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Analysis of 433 MHz LoRa Communication Quality Based on RSSI and SNR Parameters in A Solar-Powered IoT Chili Irrigation System in Hilly Forest Farmland

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ABSTRACT

Agricultural areas in tropical hilly regions generally face challenges due to dense vegetation and uneven topography, which can cause signal attenuation and unstable communication performance. Therefore, this study analyzed the communication quality of a 433 MHz LoRa network based on the parameters of Received Signal Strength Indicator (RSSI), Signal-to-Noise Ratio (SNR), and Packet Delivery Ratio (PDR) in an Internet of Things (IoT)-based chili irrigation system implemented in a tropical hilly agricultural area at an altitude of 210 meters above sea level. This study employed a quantitative experimental method through direct field measurements and descriptive analysis to evaluate wireless communication performance under Non-Line-of-Sight (NLOS) conditions. The system utilized an ESP32 microcontroller and a LoRa SX1278 module operating at 433 MHz to evaluate the reliability and effectiveness of wireless data transmission. Over a continuous monitoring period of approximately 2 hours and 27 minutes, 303 LoRa packets were transmitted, of which 186 were successfully received, yielding a Packet Delivery Ratio of 61.4% and a packet loss rate of 38.6%. RSSI values fluctuated between −92 dBm and −97 dBm, with an average of approximately −93 to −94 dBm, while SNR values ranged from 6.7 dB to 10.8 dB, with most communication sessions maintaining values of approximately 8 dB. Two distinct communication gaps, lasting approximately 8.5 and 33 minutes, respectively, were observed during the monitoring period. The results demonstrate that the 433 MHz LoRa network was able to maintain wireless communication under the tested tropical hilly NLOS conditions, although the relatively low PDR indicates that communication reliability remains a challenge. Further optimization of antenna placement, network configuration, and error-correction mechanisms is recommended to improve communication reliability for more demanding IoT irrigation applications.

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1. INTRODUCTION

Indonesia remains an agriculturally dependent nation where the farming sector constitutes a critical component of national economic development. Among high-value horticultural commodities widely cultivated in Indonesia, chili pepper (Capsicum annuum L.) holds significant importance, requiring precise irrigation management to maintain optimal crop productivity and quality. Soil moisture conditions directly influence chili plant growth and yield; inadequate or improper irrigation management can trigger drought stress and substantially reduce crop productivity and market quality (Manono et al., 2026).

Conventional irrigation methods commonly applied in hilly forest agricultural areas suffer from significant operational inefficiencies due to difficult terrain access, high labor requirements, and limited agricultural infrastructure availability. Implementing Internet of Things (IoT)-based smart irrigation systems represents an effective technological solution for enhancing irrigation efficiency and agricultural productivity in such challenging environments. ESP32-based IoT systems have demonstrated substantial capability for performing real-time environmental monitoring and providing autonomous irrigation control through integration of soil moisture sensors and relay-controlled pump systems (Irianto, 2022).

A fundamental challenge in deploying IoT systems in tropical hilly forest agricultural areas involves the absence of reliable conventional electrical infrastructure. Off-grid photovoltaic (PV) systems have emerged as a practical alternative for supporting autonomous agricultural monitoring systems in remote environments (Mokrani et al., 2025). Solar-powered irrigation systems offer significant advantages including continuous energy availability without dependence on conventional electrical grids, particularly important in isolated agricultural regions.

Beyond energy availability, selecting appropriate wireless communication technology for transmitting sensor data in hilly forest agricultural environments represents another critical implementation challenge. Conventional wireless technologies including Wi-Fi and cellular communication exhibit limited transmission range and elevated power consumption, rendering them unsuitable for remote agricultural deployments. LoRa (Long Range) technology has emerged as an efficient Low Power Wide Area Network (LPWAN) solution, offering low energy consumption and robust long-range communication capabilities particularly suited for agricultural IoT applications (Correia et al., 2023).

LoRa communication operating at sub-GHz frequencies, particularly 433 MHz, demonstrates superior diffraction and vegetation penetration characteristics compared with higher-frequency wireless systems such as 2.4 GHz Wi-Fi. The longer wavelength of 433 MHz signals permits improved propagation through vegetation obstacles and uneven terrain typically encountered in tropical hilly forest agricultural areas. However, Non-Line-of-Sight (NLOS) propagation conditions in densely vegetated hilly terrain can significantly degrade communication quality and introduce packet loss, potentially affecting the reliability of IoT monitoring systems.

