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Design and Performance Evaluation of an ESP32-Based Internet of Things Smart Lighting Control System

Dea Saputri [1*], Novelia Prima[1], Naila Fauza[1]

[1] *Physics Education, Faculty of Teacher Training and Education, Universitas Riau, Indonesia*

Corresponding author's email: dea.saputri7320@student.unri.ac.id

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Abstract- The rapid advancement of Internet of Things (IoT) technology has significantly transformed smart home automation by enabling real-time monitoring and remote control of household electrical devices. Among various smart home applications, lighting control systems have attracted considerable attention due to their potential to improve energy efficiency, operational convenience, and user accessibility. However, conventional lighting systems still rely primarily on manual switching, often resulting in unnecessary electricity consumption and inefficient energy utilization. Therefore, this study aimed to design, implement, and evaluate the performance of an ESP32-based Internet of Things smart lighting control system employing Wi-Fi communication and the Blynk cloud platform. An engineering design and experimental evaluation approach was adopted, consisting of system design, hardware and software development, prototype implementation, and functional performance testing. The developed prototype integrates an ESP32 microcontroller, relay module, Wi-Fi communication, and smartphone-based control into a compact smart lighting system. Experimental results demonstrated that the prototype successfully established stable wireless communication between the ESP32 and the Blynk application, enabling real-time remote operation with reliable relay switching performance. The lighting devices responded accurately to ON/OFF commands transmitted through the smartphone application, while the overall system exhibited stable operation during repeated testing. The integrated architecture effectively combines embedded systems, cloud computing, wireless networking, and electrical switching into a practical smart home automation platform. Furthermore, the proposed system provides a low-cost, energy-efficient, and user-friendly solution for residential lighting management while demonstrating the practical application of Internet of Things technology in engineering education. Future research should focus on integrating occupancy sensors, ambient light sensors, energy consumption monitoring, artificial intelligence algorithms, and enhanced cybersecurity mechanisms to improve system autonomy, operational efficiency, and data security in next-generation smart home applications.

Keywords: Blynk; ESP32; Internet of Things; Smart home; Smart lighting; Wi-Fi.

1 Introduction

The rapid evolution of digital technology has significantly transformed modern lifestyles by enabling the integration of intelligent systems into everyday activities. One of the most influential technological developments is the Internet of Things (IoT), which refers to a network of interconnected physical devices

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capable of collecting, exchanging, and processing data through internet communication. IoT has become a fundamental technology supporting the Fourth Industrial Revolution (Industry 4.0) by facilitating automation, real-time monitoring, and intelligent decision-making across numerous sectors, including healthcare, agriculture, transportation, environmental monitoring, manufacturing, and residential automation (Atzori et al., 2010; Al-Fuqaha et al., 2015).

Among these applications, smart home technology has experienced remarkable growth over the past decade. A smart home integrates embedded systems, communication networks, sensors, actuators, and cloud computing to provide automated control of household appliances while improving convenience, security, and energy efficiency. Lighting systems represent one of the most frequently used electrical loads in residential buildings and therefore offer considerable opportunities for energy optimization. Conventional lighting systems generally rely on manual mechanical switches, requiring users to physically operate each lamp. In many cases, lights remain unintentionally switched on when rooms are unoccupied, leading to unnecessary electricity consumption and increased operational costs. Consequently, intelligent lighting management has become an important research topic in modern smart building development.

According to the International Energy Agency (IEA, 2023), improving building energy efficiency is one of the most effective strategies for reducing global electricity demand and greenhouse gas emissions. Residential buildings account for a significant proportion of worldwide electricity consumption, with lighting representing one of the largest energy-consuming components. The implementation of smart lighting technologies capable of remote operation, automatic scheduling, and real-time monitoring can substantially reduce unnecessary electricity usage while improving user convenience. These technologies also support global initiatives toward sustainable development by promoting more efficient utilization of electrical energy.

The rapid expansion of wireless communication technology has further accelerated the implementation of IoT-based lighting systems. The widespread availability of Wi-Fi networks, cloud computing platforms, and smartphone applications enables users to control household electrical appliances remotely through internet connectivity. Unlike conventional automation systems that require dedicated control panels or extensive wired installations, IoT-based systems provide flexible remote access regardless of geographical location. Users can monitor device status, send operational commands, and receive real-time feedback using mobile applications connected to cloud servers. These capabilities have positioned IoT lighting systems among the most promising technologies in smart homes and intelligent building management.

