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A Zonal Energy-Efficient Smart Laboratory Lighting System

Havva KAYA [1*], Mehmet Erdal ÖZBEK [2]

Abstract
Existing centralized lighting systems in large-scale educational environments often lead to significant energy inefficiencies due to non-uniform occupancy and varying daylight conditions. Although Internet of Things (IoT)-based smart lighting solutions have been widely investigated, many existing approaches rely on centralized control or lack sufficiently granular zonal adaptability. In this study, an IoT-based, zonal, and energy efficient smart lighting architecture, named as the Lighting and Energy Automation Framework, is proposed. The system employs a star topology and the message queueing telemetry transport protocol to enable efficient communication between edge nodes and a central controller. A context-aware control algorithm is implemented to activate lighting only when occupancy is detected and ambient illumination is insufficient, while unnecessary lighting is automatically deactivated after a predefined timeout period. Experimental results demonstrate that the proposed system effectively reduces unnecessary energy consumption and provides adaptive, real-time lighting control suitable for the laboratory environments.
Keywords: Energy Efficiency; Internet of Things; Message Queuing Telemetry Transport; Smart Lighting.

1. Introduction

Lighting systems constitute a significant portion of total electrical energy consumption in modern buildings and educational institutions, making energy-efficient lighting control a critical research area. Driven by the need to balance energy optimization with user comfort, the global smart lighting market has experienced rapid growth, reaching approximately US$5.9 billion in recent years [1]. Traditional lighting systems, which rely on centralized control strategies and fixed schedules, often lead to unnecessary energy consumption due to their inability to adapt to dynamic environmental and occupancy conditions. In contrast, recent Internet of Things (IoT)-based smart lighting systems have demonstrated considerable energy savings, reaching up to 36.42% in office environments through fine-grained activity recognition techniques [2]. Furthermore, performance evaluations of intelligent lighting infrastructures have reported system availability levels as high as 99.74%, highlighting their reliability for continuous operation in real-world deployments [3].

In order to enhance energy efficiency, modern lighting systems increasingly rely on dynamic environmental sensing and adaptive control mechanisms. Recent studies emphasize the transition from simple motion detection to multimodal sensing approaches, where illumination levels are adjusted based on real-time environmental and user-side data [4]. In addition, the integration of context-aware computing enables systems to utilize environmental conditions, user behavior, and temporal patterns to optimize lighting decisions [5]. Such approaches are further supported by power-aware middleware solutions that dynamically reconfigure system operations based on user activity and environmental conditions [6], as well as intelligent daylight harvesting techniques that leverage natural illumination to reduce artificial lighting usage [7]. From an architectural perspective, conventional centralized systems are being replaced by distributed IoT frameworks, such as Leader–Follower architectures, where a master node coordinates multiple sensor and actuator units [8]. The adoption of low-cost and high-performance microcontrollers, particularly ESP-based platforms [9], has enabled the development of scalable and real-time lighting control systems [10]. These hardware advancements support the deployment of energy-efficient wireless sensor network infrastructures [11], as well as multi-zone lighting control strategies that effectively manage the interaction between artificial lighting and daylight [12]. At the communication layer, lightweight protocols such as Message Queuing Telemetry Transport (MQTT) play a key role in enabling efficient data exchange and resource allocation in smart building applications [13].

These communication mechanisms facilitate the integration of heterogeneous IoT devices and support energy-aware system operation. Moreover, the increasing adoption of energy harvesting techniques contributes to the sustainability of IoT-based lighting systems by reducing dependency on conventional power sources [14]. The impact of these technologies is evident in applications ranging from automated highway lighting systems [15] to

*Corresponding author

HAVVA KAYA; Izmir Katip Celebi University, Faculty of Engineering and Architecture, Electrical and Electronics Engineering Department, Türkiye; e-mail: 210403082@ikc.edu.tr; 0009-0000-0051-9812

MEHMET ERDAL ÖZBEK; Izmir Katip Celebi University, Faculty of Engineering and Architecture, Electrical and Electronics Engineering Department, Türkiye; e-mail: merdal.ozbek@ikcu.edu.tr; 0000-0001-5840-7960

large-scale urban lighting infrastructures utilizing Long Range Wide Area Network (LoRaWAN)-based communication networks [16]. In an effort to address these limitations, an IoT-based, zonal, and energy-efficient smart lighting system, referred to as the Lighting and Energy Automation Framework (LEAF), is proposed in this study. The proposed system provides adaptive lighting control by considering both occupancy and daylight conditions at the zonal level, thereby improving energy efficiency and operational responsiveness in laboratory environments. The rest of this article is organized as follows. Section 2 details the proposed system architecture, including the physical laboratory environment and the hardware framework. Section 3 explains the operational logic and the context-aware decision-making algorithm of the system. Section 4 presents the system implementation and discusses the experimental results regarding zonal control and power consumption. Finally, Section 5 concludes the study.

