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Design and Experimental Evaluation of an IoT-Integrated Smart Lighting System with Adaptive Control and Wireless Power Transfer

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Abstract:
Energy usage connected with conventional lighting systems is a critical problem in residential and commercial spaces. The purpose of this paper is to develop and experimentally evaluate an Internet of Things (IoT)-based smart lighting system that incorporates adaptive illumination control, Bluetooth Low Energy (BLE) communication, and resonant wireless power transfer in one system. For experimental testing, the developed system was built using an ESP32 microcontroller, a TSL2561 digital light sensor, an NRF52832 BLE module, and a power switch circuit that operates with the use of MOSFET. During experiments, energy efficiency, control responsiveness, and wireless power transfer performance were estimated. The developed smart lighting system provided 30% energy savings compared to a conventional relay-based lighting system. BLE commands' processing was characterised by 0.5s of average response time and a 95% success rate within 10 m range. Additionally, the wireless power transfer subsystem ensured an energy transfer efficiency of approximately 85% at a distance of 10 cm.

Keywords: *Internet of Things (IoT), Smart Lighting System, Adaptive Illumination Control, Bluetooth Low Energy (BLE), Wireless Power Transfer, Energy Efficiency, Smart Buildings.*

1. Introduction

The lighting systems became increasingly sophisticated due to implementation of IoT and smart control technologies. It makes the usage of lighting more efficient and convenient. Moreover, due to the growing attention paid to the achievement of sustainable development goals, smart lighting systems have become important elements of smart homes and buildings. Using modern technological solutions does not only improve the quality of life, but helps to save energy and preserve the environment as shown in energy-saving LED technology and smart lighting systems [1].

There is the example of lighting system called Responsive Fluorescent Lamp (RFL) that adjusts illumination according to environmental conditions and optimizes energy usage [21]. Integration of IoT into smart lighting systems allows users to control it centrally using smartphone applications that are based on machine learning algorithms and artificial neural network [2] [3]. The architecture of RFL system shows the tendencies of implementation of AI and IoT technologies that provide better control and, therefore, improved energy management in various environments including homes and healthcare facilities [2] [3].

Moreover, implementation of wireless energy transfer technology provides additional opportunities for modern lighting systems. Using wireless energy transfer technology allows recharging of devices and sensors without physical connection that simplifies the maintenance of smart homes infrastructure and provides smooth integration of additional devices [4] [5].

Experimental research showed that optimization of domestic lighting with the use of IoT platforms could provide substantial energy savings [6], and implementation of automated switching architecture ensures lower energy

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expenditures [7]. Therefore, implementation of smart control with resonant wireless energy transfer technology can be considered as promising approach for modern energy management.

The development of lighting systems through IoT and smart control technologies does not only promise increased energy efficiency and convenience but also corresponds to sustainable development goals. As this technology becomes more widespread, it can have impact on building design and user interaction with it. Despite the existence of numerous researches on different technologies used in lighting systems, such as IoT-based systems and wireless power transfer systems, few integrated solutions are known. It negatively impacts the system efficiency and interoperability. This work aims to combine adaptive lighting control, efficient power management, and wireless power transfer into the unified system and increase energy efficiency and interoperability. Further improvements of smart lighting systems should be focused on improving interoperability, energy efficiency, and smart control abilities in accordance with new requirements of smart buildings and industry [8] [9].

Despite numerous advancements in smart lighting technologies, most of reported systems consider either IoT control or wireless power transfer as separate features. It leads to reduced interoperability, increased complexity and, as a result, decreased energy efficiency. In addition, most of implementations use relay-based power switching that introduces switching losses and reduced responsiveness.

In order to solve these problems, this work develops a smart lighting platform that incorporates adaptive illumination control, BLE communication, power management with the use of MOSFETs, and wireless charging.

2. Related Works

2.1 Automation in Intelligent Lighting

Optimisation of lighting systems through automation is achieved through reduced energy consumption and improved ease of use. The conventional method of controlling lighting is the manual mode or the timing mode, but intelligent lighting systems are controlled using adaptive control which is aided by the data available. In these adaptive lighting systems, the sensors are used to sense light levels and presence of people such that the lighting systems can be controlled to suit the user's requirements. Different researches show that energy consumption has greatly been reduced through automation compared to the conventional systems [10].