Recent advances in embedded system technology have also contributed significantly to the development of low-cost IoT applications. Microcontrollers equipped with integrated wireless communication capabilities have simplified hardware architecture while reducing implementation costs. Among various embedded platforms currently available, the ESP32 microcontroller has become one of the most widely adopted devices for IoT development because of its integrated Wi-Fi and Bluetooth connectivity, high processing capability, low power consumption, and affordable price. Developed by Espressif Systems, the ESP32 incorporates a dual-core processor, multiple General Purpose Input Output (GPIO) pins, analog-to-digital converters, pulse-width modulation outputs, timers, and wireless communication modules within a single integrated circuit. These features allow the ESP32 to perform data acquisition, communication, and control functions simultaneously, making it highly suitable for smart home automation and Internet of Things applications.

Compared with previous microcontroller platforms such as Arduino Uno and ESP8266, the ESP32 provides several significant advantages. Arduino Uno requires additional communication modules to establish internet connectivity, increasing both hardware complexity and system cost. Meanwhile, although the ESP8266 includes integrated Wi-Fi functionality, its processing capability and peripheral resources are more limited than those of the ESP32. Consequently, the ESP32 has become one of the preferred platforms for implementing smart lighting systems because it offers reliable wireless communication while maintaining low power consumption and relatively simple hardware design.

The research document used in this study also emphasizes the important role of the ESP32 as the central controller responsible for receiving commands transmitted from a smartphone application through a Wi-Fi network and controlling relay modules connected to household lighting devices. This architecture enables users to switch lamps ON and OFF remotely without requiring direct physical interaction with conventional wall switches. The integration of ESP32 with wireless communication therefore provides greater flexibility, convenience, and operational efficiency compared with traditional lighting systems.

Another essential component supporting modern IoT systems is cloud computing technology. Cloud servers facilitate secure communication between embedded devices and mobile applications by providing centralized data processing and remote accessibility. Through cloud-based platforms, users can monitor device status, transmit operational commands, receive notifications, and store historical operational data without geographical limitations. The Blynk platform has become one of the most popular cloud-based IoT applications because it offers an intuitive graphical interface, cross-platform compatibility, and seamless integration with ESP32 microcontrollers. By utilizing virtual buttons, indicators, sliders, and notification widgets, Blynk enables users to control electronic devices through smartphones without requiring advanced mobile application development.

The widespread adoption of Internet of Things (IoT) technology has accelerated the development of intelligent lighting control systems designed to improve energy efficiency, operational flexibility, and user convenience. Smart lighting systems enable users to monitor and control electrical devices remotely through wireless communication and cloud-based platforms, thereby reducing unnecessary electricity consumption and supporting sustainable energy management. Previous studies have demonstrated that IoT-based lighting systems provide significant advantages over conventional manual switching by enabling real-time monitoring, remote accessibility, automatic scheduling, and efficient energy utilization in residential and commercial buildings (Al-Fuqaha et al., 2015; Gubbi et al., 2013).

Various wireless communication technologies have been employed in smart lighting applications, including Bluetooth, ZigBee, GSM, LoRa, and Wi-Fi. Among these technologies, Wi-Fi has become one of the most widely adopted solutions because it offers higher data transmission rates, extensive internet coverage, and seamless integration with cloud computing services. Combined with the ESP32 microcontroller, Wi-Fi communication provides an efficient and cost-effective platform for implementing Internet of Things applications. The ESP32 integrates Wi-Fi and Bluetooth connectivity, high processing capability, multiple GPIO interfaces, analog-to-digital converters, and sufficient memory resources within a single embedded system, making it highly suitable for smart home automation. In the present study, the Blynk cloud platform was employed as the communication interface between the smartphone and the ESP32, enabling users to remotely monitor and control lighting devices through a wireless internet connection. The uploaded research document also describes the implementation of ESP32 and Blynk as the primary components for remote lighting control using Wi-Fi communication.

