Performance Evaluation of IoT Communication Protocols (LoRa, Wi-Fi and Zigbee) for Smart Environment

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Abstract - The Internet of Things (IoT) constitutes a core component in the development of Smart Environment systems for real-time environmental monitoring. Selecting an appropriate communication protocol remains a major challenge, particularly in semi-rural areas characterized by limited network infrastructure and heterogeneous geographical conditions. This study aims to evaluate and compare the performance of three IoT communication protocols, namely LoRa, WiFi (ESP32), and Zigbee (XBee), through real-field prototype-based testing conducted in the semi-rural region of Banyuwangi. The evaluated parameters include communication range, transmission latency, and packet delivery ratio (PDR). The experiments were performed by periodically transmitting data packets under multiple distance scenarios. The results indicate that LoRa achieves the longest communication range of approximately ±1750 meters with an average latency of 2.1 seconds, WiFi exhibits the lowest latency of about 0.2 seconds with an effective range of ±200 meters, while Zigbee demonstrates stable transmission performance with a PDR of 100% up to a distance of ±600 meters. The main contribution of this study lies in providing empirical performance data obtained from real-field experiments in a semi-rural Indonesian environment, which can serve as a reference for selecting appropriate IoT communication protocols for Smart Environment implementations.

Keywords *Internet of Things, Smart Environment, LoRa, WiFi, Zigbee, semi-rural*

I. Introduction

The Internet of Things (IoT) has become a key enabling technology in the development of Smart Environment systems, which allow environmental parameters such as temperature, humidity, and air quality to be monitored in real time[1]. The integration of environmental sensors with wireless communication networks enables continuous data collection to support data-driven decision-making processes[2]. Furthermore, IoT technology has become an essential component in the implementation of Smart City and Smart Village concepts, where real-time environmental information is required to improve public services and environmental management[3]. One of the critical challenges in implementing IoT systems is the selection of an appropriate communication protocol that can operate efficiently under different environmental conditions[4]. Several wireless communication technologies are commonly used in IoT systems, including LoRa, WiFi, and Zigbee. LoRa is widely recognized as a Low Power Wide Area Network (LPWAN) technology that provides long communication range with low energy consumption[5], In contrast, WiFi offers high bandwidth and relatively low latency but generally requires higher power consumption and has limited coverage compared to LPWAN technologies[6], Meanwhile, Zigbee is designed for low-power wireless communication and offers advantages in network stability through its mesh topology-based communication architecture[7]. The performance characteristics of each communication protocol can be significantly influenced by physical environmental conditions and network interference levels[8]. Various studies have evaluated the performance of IoT communication protocols under different experimental conditions. However, most previous studies have conducted experiments in controlled environments such as laboratories, simulations, or urban areas with stable communication infrastructure[9].

Table 1. Summary of Previous Studies on IoT Communication Protocols

Author & Year	Article / Journal Title	Communication Module	Test Environment	Evaluation Parameters
Ardita & Orisa (2021) [10]	*Wi-Fi-Based IoT Data Communication Performance in Dense Wireless Network Traffic Conditions*	WiFi	Dense urban environment	Latency, packet loss
Dani & Adi (2021) [11]	*Performance Evaluation of ZigBee Mesh Communication on the Internet of Things (IoT)*	Zigbee	Limited indoor and outdoor environments	Packet Delivery Ratio (PDR), delay
Maslouhi & Ghoumid (2022) [12]	*Analysis of End-to-End Packet Delay for Internet of Things in Wireless Communications*	Wireless Sensor Network (WSN)	Simulation environment	End-to-end delay, throughput

Pebrian (2025) [13]	Alat Ukur Sinyal LoRa untuk Mengetahui Kinerja Jaringan Komunikasi IoT	LoRa	Open outdoor environment	Received Signal Strength Indicator (RSSI), communication range
Setiawati (2025) [14]	*Sistem Monitoring Realtime Berbasis IoT untuk Kualitas Lingkungan*	IoT system	Limited field deployment	Delay, data stability

As summarized in Table 1, many previous studies focus on evaluating only one or two network performance parameters, such as latency or communication range, without providing a comprehensive comparison across multiple metrics. Moreover, most existing studies evaluate a single communication protocol or rely mainly on simulation environments. Empirical field-based comparisons of multiple IoT communication protocols in semi-rural environments remain limited. Semi-rural areas often have different environmental characteristics compared to urban regions, including lower building density, varied terrain, and less congested network infrastructure, which can significantly influence the performance of IoT communication systems. In this study, system testing was conducted in a semi-rural area of Banyuwangi Regency, specifically in Dusun Kabat, which represents a rural environment with relatively low building density and minimal network congestion. Therefore, this research aims to perform a prototype-based empirical evaluation of three IoT communication protocols LoRa, WiFi, and Zigbee in a semi-rural environment. The evaluation focuses on several key network performance parameters, including communication range, latency, and Packet Delivery Ratio (PDR). The results are expected to provide insights for selecting appropriate communication technologies for IoT-based environmental monitoring systems deployed in semi-rural areas.