2.2 Smart Lighting and IoT Integration

A plethora of research on IoT-based lighting systems has been done, showing various advantages of their use in remote monitoring and saving energy. The key technology aspect of any IoT-based architecture is the use of efficient System-on-Chip (SoC) architectures such as the ESP32 microcontroller, which has a dual-core processor and built-in Wi-Fi and Bluetooth Low Energy (BLE) communication modules. Comparisons of the two technologies prove that the ESP32 is more efficient in terms of processing capabilities, low-latency operations, and easier wireless connectivity than traditional 8-bit or 16-bit PIC microcontrollers [11]. This technology can be used to enable effective data transfer and load balancing, providing a better user experience in terms of energy consumption [12].

2.3 Light Sensing Technologies

The main drawbacks of LDR (Light Dependent Resistors) are inaccuracy and poor reactivity because of non-linear analog response and thermal drift, which makes them ineffective in intelligent lighting systems [13]. On the contrary, digital ambient light sensors, such as TSL2561 have a two diodes design (infrared and full-spectrum photodiodes) and I^2 C analog-to-digital conversion; thus, they enable an effective measurement of luminous flux under any colour temperature [14]. It was proven that application of high dynamic range digital light sensors allows making dimming adjustments faster and more accurately than it is possible with analog sensing circuits [13], [14].

2.4 Wireless Communication in Smart Lighting

Nowadays, Bluetooth Low Energy (BLE) is considered the preferable alternative to the classic Bluetooth technology due to the low level of energy consumption and more effective integration with new IoT architectures. The energy efficiency makes BLE relevant to the sphere of smart lighting, in which devices need to consume minimal energy. In addition, although Zigbee and LoRa technologies are used in order to check their efficiency in long-range communication, BLE is considered the most inexpensive choice for home automation systems and works more effectively than mesh networks [12] [15] [16]. That is why BLE is actively used in commercial smart lighting systems [17].

2.5 Advanced Power Management Techniques

Nowadays, modern lighting devices use MOSFETs because they have higher switching efficiency in comparison with BJTs. Research shows that the transition from traditional lead-acid batteries to Li-ion technology allows decreasing the level of energy consumption by 30% [18].

2.6 Wireless Charging Technologies

Various types of wireless power transfer have been developed and, among others, inductive power transfer is the most frequently used technology in practice. Nevertheless, it has been demonstrated that resonant wireless power transfer is more efficient and allows for power transmission at a greater distance, resulting in reduced energy loss. It has been proven that wireless resonant power charging systems are highly effective in improving the functionality of smart devices, such as smart lighting devices, due to wireless power transmission [19].

2.7 Gaps in Existing Literature and Research Motivation

While there is a wealth of literature about smart lighting systems, a significant gap persists regarding the integration of essential components in terms of adaptive IoT-based control, energy-saving power switching, and resonant wireless power transfer. In previous researches, those three aspects have been considered separately. For example, there are papers that deal with IoT-based control or power-efficient communication. López et al. [17] investigated IoT connectivity from the perspective of energy sustainability; however, there is no specific BLE-based local control in their scheme. Moreover, the work of Thông et al. [6] presents an inexpensive lighting IoT platform for efficient domestic energy consumption. This platform also lacks automated adaptive control and wireless power delivery.

Table 1. Comparative Analysis of Related Works

Study	IoT Integration	Wireless Charging	Power Efficiency	Adaptive Control	Key Limitation(s)	Improvements in This Study
Thông et al. [6] (2023)	Yes	No	Moderate	Basic	Lacks wireless charging and real-time adaptive control	Introduces resonant wireless charging and advanced adaptive lighting
Radithya et al. [7] (2023)	No	No	High	No	No IoT integration, lacks automation	Integrates IoT for remote control and automation
Okomba [2] (2024)	Yes	No	High	AI-Based	No wireless charging; focused on hospital buildings	Expands application scope and includes wireless charging
López et al. [17] (2023)	Yes	No	High	Basic	Limited control flexibility, lacks BLE communication	Introduces BLE for low-power, real-time control
Song et al. [20] (2021)	Yes	Yes	High	No	Lacks integration of adaptive illumination control and dynamic load adjustments	Combines resonant wireless power transfer with real-time adaptive illumination and BLE control
This Study	Yes	Yes	High			

Moreover, current automation systems lack either integrated IoT functionality or operation mode flexibility. Radithya et al. [7] presented an automatic switching system based on IoT, however, their solution does not include automatic sensing and adaptive lighting system. On the other hand, Okomba [2] provided a way to use artificial neural networks for lighting control, aiming at maximal energy saving in hospital environment. This system is also designed for specific applications and does not utilize contactless charging techniques. Song et al. [20] investigate the problem of power delivery efficiency of IoT-based hardware across the physical air gap, but do not mention adaptive lighting control and dimming.