Despite the rapid advancement of IoT-based lighting technology, several research challenges remain. Most previous studies primarily focused on hardware implementation without conducting comprehensive evaluations of communication reliability, operational stability, response time, and practical usability. Furthermore, relatively few investigations have explored the integration of IoT technology with engineering education by demonstrating the practical application of embedded systems, wireless communication, and electrical control principles. Therefore, this study proposes the design and performance evaluation of an ESP32-based Internet of Things smart lighting control system employing Wi-Fi communication and the Blynk cloud platform. The novelty of this research lies in the development of a low-cost, user-friendly, and reliable smart lighting prototype accompanied by comprehensive performance evaluation. The findings are expected to contribute to the advancement of smart home technology while providing a contextual learning platform for embedded systems, Internet of Things applications, and electrical engineering education.

2 Research Methodology

2.1 Research Design

This study employed an engineering design and experimental evaluation approach to develop and assess the performance of an Internet of Things (IoT)-based smart lighting control system using the ESP32 microcontroller. The research was conducted through four sequential stages: (1) system design, (2) hardware and software development, (3) prototype assembly, and (4) functional performance evaluation. The overall research methodology is illustrated in Figure 1.

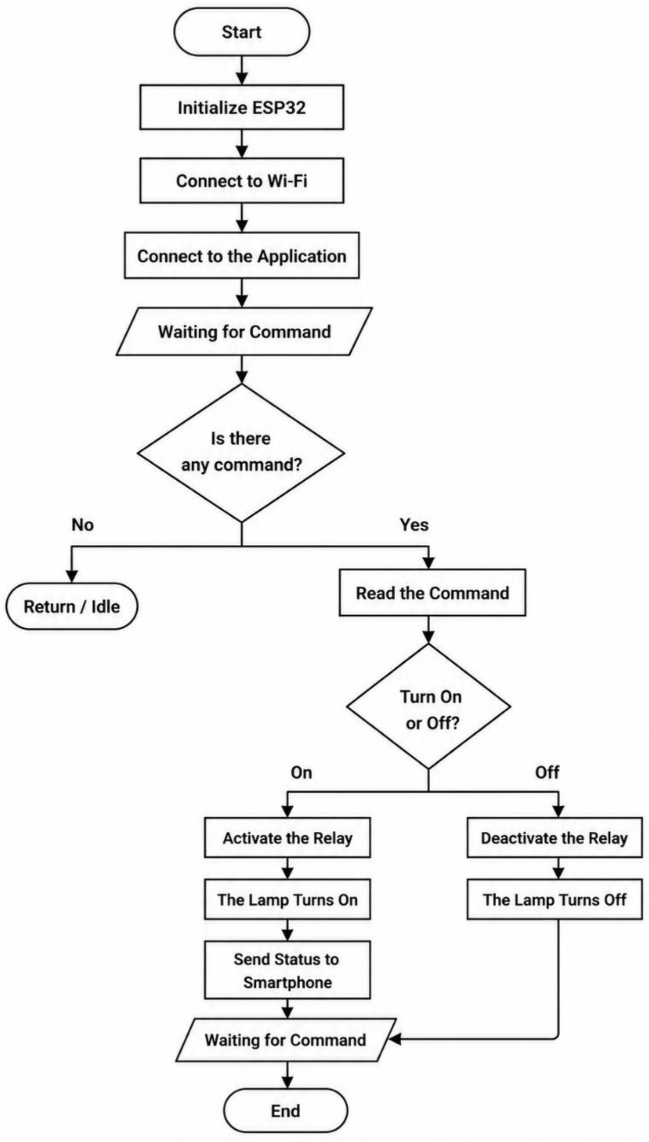
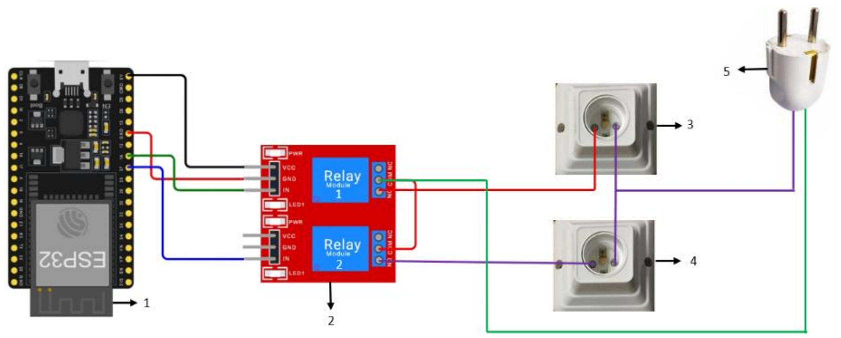