Recent studies have investigated LoRa communication performance in various environments. Mokrinsky et al. (2024) evaluated LoRa network performance in densely vegetated forest areas, demonstrating that vegetation density and topographical features significantly influence signal propagation characteristics. Wiyadi et al. (2020) specifically examined the effects of vegetation profile and data rate on packet loss in LoRa 433 MHz systems, identifying vegetation density as a critical factor affecting communication reliability. Ferreira et al. (2020) conducted comparative propagation analysis across diverse environments including forest, urban, and suburban settings, revealing substantial differences in signal attenuation and communication quality across these environments.

Communication quality in LoRa systems is conventionally evaluated using two primary parameters: Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR). RSSI represents the received signal power level, while SNR indicates signal quality relative to environmental noise and interference (Aarif et al., 2024). Additionally, Packet Delivery Ratio (PDR) serves as a critical metric for evaluating communication reliability in time-series monitoring applications (Szafranski & Reinhardt, 2025). Stable RSSI and SNR values combined with acceptable PDR levels indicate reliable communication performance suitable for IoT-based agricultural monitoring systems.

Prior studies have examined LoRa propagation in vegetated and forested environments through simulation and theoretical modeling (Atmoko et al., 2026), comparative analysis across forest, urban, and suburban settings (Ferreira et al., 2020), and the influence of vegetation profile and data rate on packet loss (Wiyadi et al., 2020). However, these studies were largely conducted through simulation, theoretical modeling, or controlled testing rather than within a fully operational, solar-powered IoT system deployed under real agricultural field conditions. Furthermore, none of these studies jointly evaluated RSSI, SNR, and PDR as combined indicators of temporal communication stability in a functioning irrigation system. This gap is practically significant because communication reliability directly determines the feasibility of deploying autonomous LoRa-based monitoring in remote, off-grid agricultural settings where maintenance access is limited. Therefore, this study addresses this gap through direct field measurement of RSSI, SNR, and PDR within an integrated, operational solar-powered IoT chili irrigation system deployed in tropical hilly forest terrain under genuine NLOS conditions.

The research aims to assess the feasibility of LoRa 433 MHz for supporting smart farming applications while identifying communication gaps and anomalies that may guide future optimization of wireless infrastructure in challenging tropical agricultural environments.

2. SYSTEM DESIGN AND METHODS

2.1. System Architecture

The proposed solar-powered smart irrigation system comprises four integrated subsystems:

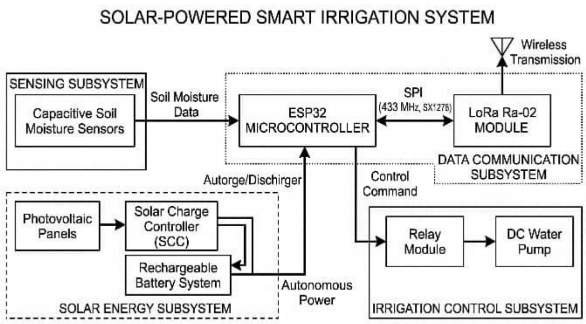

Fig. 1 Architecture of the proposed solar-powered smart irrigation system

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2.2 LoRa Communication System and Measurement Parameters

The communication subsystem utilizes LoRa modulation based on Chirp Spread Spectrum (CSS), which provides robust resistance against interference and multipath fading. The Received Signal Strength Indicator (RSSI) represents the received signal power level and is expressed as a negative value in dBm. Signal-to-Noise Ratio (SNR) measures the ratio of signal power to environmental noise power, calculated as:

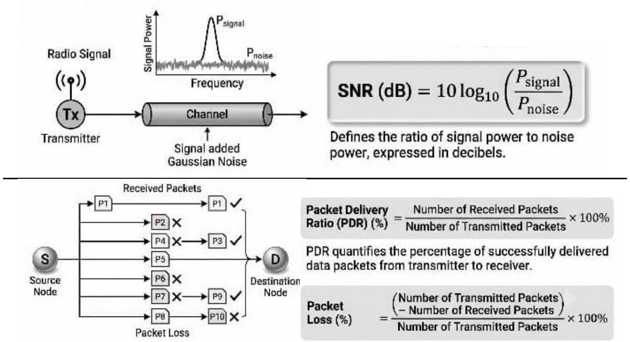

Fig. 2 SNR and packet delivery performance metrics for LoRa communication.