II. Research Method

2.1 Research Design

This study employs a prototype-based experimental method with a field testing approach to evaluate the performance of three Internet of Things (IoT) communication protocols in the implementation of a Smart Environment system. This approach was selected because it can provide a realistic representation of wireless communication network performance under semi-urban environmental conditions, which often involve variations in topography and signal interference that cannot be fully represented through laboratory simulations. In the experimental setup, the system prototype was developed using three different communication modules, namely LoRa, WiFi (ESP32), and Zigbee (XBee). The performance of each communication protocol was then evaluated and compared based on three key network performance parameters, namely communication range, transmission latency, and Packet Delivery Ratio (PDR). By employing this experimental approach, this study not only aims to assess the technical performance of each communication protocol but also to provide an empirical analysis of the suitability and efficiency of these IoT communication technologies in supporting Smart Environment systems deployed in semi-urban areas of Banyuwangi.

2.2. Devices and Research Materials

The prototype system consists of three sensor nodes, each integrated with a different communication module: LoRa (915 MHz), WiFi (ESP32), and Zigbee (XBee). Each node is equipped with a DHT11 sensor for measuring temperature and humidity, as well as an MQ-135 sensor for detecting air quality, particularly harmful gases in the surrounding environment. The experimental evaluation was conducted in a semi-urban area of Banyuwangi, Indonesia, which was selected as the testing environment to analyze the performance of the wireless communication protocols under real-field conditions

Table 2. Specifications of Research Devices

Component	Specification	Description
Microcontroller	Arduino Uno, Arduino Mega, ESP32	Sensor data processing unit
Sensors	DHT11, MQ-135	Measurement of temperature, humidity, and air quality
Communication Modules	LoRa (915 MHz), Zigbee XBee, WiFi ESP32	Wireless data transmission media
Gateway	Raspberry Pi 4 Model B	Data collector and forwarder
Software	Arduino IDE, Node-RED, Python	Programming and data visualization tools
Test Area	Banyuwangi (semi-urban area)	Location for network performance evaluation

2.3. System Design and Architecture

The IoT system architecture in this study was designed using a modular and distributed approach, allowing each communication protocol to be evaluated independently while maintaining identical sensor and system configurations.

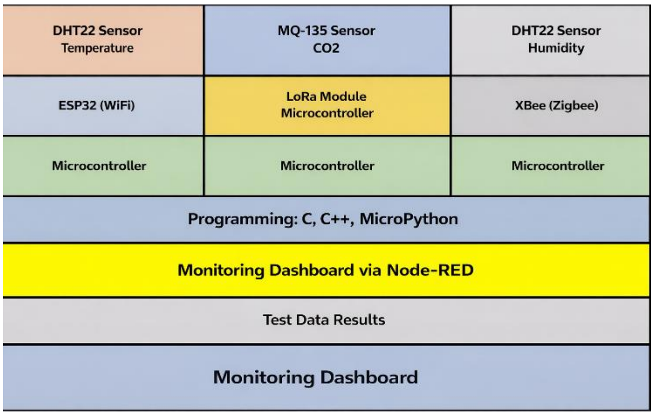


Figure 1. System Architecture

Conceptually, the system architecture consists of three main layers and one communication layer, as described below:

1. Sensor Node (End Device**)**
   The sensor node is responsible for collecting environmental data using two types of sensors: the DHT11 sensor for temperature and humidity measurements and the MQ-135 sensor for air quality monitoring. This node acts as the primary data source, generating raw environmental data that are transmitted through the communication layer to the gateway system.
2. Communication Protocol Layer
   This layer functions as the data transmission medium that transfers information from the end devices to the gateway. In this study, three different communication protocols are evaluated: LoRa, WiFi, and Zigbee.
   a. LoRa
   The LoRa protocol is tested using a LoRa communication module operating in the 915 MHz Industrial, Scientific, and Medical (ISM) band.

Table 3. LoRa Configuration Parameters

Parameter	Configuration Value
Operating Frequency	915 MHz
Bandwidth	125 kHz
Spreading Factor	SF7 and SF10
Preamble Length	8 symbols
Payload Size	16 bytes
Communication Mode	Point-to-Point
Module Used	SX1278 LoRa Module
Antenna	3 dBi external antenna

   b. WiFi (ESP32)
   The WiFi protocol is evaluated using a WiFi-enabled microcontroller module connected to a local wireless network to transmit sensor data to the IoT server.

Table 4. WiFi Configuration Parameters

Parameter	Configuration Value
WiFi Standard	IEEE 802.11 b/g/n
Operating Frequency	2.4 GHz
Operating Mode	Station Mode (STA)
Application Protocol	MQTT
MQTT Broker	Mosquitto Broker
MQTT Port	1883
Module Used	ESP8266 / ESP32

   c. Zigbee (XBee Series 2)
   The Zigbee communication protocol is tested using XBee modules based on the IEEE 802.15.4 standard.

