kWh
B. Fixed LED	30 W $\times$ 10	100% for 12 h	3.600 kWh	0	3.600 kWh
C. Proposed IoT LED	30 W $\times$ 10	100% 4 h + 35% 8 h	2.040 kWh	0.144 kWh	2.184 kWh

The state-transition tests are expected to show a direct response to local sensing because the PIR signal is processed on the controller rather than routed through the cloud. A properly configured ESP32 implementation can issue a PWM update within a few tens of milliseconds, leaving sensor detection and driver ramping as the dominant response factors. In the proposed acceptance test, all 50 motion events must produce a full-brightness state, the light must return to the dim state only after the hold timer expires, and a

network interruption must not alter local illumination. These tests are more important than dashboard refresh speed because safe night operation must remain independent of Internet availability.

From a cost perspective, the hardware in Table 1 represents a low-cost academic prototype. The estimated per-node electronics cost excluding the luminaire is approximately INR 1,800, while the complete laboratory node including a 30 W

LED is approximately INR 2,700. In a municipal deployment, certified drivers, surge protection, weatherproof enclosures, poles, installation, metering, and network management would increase capital cost. Nevertheless, the modular architecture allows the controller and sensors to be retrofitted to compatible LED luminaires and makes it possible to start with a small pilot before scaling to a larger road network.

Conclusion and Discussion

This paper presented a methodology for an energy-efficient street-lighting system that combines IoT connectivity with dimmable LED technology and local sensing. The design uses an ESP32-class embedded controller, LDR-based day/night identification, PIR-based movement detection, PWM dimming, electrical feedback, and MQTT telemetry. The central methodological decision is to keep the essential lighting logic inside the pole controller while using the IoT layer for monitoring, configuration, data storage, and maintenance. This distributed structure reduces dependence on continuous network availability and is consistent with the evolution of smart-streetlight systems from simple remote switching toward adaptive, sensor-rich and networked infrastructure [8]-[10]. For the defined ten-lamp, 12 h night profile, the proposed system consumed an estimated 2.184 kWh compared with 3.60 kWh for fixed 30 W LEDs and 8.40 kWh for a 70 W conventional baseline. The resulting 39.3% reduction relative to fixed LEDs illustrates why adaptive control should be considered as a second efficiency layer after LED replacement. The exact field saving will depend on traffic density, dimming level, night duration, driver efficiency, sensor placement, and required illumination class. Therefore, the numerical results should be interpreted as a transparent prototype-level engineering estimate rather than a municipal field trial. Field validation should record actual power, lux levels, traffic activity, fault frequency, communication availability, and maintenance effort over several months. The literature up to 2020 shows a clear progression from wireless remote control [1], low-cost sensor-based LED control [2], traffic-adaptive algorithms [4], intelligent city-level architectures [5], and energy-performance case studies [6], [7] to comprehensive IoT street-light management platforms [9]-[11]. The proposed methodology synthesizes these directions into a compact prototype suitable for student research and pilot deployment. Future work can extend the architecture using LoRaWAN or cellular communication for longer range, solar-battery integration for off-grid roads, secure over-the-air firmware updates, predictive fault diagnosis, and

traffic forecasting. Before public-road deployment, electrical isolation, surge protection, enclosure ingress protection, cybersecurity, photometric compliance, and local road-lighting standards must be addressed as formal design requirements.

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