Sequence numbers embedded in transmitted packets were utilized to identify lost packets and detect temporal communication gaps. Free Space Path Loss (FSPL) modeling was applied to interpret propagation behavior in the study environment.

2.3 System Prototype Implementation Overview

Field testing was conducted directly in a tropical hilly forest agricultural environment characterized by dense vegetation and uneven topography. The testing location featured Non-Line-of-Sight (NLOS) propagation conditions with significant terrain obstruction and vegetation blockage. The LoRa communication system was configured with 433 MHz operating frequency, 17 dBm transmission power, 125 kHz bandwidth, spreading factor SF7 , and coding rate 4/5. Continuous packet transmission and reception monitoring was maintained for approximately 2 hours and 27 minutes to evaluate communication stability and identify potential temporal anomalies. Communication logs were continuously recorded through serial interface connection to document RSSI, SNR, and packet sequence information.

3. RESULTS AND DISCUSSION

3.1 System Prototype Implementation Overview

The developed prototype successfully integrated ESP32 microcontrollers, LoRa SX1278 communication modules, capacitive soil moisture sensors, relay-based irrigation control systems, and photovoltaic energy infrastructure. All electronic components were enclosed within weather-protected casing to ensure stable operation under tropical outdoor environmental conditions. The photovoltaic subsystem successfully supplied continuous electrical energy to support sensor monitoring, wireless communication, and irrigation control operations independently without dependence on grid electricity. Sensor nodes successfully transmitted soil moisture telemetry data to the gateway through LoRa wireless communication links, with data packets continuously received and monitored through serial interfaces.

3.2 Packet Delivery Performance and Communication Overview

During a 2-hour and 27-minute field deployment in a hilly forest environment, a total of 303 LoRa packets were transmitted. As shown in Fig. 3(a), 186 packets were successfully received, resulting in a Packet Delivery Ratio (PDR) of 61.4% and a packet loss rate of 38.6%. This packet loss represents a significant communication challenge typical of Non-Line-of-Sight (NLOS) tropical hilly terrains.

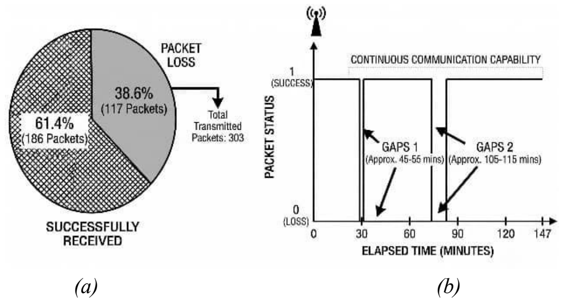

Fig. 3. (a) Packet delivery ratio and packet loss distribution;(b) Communication status over time showing two communication gaps.

Despite these losses, the system maintained continuous communication capability without complete link failure. As illustrated in Fig. 3(b), the packet drops were not uniform but clustered into two prominent communication gaps. This temporal pattern suggests that signal degradation was driven by dynamic environmental factors rather than permanent hardware limitations.

3.3 RSSI Performance and Propagation Stability

RSSI measurements from successfully received packets demonstrated consistent values within a relatively narrow range. RSSI values were observed to fluctuate between −97 dBm (minimum) and −92 dBm (maximum), with an average value of approximately −93 to −94 dBm. This narrow range suggests relatively stable propagation conditions despite the NLOS environment, indicating that while signal attenuation was present, it remained within manageable levels for LoRa receiver sensitivity. The stability of RSSI values around −93 to −94 dBm represents an acceptable reception level for LoRa modulation and indicates adequate signal margin above the typical LoRa receiver sensitivity threshold of approximately −120 dBm for SF7 spreading factor.