Table 5. Zigbee Configuration Parameters

Parameter	Configuration Value
Standard	IEEE 802.15.4
Operating Frequency	2.4 GHz
Network Topology	Point-to-Point
Configuration Mode	AT Mode
Channel	Channel 15
Data Rate	250 kbps
Serial Baudrate	9600 bps
PAN ID	0x1234
Transmission Power	3 dBm
Module Used	XBee Series 2
Antenna	Internal PCB antenna

3. Gateway / Receiver Layer
   This layer utilizes a Raspberry Pi 4 Model B as the gateway device responsible for receiving data from the three communication protocols. The gateway performs data aggregation and forwards the collected information to the monitoring system for further processing.
4. Monitoring Dashboard Layer
   This layer consists of a Node-RED-based data visualization system that displays real-time environmental monitoring results, including temperature, humidity, and air quality measurements. The dashboard also facilitates the comparative analysis of communication protocol performance through graphical visualization of environmental parameter variations and system transmission metrics.

a. LoRa Communication Circuit
The LoRa communication circuit utilizes an Arduino Uno microcontroller connected to an SX1278 LoRa module operating at 915 MHz. Environmental data obtained from the sensors are periodically transmitted through the LoRa module to a LoRa receiver gateway connected to a Raspberry Pi. This configuration enables long-range wireless communication between the sensor node and the gateway device. The complete circuit configuration is illustrated in Figure 2, which shows the interconnection among the main components in the LoRa communication system.

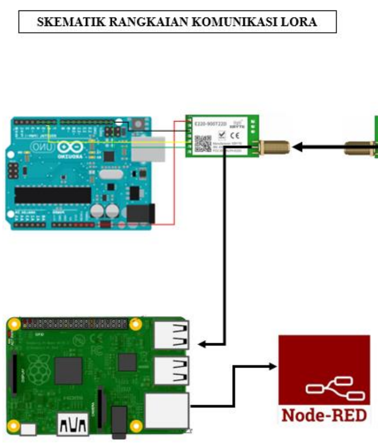


Figure 2. LoRa Communication Circuit Schematic

b. Zigbee (XBee) Communication Circuit

The Zigbee communication system employs XBee Series 2 modules configured in peer-to-peer communication mode to facilitate direct data transmission between nodes without requiring an additional router device. This configuration simplifies the network structure while maintaining reliable wireless communication for sensor data transmission. The schematic of the Zigbee communication circuit is shown in Figure 3.

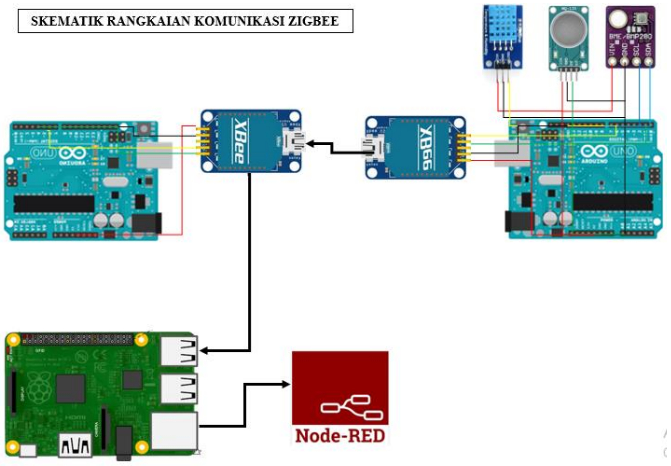


Figure 3. Zigbee Communication Circuit Schematic

c. WiFi Communication Circuit (ESP32)

the WiFi communication circuit utilizes an ESP32 microcontroller, which functions both as the processing unit and the main communication module. The DHT11 and MQ-135 sensors are directly connected to the GPIO pins of the ESP32 without the need for an additional Arduino board. The ESP32 transmits sensor data to the gateway using the TCP/IP protocol over a local WiFi network, enabling real-time data communication between the sensor node and the monitoring system. The schematic of the WiFi communication circuit is presented in Figure 4**.**

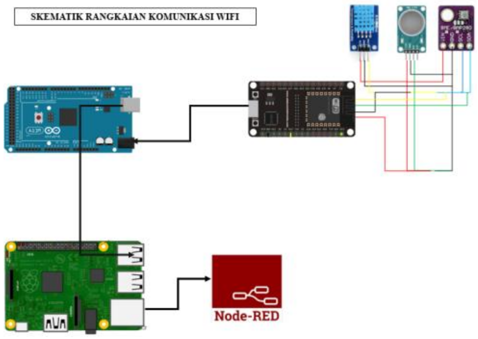


Figure 4. WiFi Communication Circuit Schematic

d. 3D-Printed Enclosure Design

To improve the durability and protection of the hardware during field deployment, a custom device enclosure was designed using Autodesk Fusion 360 and manufactured through 3D printing technology. The enclosure is made from PLA (Polylactic Acid) material, which provides sufficient structural strength while remaining lightweight for prototype deployment. The design of the 3D-printed casing is illustrated in Figure 5**.**

Figure 5. 3D-Printed Enclosure Design

2.4 Performance Evaluation Parameters

The performance evaluation parameters in this study are used to assess the communication protocol performance in the Smart Environment Monitoring system. The evaluation is conducted using several network performance indicators, including communication range, latency, Packet Delivery Ratio (PDR), latency standard deviation, and power consumption.

