Performance Analysis of Wi-Fi HaLow Extender on an IoT-Based Soil Moisture Sensor Device

Devita Rahma Safitri
Telkom University
Purwokerto, Indonesia
devitarasa@student.telkomuniversity.ac.id

Fauza Khair
Telkom University
Purwokerto, Indonesia
fauzakhair@telkomuniversity.ac.id

Alfin Hikmaturokhman
Telkom University
Purwokerto, Indonesia
alfinh@telkomuniversity.ac.id

Fikri Nizar Gustiyana
Telkom University
Bandung, Indonesia
fikrinizargustiana7899@gmail.com

I Ketut Agung Enriko
Telkom University
Bandung, Indonesia
iketutagungenriko@telkomuniversity.ac.id

Lailatuz Zumaroh Itsnain
Telkom University
Purwokerto, Indonesia
lailatz@student.telkomuniversity.ac.id

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***Abstract*— Indonesia, as an archipelagic country with vast agricultural resources, faces significant challenges in achieving food security. The 2022 Global Food Security Index (GFSI) ranked Indonesia 63rd out of 113 countries, highlighting the need for efficient agricultural monitoring solutions. One promising technology is Wi-Fi HaLow, an IEEE 802.11ah-based wireless standard operating in the sub-1 GHz frequency band, offering low power consumption and long-range communication suitable for remote farming. This study evaluates the performance of a Wi-Fi HaLow Extender-based Internet of Things (IoT) system for soil moisture monitoring. Quality of Service (QoS) parameters, including packet loss, delay, and jitter, were tested at distances of 65 m, 105 m, 160 m, 215 m, 230 m, 300 m, and 450 m, following ITU-T G.1010 standards. Results showed 0% packet loss at all distances (Very Good), delays between 1.21 ms and 1.71 ms (Very Good), and jitter ranging from 1.20 ms to 1.72 ms (Good). Stable communication was achieved up to 300 m, with slight degradation at 450 m. The YL-69 soil moisture sensor validation yielded a maximum error of 3.7%, confirming acceptable accuracy. Overall, the system demonstrated reliable, energy-efficient, and low-latency data transmission, making it suitable for large-scale agricultural deployment to support sustainable smart farming.**

***Keywords*— internet of things, smart farming, soil moisture monitoring, wi-fi halow, quality of service**

I. INTRODUCTION

Indonesia, as an archipelagic nation with extensive agricultural land, faces significant challenges in ensuring food security. These challenges arise from climate change, land degradation, and population growth. According to the Global Food Security Index (GFSI) 2022, Indonesia ranks 63rd out of 113 countries, with a score of 60.2, indicating relatively low food security compared to other Southeast Asian nations [1]. To address this issue, effective technological solutions are essential, particularly those based on the Internet of Things (IoT) [2].

IoT facilitates smart agriculture by enabling real-time monitoring of environmental parameters, including soil moisture. Accurate monitoring of soil moisture is crucial for effective irrigation management, as both under-irrigation and over-irrigation can negatively impact crop growth. Optimal soil moisture also affects microbial activity, organic matter decomposition, and nutrient availability. By integrating soil moisture sensors with IoT systems, farmers can access timely and precise data, allowing for better irrigation and fertilization decisions that enhance productivity and land sustainability [3].

However, implementing IoT systems in agricultural fields often encounters connectivity limitations, especially in large rural areas with minimal infrastructure. Wired networks are impractical due to high installation costs and complexity [4]. Therefore, a wireless communication technology that offers long-range, low-power, and stable connectivity is essential [5]. Wi-Fi HaLow, based on the IEEE 802.11ah standard and operating in the sub-1 GHz band, provides significant advantages over alternatives like LoRa, particularly concerning throughput, latency, and native IP support. These features make Wi-Fi HaLow suitable for real-time IoT applications [6].

This research aims to analyze the performance of a Wi-Fi HaLow extender in supporting an IoT-based soil moisture monitoring system. The evaluation will focus on Quality of Service (QoS) metrics packet loss, delay, and jitter according to ITU-T G.1010 standards, which are critical for ensuring reliable and efficient data transmission in smart farming.