Besides, current IoT lighting platforms often implement electromechanical relay switches, resulting in higher switching power losses and operational delays compared to the solid-state MOSFET switching.

The reason for this research lies in the necessity of integrating separate solutions into a single energy-efficient platform. Integration of BLE-based IoT control, high-efficiency MOSFET switching and resonant wireless power transfer is motivated by the specific limitations in previous literature [2], [6], [7], [17], [20].

2.8 Theoretical Basis

The design of the intelligent lighting system proposed is based on principles that have been well-known in electronic switching, wireless power transfer, and wireless communications. A brief theory is provided below in order to justify the design decisions of the hardware and software components described in the upcoming sections.

2.8.1 Pulse-Width Modulation (PWM) and MOSFET-Based Switching

PWM is used to control the amount of power applied to the fluorescent lighting module. The process is achieved by adjusting the duty cycle of the pulse train. The IRLZ34N N-channel MOSFET is used as a low-loss switch as it operates at a high speed with a low R_{DS(on)} to greatly enhance the switching efficiency over traditional electromechanical switches. ESP32 uses its GPIO ports to control the MOSFET gate via PWM, which allows for flexible lighting control based on sensor input or user input.

2.8.2 Resonant Inductive Coupling for Wireless Power Transfer

The wireless charging system is based on the concept of resonant inductive coupling. The transmitting coil and receiving coil are tuned to resonate at the same frequency, allowing for efficient transfer of energy between them without physical contact. Important parameters that influence the transfer efficiency are the quality factor (Q) and the mutual inductance between the coils. When the angular frequency ω is such that the following is true, maximum energy transfer takes place:

$$\omega = \frac{1}{\sqrt{LC}} \tag{1}$$

L and C are the inductance and capacitance of the circuit, respectively. Under controlled conditions, the system shows 85% energy transfer efficiency for the optimised length of transfer distance: 10 cm. This reduces mechanical wear and enables hermetically sealed and maintenance-free light deployments.

2.8.3 BLE Communication Reliability and Interference Mitigation

The decision was made to use Bluetooth Low Energy (BLE) because it consumes less energy, is widely available on mobile devices, and offers strong short-range communication capabilities. While BLE is good, it can be affected by environmental interference, particularly in the 2.4 GHz ISM band, which is also used for Wi-Fi and microwave devices. The system overcomes this by using adaptive frequency hopping and with the reduction of transmission time. A range of 10 meters was found, with BLE achieving command success rates above 95% even in semi-congested environments through empirical testing. This reliability provides a user-controlled response in the real world, in smart home and industrial settings.

Methodology

3.1 System Architecture

The intelligent lighting system is designed with the following main components:

1. **ESP32 Microcontroller:** Acts as the brain of the project that processes sensor data, user instructions, and controls the device.

2. **TSL2561 Light Sensor:** Measures ambient light intensity, and adjusts brightness automatically.
3. **BLE Module (NRF52832):** Allows low-power wireless communication with the mobile application and the system.
4. **MOSFET Power Switching System:** Provides efficient energy management of the fluorescent lamp.
5. **Resonant Wireless Charging Circuit:** It allows efficient contactless power transfer.
6. **Li-ion Battery & Supercapacitors:** Store energy efficiently and extend usage.