1. Communication Range

Communication range refers to the maximum distance at which a device can transmit data reliably while maintaining acceptable signal quality[15].

$$R = d_{max} \quad (1)$$

where:

R = maximum communication range (m)

d_{max} = maximum distance at which the device can still communicate with signal quality above the predefined threshold

2. *Latency*

Latency represents the time delay between the transmission and the reception of a data packet[9].

$$L = t_{receive} - t_{trans} \quad (2)$$

where :

L = transmission latency (ms)

t_{trans} = packet transmission time

$t_{receive}$ = packet reception time

3. Packet Delivery Ratio (PDR)

Packet Delivery Ratio (PDR) indicates the percentage of successfully received data packets compared to the total number of transmitted packets[16].

$$\text{PDR} = \frac{N_{received}}{N_{trns}}\ x\ 100\% \quad (3)$$

where :

$N_{received}$ = number of received data packets

N_{trans} = number of transmitted data packets

4. Latency Standard Deviation Analysis

Standard deviation is used to measure the variability or stability of communication latency for each protocol. A lower standard deviation value indicates more stable communication performance[17].

The standard deviation is calculated using the following formula:

$$\sigma = \sqrt{\frac{\Sigma(x_i - \bar{x})}{n}} \quad (4)$$

where :

σ = standard deviation

x_i = i-th data value

$\bar{x}$ = sample mean

n = number of samples

5. Power Consumption

Power consumption analysis is used to determine the electrical energy required by each communication protocol during system operation[18], The power consumption is calculated using the following equation :

$$P = V\ x\ I$$

where :

P = power (w)

V = voltage (v)

I = current (i)

III. Result and Discussion

3.1. System Testing Scenario

The Smart Environment Monitoring system was evaluated using three IoT communication protocols, namely WiFi, Zigbee, and LoRa. The system consists of sensor nodes that measure several environmental parameters and transmit the collected data to a server, where the information is displayed on a monitoring dashboard. The environmental parameters measured in this study include; (a) CO_2 gas concentration**,** (b) Air temperature (DHT Temperature)**,** and (c) Air humidity (DHT Humidity). The system testing was conducted in a semi-rural area in Banyuwangi Regency, specifically in Dusun Kabat. This location was selected due to its rural environmental characteristics and relatively low network density, making it suitable for evaluating the performance of IoT communication protocols over medium to long-range distances**.**

The parameters used in the system testing process are described as follows:

1. Communication Distance
   The experiment was conducted by varying the distance between the sensor node and the gateway. The testing distance started from 25 meters and was gradually increased until reaching the maximum communication range supported by each communication protocol.
2. Data Transmission Interval
   The sensor node was configured to transmit environmental data periodically with a data transmission interval of 120 seconds during the testing process. The total testing duration for each scenario was approximately ±3600 seconds (1 hour).
3. Number of Test Packets
   In each distance testing scenario, the sensor node continuously transmitted data packets to the gateway. With a transmission interval of 120 seconds over a total testing duration of 3600 seconds, the total number of transmitted packets can be calculated as:

$$\text{Number of packets} = \frac{3600}{120} = 30\ packets$$

3.2. *Data Monitoring Visualization*

The transmitted data were visualized through the Smart Environment Banyuwangi monitoring dashboard, as shown in Figure 6.

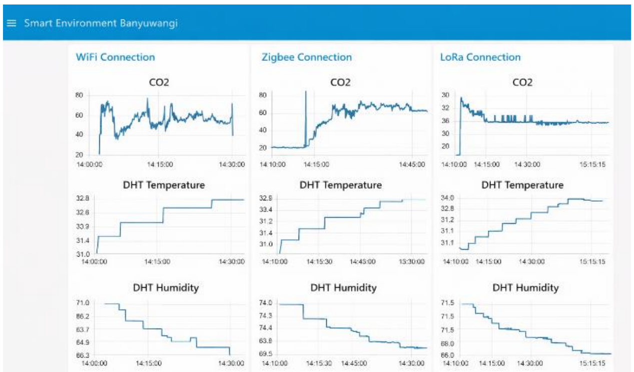


Figure 6. Smart Environment Banyuwangi Monitoring Dashboard

Based on the visualization displayed on the Smart Environment Banyuwangi dashboard, the average values of each environmental parameter measured by the sensor nodes were calculated and summarized in Table 6.