2. Proposed System Architecture

The laboratory environment in which the proposed system was implemented and evaluated is presented in Figure 1. The workspace consists of multiple zones with non-uniform illumination conditions, influenced by both artificial lighting and natural daylight. Such spatial variability makes it difficult for conventional centralized lighting systems to operate efficiently.

Figure 1. *General view of the laboratory where the system was implemented and tested*.

In order to address these physical and operational challenges, an IoT-based zonal smart lighting architecture is proposed. Rather than relying on a conventional single-point control mechanism, the system is designed to operate upon a distributed Leader-Follower framework. Within this architecture, a network of sensor-enabled edge nodes is strategically deployed across spatially diverse zones of the laboratory to capture localized data. These peripheral nodes are dedicated to the continuous and independent monitoring of critical environmental conditions, specifically real-time human occupancy and ambient daylight intensity. By acquiring this sensory data, the system accurately determines the distinct illumination requirements of each specific region.

Figure 2 illustrates the star topology established between three sensor nodes positioned at different locations of the laboratory and one central controller. The illumination of only specific regions where motion is detected and daylight is insufficient is targeted, maximizing energy savings through hardware sensor fusion and software data processing.

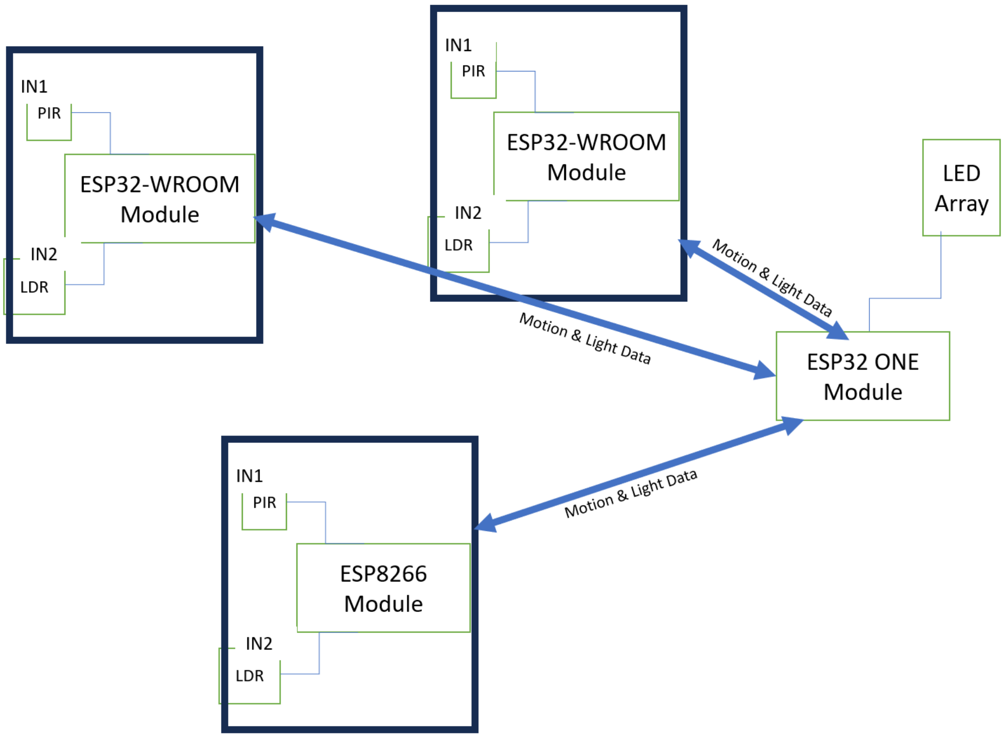


Figure 2. *LEAF architecture based on star topology and MQTT.*

For this purpose, the architecture is systematically integrated into data acquisition, communication, and control stages. The peripheral sensing mechanism comprises two ESP32-WROOM modules and one ESP8266 microcontroller, acting as edge nodes. Each node utilizes a Passive InfraRed (PIR) sensor for zonal occupancy detection and a Light Dependent Resistor (LDR) module for instantaneous ambient light measurement. Adhering to the star topology, these environmental data are continuously published to a cloud-based MQTT Broker (broker.emqx.io) over a local Wi-Fi network, which eliminates wiring complexities and ensures scalability.

