

Performance Analysis of Hybrid IEEE 802.15.4-802.11 Network for Smart Buildings

Jauzaa Maylia Suhendro¹, I Made Sastra Dwikiarta², Kadek Agus Mahabojana Dwi Prayoga³,
I Nengah Ludra Antara⁴

¹ Information Systems Program, Faculty of Information Technology and Design, Primakara University, Indonesia

^{2,3} Study Program of Computer Engineering, Faculty of Engineering and Planning of Warmadewa University

⁴ Department of Mechanical Engineering, Bali State Polytechnic

Article Info

Article history:

Received February 09, 2026

Revised March 30, 2026

Accepted April 01, 2026

Keywords:

Internet of Things

Wireless Sensor Network

Hybrid Network

Smart Building

Quality of Service

ABSTRACT

The rapid development of the Internet of Things (IoT) has increased the demand for low-power and reliable environmental monitoring systems with real-time internet connectivity. This paper proposes the design and performance evaluation of a hybrid network integrating IEEE 802.15.4 (Zigbee) and IEEE 802.11 (Wi-Fi) for smart building applications. The system consists of multiple sensor nodes that monitor temperature, humidity, light intensity, and vibration, with an ESP8266 module acting as a gateway to a cloud-based web server. An experimental method was applied to evaluate Quality of Service (QoS) parameters, including delay and packet loss, as well as power consumption under different transmission distances and data intervals. The results show that the proposed system is capable of transmitting multi-node sensor data in real time. However, delay and packet loss increase as the number of transmitted data and communication distance grow, mainly due to interference in the 2.4 GHz frequency band. Furthermore, the data transmission interval significantly affects system power consumption. These findings indicate that the hybrid IEEE 802.15.4–IEEE 802.11 network is feasible for smart building monitoring, although further optimization in channel management and data transmission mechanisms is required to improve performance.

Corresponding Author:

I Made Sastra Dwikiarta

Study Program of Computer Engineering, Faculty of Engineering and Planning of Warmadewa University

Email: sastradwikiarta@warmadewa.ac.id

1. INTRODUCTION

The rapid advancement of the Internet of Things (IoT) has enabled the integration of physical devices, sensors, and communication networks to support real-time monitoring and control across various application domains, including smart buildings, smart cities, and industrial systems [1], [2], [3]. IoT allows physical entities to autonomously collect, process, and exchange data through communication networks, thereby improving operational efficiency, situational awareness, and decision-making capabilities [4], [5].

One of the key infrastructures supporting IoT implementations is the Wireless Sensor Network (WSN), which consists of spatially distributed sensor nodes with limited computational capability, communication bandwidth, and energy resources [6], [7]. In smart building applications, WSNs are widely deployed to monitor environmental parameters such as temperature, humidity, light intensity, and vibration for energy management, safety monitoring, and system automation [8], [9]. Due to their low power consumption and flexible network topology, IEEE 802.15.4 based technologies, such as Zigbee, are commonly adopted for WSN deployments [10].

Despite these advantages, Zigbee-based networks do not natively support TCP/IP communication, which limits their ability to connect directly to internet-based services and cloud platforms [11]. To overcome

this limitation, a gateway mechanism is required to forward sensor data from IEEE 802.15.4 networks to IP-based networks. IEEE 802.11 (Wi-Fi) is frequently used to provide internet connectivity because of its wide availability and high data rate; however, relying solely on Wi-Fi at the sensor node level may result in higher energy consumption and reduced network lifetime [12], [13].

Previous studies have primarily focused on single-standard communication networks, particularly IEEE 802.11, without sufficiently considering energy efficiency at the sensor layer [8], [14]. Other works that attempted to integrate IEEE 802.15.4 and IEEE 802.11 were limited in terms of the number of sensor nodes, data types, and performance metrics evaluated. In particular, comprehensive experimental analysis of Quality of Service (QoS) parameters such as delay and packet loss together with power consumption in multi-node hybrid networks remains limited [9], [15].

To address these limitations, this paper proposes a hybrid network architecture that integrates IEEE 802.15.4 and IEEE 802.11 for smart building monitoring applications. The proposed system enables multi-node sensor data transmission to a cloud-based web server through an ESP8266 gateway. The main contribution of this study is the experimental evaluation of QoS performance, including delay and packet loss, as well as power consumption characteristics of a multi-node hybrid network under real deployment conditions.