Table 6. Environmental Parameter Monitoring Results

Protocol	**Average Temperature (°C)**	**Humidity (%)**	**CO_2 (ppm)**
LoRa	28.6	70.3	208
Zigbee	28.7	70.1	211
WiFi	28.5	70.2	209

As shown in Table 6, the average temperature values obtained from the three communication protocols exhibit relatively similar results, ranging from 28.5°C to 28.7°C. The humidity values range between 70.1% and 70.3%, while the measured CO_2 concentration ranges from 208 ppm to 211 ppm. These results indicate that the environmental data transmitted by each sensor node demonstrate good consistency, even though different communication protocols were used. This consistency suggests that the system is capable of maintaining reliable data acquisition and transmission performance across multiple IoT communication technologies.

3.3 Packet Delivery Ratio (PDR) Analysis

An analysis was conducted to evaluate the success rate of data packet transmission from the sensor nodes to the gateway using three communication protocols: WiFi, Zigbee, and LoRa. The evaluation parameter used in this study is the Packet Delivery Ratio (PDR), which represents the percentage of successfully received packets compared to the total number of transmitted packets. In each distance testing scenario, the sensor node was configured to transmit 30 data packets to the gateway.

Table 7. PDR Testing Results

Distance (m)	Packets Sent	WiFi Received	WiFi PDR (%)	Zigbee Received	Zigbee PDR (%)	LoRa Received	LoRa PDR (%)
25	30	30	100	30	100	30	100
50	30	30	100	30	100	30	100
100	30	29	96.7	30	100	30	100
200	30	26	86.7	29	96.7	30	100
300	30	0	0	28	93.3	30	100
400	30	0	0	26	86.7	30	100
500	30	0	0	24	80	30	100
550	30	0	0	22	73.3	30	100
600	30	0	0	0	0	30	100
800	30	0	0	0	0	30	100
1000	30	0	0	0	0	29	96.7
1500	30	0	0	0	0	28	93.3
1750	30	0	0	0	0	26	86.7

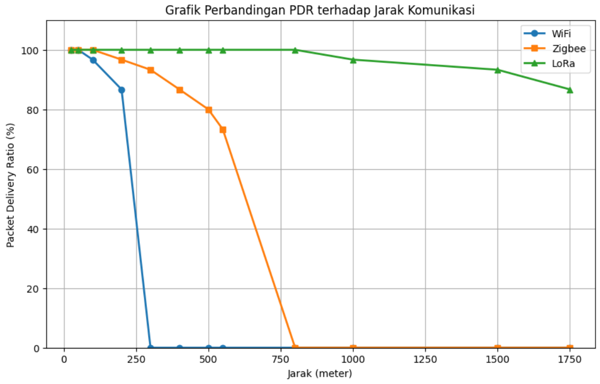


Figure 7. PDR Performance Graph versus Distance

Based on the experimental results presented in Table 7 and Figure 7, which illustrate the relationship between Packet Delivery Ratio (PDR) and communication distance, it can be observed that each communication protocol exhibits different characteristics in terms of transmission range and packet delivery performance. For the WiFi protocol, data communication remains reliable up to a distance of approximately 200 meters, with a PDR value of 86.7%. Beyond this distance, no data packets were successfully received by the gateway, resulting in a PDR value of 0%. This result indicates that WiFi communication performance is significantly affected by the limited signal coverage and potential signal attenuation within the testing environment. The Zigbee protocol demonstrates better communication performance than WiFi in terms of transmission range. Based on the testing results, the system was still able to transmit data packets up to a distance of approximately 550 meters, with a PDR value of 73.3%. The gradual decrease in PDR at longer distances indicates the influence of signal weakening and possible environmental interference, which may affect the reliability of data transmission. The LoRa protocol shows the most stable communication performance among the three evaluated protocols. The system was able to maintain data communication up to a distance of 1750 meters, with a PDR value of 86.7%. This result confirms that LoRa is highly suitable for long-range IoT communication applications, particularly in environments requiring wide-area monitoring with low power consumption.

3.4 Communication Latency and Standard Deviation Analysis

In addition to Packet Delivery Ratio (PDR), another important parameter used to evaluate the communication performance of the Smart Environment Monitoring system is communication latency. Latency refers to the time required for a data packet to be transmitted from the sensor node to the gateway.

Table 8. Latency Testing Results

Distance (m)	WiFi (ms)	Zigbee (ms)	LoRa (ms)
25	12	25	120
50	14	28	130
100	18	32	145
200	25	40	160
300	-	48	180
400	-	55	210
500	-	65	230
550	-	72	250
800	-	-	320
1000	-	-	380
1500	-	-	480
1750	-	-	550

To evaluate the communication stability of each protocol, a standard deviation analysis of latency was performed based on the experimental data. The standard deviation value is used to measure the variation of packet transmission time relative to the average latency value.

Table 9 presents the average latency and standard deviation values at the maximum communication distance for each protocol.