The autonomous decision-making process is executed by an ESP32 One central controller. By subscribing to the relevant MQTT topics, the central unit evaluates the synchronized zonal parameters. If simultaneous occupancy and insufficient lighting are detected in a specific zone, a relay module is triggered by the central controller to activate zonal lighting. Concurrently, all system telemetry is monitored by a local server hosting a Node-RED dashboard for real-time visualization and remote energy tracking.

3. System Algorithm and Operational Logic

The operational efficiency of the LEAF system is governed by a context-aware decision-making algorithm executed at the central controller. The primary objective is to ensure that illumination is provided only when both environmental and occupancy conditions necessitate it. To achieve this, a logic-gate-based approach is implemented, processing inputs from localized PIR and LDR sensors.

The decision-making process is initiated by the real-time data flow from the edge nodes. As depicted in the zonal layout given in Figure 2, each zone is evaluated independently to account for non-homogeneous light distribution within the laboratory. The activation of the lighting relay is restricted to scenarios where the light intensity remains below a pre-defined threshold indicating insufficient daylight, and motion is concurrently detected by the PIR sensors. In instances where the environment is adequately illuminated by natural daylight, the lighting remains inactive regardless of occupancy, thereby preventing unnecessary energy consumption.

Furthermore, a time-based optimization is integrated into the algorithm to handle transient occupancy. Upon the detection of motion, a timer is initialized. If no subsequent motion is detected within a designated 15-minute interval, the corresponding zonal relay is automatically deactivated. This zonal control strategy ensures that shadowed corners or areas distant from windows receive adequate lighting without necessitating the full-scale illumination of the laboratory. The synchronized execution of this algorithm across all nodes ensures a highly responsive and sustainable energy management facility. Figure 3 displays the operational flowchart of the proposed control logic summarized above.