2. METHOD

This research adopts an experimental approach to design and evaluate a hybrid communication network for smart building applications. The methodology consists of system design, data collection, and performance evaluation

2.1. System Architecture

The proposed system integrates a Zigbee-based Wireless Sensor Network (IEEE 802.15.4) with a Wi-Fi network (IEEE 802.11). Each sensor node is built using an Arduino microcontroller and equipped with temperature and humidity sensors, light sensors, and vibration sensors. Sensor data are transmitted wirelessly to a Zigbee coordinator acting as a data aggregator.

An ESP8266 module is employed as a gateway to forward aggregated sensor data from the Zigbee network to a cloud-based web server via Wi-Fi. This hybrid architecture enables low-power data collection at the sensor layer while maintaining internet connectivity for real-time monitoring.

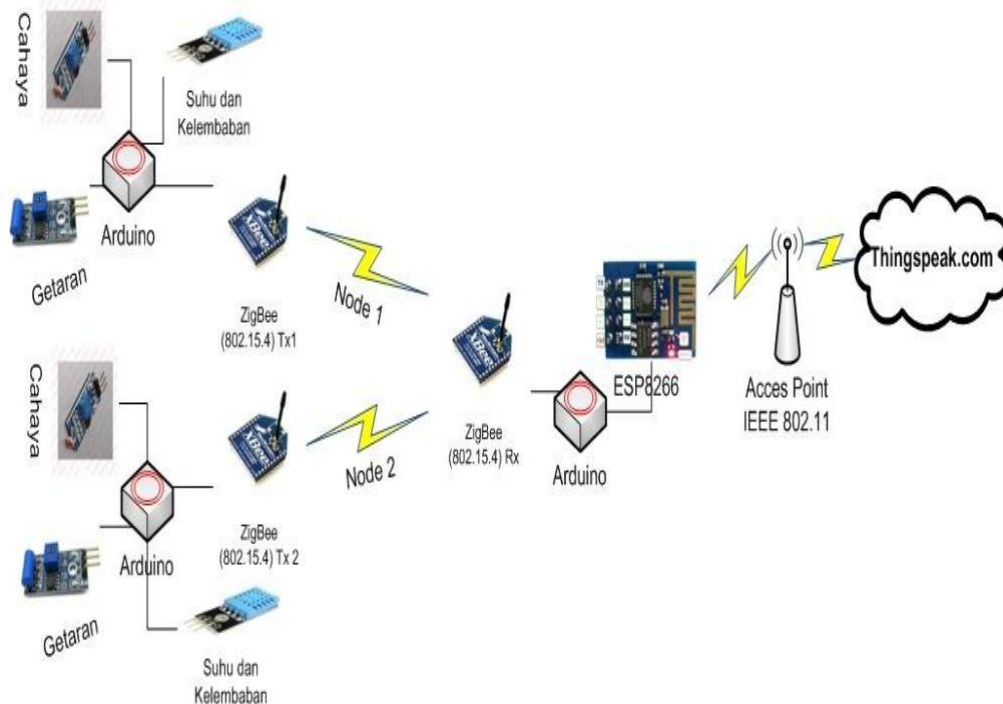


Figure 1. Hybrid Network Design in Wireless Sensor Network Communication

2.2. Data Collection Procedure

Data collection was conducted through direct experimentation using the developed prototype. Primary data were obtained from measurements of QoS parameters, including delay and packet loss, as well as power consumption. Experiments were performed under different transmission distances and data transmission intervals. Secondary data were obtained from device datasheets and relevant scientific literature