Table 9. Average Latency and Standard Deviation

Protocol	Maximum Distance (m)	Average Latency (ms)	Standard Deviation (ms)
WiFi	200	17.25	5.6
Zigbee	550	45.6	15.2
LoRa	1750	307.1	146.5

Based on the experimental results, the latency values show a tendency to increase as the communication distance becomes greater. This behavior is influenced by the increase in signal propagation time as well as the possibility of packet retransmissions under certain communication channel conditions. For the WiFi protocol, latency remains relatively low, approximately 12 ms at a distance of 25 meters and increasing to 25 ms at 200 meters. The relatively small standard deviation value indicates that WiFi communication demonstrates good transmission stability at short distances. However, beyond this range, communication could no longer be established, and therefore latency could not be further analyzed. In the Zigbee protocol, latency increases from approximately 25 ms at 25 meters to around 72 ms at 550 meters. The standard deviation value is higher than that of WiFi, indicating **a** greater variation in packet transmission time, although communication remains relatively stable over medium-range distances. Meanwhile, the LoRa protocol exhibits higher latency compared to the other two protocols, with values of approximately 120 ms at 25 meters and increasing to 550 ms at 1750 meters. The latency performance across distances is illustrated in Figure 8, while the comparison of average latency and standard deviation values is presented in Figure 9.

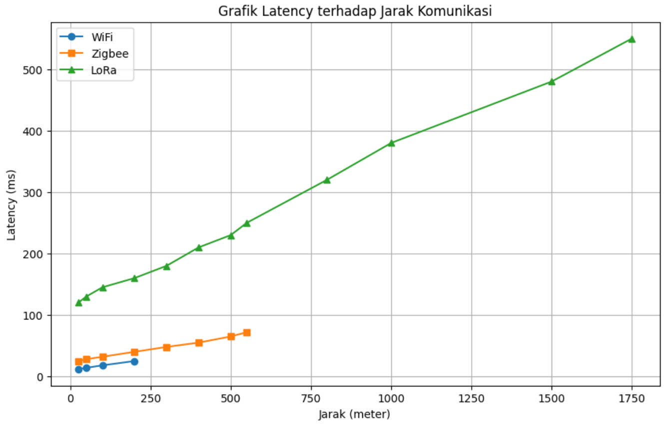


Figure 8. Latency versus Distance Graph

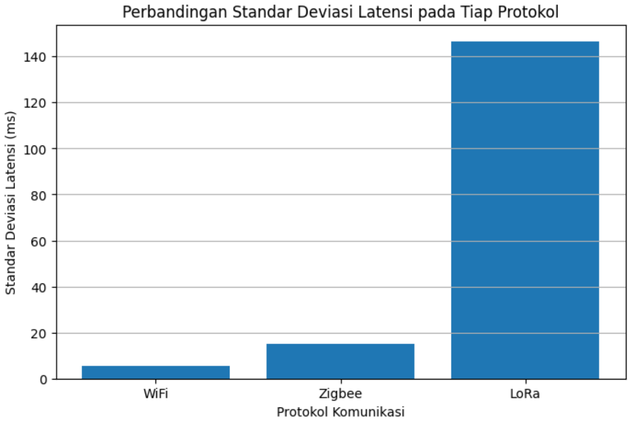


Figure 9. Comparison of Latency Standard Deviation Across Communication Protocols

The relatively larger standard deviation observed in LoRa indicates a higher variation in transmission time, which is primarily due to the inherent characteristics of LoRa technology that are optimized for long-range communication with lower data rates. These results highlight a trade-off between communication range and transmission time performance, indicating that the selection of communication technology should be carefully aligned with the specific requirements of the IoT application being developed.

3.5 Graph Interpretation Analysis

Grafik trade-off menunjukkan hubungan antara jarak komunikasi, latensi rata-rata, dan Packet Delivery Ratio (PDR) pada masing-masing protokol IoT.