II. RELATED WORK

Several studies have investigated the use of IoT-based monitoring systems in agriculture. One particular study implemented the YL-69 soil moisture sensor in conjunction with an ESP32 microcontroller to create an automatic irrigation system [7]. The findings indicated that real-time monitoring could enhance water and energy efficiency, confirming the effectiveness of the YL-69 sensor in agricultural applications. The potential of Wi-Fi HaLow, which is based on the IEEE 802.11ah standard, has also been extensively researched for IoT applications in both agriculture and smart cities. Operating in the sub-1 GHz frequency band, Wi-Fi HaLow provides low power consumption and a long communication range, making it ideal for deployment in rural areas with limited infrastructure. In comparison to LoRaWAN, Wi-Fi HaLow offers higher throughput and native IP support, which are beneficial for real-time data transmission [8].

A comparative study on LoRaWAN and Wi-Fi HaLow for smart metering in Bekasi, Indonesia, revealed that LoRaWAN achieved full coverage (100%) with a single site, delivering stable signals but limiting data rates to about 5.47 kbps. Conversely, Wi-Fi HaLow reached much higher throughput of up to 4.4 Mbps but required significantly more sites up to 211 to cover the same area [9]. This illustrates the trade-off between coverage efficiency and data performance.

In assessing network performance, the ITU-T G.1010 standard is commonly applied to evaluate communication quality through parameters such as packet loss, delay, and jitter [10]. Previous research has demonstrated that factors like node distance and signal degradation significantly affect wireless performance in open agricultural fields, highlighting the need to analyze distance effects in actual deployment scenarios [11].

This study differs from prior works by integrating three key components: (1) sensor accuracy testing, (2) multi-distance Quality of Service (QoS) measurements, and (3) comparative analysis of wireless technologies. These contributions aim to validate the suitability of Wi-Fi HaLow for smart farming, with a focus on signal stability, scalability, and long-range performance.

In addition, while existing studies have primarily focused on either sensor validation or wireless performance in isolation, few have combined both aspects within a single experimental framework. This creates a gap in understanding how sensor accuracy and network quality interact under real agricultural field conditions. By addressing this gap, the present study not only verifies the reliability of the YL-69 soil moisture sensor but also evaluates Wi-Fi HaLow's capacity to deliver stable, low-latency communication over varying distances. Such a holistic approach is essential to provide practical insights for the deployment of IoT-based smart farming systems in Indonesia's diverse agricultural landscapes.

III. RESEARCH METHOD

A. Research Area

This study was conducted in the agricultural and suburban region of Telkom University in Purwokerto, Central Java, Indonesia. The location features expansive rice fields, minimal vegetation, and scattered infrastructure, such as irrigation huts and university buildings. The terrain is predominantly flat, with elevations ranging from 11 to 81 meters above sea level, which allows for a realistic evaluation of long-range wireless performance [12].

Fig. 1 illustrates the area being studied. The area exemplifies typical rural-to-suburban agricultural conditions with limited existing network infrastructure, making it ideal for assessing the effectiveness of Wi-Fi HaLow technology in supporting real-time IoT-based soil moisture monitoring. Additionally, the site selection enables the observation of environmental factors such as soil moisture variability, vegetation density, and line-of-sight constraints [13]. This test environment provides valuable insights into smart farming solutions that can be applied to broader deployments in similar regions of Indonesia, particularly regarding the optimization of irrigation efficiency and land resource management.

Fig. 1. Map of Telkom University Purwokerto Area.

B. System Design

The proposed IoT-based communication system for soil moisture monitoring is illustrated in Fig. 2, while the overall research workflow is shown in Fig. 3. The system is designed to provide real-time monitoring with long-distance transmission and low power consumption, making it suitable for large-scale farming applications.

The system comprises a Wi-Fi HaLow Extender SST-AHWIFI series (functioning as transmitter and receiver), an ESP32 microcontroller, and a YL-69 soil moisture sensor. The sensor measures soil moisture and sends the data to the ESP32, which forwards it wirelessly to the HaLow Receiver. Data are then transmitted through a UTP cable to an RB962UiGS hAP router, enabling internet connectivity.

Collected data are delivered to the EMQX Message Queuing Telemetry Transport (MQTT) Broker using the MQTT protocol and subsequently processed in Node-RED, where results are displayed on a user-friendly dashboard. The MQTT Broker also maintains a historical record of soil moisture readings. By leveraging Wi-Fi HaLow, the system achieves stable, long-range communication with reduced energy consumption, ensuring reliability in agricultural deployment.