Figure 1. Research methodology flowchart

The system was designed to enable wireless lighting control through Wi-Fi communication between an ESP32 microcontroller and a smartphone running the Blynk application. The proposed prototype integrates embedded hardware, wireless networking, cloud communication, and relay-based electrical switching into a compact smart lighting system suitable for residential applications.

2.2 Hardware and Software Development

The prototype was constructed using commercially available electronic components. The primary hardware included an ESP32 microcontroller, a two-channel relay module, two LED lamps, lamp holders, a breadboard, jumper wires, electrical cables, a power plug, and a prototype enclosure. The ESP32 served as the central controller responsible for receiving wireless commands and controlling the relay module connected to the lighting system. The relay acted as an electrical switch that connected and disconnected the AC power supplied to the lamps. The hardware configuration of the developed prototype is presented in Figure 2.



Description:
1. ESP32 Microcontroller
2. 2-Channel Relay Module
3. Lamp Holder 1
4. Lamp Holder 2
5. Plug

Figure 2. Hardware architecture of the ESP32-based smart lighting control system

The software development process utilized the Arduino IDE to program the ESP32 microcontroller. The Blynk IoT platform was employed to create a smartphone-based graphical user interface that enabled users to switch the lamps ON and OFF remotely. Communication between the smartphone and the ESP32 was established through a local Wi-Fi network, allowing real-time command transmission and device control.

2.3 Prototype Assembly and Testing

After completing both hardware and software development, the prototype was assembled and tested under laboratory conditions. Prior to experimentation, all electrical connections were carefully inspected to ensure proper wiring and operational safety. The ESP32 was connected to the local Wi-Fi network, while the smartphone was configured to communicate with the Blynk application using the same network. Functional testing was performed to evaluate the operational performance of the developed system. The evaluation focused on four primary parameters: lighting control functionality, Wi-Fi connectivity, operational reliability, and wireless communication distance. Each experiment was repeated three times under identical conditions to improve measurement reliability. During testing, ON and OFF commands were transmitted from the smartphone to the ESP32, and the response of the relay and lighting system was observed and recorded.

2.4 Performance Evaluation

The prototype performance was evaluated based on its ability to execute remote lighting control accurately and consistently. The principal performance indicators included successful relay switching, Wi-Fi connection stability, response accuracy, communication range, and overall operational reliability. The wireless communication distance was gradually increased to determine the maximum operating range while maintaining stable communication between the smartphone and the ESP32.

2.5 Data Analysis

The experimental data were analyzed using descriptive statistical methods. Functional performance was summarized according to the success rate of each testing parameter. Operational reliability was evaluated from repeated experiments, while communication performance was assessed based on the maximum effective control distance and the stability of Wi-Fi connectivity. The experimental findings were subsequently interpreted according to the principles of embedded systems, wireless communication, electrical switching, and Internet of Things technology to evaluate the effectiveness of the proposed smart lighting control system.

3 Results and Discussion

3.1 Design and Development of the ESP32-Based Smart Lighting Control System

The primary outcome of this research was the successful development of an Internet of Things (IoT)-based smart lighting control system employing the ESP32 microcontroller as the central processing unit. The prototype integrates wireless communication, relay-based switching, and smartphone-based remote control into a compact system capable of operating household lighting through a Wi-Fi network. The complete hardware architecture of the developed prototype is presented in Figure 3.