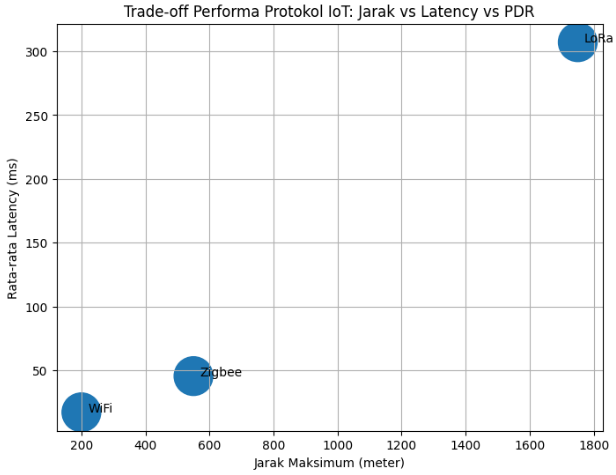


Figure 10. Trade-off Performance Graph

The WiFi protocol exhibits the lowest latency, with an average value of approximately 17.25 ms. However, its communication range is limited to approximately 200 meters. This indicates that WiFi is more suitable for short-range IoT applications that require **f**ast data transmission and low communication delay. The Zigbee protocol provides a balanced compromise between communication range and latency performance. Based on the experimental results, Zigbee is capable of achieving a communication range of up to 550 meters with an average latency of approximately 45.6 ms. This makes Zigbee suitable for medium-range IoT networks, particularly in applications that require moderate latency with extended coverage compared to WiFi. the LoRa protocol demonstrates the longest communication range, reaching up to approximately 1750 meters. However, this extended coverage comes with the consequence of significantly higher latency, with an average value of approximately 307.1 ms. This behavior is consistent with the design characteristics of LoRa technology, which prioritizes long-range communication and energy efficiency over transmission speed**.** As illustrated in Figure 10, each communication protocol exhibits distinct performance characteristics. Therefore, the selection of IoT communication technology should be carefully aligned with the specific requirements of the target application, including factors such as communication range, data transmission speed, and transmission reliability

3.6. Power Consumption Analysis

The power consumption analysis was conducted to evaluate the energy efficiency of each communication protocol used in the Smart Environment Monitoring system. This parameter is particularly important for IoT-based sensor systems, which typically operate using limited power sources such as batteries. In this study, the estimated power consumption was calculated based on the average current consumption characteristics of each communication module during data transmission. The voltage used by the communication modules is 3.3 V, which is commonly applied in embedded IoT devices

Table 10 presents the estimated power consumption of each communication protocol.

Table 10. Power Consumption Comparison of Each Protocol

Protocol	Voltage (V)	Transmission Current (mA)	Power (mW)
WiFi	3.3	170	561
Zigbee	3.3	45	148.5
LoRa	3.3	120	396

Based on the calculation results, the WiFi protocol exhibits the highest power consumption, approximately 561 mW. This higher energy requirement is mainly due to the high data rate and continuous connectivity characteristics of WiFi communication. The Zigbee protocol shows the lowest power consumption**,** approximately 148.5 mW, making it more suitable for low-power sensor network applications. Zigbee is specifically designed for low-energy IoT communications, which allows sensor nodes to operate efficiently over longer periods when powered by batteries. the LoRa protocol consumes approximately 396 mW, which places it between WiFi and Zigbee in terms of power usage. Although its power consumption is higher than that of Zigbee, LoRa provides the advantage of long-range communication capabilities exceeding 1 km**.** Therefore, LoRa remains an efficient option for large-scale environmental monitoring applications, where wide coverage is required. The comparison of power consumption across the evaluated communication protocols is illustrated in Figure 11.

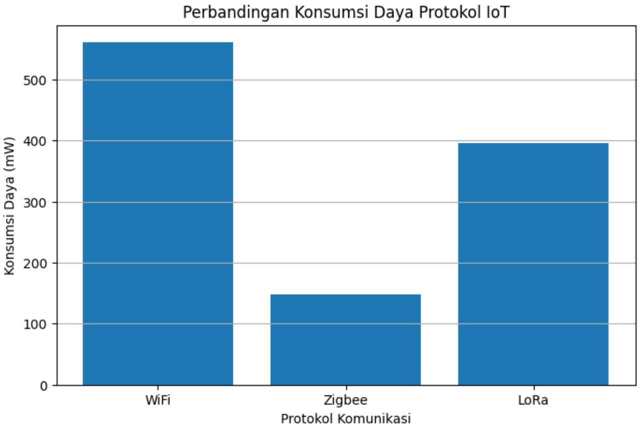


Figure 10. Power Consumption Comparison of IoT Communication Protocols

The results indicate that each protocol demonstrates different trade-offs between power consumption and communication performance**.** Consequently, the selection of an appropriate IoT communication technology should consider energy efficiency, communication range, and system requirements to ensure optimal performance in environmental monitoring applications.

3.7 System Performance Analysis

Based on the experimental evaluation of three IoT communication protocols WiFi, Zigbee, and LoRa implemented in the Smart Environment Monitoring system, each technology demonstrates distinct performance characteristics in terms of communication range, Packet Delivery Ratio (PDR), latency, and power consumption. The overall comparison of these protocols is summarized in Table 11.

Table 11. Performance Comparison of IoT Communication Protocols

Protocol	Max Distance (m)	Latency (ms)	PDR (%)	Power Consumption	Characteristics
WiFi	200	17	100	High	Low latency
Zigbee	550	45	100	Low	Energy efficient
LoRa	1750	307	100	Medium	Long communication range

From the perspective of communication range, the LoRa protocol demonstrates the best performance, supporting data transmission distances of up to approximately 1750 meters. This range is significantly greater than that of Zigbee, which reaches approximately 550 meters, and WiFi, which remains stable up to approximately 200 meters.