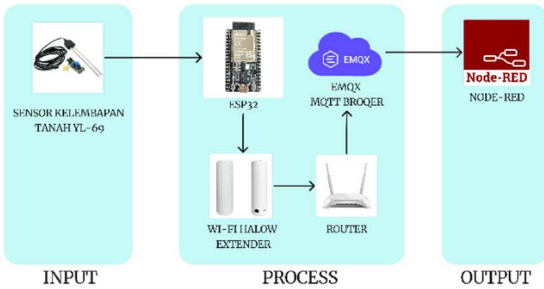

Fig. 2. System Block Diagram.

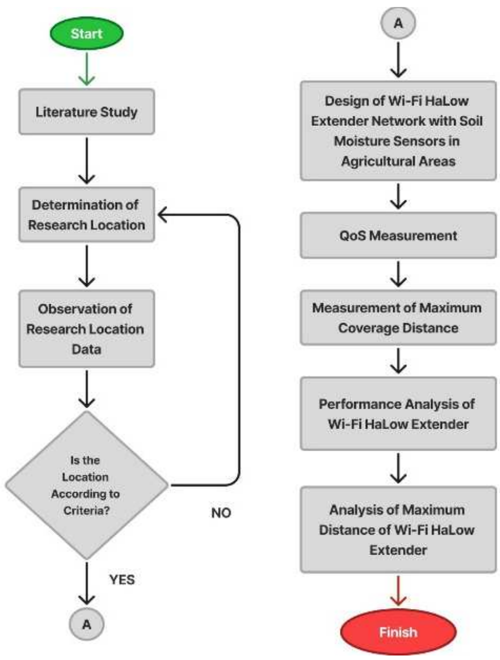

Fig. 3. Flowchart Design System.

C. Sensor Accuracy Validation

In the IoT Device section, there are components tested starting from the validation of YL-69 Sensor data sent to the IoT Gateway. Illustration of component wiring on the ESP32 microcontroller for sensor data validation can be presented in Fig. 4.

The validation of the YL-69 sensor was conducted to verify the accuracy of its soil moisture measurements. This involved comparing its readings with those from a calibrated digital soil moisture meter, referred to as PMS710, which provides output in percentage units. The YL-69 sensor initially outputs an analog signal representing soil moisture, which is converted into a percentage using a formula running on the Arduino IDE. The moisture values from the YL-69 sensor were then compared to those from PMS710

Validation took place under five different soil moisture conditions, from dry to fully saturated. Measurements were repeated five times for each condition, and the average values were used for error calculation. The percentage error was determined by comparing the converted YL-69 values with the readings from PMS710. This process ensures a reliable evaluation of the YL-69 sensor's accuracy in real field conditions and assesses its suitability for real-time agricultural monitoring applications.

To ensure the validity of the results, this comparison is performed repeatedly under various soil moisture conditions. The percentage error (P_e) between the two measurement values is then calculated using the appropriate formula:

$$P_e = \frac{|\text{Standard Value} - \text{Measurement Value}|}{\text{Standard Value}} \times 100\% \quad (1)$$

D. Quality of Service (QoS) Testing

The Quality of Service (QoS) testing was conducted to measure the performance of data transmission in IoT-based systems, specifically for soil moisture monitoring, based on the ITU-T G.1010 standard [14]. The key parameters evaluated were Packet Loss, Delay, and Jitter, which are essential for assessing the reliability and responsiveness of real-time communication in agricultural applications.

In the Packet Loss test, the system was configured to transmit 50 data packets with varying payload sizes of 10 bytes, 25 bytes, and 40 bytes from the End Device to the Application Server. Tests were performed at seven distances: 65 m, 105 m, 160 m, 215 m, 230 m, 300 m, and 450 m. Each transmission scenario was repeated three times, and the average percentage of lost packets was calculated to evaluate data reliability under various conditions.

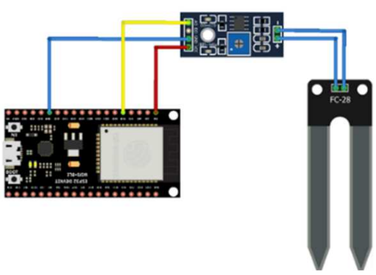

Fig. 4. End Device Connection Design.