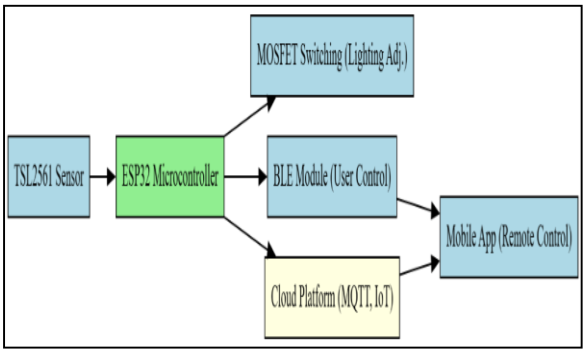

Figure 1. Block diagram of the IoT-based smart lighting system

3.2 Hardware Design and Integration

The system is based on the ESP32 microcontroller that acts as the processing and control unit. Each component is integrated into the system as described below:

- **TSL2561 Light Sensor to ESP32:** The TSL2561 sensor is connected to the ESP32 using the I2C bus. The ESP32 is constantly sampling the ambient light level and will switch the lamp on or off depending on pre-programmed light levels.
- **MOSFET-Based Power Switching:** The ESP32 uses an IRLZ34N MOSFET to switch the LED module. The microcontroller controls the power to the lamp by sending a PWM signal to the MOSFET gate, depending on the environmental conditions and the user's command.
- **NRF52832 BLE Module to ESP32:** NRF52832 BLE module is connected to ESP32 using UART. The user sends commands to it via the mobile app, and it sends those commands to the microcontroller, which then performs the correct action.
- **Resonant Wireless Charging System:** The charging transmitter circuit is plugged into the mains power and creates a resonant magnetic field. This energy is absorbed by a receiver coil which is integrated into the lamp and generates a DC voltage that charges the Li-ion battery.
- **Battery and Energy Management:** Power stability is achieved by a Li-ion battery and supercapacitors. The ESP32 is capable of measuring the battery voltage through an ADC pin and can switch to low power mode when needed to conserve energy.

3.3 Software Implementation and Control Logic

The overall system operation is sequentially structured and is shown in Figure 2, which explains the decision-making procedure for adaptive lighting control.

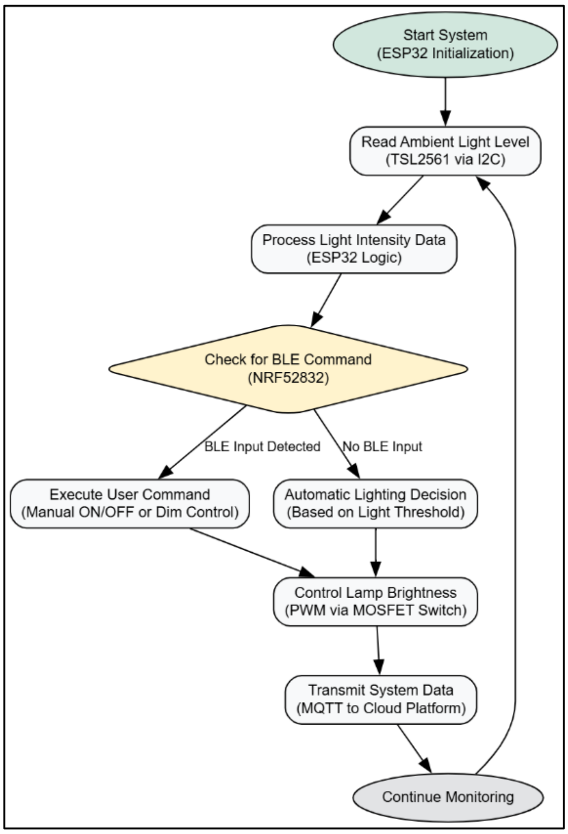

Figure 2. Adaptive Lighting Control Flowchart

The operational sequence of the smart lighting control system is shown in the flowchart given in figure 2. The first step is to read the ambient light data from the TSL2561 sensor, and then process the data in the ESP32 microcontroller.

The system then looks for a BLE (Bluetooth Low Energy) input from the user. When a BLE input is detected, the system reacts to it, but if no input is detected, it automatically adjusts the lighting by using a MOSFET switch. Finally, the data is sent to the cloud platform via the MQTT protocol, thereby closing the loop and enabling IoT-based monitoring and control.

Microcontroller Programming

- Programming of the ESP32 was done in MicroPython through the Arduino IDE.
- Real-time ambient light intensity and battery voltage monitoring were added to the control logic.
- The mobile app sent BLE commands to the microcontroller, which controlled the MOSFET-based switching mechanism.

Android Application Development

- The mobile app was created with Flutter and Android Studio.
- The application sent BLE commands to the ESP32 to manually control the lighting system.
- The ambient light intensity and battery status were shown in real time on the user interface.