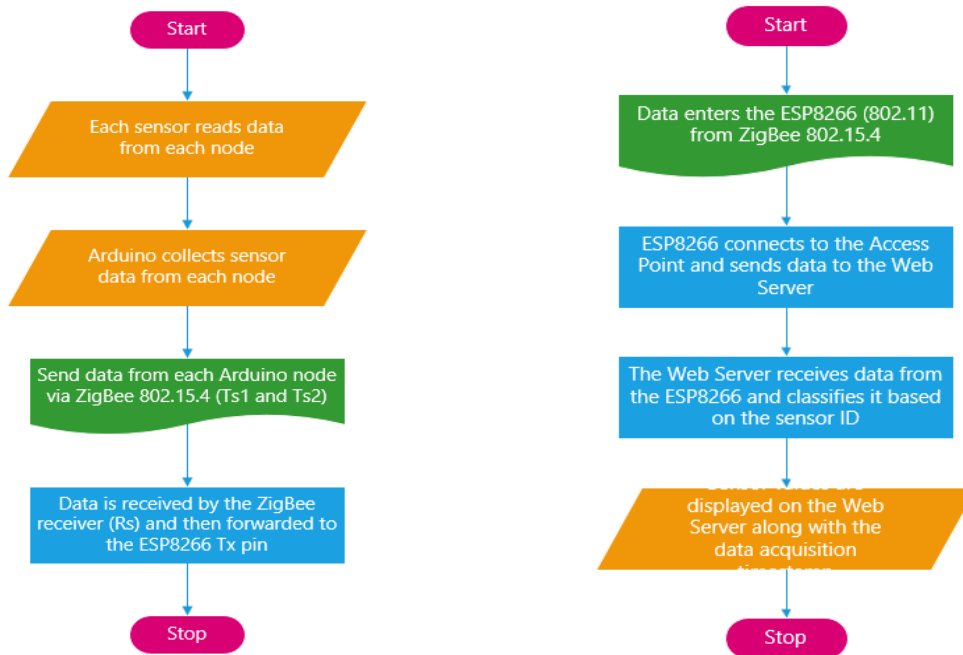


Figure 2. General Circuit Flowchart

2.3. Quality of Service Evaluation

Delay was calculated as the time difference between data transmission at the sensor node and data reception at the web server. Packet loss was determined by comparing the number of transmitted packets with the number of successfully received packets. Measurements were conducted under multiple test scenarios to evaluate the impact of communication distance and data volume on network performance.

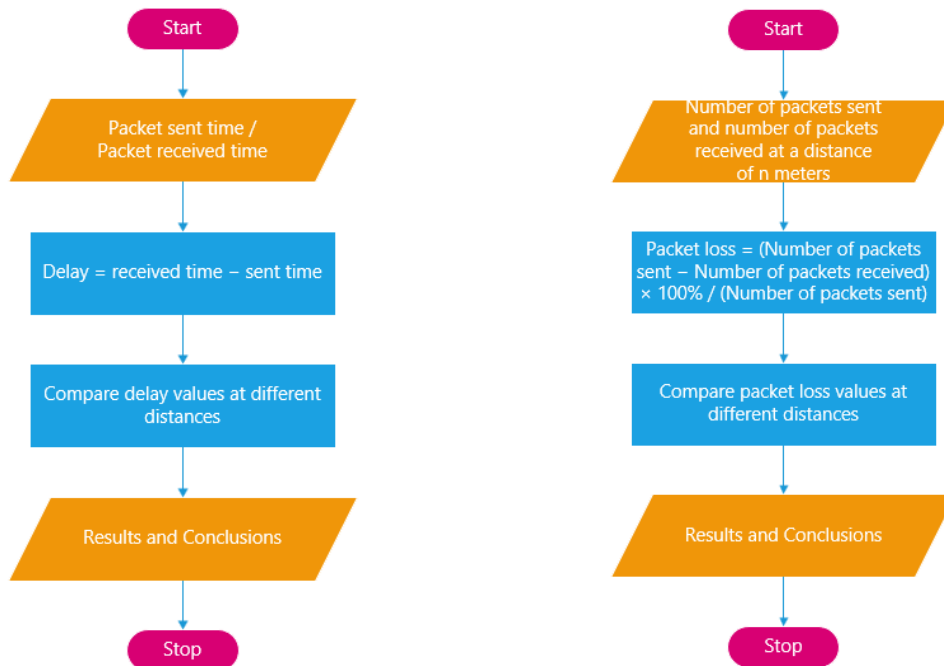


Figure 3. The process of taking data delay and packet loss

2.4. Power Consumption Analysis

Power consumption was analyzed by measuring the energy usage of the sensor nodes and communication modules under different data transmission intervals. The analysis focused on identifying the relationship between transmission frequency and system energy efficiency.