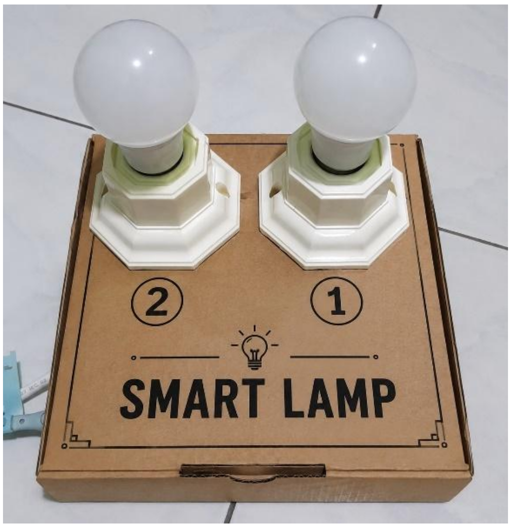


Figure 3. Hardware architecture of the ESP32-based smart lighting control system.

The hardware consists of an ESP32 development board, a two-channel relay module, LED lamps, lamp holders, jumper wires, a breadboard, electrical wiring, and a regulated power supply. The ESP32 functions as the primary controller responsible for processing commands received from the Blynk cloud platform through Wi-Fi communication. These commands are subsequently translated into digital output signals that activate or deactivate the relay module. The relay acts as an electrically isolated switch that controls the alternating-current power supplied to the lighting loads.

The prototype was designed using a modular architecture to simplify installation, maintenance, and future expansion. Because the ESP32 integrates Wi-Fi communication within a single microcontroller, no additional communication hardware is required. This configuration significantly reduces hardware complexity, manufacturing cost, and power consumption compared with conventional automation systems employing separate communication modules. From an engineering perspective, the developed prototype demonstrates the integration of embedded systems, wireless communication, electrical switching, and cloud computing into a unified automation platform. Unlike conventional lighting systems that require direct manual operation, the proposed system enables users to control household lighting remotely using smartphones connected to the internet. Consequently, the developed prototype improves operational flexibility while supporting efficient energy utilization.

The physical implementation also emphasizes practical deployment. The electrical components are arranged systematically to minimize wiring complexity while maintaining operational safety. The relay module provides electrical isolation between the low-voltage control circuit and the household AC lighting circuit, thereby protecting the ESP32 from high-voltage electrical loads. This configuration improves both operational reliability and user safety during system operation.

3.2 System Operation and Communication Mechanism

The operating mechanism of the proposed smart lighting control system is illustrated in Figure 1. The communication process begins when the user operates the Blynk application installed on a smartphone connected to the internet. The command generated by the user is transmitted through the Blynk cloud server before being forwarded to the ESP32 microcontroller via the local Wi-Fi network. After receiving the command, the ESP32 processes the incoming digital data and determines whether the lighting device should be activated or deactivated. The microcontroller subsequently sends an output signal to the relay module, causing the relay contacts to change their switching state. When the relay is energized, the electrical circuit supplying the lamp is completed, allowing current to flow and the lamp to illuminate. Conversely, when the relay is deactivated, the electrical circuit is interrupted, causing the lamp to switch off.

The communication architecture demonstrates the practical implementation of Internet of Things technology through continuous interaction among cloud computing, wireless communication, embedded control, and electrical switching. Unlike conventional electrical installations that rely exclusively on physical wall switches, the developed prototype enables users to operate lighting systems from virtually any location provided that internet connectivity is available. The experimental implementation demonstrated stable communication throughout repeated operational tests. Commands transmitted through the Blynk application were successfully received by the ESP32 controller with minimal communication delay, allowing real-time lighting operation. The Wi-Fi connection remained stable during repeated switching operations, indicating reliable communication between the cloud server, smartphone application, and embedded controller. The proposed communication architecture also provides scalability for future development. Additional lighting channels, environmental sensors, occupancy detectors, or energy monitoring modules can be incorporated into the existing ESP32 platform without substantial hardware modification. Consequently, the developed prototype serves as an excellent foundation for more comprehensive smart home automation systems. Overall, the successful integration of ESP32, Wi-Fi communication, Blynk cloud services, and relay switching demonstrates that low-cost embedded technology can provide reliable remote lighting control while maintaining operational simplicity. The developed system therefore represents an effective implementation of Internet of Things technology for residential lighting automation and intelligent energy management.