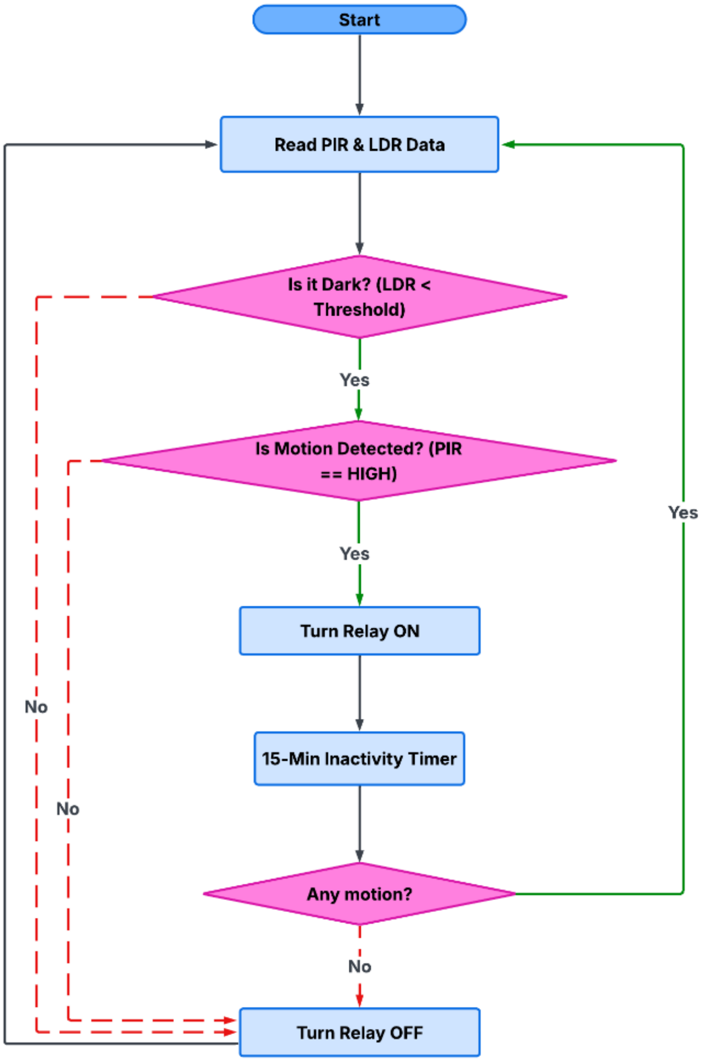
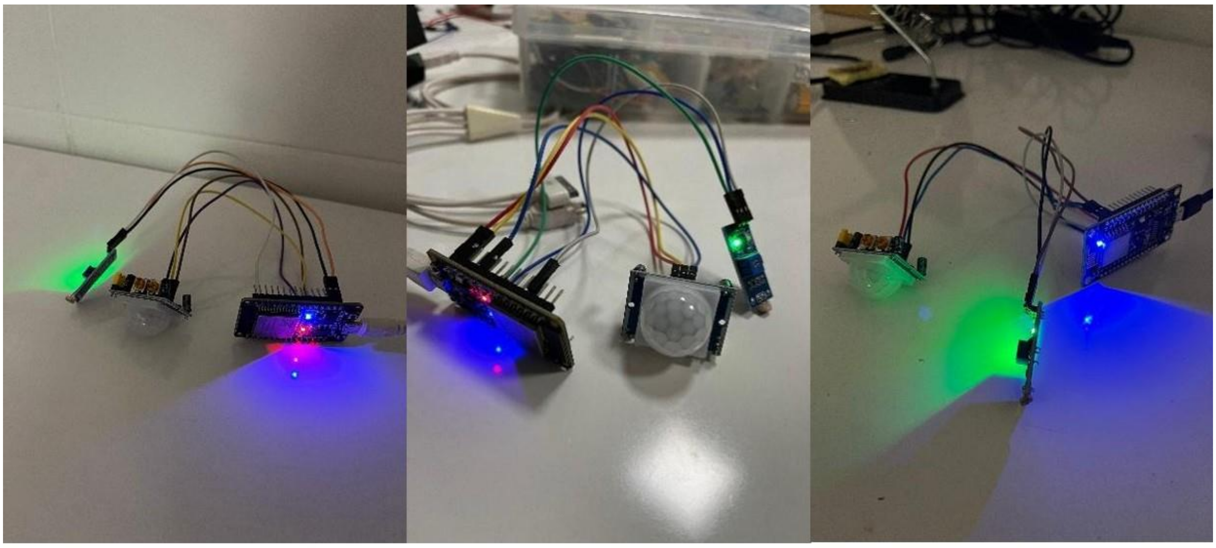


Figure 3. *Flowchart of the proposed system*.

4. System Implementation and Experimental Results

With the aim of validating the feasibility and operational stability of the proposed LEAF architecture, a complete prototype was implemented and tested within the physical laboratory environment previously described. The core of the system is managed by an ESP32 One module, which serves as the central Leader controller. This primary unit is designated to execute the context-aware decision-making algorithm, aggregate sensory data, and directly operate the multi-channel relay to adjust zonal lighting.

In order to facilitate distributed environmental monitoring, the peripheral data acquisition mechanism was configured using a heterogeneous network comprising two ESP32-WROOM modules and one ESP8266 microcontroller. Acting as decentralized sensing endpoints, these edge nodes were strategically deployed at the non-homogeneously illuminated corners of the workspace. This targeted placement was established as a critical design choice to address localized variations in natural daylight penetration and spatial occupancy patterns that a single centralized sensor could not capture. Each edge node is tasked with continuously sampling real-time motion events and ambient light intensity within its specific designated zone. The acquired sensory data is then transmitted wirelessly to the central ESP32 One Leader controller via the MQTT protocol, thereby establishing a low-latency, reliable communication link that enables highly granular and context-aware zonal lighting control without the constraints of a complex wired infrastructure. Figure 4 illustrates these edge nodes, which were positioned at the non-homogeneously illuminated corners of the workspace to monitor zonal occupancy and light intensity independently.



(a) (b) (c)

Figure 4. *Deployed edge nodes: (a) Edge Node 1, (b) Edge Node 2, (c) Edge Node 3.*

During the experimental phase, various environmental scenarios were simulated to evaluate the responsiveness of the context-aware algorithm. All system telemetry and relay activities were monitored via a localized Node-RED dashboard. As depicted in Figure 5, in the initial scenario, localized occupancy was detected at Edge 2 while zonal daylight was insufficient, resulting in the successful and isolated activation of the corresponding lighting relay.