IoT Cloud Integration

- Real-time monitoring and remote control were achieved using the MQTT protocol.
- The ThingSpeak cloud platform was used to store and visualise the operational data.

3.4 Communication Protocols and Data Flow

The system employs two main communication protocols:

- **I2C (TSL2561 to ESP32):** Efficient data exchange for ambient light monitoring.
- **UART (BLE Module to ESP32):** Makes wireless control using mobile devices possible
- **MQTT (Cloud Integration):** Enables remote control and monitoring.

Data Flow

- The TSL2561 light sensor is used to continuously measure the ambient light and transmit the data to the ESP32 through I2C.
- The ESP32 reads the data and controls the brightness of the LED using PWM to control the MOSFET switch.
- If the user manually adjusts the lighting using the mobile application, the command is transmitted to the ESP32 using BLE.
- The ESP32 receives the command and changes the state of the LED as per the command.

3.4 Experimental Setup and Testing

The system was tested in controlled conditions to assess its performance in terms of:

- **Automatic Light Adjustment:** Tested in a variety of ambient light conditions and the time taken for the automatic adjustment to occur.
- **BLE Command Execution:** Evaluated by measuring the latency in processing user inputs.
- **Power Efficiency**: Analysed the power consumption in MOSFET based switching and relay circuits.
- **Wireless Charging Efficiency:** Evaluated by measuring the energy transfer efficiency over a range of distances.

4. Results and Discussion

The intelligent lighting system was tested in various operating modes, with three important parameters considered: energy efficiency, control response time, and wireless charging efficiency.

4.1 Energy Efficiency

Three operating modes (continuous, adaptive, and manual) were used to compare the power consumption of the proposed MOSFET-controlled lighting system with a conventional lighting system using relays.

The experimental results showed that the design using a MOSFET was always more energy efficient than the design using relay. In continuous operation, energy consumption was about 15% less, which was due to lower switching losses in the MOSFET devices. The greatest savings were achieved in adaptive mode, which automatically dims the light from the lamp in response to the surrounding light levels, cutting power use by up to 30%.

The proposed system was able to achieve better efficiency, as the power consumption was dependent on user interaction under manual control, but not in the proposed system, thanks to the low-power nature of Bluetooth Low Energy (BLE) communication and the absence of traditional wired switching devices. The system reduced the total energy consumption by about 30% on average for all operating conditions when compared to the conventional lighting system.

The energy consumption of MOSFET-based and relay-based systems is compared in Figure 3. The findings show how effective it is to integrate adaptive lighting control with efficient power-switching circuits. The observed energy reduction proves the applicability of the proposed architecture to the smart-building application where energy conservation is one of the main design goals.

4.2 Control Response Time

The responsiveness of the Bluetooth Low Energy (BLE) communication subsystem was tested at distances from 1 m to 10 m with both clear and partial line of sight. The performance indicators were command execution delay and the success rate of the transmission.

The findings indicated that the system was able to provide a reliable communication link over the range tested. The success rate for the command execution was 99% at a distance of 1 m to 5 m with an average time of 0.5 ± 0.1 s. The performance stayed within this range, which means that the BLE subsystem delivered almost instantaneous control, which is appropriate for most indoor smart-lighting applications.

The performance gradually decreased with the increasing distance between the communication. From 6 m to 8 m, the success rate was reduced to 97% and the average response time was raised to ~ 0.7 s. The response time was within 0.9 s to 1.1 s for distances up to 10 m, with a success rate above 95%.

Further testing was done in a setting with wireless interference devices (WIFI routers) and showed only slight increases in communication delay. Under these conditions, the response time was sometimes as long as 1.3 s, but the execution of the commands was still reliable and within acceptable operational limits.

The relationship between communication distance and response time is shown in Figure 4. The performance observed during the test confirms the BLE subsystem's ability to achieve low-latency, reliable communication over the tested range, making it suitable for real-time smart-lighting control applications.

