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IoT-based smart street lighting system for reducing energy consumption

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ABSTRACT

Street lighting systems are essential components of urban infrastructure due to their critical role in ensuring citizens' safety, comfort, and quality of life. Moreover, they are among the largest consumers of energy in urban environments. This paper investigates the performance and feasibility of a prototype smart street lighting system based on the Internet of Things (IoT) and wireless communication technologies. The system was implemented and tested at a pilot site to improve energy efficiency. It provides adaptive lighting by ensuring that the area in front of the user is illuminated more brightly than the area behind them. This functionality is achieved through data exchange between lampposts using the ESP-NOW protocol. A passive infrared (PIR) sensor is used to detect user movement. Power consumption data are collected and stored on the ThingSpeak cloud platform, while street images are captured using an ESP32-CAM module and saved to Google Drive. The results demonstrate the effectiveness of the proposed system in reducing energy consumption, achieving a reduction rate of 49.54% over three days of experimentation. Consequently, the system contributes to lower carbon dioxide (CO_2) emissions and generates positive impacts on both people and the environment.

KEYWORDS

Smart street lighting
IoT
ESP-NOW
Energy consumption

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1 Introduction

Street lighting systems (SLSs) represent a fundamental component of modern infrastructure, serving cities, towns, road networks, and other essential facilities. They are widely regarded as indispensable due to the numerous benefits they provide in daily life. Beyond illuminating public spaces, these systems create safer and more attractive environments for nighttime activities, while enhancing security and contributing to a reduction in traffic accidents [1, 2]. In contrast, poorly illuminated areas are often associated with higher risks and reduced levels of safety [3].

Nevertheless, despite their significant contribution to improving quality of life, traditional street lighting systems present notable drawbacks, most prominently high energy consumption and the resulting increase in carbon dioxide (CO_2) emissions, which adversely affect both human health and the environment.

The emergence of smart street lighting systems (SSLs) has addressed many of the limitations inherent in conventional lighting technologies, primarily through the application of the energy-on-demand principle [4, 5]. By providing adaptive illumination tailored to users' needs, these systems significantly enhance both energy efficiency and sustainability. Moreover, advances in digital and communication technologies have enabled smart lighting systems to evolve into interconnected networks capable of transmitting traffic-related data and supporting environmental monitoring. Such multifunctional capabilities establish smart lighting as a valuable tool for improving the management and organization of urban activities [6].

2 Methodology

2.1 Smart Street Lighting Architecture

The prototype smart street lighting system was implemented and tested on a pilot street equipped with nine LED luminaires. Figure 1 presents the overall architecture of the proposed system, while Figure 2 shows the pilot site.

The selected street experiences low traffic during nighttime hours because it is located within a university campus. It is primarily used by students conducting research activities during the evening and night, owing to its proximity to the university research center. In addition, the street is used by security personnel responsible for ensuring the safety and security of the campus during nighttime hours.

The developed system consists of three responsive control units, each responsible for managing three LED luminaires. These units are installed beneath the luminaires and interconnected through a wireless network based on the ESP-NOW protocol. Each control unit integrates an ESP32 microcontroller, a PIR motion sensor for detecting user movement, a power supply module to power the ESP32, PIR sensor, and relay, as well as a relay for controlling the LED luminaires. Both the control units and the luminaires are powered by a common power source. In addition, user movement detection is supported by an ESP32-CAM module. Figure 3 illustrates the control units, while Figure 4 presents a photograph of a control unit.

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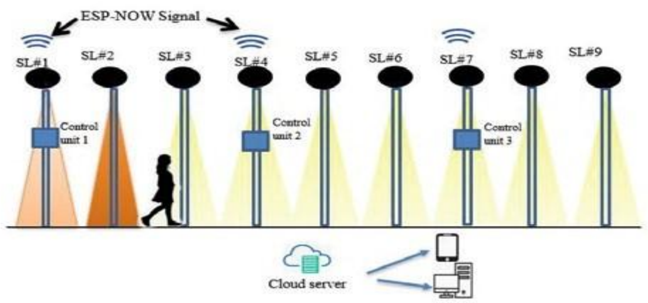

Fig. 1. The architecture of the system.