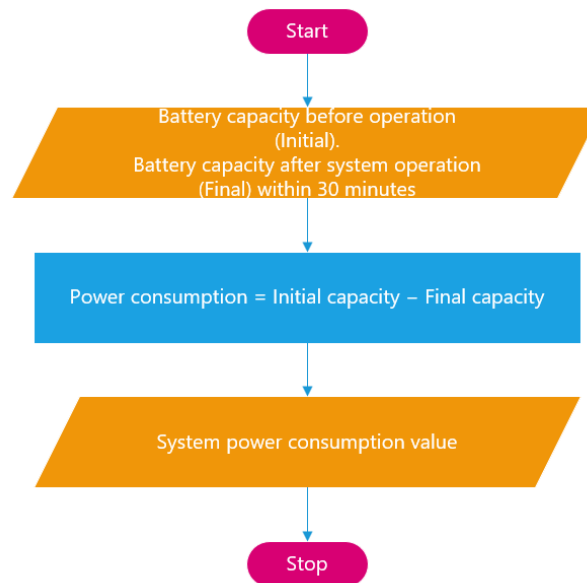


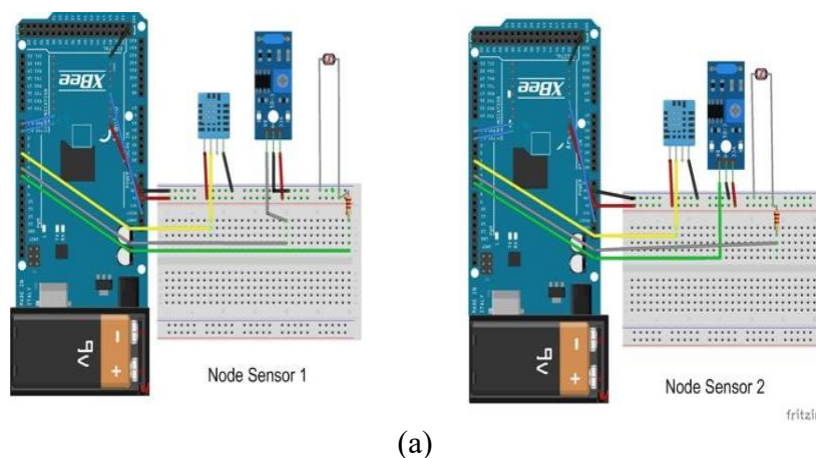
Figure 4. Power consumption data collection process

3. RESULTS AND DISCUSSION

This study evaluates the performance of a hybrid network integrating IEEE 802.15.4 (Zigbee) and IEEE 802.11 (Wi-Fi) for smart building applications. The evaluation focuses on sensor data dissemination, Quality of Service (QoS) performance, and system power consumption.

3.1. Data Dissemination in Hybrid Networks

The experimental results show that the proposed system is able to disseminate data from two Zigbee sensor nodes to a cloud-based web server in real time through the ESP8266 module. The gateway mechanism, which utilizes a microcontroller to bridge Zigbee and Wi-Fi networks, successfully overcomes the limitation of Zigbee that does not natively support TCP/IP communication. The transmitted sensor data are displayed on the web server in the form of graphs and timestamps, enabling continuous remote monitoring.