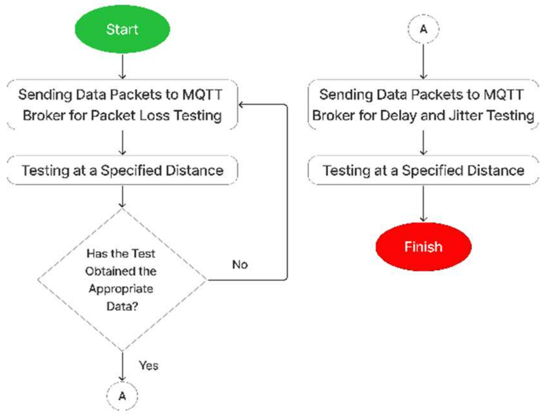

Fig. 5. Flowchart Quality of Service (QoS) Testing.

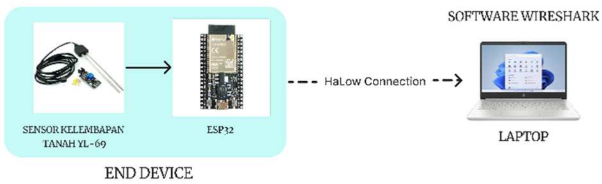

Fig. 6. Quality of Service (QoS) Test Block.

The delay test measured the time required for a packet to travel from the sender to the receiver. For consistency, a 40-byte packet size was used, and measurements were taken at the same seven distances. The average delay was calculated by determining the difference between the transmission and reception timestamps.

Jitter testing focused on measuring the variation in packet arrival times across the same distances, again using the 40-byte packet size. Jitter is a critical parameter for real-time systems, reflecting stability and predictability in communication.

Data sniffing was conducted using Wireshark, and all QoS metrics were calculated manually using Microsoft Excel. The results provide insight into how signal strength, distance, and environmental conditions influence communication performance. These findings support the development of more robust and efficient wireless systems for smart agriculture.

1) Packet Loss

Packet loss can be defined as the percentage of data packet transmission failures that do not reach their destination. Packet loss is defined as the failure of IP packet transmission to reach its destination. Packet loss describes the total number of lost packets, caused by collisions and congestion on the network. The following (2) can be used to calculate the percentage of packet loss.

The Packet Loss Degradation Category assesses communication system performance based on the percentage of packets lost. Packet loss (P_l) in percent is calculated by comparing sent and received packets. The Very Good category (0%) indicates no loss, while Good (1-3%) shows minimal, acceptable loss. Currently (4-15%) represents moderate loss with occasional disruptions, and Bad (16-25%) indicates significant performance issues, leading to noticeable interruptions. This classification helps evaluate transmission quality and pinpoint areas for improvement [16].

$$P_l = \frac{\sum Package\ Sent - \sum Package\ Received}{\sum Package\ Sent} \times 100\% \qquad (2)$$

2) Delay

$$Delay\ (ms) = Time\ 2 - Time\ 1 \qquad (3)$$

Delay refers to the time it takes for data to travel from the sender to the receiver. Factors such as distance, the type of physical media, network congestion, and lengthy processing times can all impact the delay. The following (3) can be used to calculate delay [14].

The Delay Degradation category evaluates system performance based on transmission delay measured in milliseconds. Delay is calculated as the difference between Time 2 and Time 1, representing the time for a data packet to travel from the End Device to the Application Server. Categories include: Excellent (<150 ms) for minimal delay; Good (150-300 ms) for acceptable performance; Current (300-450 ms) for moderate delay with occasional outages; and Poor (>450 ms) indicating significant degradation and performance issues. This classification aids in assessing delay impacts and optimizing the network [16].

3) Jitter

Jitter refers to the variation in queue length, processing time, and packet retrieval time at the destination. It represents fluctuations in the delay of data packets between the source and destination, measured in milliseconds. Jitter commonly arises from factors such as network congestion, variable packet sizes, and unstable network conditions. Equation (4) provides the formula for calculating jitter.

The Jitter Degradation Category is used to assess communication system performance based on variations in packet arrival times. Jitter is particularly critical for real-time applications that require consistent data delivery. The Very Good category (0 ms) indicates no variation, representing ideal performance for real-time IoT systems. The Good category (1–75 ms) indicates minimal variation, which is acceptable for most IoT applications. The Fair category (76–125 ms) shows moderate variation, which may cause occasional instability.