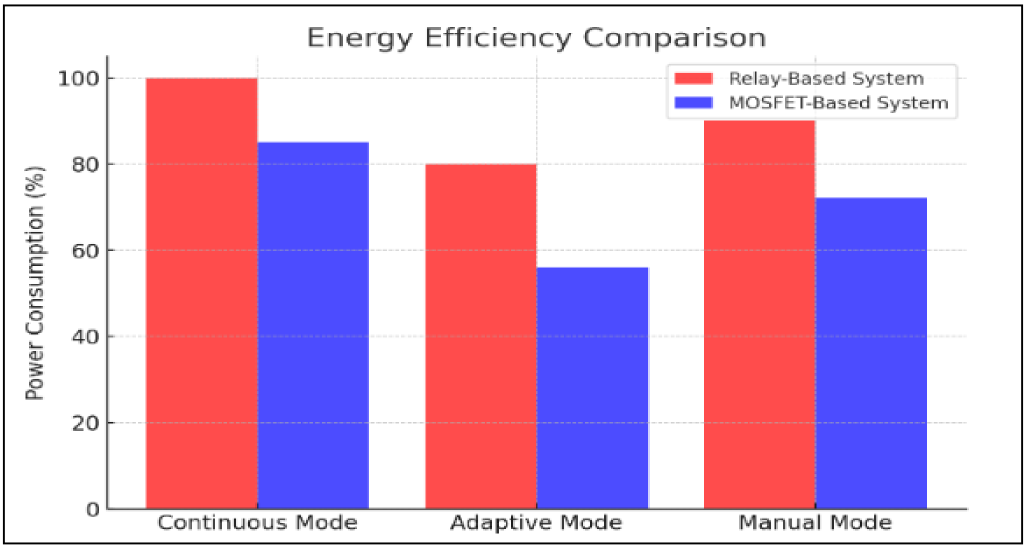

Figure 3: Power Consumption Comparison

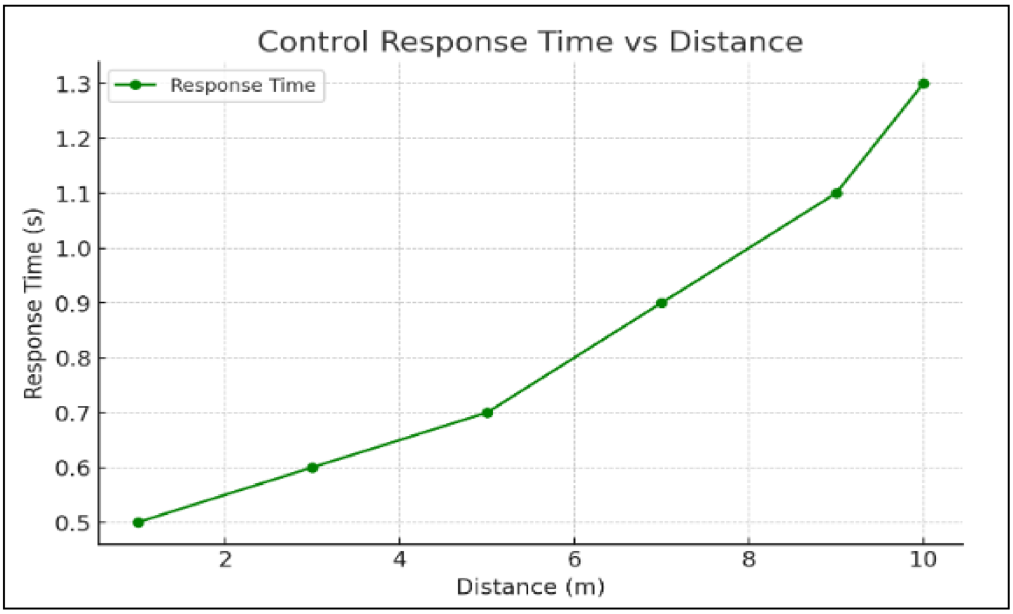

Figure 4. Control Response Time versus Distance

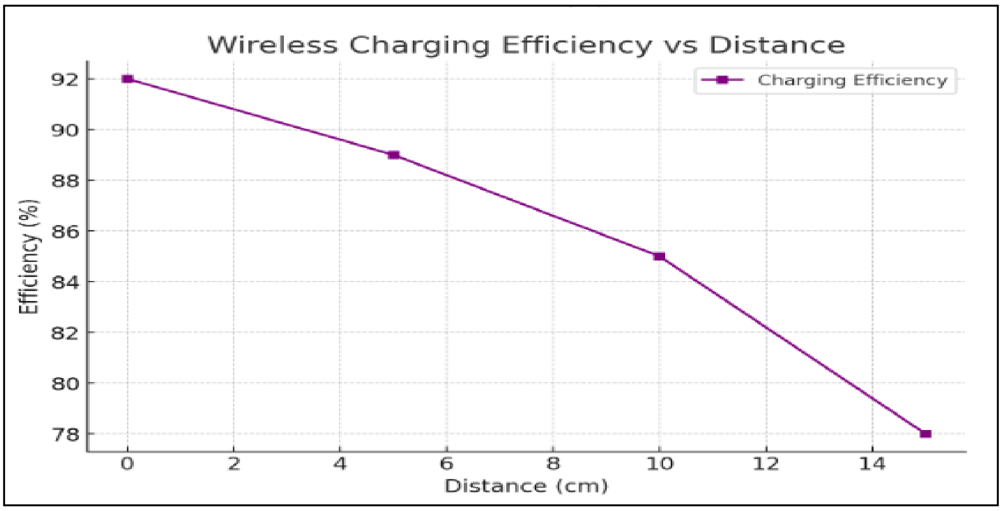

Figure 5. Wireless Charging Efficiency versus Distance

4.3 Wireless Charging Efficiency

The energy transfer efficiency of the resonant wireless charging subsystem was tested by measuring the energy transfer efficiency at separation distances of 0 cm, 5 cm, 10 cm, and 15 cm.

The results showed that the charging efficiency decreased gradually with the distance between the transmitting coil and receiving coil. The energy transfer efficiency was a maximum of 92% in direct-contact conditions (0 cm), which means that there were very few transmission losses. The efficiency was slightly reduced to 89% at a separation distance of 5 cm, demonstrating that the resonant coupling mechanism is still very efficient over short distances.

The system achieved an efficiency of around 85% at the design operating distance of 10 cm, which indicates its potential for reliable wireless power transfer with flexibility for practical implementation. Further away, there was a greater drop in performance. The charging efficiency at 15 cm was 78%, indicating that the losses due to magnetic coupling increased as the coil separation increased.

The transfer distance charging efficiency relationship is shown in figure 5. The results show that the developed wireless charging subsystem is capable of maintaining an efficient energy transfer at a distance of up to 0.5 meters without any electrical contact. An efficiency exceeding 85% at 10 cm makes it possible to integrate resonant wireless charging in intelligent lighting systems that need to be operated continuously and without maintenance.

4.4 System's Performance Summary

The experimental assessment showed the following improvements: energy efficiency, responsiveness of communication, wireless power delivery. Switching with MOSFETs, Bluetooth Low Energy (BLE) communication and resonant wireless charging allowed for reliable operation throughout the tested scenarios. Overall, the findings suggest that the proposed system architecture offers a promising approach for smart-lighting applications in the IoT context, enabling energy-efficient operation and improved user control.