Fig. 2. Pilot site.

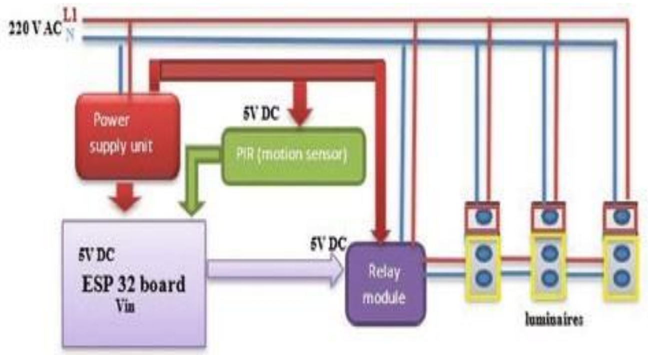

Fig. 3. Control unit.

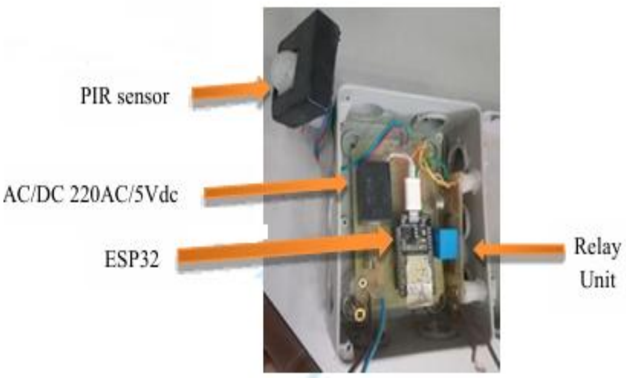

Fig.4. Real photo of control unit.

For a better understanding of the proposed system architecture, the system can be divided into five layers: the sensing layer, the processing layer, the actuator layer, the communication layer, and the monitoring and storage layer. Figure 5 depicts these layers and their associated components.

2.2 *Measurement of the electric variable and sensing users' images*

Figure 6 illustrates the wiring diagram of the electrical variable measurement system. Voltage and current are measured using a ZMPT101B voltage sensor and an SCT-013 current sensor, respectively. These measurements are subsequently used to calculate the electrical power (P). Furthermore, Figure 7 depicts the system architecture for electrical variable measurement and user image acquisition using the ESP32-CAM module.

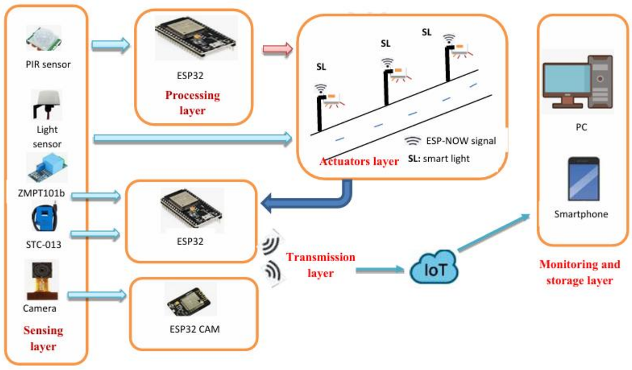

Fig. 5. Layers.

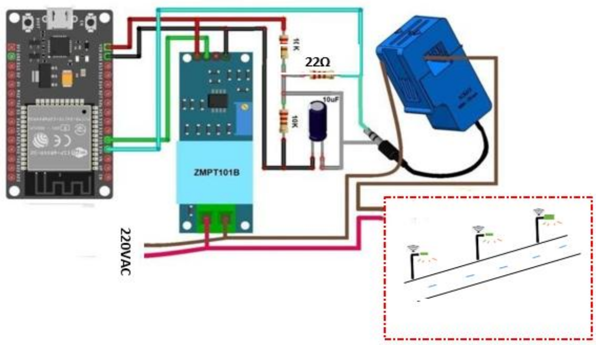

Fig. 6. Wiring diagram.