TABLE I. PACKET LOSS DEGRADATION CATEGORY ITU-T G1010 [15]

Degradation Category	Packet Loss (%)
Bad	16 – 25
Currently	4 – 15
Good	1 – 3
Very Good	0

TABLE II. DELAY DEGRADATION CATEGORY ITU-T G1010 [15]

Degradation Category	Delay (ms)
Bad	> 450
Currently	300 – 450
Good	150 – 300
Very Good	< 150

TABLE III. JITTER DEGRADATION CATEGORY ITU-T G1010 [15]

Degradation Category	Peak Jitter (ms)
Bad	126 – 225
Currently	76 – 125
Good	1 – 75
Very Good	0

Finally, the Bad category (126–225 ms) indicates significant variation, resulting in noticeable disruptions and reduced reliability for real-time services. This classification provides a clear framework for evaluating jitter's impact on data transmission quality and identifying areas for network performance improvement [17].

$$Jitter\ (\text{ms}) = \frac{\sum Delay\ Variation}{\sum Package\ Received - 1} \qquad (4)$$

E. Maximum Range Testing

To evaluate the practical coverage limit of the Wi-Fi HaLow Extender, we conducted additional range tests at distances beyond the standard Quality of Service (QoS) evaluation points. This extended testing included measurements at 230 meters, 300 meters, and 450 meters. The purpose of these tests was to explore the limits of signal stability and to identify the maximum effective communication range in open field conditions. The results of this test are discussed in Section IV.

IV. RESULT AND DISCUSSION

This study involved the development of a soil moisture monitoring system that utilizes a Wi-Fi HaLow extender as its primary communication backbone. The main objective was to assess the system's network performance and coverage reliability by analyzing Quality of Service (QoS) parameters in accordance with the ITU-T G.1010 standard. The evaluation concentrated on three key QoS metrics: packet loss, delay, and jitter. These metrics were measured at various distances to evaluate the stability and effectiveness of Wi-Fi HaLow for supporting real-time data transmission in agricultural environments.

A. Yl-69 Sensor Device Testing Results

The YL-69 soil moisture sensor was evaluated for accuracy against a calibrated soil moisture meter, the PMS710, which served as the reference device. Five soil conditions were prepared, ranging from completely dry to fully saturated, to simulate realistic field variations. For each condition, five measurements were recorded, and the average values were compared with the corresponding PMS710 readings. The detailed outcomes are summarized in Table IV.

The analysis revealed that the YL-69 exhibited an average error ranging between 0.04% and 3.7%. The largest deviation occurred under fully saturated conditions, likely due to

TABLE IV. YL-69 SENSOR TEST RESULTS RECAP

No	Soil Conditions (Added Water)	Standard Value/ PMS710 (%)	Measurement Value/ YL-69 (%)	Percentage of Error (%)
1	0 ml	27.16	26.6	2.06
2	25 ml	40.00	40.4	1.00
3	50 ml	42.22	42.2	0.04
4	75 ml	46.52	47.6	2.32
5	100 ml	49.18	51.0	3.70

TABLE V. AVERAGE RESULTS OF QUALITY OF SERVICE (QOS) PARAMETERS

No	Parameter	Average Parameter Value	Category
Distance of 65 Meter			
1	Packet Loss (%)	0	Very Good
2	Delay (ms)	1.643	Very Good
3	Jitter (ms)	1.645	Good
Distance of 105 Meter			
1	Packet Loss (%)	0	Very Good
2	Delay (ms)	1.712	Very Good
3	Jitter (ms)	1.716	Good
Distance 160 Meter			
1	Packet Loss (%)	0	Very Good
2	Delay (ms)	1.662	Very Good
3	Jitter (ms)	1.663	Good
Distance of 215 Meter			
1	Packet Loss (%)	0	Very Good
2	Delay (ms)	1.210	Very Good
3	Jitter (ms)	1.209	Good
Distance of 230 Meter			
1	Packet Loss (%)	0	Very Good
2	Delay (ms)	1.335	Very Good
3	Jitter (ms)	1.333	Good
Distance of 300 Meter			
1	Packet Loss (%)	0	Very Good
2	Delay (ms)	1.388	Very Good
3	Jitter (ms)	1.387	Good
Distance 450 Meter			
1	*Packet Loss* (%)	0	Very Good
2	*Delay* (ms)	1.296	Very Good
3	*Jitter* (ms)	1.291	Good

increased sensitivity of the sensor to waterlogging. Overall, the relatively low error margin indicates that the YL-69 is sufficiently accurate for agricultural monitoring applications, particularly in smart farming scenarios where minor deviations are tolerable.