The consistency of RSSI measurements suggests that the hilly forest environment, while introducing significant attenuation compared to free-space conditions, did not cause

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rapid fluctuations in received signal power. This relatively stable RSSI behavior may be attributed to the CSS modulation scheme's inherent robustness against multipath effects and the 433 MHz sub-GHz frequency's favorable propagation characteristics through vegetation and terrain obstacles. However, RSSI stability alone does not explain the observed 38.6% packet loss, suggesting that packet loss was more closely associated with SNR degradation or temporary propagation anomalies rather than overall signal weakness.

3.4 SNR Performance and Communication Quality Classification

Signal-to-Noise Ratio (SNR) analysis revealed more variability compared to RSSI measurements. SNR values ranged from a minimum of 6.7 dB to a maximum of 10.8 dB, with an average value of approximately 8 dB. While the average SNR remained above 5 dB (the theoretical minimum threshold for LoRa packet decoding), individual measurements near the lower boundary of this range indicate marginal communication quality. SNR values in the 6.7–7.5 dB range represent borderline conditions where packet reception success becomes probabilistic rather than assured, potentially explaining the observed packet losses despite adequate RSSI levels.

The variability in SNR values, contrasting with RSSI stability, suggests that environmental noise levels may have fluctuated more substantially than signal power. In hilly forest environments, noise can originate from diverse sources including electrical infrastructure, industrial equipment, atmospheric phenomena, and multipath interference. The dominant SNR values clustered around 8 dB reflect adequate communication quality under normal conditions, while occasional lower values indicate periods of elevated noise or interference affecting decoding probability.

Communication status classification follows a conjunctive criterion, in which a packet is assigned to a given category only when both its RSSI and SNR values fall within the corresponding range. When RSSI and SNR values indicate different categories, the lower (more conservative) category is assigned, ensuring that classification reflects the limiting parameter for reliable communication.

Based on the experimental measurements, the dominant communication quality was classified as "moderately stable," with RSSI averaging −93 to −94 dBm and SNR averaging 8 dB. This classification indicates that the LoRa 433 MHz system operated at an acceptable quality level for basic IoT telemetry applications, though not optimal for mission-critical monitoring requiring guaranteed packet delivery.

3.5 Temporal Communication Gaps and NLOS Anomalies

Temporal analysis of packet sequence numbers revealed two distinct communication interruption events during the monitoring period:

First Communication Gap (Sequence 116–130):

Table 1. RSSI and SNR Measurements During the First Communication Gap (Sequence 116–130)

Timestamp	Sequence Number	RSSI (dBm)	SNR (dB)
2026-06-12 18:11:33	113	-94	8
2026-06-12 18:11:58	114	-94	8
2026-06-12 18:12:26	115	-93	9
2026-06-12 18:12:57	116	-95	7.7
18:12:58–18:21:26	*117–129*	*N/A*	*N/A*
2026-06-12 18:21:27	130	-93	7.7
2026-06-12 18:21:36	131	-96	8.5

Between sequence 116 and 130, packets 117–129 (18:12:58–18:21:26) were not received, and consequently no RSSI or SNR values could be recorded for this interval reported as N/A in Table 1. This is a methodological outcome rather than a signal-quality classification: RSSI and SNR are only generated by the receiver's radio module upon successful demodulation and CRC validation of an incoming packet, so a packet that never arrives produces no metadata to record.

The RSSI and SNR values immediately preceding the gap (-95 dBm, 7.7 dB at sequence 116) were already near the lower bound of values observed under normal conditions, suggesting the link had degraded before communication failed entirely. Upon resumption at sequence 130, RSSI and SNR returned to typical levels (-93 dBm, 7.7 dB), indicating the interruption was transient rather than a permanent link failure. Over this approximately 8.5-minute interval, the Packet Delivery Ratio (PDR) was 0%, with 13 consecutive packets lost. This pattern is consistent with a temporary deep fade or NLOS obstruction such as vegetation movement or a moving obstacle along the propagation path rather than a random or isolated packet error.