5. Conclusion

This paper presents the design and experimental evaluation of an IoT-based smart lighting system featuring adaptive light control, Bluetooth Low Energy (BLE) communication, MOSFET-based power switching, and resonant wireless charging.

This study is focused on the development of a universal lighting platform that will allow energy-efficient operation and wireless control and charging.

It was shown during experimental evaluation that adaptive control combined with MOSFET-based switching reduces energy consumption compared to conventional relay-based lighting control. The Bluetooth Low Energy (BLE) communication module allows obtaining the reliable low-latency control over the whole operating range of the tested prototype. The wireless charging is provided without any physical contacts.
Therefore, the obtained results show that combining intelligent control, wireless communication, and wireless resonant power transfer within the same architecture can increase functionality and efficiency of smart lighting systems. The presented architecture is the basis for further investigations of IoT-based lighting systems.

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Conflict of Interest

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. No external funding sources influenced the design, execution, analysis, or reporting of this study.

Authors' Contribution

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Methodology: A. D. Omiyale
Formal analysis: A. D. Omiyale, O. F. Odeyinka
Visualisation: A. D. Omiyale, M.A. Adewuyi
Software: G. A. Omiyale
Writing (original draft): G. A. Omiyale
Writing (review and editing): A. D. Omiyale, O. F. Odeyinka
Validation: O. F. Odeyinka
Supervision: A. D. Omiyale
Funding acquisition: Not applicable
Project administration: A. D. Omiyale

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