B. *Quality of Service (QoS) Testing Results*

The Quality of Service (QoS) testing at distances of 65 to 450 meters showed strong network performance with 0% packet loss, classified as "Very Good" by ITU-T G.1010 standards. Delay values remained well below 150 ms, indicating low latency suitable for real-time applications, while jitter remained low under 2 milliseconds, categorized as "Good." These results demonstrate that the Wi-Fi HaLow Extender offers reliable communication over long distances, supporting its use for real-time IoT-based agricultural monitoring. Further analysis on coverage stability and signal reliability will follow.

1) *Packet Loss Test Results for Data Delivery*

Packet loss refers to the percentage of transmitted packets that fail to reach the receiver. Across all tested distances, the system consistently recorded a 0% packet loss rate, classified as Very Good under ITU-T G.1010 standards. The detailed packet loss results are shown in Table VI and illustrated graphically in Fig. 7. These results confirm the reliability and integrity of data transmission over varying distances, achieving up to 450 meters in open-field conditions.

. TABLE VI. AVERAGE PACKET LOSS IN QUALITY OF SERVICE (QOS) MEASUREMENT

No	Distance (m)	Packet Loss (%)	Degradation Category
1	65	0	Very Good
2	105	0	Very Good
3	160	0	Very Good
4	215	0	Very Good
5	230	0	Very Good
6	300	0	Very Good
7	450	0	Very Good
Average		0	Very Good

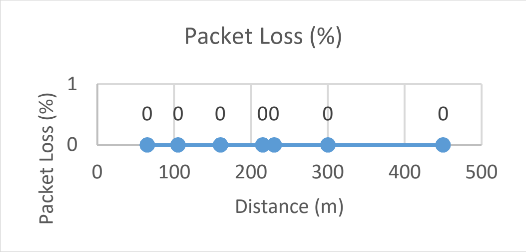

Fig. 7. Packet Loss in Quality of Service Measurement.

2) *Delay Test Results for Data Delivery*

Delay was measured as the time between data transmission and reception. The delay remained low and stable across all distances, with values well below the 150 ms threshold defined by ITU-T G.1010 for "Very Good" performance. The average results of the delay test at each of these distances are presented in Table VII and visualized by the graph in Fig. 8.

Interestingly, the lowest delay value was observed at a distance of 215 meters, which appears as an anomaly in the measurement results. This unexpected outcome may have been influenced by temporary environmental factors, including signal reflections, momentary reduction in interference, or channel fluctuations. Such conditions can occasionally produce atypical results in wireless communication testing.

3) *Jitter Test Results for Data Delivery*

Jitter is the variability in packet arrival times, which can affect real-time applications. Jitter values remained consistent

TABLE VII. AVERAGE DELAY IN QUALITY OF SERVICE (QOS) MEASUREMENT

No	Distance (m)	Delay (ms)	Degradation Category
1	65	1.643	Very Good
2	105	1.712	Very Good
3	160	1.662	Very Good
4	215	1.210	Very Good
5	230	1.335	Very Good
6	300	1.388	Very Good
7	450	1.296	Very Good
Average		1.464	Very Good

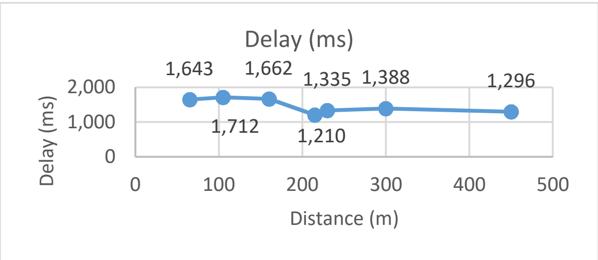

Fig. 8. Delay in Quality of Service Measurement.

and below 2 ms across all distances, classified as "Good" according to ITU-T G.1010. The average results of the jitter test at each of these distances are summarized in Table VIII and visualized by the graph in Fig. 9. The results show minimal jitter variation, indicating stable and consistent data delivery that is suitable for real-time IoT applications.