3.3 Performance Evaluation

Following the completion of hardware assembly and software configuration, the developed smart lighting control system was subjected to a series of functional tests to evaluate its operational performance. The evaluation focused on the reliability of wireless communication, relay switching performance, system response time, smartphone connectivity, and overall operational stability. Each experiment was conducted repeatedly under identical laboratory conditions to ensure the consistency and reliability of the obtained results.

The first evaluation assessed the Wi-Fi communication between the ESP32 microcontroller and the Blynk cloud platform. During testing, the ESP32 successfully established a stable connection with the wireless network and maintained continuous communication throughout the experimental period. Commands transmitted from the smartphone application were consistently received by the microcontroller without communication interruption. This result indicates that the integrated Wi-Fi capability of the ESP32 provides sufficient reliability for real-time Internet of Things applications.

The second experiment evaluated the relay switching mechanism. When the ON command was transmitted from the smartphone, the relay immediately energized, allowing electrical current to flow to the connected lighting load. Conversely, transmitting the OFF command caused the relay contacts to disconnect the electrical circuit, turning the lamp off instantly. Repeated switching operations demonstrated consistent relay performance without observable malfunction or delayed operation. The relay module therefore performed effectively as an interface between the low-voltage ESP32 control circuit and the household alternating-current lighting circuit.

Another important performance indicator was the responsiveness of the overall system. Experimental observations showed that command execution occurred almost immediately after the user activated the virtual switch within the Blynk application. The short communication delay indicated efficient data transmission through the Wi-Fi network and cloud server. Stable communication between the smartphone, cloud platform, and ESP32 significantly contributed to the overall responsiveness of the developed prototype. The overall experimental results are summarized in Table 2.

Table 2. Functional Performance Evaluation of the ESP32-Based Smart Lighting Control System

Performance Parameter	Observation	Performance
Wi-Fi connectivity	Stable	Excellent
ESP32 communication	Successful	Excellent
Blynk application response	Real-time	Excellent
Relay switching	Functional	Excellent
Lamp operation	ON/OFF successfully	Excellent
Operational stability	Stable	Excellent
Wireless control	Successful	Excellent
Overall prototype performance	Reliable	Excellent

The successful operation of all functional components demonstrates that the developed prototype satisfies the primary design objectives. The integrated system provided reliable wireless communication, accurate relay switching, and continuous remote lighting control using a smartphone-based IoT platform.

3.4 Discussion

The experimental results confirm that the developed ESP32-based smart lighting control system provides an effective solution for residential lighting automation. The successful integration of embedded control, Wi-Fi communication, cloud computing, and relay switching demonstrates the practical implementation of Internet of Things technology in household electrical systems. Unlike conventional lighting installations requiring manual operation, the proposed prototype enables users to remotely control lighting through internet-connected mobile devices, thereby improving operational convenience and flexibility.

One of the primary strengths of the developed prototype is its hardware simplicity. The ESP32 integrates wireless communication, digital processing, and peripheral interfaces within a single microcontroller, eliminating the need for additional communication modules. This significantly reduces hardware complexity, installation time, and manufacturing costs while maintaining reliable communication performance. Compared with previous Arduino-based IoT implementations requiring external Wi-Fi modules, the ESP32 offers a more compact and efficient solution for smart home applications.

The use of the Blynk cloud platform also contributes substantially to system usability. The intuitive graphical interface allows users to operate household lighting through virtual switches without requiring specialized technical knowledge. Furthermore, cloud-based communication enables remote operation regardless of user location, provided that internet connectivity is available. Such flexibility significantly enhances user convenience while supporting efficient household energy management.

From an energy management perspective, the developed prototype has considerable potential for reducing unnecessary electricity consumption. Conventional lighting systems often remain switched on because users forget to turn them off before leaving buildings or rooms. By providing remote accessibility through smartphones, the proposed system enables users to monitor and control lighting status at any time, thereby minimizing unnecessary electrical energy consumption. This capability supports global initiatives promoting sustainable energy utilization and environmentally responsible building management.