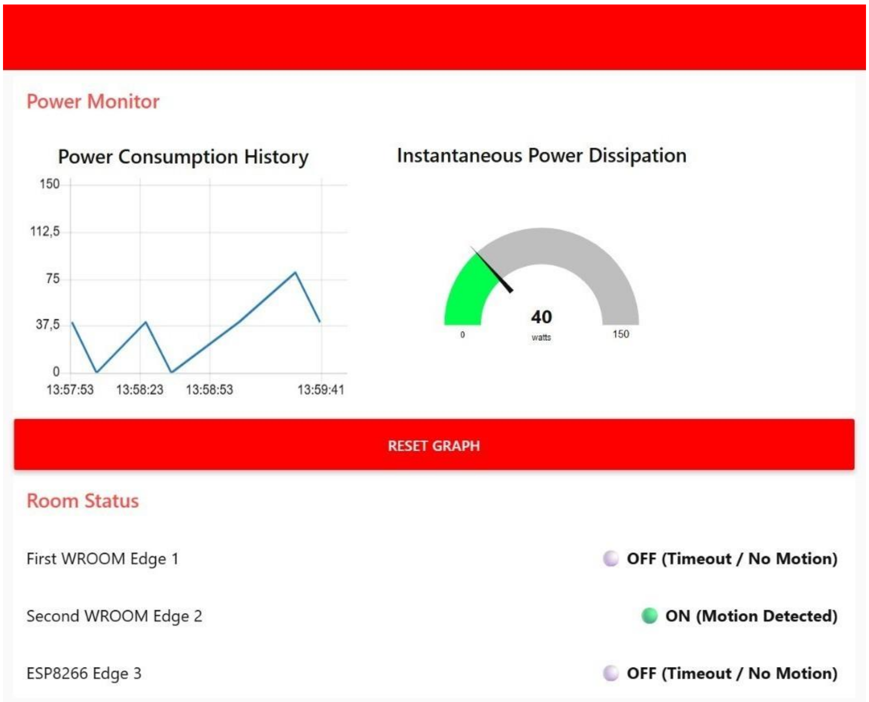


Figure 5. *Dashboard visualization of zonal lighting activation at Edge 2.*

Subsequently, it was observed that Edge 2 maintained its lighting in the "OFF" state due to sufficient daylight, successfully overriding the detected occupancy. Concurrently, as illustrated in Figure 6, Edge 3 correctly triggered its localized lighting upon motion detection under insufficient lighting conditions, demonstrating the independent zonal control capability of the architecture.

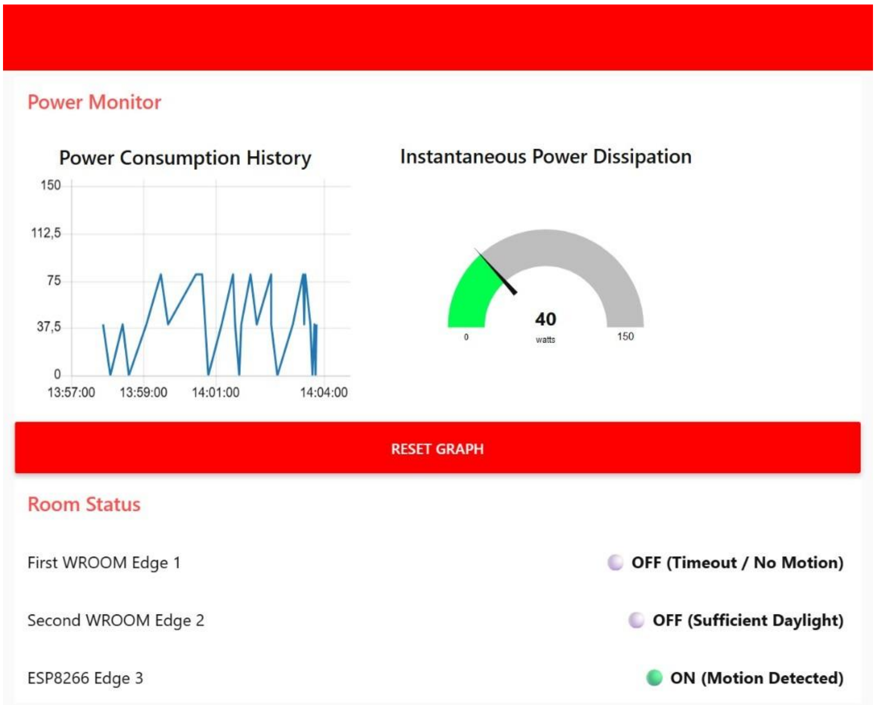


Figure 6. *Zonal control scenario demonstrates daylight override at Edge 2 and zonal activation at Edge 3.*