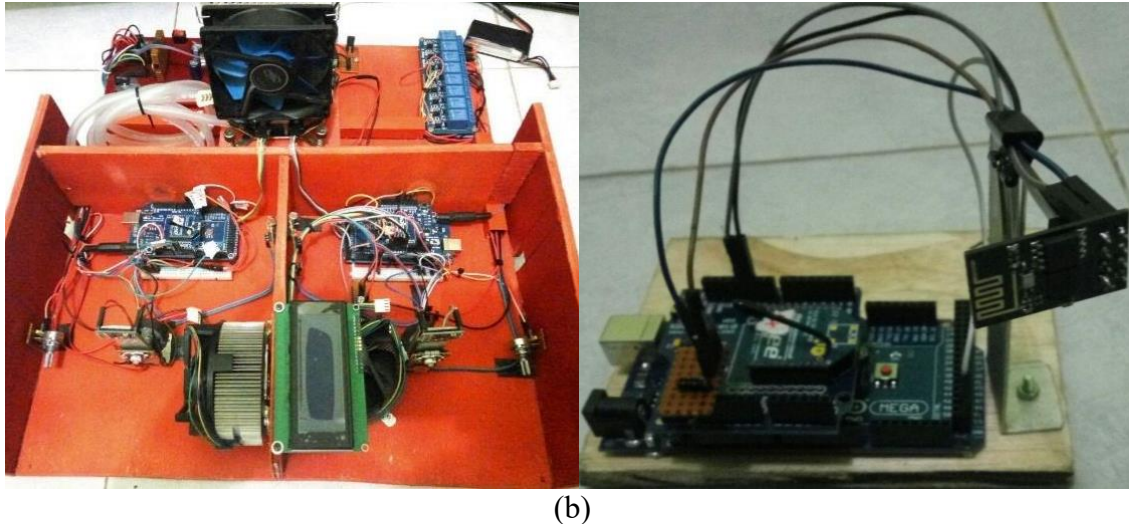


Figure 5. (a) Schematic design (b) Hardware design results on the transmitter (Tx) and receiver (Rx) sides.

The use of data headers for each sensor node proves effective in identifying and classifying sensor data at the receiver side. In addition, the data parsing technique implemented on the microcontroller allows the system to remain operational even when one of the sensor nodes experiences a failure, thereby improving overall system reliability.

3.2. Delay Analysis

Delay measurements were conducted under three scenarios: data transmission from a single sensor node, data transmission from two sensor nodes with two types of data, and data transmission from two sensor nodes with eight types of data. The results indicate that delay increases as the amount of transmitted sensor data and the communication distance between Zigbee nodes increase.

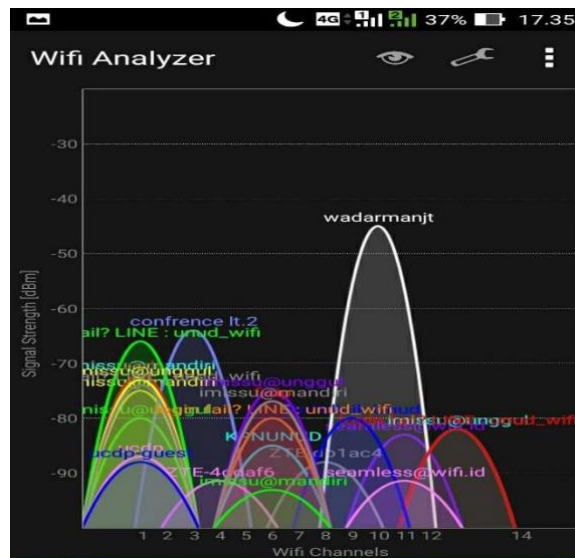


Figure 6. Wi-Fi Analyzer Measurement During Testing

At a Zigbee communication distance of 3 meters, the average system delay ranges from 7 to 7.5 seconds. When the distance is increased to 6 meters, the delay rises to approximately 8–9 seconds. The largest contribution to delay originates from internal system processes, particularly data processing, classification, and sequential transmission to the web server. In contrast, the delay introduced by the ESP8266 to the access point and from the access point to the server remains relatively constant.

Based on Quality of Service (QoS) standards, the delay observed in this system can be considered relatively high compared to typical real-time communication systems. However, it should be noted that the

proposed system employs a multi-node architecture with sequential data transmission through a gateway, which introduces additional processing delays. Compared to previous studies that mainly utilize single-node configurations or smaller data volumes, the increased delay in this system remains acceptable for environmental monitoring applications that are not time-critical. Therefore, the system performance can still be considered suitable for IoT-based smart building applications.

The relatively high delay (7–9 seconds) is influenced by several factors, including data parsing processes in the microcontroller, sequential data transmission from multiple sensor nodes, and latency introduced by communication with the cloud-based web server. In addition, the use of cloud platforms such as Thing Speak contributes additional delay due to inherent update interval limitations. Therefore, the observed delay is not solely caused by network performance, but also by system architecture and data processing mechanisms.