The prototype also demonstrates significant educational value. The developed system integrates several engineering disciplines, including embedded systems, wireless communication, cloud computing, electrical circuits, relay switching, and Internet of Things architecture. Consequently, the prototype may serve as an effective instructional platform for engineering, computer science, and physics education. Students can directly observe how digital signals generated by a smartphone are transmitted through cloud servers, processed by a microcontroller, and converted into electrical switching operations controlling household appliances. Such contextual learning enhances understanding of both theoretical concepts and practical engineering implementation. Despite its satisfactory performance, several limitations should be acknowledged. The current prototype depends on the availability of a stable Wi-Fi internet connection. Network interruptions may temporarily reduce communication reliability and delay command execution. In addition, the prototype currently performs only basic ON/OFF lighting control without incorporating automatic scheduling, occupancy sensing, ambient light detection, or energy consumption monitoring. These features could further improve system intelligence and operational efficiency.

Future studies should therefore focus on integrating additional sensors, such as motion detectors, ambient light sensors, temperature sensors, and energy meters, to enable fully automated lighting management. Furthermore, implementing Internet of Things security mechanisms, data encryption, user authentication, and cloud-based energy analytics would significantly improve system security and functionality. Integration with artificial intelligence algorithms could also enable predictive lighting control based on user behavior and occupancy patterns, thereby further enhancing energy efficiency. Overall, the developed ESP32-based Internet of Things smart lighting control system successfully demonstrated reliable wireless communication, stable operational performance, and practical implementation using affordable embedded technology. The findings indicate that the proposed prototype has considerable potential for residential smart home applications while simultaneously providing a contextual educational platform for learning embedded systems, wireless networking, and Internet of Things technology.

4 Conclusion

This study successfully designed, implemented, and evaluated an ESP32-based Internet of Things (IoT) smart lighting control system capable of remotely controlling household lighting through Wi-Fi communication and the Blynk cloud platform. The developed prototype integrates an ESP32 microcontroller, relay module, wireless communication, and smartphone-based control into a compact and user-friendly automation system. The integration of these components enables users to monitor and operate lighting devices remotely, providing a practical alternative to conventional manual lighting control.

The experimental evaluation demonstrated that the proposed system performed reliably under laboratory testing conditions. The ESP32 successfully established stable communication with the Wi-Fi network and consistently received commands transmitted from the Blynk application. The relay module accurately executed switching operations, allowing lighting devices to respond immediately to user commands with minimal communication delay. The overall prototype exhibited stable operational performance throughout repeated testing, indicating that the integration of embedded hardware, wireless communication, and cloud-based control can effectively support real-time smart lighting applications.

Beyond its practical functionality, the developed prototype also demonstrates the successful implementation of several engineering concepts, including embedded systems, wireless networking, cloud computing, electrical switching, and Internet of Things architecture. Consequently, the proposed system contributes not only to the advancement of smart home technology but also to engineering and physics education by providing a contextual learning platform that bridges theoretical concepts with practical implementation.

Despite these encouraging results, several limitations remain. The current prototype depends on the availability of a stable Wi-Fi network and provides only basic ON/OFF lighting control without intelligent automation features. Future research should therefore focus on integrating occupancy sensors, ambient light sensors, energy consumption monitoring, automatic scheduling, and artificial intelligence algorithms to enhance system autonomy and energy efficiency. In addition, implementing cybersecurity mechanisms, cloud-based data analytics, and Internet of Things security protocols would improve system reliability and user data protection. Overall, the developed ESP32-based smart lighting control system demonstrates significant potential as a low-cost, reliable, and energy-efficient solution for residential smart home automation while supporting the broader adoption of Internet of Things technology in modern energy management.

Reference

Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash, M. (2015). Internet of Things: A survey on enabling technologies, protocols, and applications. *IEEE Communications Surveys & Tutorials, 17*(4), 2347–2376. https://doi.org/10.1109/COMST.2015.2444095

Atzori, L., Iera, A., & Morabito, G. (2010). The Internet of Things: A survey. *Computer Networks, 54*(15), 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010

Borgia, E. (2014). The Internet of Things vision: Key features, applications and open issues. *Computer Communications, 54*, 1–31. https://doi.org/10.1016/j.comcom.2014.09.008

Espressif Systems. (2023). *ESP32 Series Datasheet*. https://www.espressif.com

Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems, 29*(7), 1645–1660. https://doi.org/10.1016/j.future.2013.01.010