In terms of communication latency, WiFi exhibits the best performance, with an average latency of approximately 17.25 ms. This is followed by Zigbee, which shows an average latency of approximately 45.6 ms, while LoRa presents a higher latency, averaging around 307.1 ms due to its long-range communication design and lower data rate characteristics. Based on the Packet Delivery Ratio (PDR) parameter, all three communication protocols demonstrate excellent packet transmission reliability, achieving 100% PDR within their respective effective communication ranges. This indicates that the system is capable of maintaining reliable data transmission when operating within the supported coverage area of each protocol. From the perspective of power consumption, Zigbee is the most energy-efficient protocol, with an estimated power consumption of approximately 148.5 mW. This is followed by LoRa, which consumes approximately 396 mW, while WiFi exhibits the highest power consumption, reaching approximately 561 mW.

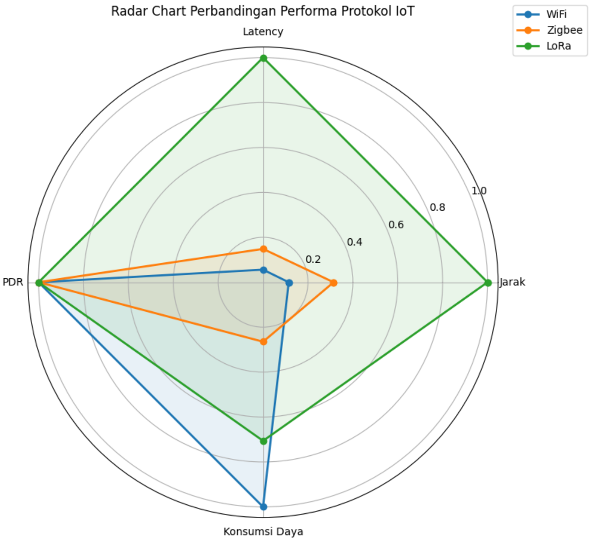


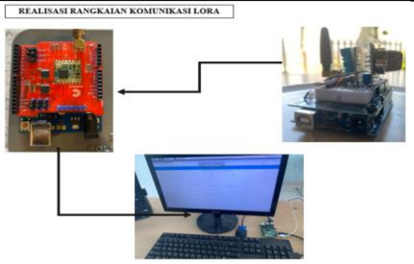
Figure 11. Performance Comparison of IoT Communication Protocols

the results of this study indicate that the selection of IoT communication technology should consider a balance between communication range, latency, data transmission reliability, and energy consumption. For the implementation of a Smart Environment Monitoring system in semi-rural areas such as Dusun Kabat, Banyuwangi Regency**,** the LoRa protocol emerges as the most suitable solution for long-range communication scenarios. Meanwhile, Zigbee and WiFi are more appropriate for smaller coverage areas that require lower communication latency and faster data transmission.

3.8 Hardware Implementation and System Documentation

This section presents the hardware implementation results of the three IoT communication systems evaluated in this study, namely LoRa, Zigbee, and WiFi, along with the modular enclosure design produced using 3D printing technology**.** The documentation serves as evidence of the practical realization of the system architecture described in the research methodology section. The implemented hardware consists of sensor nodes equipped with environmental sensors and communication modules, which are integrated into a modular casing to ensure protection, portability, and ease of deployment in field environments. The modular casing was designed using 3D printing fabrication, enabling flexible hardware integration and efficient system assembly. The documentation of the implemented hardware components is summarized in Table 12.

Table 12. Hardware Implementation Documentation

No	Documentation
1	 Figure 12. Documentation of the LoRa Communication Node
2	 Figure 13. Documentation of the Zigbee Communication Node
3	 Figure 14. Documentation of the WiFi Communication Node
4	 Figure 15. Documentation of the IoT Modular Casing

IV. Conclusion

4.1 Conclusion

This study has successfully conducted an empirical evaluation of three Internet of Things (IoT) communication protocols, LoRa, WiFi (ESP32), and Zigbee (XBee), in the implementation of a Smart Environment Monitoring system in a semi-rural area of Banyuwangi.

1. The experimental results indicate that LoRa provides the widest communication coverage, reaching distances of up to approximately 1750 meters, compared to Zigbee, which achieves around 550 meters, and WiFi, which remains stable up to approximately 200 meters.
2. In terms of communication performance, all three protocols demonstrate a Packet Delivery Ratio (PDR) of up to 100% within their effective communication ranges. Among the evaluated protocols, WiFi exhibits the lowest latency (~17 ms), followed by Zigbee (~45 ms), while LoRa shows a significantly higher latency (~307 ms) due to its design characteristics optimized for long-range communication.
3. From the perspective of energy efficiency, Zigbee demonstrates the lowest power consumption (approximately 148 mW) compared to LoRa (approximately 396 mW) and WiFi (approximately 561 mW). Therefore, the selection of IoT communication protocols should carefully consider the trade-offs between communication range, latency, data transmission reliability, and energy consumption.

V. References

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