Second Communication Gap (Sequence 222–275):

Table 2. RSSI and SNR Measurements During the Second Communication Gap (Sequence 222–276)

Timestamp	Sequence Number	RSSI (dBm)	SNR (dB)
2026-06-12 19:00:58	219	-93	8.3
2026-06-12 19:01:26	220	-95	7.7
2026-06-12 19:01:32	221	-96	7.5
2026-06-12 19:01:37	222	-96	8.8
19:01:38–19:34:26	*223–274*	*N/A*	*N/A*
2026-06-12 19:34:27	275	-93	8.5
2026-06-12 19:35:00	276	-94	8.5

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A more prolonged interruption occurred between sequence 222 and 275, where packets 223–274 (19:01:38–19:34:26) were not received and no RSSI or SNR values could be recorded, for the same reason noted above.

The values recorded immediately before the gap (-96 dBm, 8.8 dB at sequence 222) were within the normal operating range, showing no strong indication of gradual degradation prior to the failure in contrast to the first gap, where a declining trend preceded the interruption. This suggests the second interruption may have resulted from a more abrupt obstruction event rather than a gradual fade. Upon resumption at sequence 275, RSSI and SNR values returned to typical levels (-93 dBm, 8.5 dB), confirming the link remained functional and the interruption was environmental rather than a permanent hardware or configuration fault. Over this approximately 33-minute interval, PDR was 0%, with 52 consecutive packets lost substantially longer than the first gap, potentially reflecting a more persistent NLOS condition such as sustained vegetation cover or a longer-duration obstruction along the propagation path.

3.6 Communication Feasibility and Practical Implications

Overall experimental evaluation demonstrates that LoRa 433 MHz provides feasible communication performance for smart farming applications in tropical hilly forest agricultural areas, with important limitations. The system maintained continuous communication capability despite NLOS propagation conditions, significant vegetation density, and terrain obstruction. The 61.4% PDR, while substantially below ideal targets (>95%), proves adequate for non-critical IoT monitoring applications where periodic data loss can be tolerated through appropriate system design incorporating data buffering, retransmission protocols, or reduced data transmission frequency.

The combination of low-frequency sub-GHz propagation characteristics with CSS modulation robustness enabled communication maintenance despite environmental obstacles. The implemented solar-powered infrastructure successfully supported autonomous operation in remote agricultural areas lacking conventional electrical infrastructure, demonstrating technical feasibility of the integrated system. However, the 38.6% packet loss rate and occurrence of two significant communication gaps indicate that further optimization is essential for mission-critical applications requiring guaranteed data delivery or real-time responsiveness.

Practical considerations for implementation include: (1) optimization of node and gateway antenna placement to maximize line-of-sight or reduce terrain obstruction, (2) implementation of error-correction coding and retransmission protocols to mitigate packet loss, (3) consideration of redundant communication paths using alternative wireless technologies as fallback systems, and (4) further characterization of propagation behavior across different seasons and weather conditions to understand temporal variations in communication quality.

4. CONCLUSION

This study successfully evaluated the communication quality and temporal stability of LoRa 433 MHz in a solar-powered IoT-based chili irrigation system deployed in tropical hilly forest agricultural environments under operational NLOS conditions. Key experimental findings include: (1) RSSI values remained stable within the range of −97 dBm to −92 dBm with an average of −93 to −94 dBm, (2) SNR values fluctuated between 6.7 dB and 10.8 dB with an average of approximately 8 dB, (3) Packet Delivery Ratio was 61.4% with corresponding packet loss of 38.6%, and (4) the dominant communication quality classification was "moderately stable," indicating acceptable performance for basic IoT monitoring applications. Dense vegetation and hilly topography likely influenced signal propagation behavior and contributed to the observed packet losses. Two significant communication gaps, lasting approximately 8.5 minutes and 33 minutes respectively, indicate that NLOS propagation conditions in hilly terrain may experience temporal variations requiring robust error-handling mechanisms. The findings confirm that LoRa 433 MHz is feasible for supporting smart farming communication systems in tropical hilly forest environments utilizing autonomous solar-powered infrastructure, although further optimization of communication infrastructure, antenna placement, and error-correction protocols is recommended to reduce packet loss and improve system reliability for more demanding applications. Future research should investigate seasonal variations in propagation quality, implement advanced error-correction schemes, and evaluate multi-hop communication topologies to enhance overall system resilience in challenging tropical agricultural environments.

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