Table 1. Calculation of communication delay between Zigbee Tx_Rx

Zigbee distance	Total Delay	Delay Antar Zigbee	Delay ESP8266-AP	Delay AP-Web Server	Delay Sistem
3 meters	7,47 s	0 s	1,54 s	0,657 s	5,273 s
6 meters	7,67 s	1 s	1,54 s	0,657 s	4,473 s

3.3. Packet Loss Analysis

The packet loss analysis shows that when a small amount of data is transmitted (single sensor node), the packet loss is relatively low, at approximately 5%. However, as the volume of transmitted data increases and involves two sensor nodes operating simultaneously, packet loss can increase to more than 20%.

Table 2. Packet loss distance relationship

Distance to Access Point (m)	TX data count	Rx data count	Zigbee Tx-Rx distance (m)	Packet loss = $\frac{((N_{tx}-N_{Rx})/N_{tx}) \cdot 100}{\%}$
3	20	19	3	5
3	20	19	6	5

The increase in packet loss is mainly caused by interference in the 2.4 GHz frequency band, which is shared by both Zigbee and Wi-Fi. High Wi-Fi channel density in the test environment leads to channel overlapping, which degrades the reliability of Zigbee data transmission. These results indicate that channel selection and interference management are critical factors in the implementation of hybrid wireless networks.

Compared to general wireless communication standards, packet loss exceeding 20% indicates significant interference in the communication channel. However, this condition occurs in a high-density 2.4 GHz environment, which reflects realistic deployment scenarios for IoT systems. This result highlights that network performance is highly influenced by environmental conditions, not only by system design.

3.4. Power Consumption Analysis

The power consumption analysis reveals that the data transmission interval has a significant impact on system energy usage. Shorter transmission intervals result in higher power consumption due to more frequent transmission and data processing activities. Conversely, longer transmission intervals reduce power consumption but negatively affect data freshness. Therefore, a trade-off between real-time monitoring requirements and energy efficiency is required in the design of hybrid IoT systems.

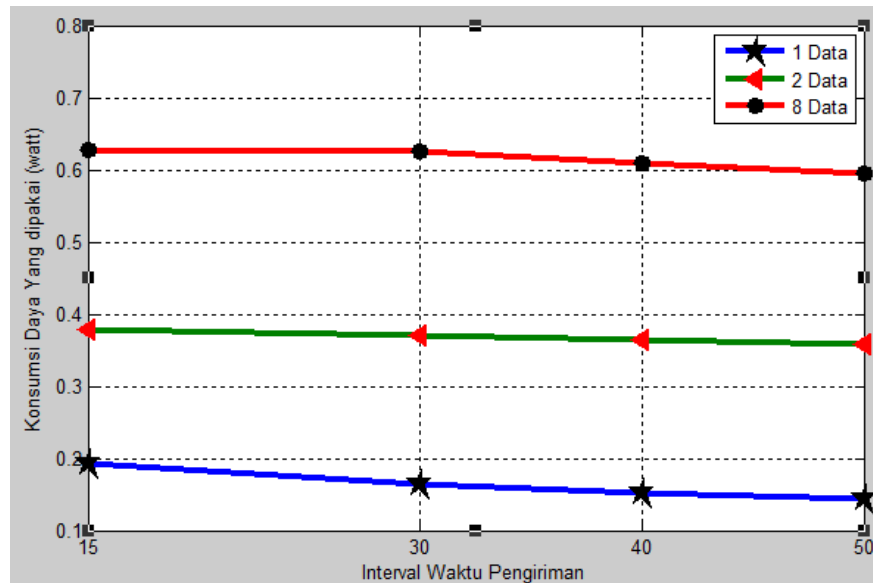


Figure 9. Power Consumption vs Transmission Interval

4. CONCLUSIONS AND SUGGESTIONS

4.1. Conclusions

This study demonstrates that a hybrid IEEE 802.15.4–IEEE 802.11 network can be effectively implemented for smart building monitoring applications. The proposed system is capable of transmitting multi-node sensor data to a cloud-based server in real time. QoS performance, particularly delay and packet loss, is influenced by communication distance, data volume, and wireless interference. In addition, data transmission intervals significantly affect system power consumption.

4.2. Suggestions

Future work should focus on improving channel management and interference mitigation techniques to enhance communication reliability. Optimization of data aggregation and transmission mechanisms is also recommended to reduce system delay. Furthermore, the adoption of adaptive power management strategies could improve the overall energy efficiency of hybrid IoT networks.