C. Maximum Range Test Results

The next test aims to determine the maximum connectivity range of the Wi-Fi HaLow Extender for the soil moisture sensor device. This test was conducted at distances of 230 m, 300 m, and 450 m to identify the operational limits of the system under realistic environmental conditions. The coordinates for each test location are detailed in Table IX, and the placement of the gateway in relation to the test area is illustrated in Fig. 10.

The maximum range testing took into account environmental variability, including terrain profile, vegetation density, and line-of-sight conditions, ensuring that the findings accurately reflect field deployment scenarios. At both 230 m and 300 m, the Wi-Fi HaLow connection remained stable, with no observed packet loss and minimal delay or jitter. These results align with expectations for sub-1 GHz wireless technologies operating in open-field conditions.

However, at 450 meters, the connection began to show signs of instability, including increased fluctuations in delay and intermittent disruptions. While the packet loss rate technically remained at 0%, the response times became less predictable. This degradation in performance is likely due to cumulative effects of signal attenuation, obstructions from nearby buildings or trees, and partial line-of-sight interference.

Based on these results, we can conclude that the Wi-Fi HaLow Extender achieves optimal and stable performance up to approximately 300 meters in typical agricultural environments. Beyond this range, particularly after 450 meters, system reliability may decrease due to increased sensitivity to environmental interference. Therefore, for the practical deployment of IoT-based soil moisture monitoring systems, it is advisable to maintain inter-device distances at or below 300 meters to ensure consistent and reliable data transmission.

TABLE VIII. AVERAGE JITTER IN QUALITY OF SERVICE (QOS) MEASUREMENT

No	Distance (m)	Jitter (ms)	Degradation Category
1	65	1.645	Good
2	105	1.716	Good
3	160	1.663	Good
4	215	1.209	Good
5	230	1.333	Good
6	300	1.387	Good
7	450	1.291	Good
Average		1.463	Good

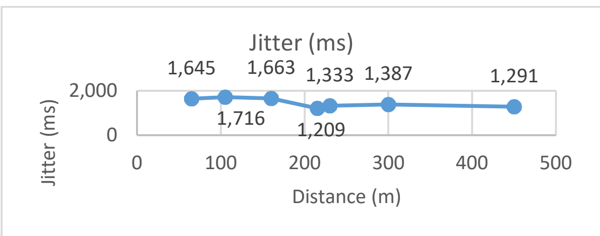

Fig. 9. Jitter in Quality of Service Measurement.

TABLE IX. WI-FI HALOW EXTENDER MAXIMUM RANGE TEST COORDINATE POINTS

No	Distance (m)	Coordinate Points	
1	230	7°25'56.34"S	109°15'5.97"E
2	300	7°25'54.03"S	109°15'5.92"E
3	450	7°25'50.85"S	109°15'0.43"E

Fig. 10. Maximum Range Testing Scenario.

V. CONCLUSION

Based on the performance evaluation of the Wi-Fi HaLow Extender in an IoT-based soil moisture monitoring system, it can be concluded that this technology provides excellent network quality and sensor performance across various distance scenarios. The YL-69 soil moisture sensor exhibited acceptable accuracy compared to a calibrated reference device, with a maximum error rate of 3.7%, confirming its reliability for field-level monitoring.

Quality of Service (QoS) testing results, based on ITU-T G.1010 standards, showed that packet loss was maintained at 0% across all distances. The average delay was recorded at 1.5132 milliseconds, while jitter ranged from 1.209 ms to 1.716 ms. These values indicate stable, low-latency, and predictable data transmission, which is suitable for real-time applications. Maximum range testing revealed that the Wi-Fi HaLow connection remained stable at distances up to 300 meters.

However, performance degradation began to occur at 450 meters due to non-line-of-sight interference and environmental obstructions. Therefore, for reliable deployment in agricultural fields, it is recommended that the maximum inter-device distance not exceed 300 meters. These findings confirm that the Wi-Fi HaLow Extender offers a practical, scalable, and energy-efficient solution for smart agriculture. Future work may explore multi-node scalability, real-time energy profiling, and comparative testing with other LPWAN technologies, such as LoRa and NB-IoT, to further refine deployment strategies in wide-area farming environments.

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