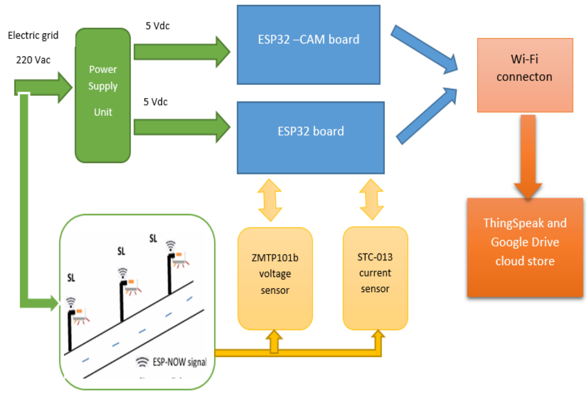

Fig. 7. System architecture for measurement of the electric variable and sensing users' images.

2.3 *Microcontrollers and Sensors*

2.3.1 ESP32 Microcontroller

The ESP32 microcontroller, developed by Espressif Systems (Shanghai, China), is a cost-effective and versatile platform widely adopted for Internet of Things (IoT) applications. It integrates a dual-core processor with built-in Wi-Fi and Bluetooth connectivity, offering a comprehensive set of features suitable for embedded systems. Key attributes of the ESP32 include low power consumption, extensive general-purpose input/output (GPIO) capabilities, and support for multiple communication interfaces such as SPI, I^2C, UART, and PWM. Furthermore, it is compatible with a range of wireless protocols, including IEEE 802.11 b/g/n for Wi-Fi, Bluetooth Classic, and Bluetooth Low Energy (BLE), thereby enabling seamless connectivity with external devices and sensors [7].

2.3.2 ESP32-CAM Microcontroller

The proposed prototype incorporates the ESP32-CAM microcontroller, a low-cost device based on the ESP32 architecture. It is equipped with an OV2640 camera, Bluetooth, an IEEE 802.11 b/g/n Wi-Fi module, and a microSD card slot [8], making it highly suitable for IoT-based applications. The ESP32-CAM enables data storage in the form of images and videos. In the proposed system, it is used to capture photographs of users.

2.3.3 PIR Sensor

In this work, the HC-SR501 passive infrared (PIR) sensor is employed. This sensor is widely recognized for its low cost, compact size, and practical functionality in detecting human presence through the thermal energy emitted by the human body. However, one limitation of PIR sensing is its susceptibility to interference from other heat sources, such as motors or fluctuations in ambient temperature [9].

2.3.4 SCT-013 Current Sensor

The SCT-013 is a non-invasive AC current sensor that employs a split-core clamp mechanism to measure currents of up to 100 A. The sensor produces a proportional output signal and was utilized in this work for monitoring alternating current. It is valued for its ease of installation, as it can be directly clamped onto either the live or neutral conductor to measure current flow [10]. In this system, the 100 A version of the sensor was selected.

2.3.5 ZMPT101B Voltage Sensor

The ZMPT101B voltage sensor module, based on the ZMPT101B voltage transformer, is designed for accurate AC voltage measurement. Capable of measuring voltages up to 250 V AC, it offers high accuracy, excellent stability, and reliable performance in power-monitoring applications. The module operates by stepping down the mains AC voltage to a lower signal level that can be safely processed by the microcontroller for voltage measurement [11].

3 Results

To evaluate the effectiveness of the proposed smart street lighting system in reducing energy consumption, power consumption was measured before and after system implementation. The system was also evaluated for its ability to provide real-time power consumption data and capture user images. Figure 8 presents the power consumption data collected over three days and stored on the ThingSpeak cloud platform. Figure 9 presents sample images of users captured by the ESP32-CAM module and stored in Google Drive.

To evaluate the energy savings achieved by the proposed system, a comparative analysis of energy consumption was performed before and after its deployment. Prior to implementation, the nighttime energy consumption was approximately 14.6 kWh. As shown in Figure 10, a noticeable reduction in energy consumption was observed following the deployment of the proposed system.