REFERENCES

- [1] M. Sigala, A. Beer, L. Hodgson, and A. O'Connor, Big Data for Measuring the Impact of Tourism Economic Development [1] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, dan M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 2, pp. 1105–1142, 2022, doi: 10.1109/COMST.2022.3147363.
- [2] P. Sethi dan S. R. Sarangi, "Internet of Things: Architectures, protocols, and applications," *Journal of Electrical Systems and Information Technology*, vol. 10, p. 100226, 2023, doi: 10.1016/j.jesit.2023.100226.
- [3] P. Yadav, R. Kumar, dan S. Kumar, "IoT-based smart greenhouse monitoring system," *Materials Today: Proceedings*, vol. 46, pp. 10589–10594, 2021, doi: 10.1016/j.matpr.2021.02.431.
- [4] E. Ancillotti, R. Bruno, dan M. Conti, "Wireless sensor networks for industrial IoT: A survey," *Computer Networks*, vol. 191, p. 108141, 2021, doi: 10.1016/j.comnet.2021.108141.
- [5] J. Haxhibeqiri, F. Van den Abeele, I. Moerman, dan J. Hoebeke, "Low-power wide-area networks: A survey of enabling technologies," *IEEE Access*, vol. 10, pp. 2594–2624, 2022, doi: 10.1109/ACCESS.2022.3145279.
- [6] R. Hassan, M. Rahman, dan M. Hossain, "Smart home automation using IoT technologies: A review," *Sustainable Cities and Society*, vol. 70, p. 102958, 2021, doi: 10.1016/j.scs.2021.102958.
- [7] E. Png dan S. Srinivasan, "Smart buildings: Systems, technologies, and applications," *Energy and Buildings*, vol. 279, p. 113007, 2023, doi: 10.1016/j.enbuild.2023.113007.
- [8] M. A. Ferrag, L. Maglaras, dan H. Janicke, "Security for IoT-based smart cities: A survey," *IEEE Communications Surveys & Tutorials*, vol. 24, no. 3, pp. 1903–1939, 2022, doi: 10.1109/COMST.2022.3143984.
- [9] E. Borgia, "The Internet of Things vision: Key features, applications, and open issues," *Computer Communications*, vol. 169, pp. 1–15, 2021, doi: 10.1016/j.comcom.2021.01.001.
- [10] Espressif Systems, ESP32 Technical Reference Manual, 2023. [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32_technical_reference_manual_en.pdf
- [11] A. Sutanto dan D. Pramono, "Sistem monitoring suhu dan kelembaban berbasis Internet of Things menggunakan ESP32," *Jurnal RESTI (Rekayasa Sistem dan Teknologi Informasi)*, vol. 5, no. 4, pp. 748–755, 2021. [Online]. Available: <https://jurnal.iaii.or.id/index.php/RESTI/article/view/3089>

- [12] R. A. Pratama dan A. Nugroho, "Rancang bangun smart home berbasis IoT menggunakan ESP8266," *Jurnal Teknologi dan Sistem Komputer*, vol. 10, no. 2, pp. 85–92, 2022. [Online]. Available: <https://ejournal.undip.ac.id/index.php/jtsiskom/article/view/42752>
- [13] R. Hidayat dan F. Maulana, "Implementasi wireless sensor network untuk monitoring lingkungan berbasis IoT," *Jurnal Infotel*, vol. 15, no. 1, pp. 45–53, 2023. [Online]. Available: <https://ejournal.st3telkom.ac.id/index.php/infotel/article/view/1034>
- [14] I. M. D. Putra dan I. B. Suryawan, "Sistem monitoring greenhouse berbasis IoT menggunakan ESP32," *Jurnal Ilmiah Teknologi Informasi Asia*, vol. 16, no. 3, pp. 210–217, 2022. [Online]. Available: <https://jurnal.stmikasi.ac.id/index.php/jitika/article/view/1357>
- [15] D. Wijaya dan A. Kurniawan, "Implementasi sensor DHT dan LDR pada sistem monitoring berbasis Internet of Things," *Jurnal Teknologi Informasi dan Ilmu Komputer*, vol. 11, no. 1, pp. 12–20, 2024. [Online]. Available: <https://jtiik.ub.ac.id/index.php/jtiik/article/view/7965>