Finally, the autonomous energy management and timeout features were verified through the real-time power consumption and energy dissipation graphs presented in Figure 7. The timeout mechanism successfully deactivated the relay at Edge 3 after 15 minutes of inactivity. In the same instance, other nodes remained in the "OFF" state due to sufficient natural daylight. These graphical analyses clearly demonstrate that transitioning from a centralized lighting mechanism to the distributed, context-aware LEAF architecture significantly mitigates unnecessary power dissipation in indoor facilities. Although timeout duration is pre-defined and applied as 15 minutes of inactivity, any other scheduling scenarios can be easily performed based on the activity inside the laboratory workspaces.

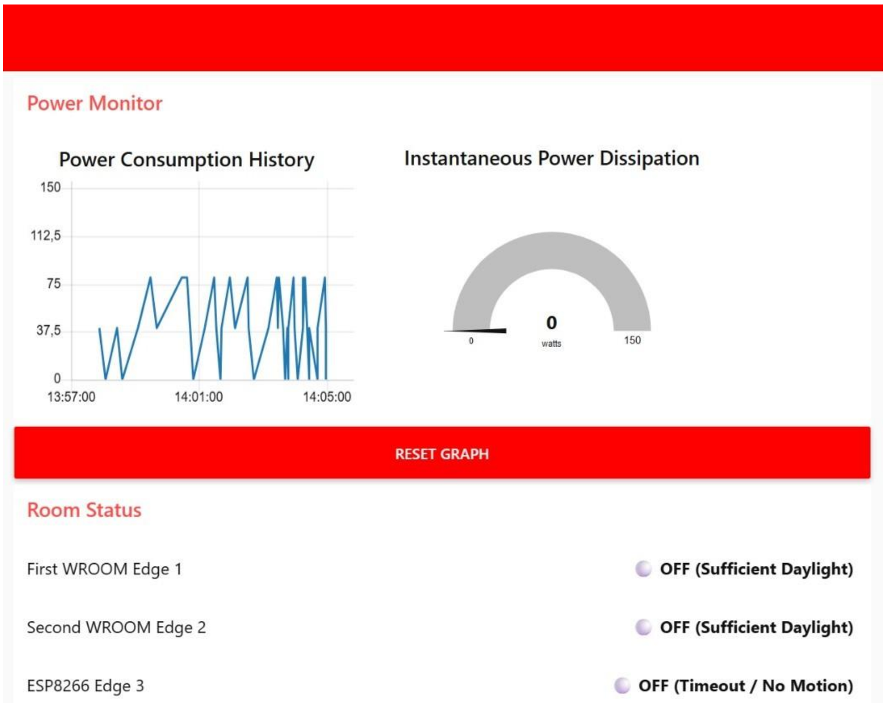


Figure 7. *Real-time power consumption analysis and timeout status monitoring via the Node-RED interface.*

5. Conclusion

In this study, the Lighting and Energy Automation Framework (LEAF) was developed to mitigate the energy inefficiencies of conventional, centralized lighting systems in large-scale laboratories. A distributed IoT architecture based on a star topology was successfully implemented utilizing cost-effective ESP32 and ESP8266 microcontrollers. By integrating a sensor fusion of PIR and LDR modules, environmental parameters such as zonal occupancy and ambient light intensity were precisely monitored at the edge nodes. The acquired data were transmitted to a central controller via the lightweight MQTT protocol, ensuring low-latency and highly reliable communication.

Experimental validations that are monitored through a real-time Node-RED dashboard confirmed the operational stability of the proposed context-aware algorithm. It was demonstrated that lighting activation was effectively restricted to specific zones only when motion was detected and natural daylight was concurrently insufficient. Furthermore, unnecessary power dissipation was significantly minimized through the integration of a 15-minute timeout mechanism and an autonomous daylight override feature. The experimental results demonstrate that the proposed system effectively reduces unnecessary energy consumption. Ultimately, it is concluded that the LEAF architecture provides a scalable, economically viable, and sustainable framework for intelligent energy management in educational facilities.

Declaration of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Havva Kaya conceptualized the research idea, designed the methodology, developed the hardware and software architectures, conducted the experiments, and drafted the manuscript. The research was supervised by Mehmet Erdal Özbek, who provided critical guidance throughout the study and contributed to the manuscript revision.

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