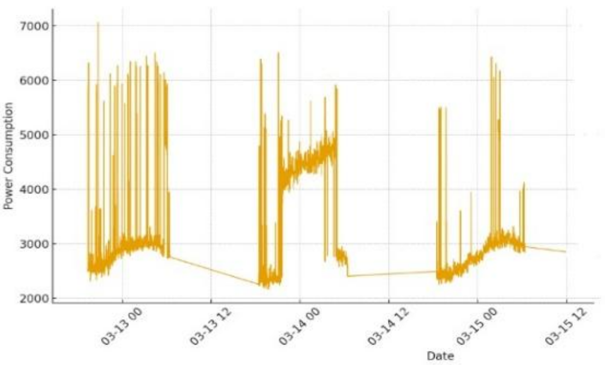

Fig. 8. Power consumption.

The results indicate that the proposed IoT-based system, evaluated at a pilot site from March 13 to March 15, 2023, successfully achieved its primary objective of providing adaptive lighting according to the selected control scenario. The system achieved significant energy savings of 49.54%, primarily through the dynamic adjustment of lighting levels, which effectively reduced overall energy consumption. Furthermore, the system provided power consumption data and user-related information through the ThingSpeak platform and Google Drive, thereby enhancing monitoring capabilities, enabling early fault detection, and supporting future optimization efforts.

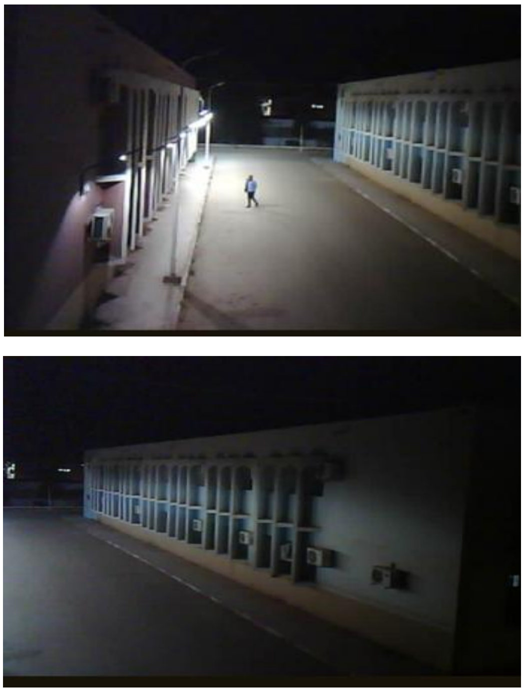

Fig.9. photo captured by esp32-CAM.

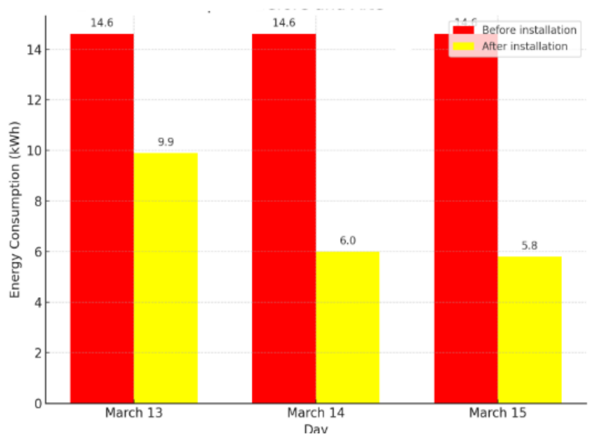

Fig.10. Energy consumption.

4 Conclusion

This paper presented a prototype smart street lighting system designed to improve energy efficiency. The proposed solution provides adaptive lighting that dynamically responds to user movement. The ESP32 microcontroller plays a central role in system operation by processing data from motion sensors and managing communication between lighting units. By leveraging the Internet of Things (IoT) paradigm, the system integrates comprehensive monitoring capabilities.

Energy consumption data were collected and stored on the ThingSpeak platform, enabling accurate analysis of consumption patterns and facilitating the extraction of insights for further system optimization. In addition, the ESP32-CAM module was used to capture images of users, which were subsequently stored on Google Drive, thereby enhancing system monitoring and performance evaluation.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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