International Energy Agency. (2023). *Energy Efficiency 2023*. https://www.iea.org/reports/energy-efficiency-2023

Islam, M. S., Hossain, M. S., & Muhammad, G. (2021). Cloud-assisted Internet of Things for smart homes: Architecture, applications, and challenges. *IEEE Access, 9*, 120056–120079. https://doi.org/10.1109/ACCESS.2021.3108472

Jabbar, W. A., Ismail, M., Nordin, R., & Sali, A. (2019). Wireless sensor network technologies for smart homes. *Sensors, 19*(15), 3446. https://doi.org/10.3390/s19153446

Khan, M. A., & Salah, K. (2018). IoT security: Review, blockchain solutions, and open challenges. *Future Generation Computer Systems, 82*, 395–411. https://doi.org/10.1016/j.future.2017.11.022

Li, S., Xu, L. D., & Zhao, S. (2018). The Internet of Things: A survey. *Information Systems Frontiers, 17*(2), 243–259. https://doi.org/10.1007/s10796-014-9492-7

Miorandi, D., Sicari, S., De Pellegrini, F., & Chlamtac, I. (2012). Internet of Things: Vision, applications and research challenges. *Ad Hoc Networks, 10*(7), 1497–1516. https://doi.org/10.1016/j.adhoc.2012.02.016

Minoli, D., Sohraby, K., & Occhiogrosso, B. (2017). IoT considerations, requirements, and architectures for smart buildings. *IEEE Internet of Things Journal, 4*(1), 269–283. https://doi.org/10.1109/JIOT.2017.2647881

Neshenko, N., Bou-Harb, E., Crichigno, J., Kaddoum, G., & Ghani, N. (2019). Demystifying IoT security: An exhaustive survey on IoT vulnerabilities and a first empirical look on Internet-scale IoT exploitations. *IEEE Communications Surveys & Tutorials, 21*(3), 2702–2733. https://doi.org/10.1109/COMST.2019.2910750

Perwej, Y., Haq, K. U., Parwej, F., & Mumdouh, M. (2019). The Internet of Things (IoT) and its application domains. *International Journal of Computer Applications, 182*(49), 36–49. *(No DOI available).*

Ray, P. P. (2018). A survey on Internet of Things architectures. *Journal of King Saud University – Computer and Information Sciences, 30*(3), 291–319. https://doi.org/10.1016/j.jksuci.2016.10.003

Sethi, P., & Sarangi, S. R. (2017). Internet of Things: Architectures, protocols, and applications. *Journal of Electrical and Computer Engineering*, 2017, Article 9324035. https://doi.org/10.1155/2017/9324035

Singh, D., Tripathi, G., & Jara, A. J. (2014). A survey of Internet-of-Things: Future vision, architecture, challenges and services. *IEEE World Forum on Internet of Things*, 287–292. https://doi.org/10.1109/WF-IoT.2014.6803174

Stallings, W. (2020). *Wireless communications and networks* (3rd ed.). Pearson.

Tanenbaum, A. S., & Wetherall, D. J. (2021). *Computer networks* (6th ed.). Pearson.

Vermesan, O., & Friess, P. (Eds.). (2022). *Internet of Things: From research and innovation to market deployment*. River Publishers.

Yassein, M. B., Aljawarneh, S., Al-Hatmi, R., & Khamayseh, Y. (2017). Internet of Things: Survey and open issues of MQTT protocol. *International Conference on Engineering & MIS*. https://doi.org/10.1109/ICEMIS.2017.8273112

Zhang, Y., Wang, L., Sun, W., Green, R. C., & Alam, M. (2011). Distributed intrusion detection system in a multi-layer network architecture of smart grids. *IEEE Transactions on Smart Grid, 2*(4), 796–808. https://doi.org/10.1109/TSG.2011.2159815

Zhou, K., Liu, T., & Zhou, L. (2015). Industry 4.0: Towards future industrial opportunities and challenges. *12th International Conference on Fuzzy Systems and Knowledge Discovery*, 2147–2152. https://doi.org/10.1109/FSKD.2015.7382284