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Vegetation Effects on LoRa-Based Wireless Sensor Communication for Remote Monitoring of Automatic Orchard Irrigation Status

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Abstract: LoRa-based sensor nodes may provide a reliable solution for wireless communication in orchard cultivation and smart farming, facilitating real-time environmental monitoring. However, the signal strength and data integrity can be affected by several factors, such as trees, terrain, weather, and nearby electrical devices. The objective of this study is to evaluate the impact of orchard trees on the performance of a LoRa sensor node under orchard conditions. A sensor node, built with a commercial LoRa transceiver and microcontroller unit (MCU), was paired with a single-channel gateway linked to an orchard irrigation system. Performance metrics such as the packet delivery ratio (PDR), received signal strength indicator (RSSI), and signal-to-noise ratio (SNR) were measured over a range of 20 to 120 m under open field conditions and in an orchard with trees averaging 3.12 and 4.36 m in height. Data were sent every 20 s using three spreading factors (SF8, SF10, and SF12) and stored as a CSV file in the MCU via a Python program. The results showed that the PDR remained consistently high (100%) under non-vegetative (open field) conditions. In the orchard under vegetative conditions, the PDR dropped significantly, with SF12 maintaining 100% only up to 120 m. For SF10, the packet delivery rates dropped to 45% at 80 m, while SF8 achieved 100% at 20 m but decreased to 52% at 40 m. SNR values also declined with an increase in distance, becoming largely undetectable beyond 40 m for SF8. These findings indicate that vegetation greatly impacts LoRa sensor node performance, reducing packet delivery and signal quality in orchards.

Keywords: smart agriculture; IoT; automatic irrigation; signal attenuation; wireless sensor network

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1. Introduction

Wireless sensor networks (WSNs) are increasingly recognized for their potential to enhance agricultural quality, productivity, and resource optimization. These networks facilitate the collection of field data with minimal wiring, straightforward installation, and low maintenance requirements [1], exemplifying a paradigm shift toward data-driven, technology-enhanced farming methods. Their integration with Internet of Things (IoT) technologies facilitates real-time monitoring of critical parameters, such as water monitoring [2,3], agriculture [4,5], and environmental monitoring [6,7], hold the distributed sensing capabilities of WSNs, enabling more precise and automated agricultural practices, such as an optimal solution for smart water management applications [8]. The integration of WSNs with IoT technologies has further advanced their utility by enabling real-time monitoring of critical parameters such as soil moisture in agricultural settings, facilitating informed decision-making, which is essential for effective irrigation management and crop health. In crop monitoring tasks, particularly those involving irrigation for fruit tree cultivation, it is crucial to maintain precise control over soil moisture levels to ensure optimal growth and productivity [8].

Monitoring expansive agricultural areas, especially for orchard irrigation, can be efficiently achieved using sensor nodes that transmit real-time data via WSNs, facilitating enhanced decision-making and resource optimization [9]. While short-range communication technologies, such as ZigBee™ and Bluetooth, are commonly employed in WSNs, their limited range and scalability render them unsuitable for large-scale agricultural applications [10–14]. A significant disadvantage of using Zigbee is the relatively short transmission range of approximately 100 m, which is insufficient for monitoring expansive orchard areas [14]. These limitations underscore the need for long-range communication solutions capable of maintaining reliable connectivity across extensive and densely vegetated landscapes.

Low-power wide-area network (LPWAN) technologies, particularly long-range (LoRa) and long-range wide-area networks (LoRaWANs), have garnered significant attention from both industry and academia [13,15,16]. Currently, there are several key participants in the LPWAN sector, including LoRa, Sigfox, Ingenu, and Weightless [17]. LoRa, in particular, offers several advantages, including low power consumption and extended transmission range, making it an attractive solution for agricultural applications. Studies indicate that LoRa can achieve communication ranges of up to 8 km in rural settings, facilitating data transmission over large areas and addressing the coverage challenges posed by short-range technologies [18]. These attributes make LoRa a promising candidate for addressing the specific requirements of orchard irrigation management, where large coverage areas and reliable data transmission are essential.

Despite these advantages, the performance of LoRa in orchard environments, characterized by dense vegetation such as leaves, branches, and tree trunks, remains insufficiently studied [19]. These factors adversely impact signal quality, thereby reducing communication reliability and coverage [8,20,21]. While LoRa's performance has been extensively evaluated in urban and maritime environments, where over 50% of packets were successfully delivered within the 5–10 km range [22], its application in agricultural contexts has received limited attention [20]. This gap highlights the necessity of conducting experimental evaluations to understand how vegetation-specific factors influence LoRa's performance in orchard scenarios.

Addressing the challenges posed by orchard environments requires a detailed evaluation of LoRa's performance to ensure reliable wireless communication for precision agriculture. Experimental analyses conducted in authentic orchard environments are essential for developing a comprehensive understanding of the effects of vegetation on signal propagation. Such investigations enable the formulation of tailored strategies to enhance the reliability and resilience of wireless sensor networks in agricultural applications. The objective of this study is to evaluate the effect of vegetation on the performance of a low-cost LoRa-based sensor node for orchard irrigation management.

2. Materials and Methods

Extensive agricultural regions can be effectively monitored using sensor nodes that transmit data wirelessly to a receiving gateway. WSNs can be employed across various agricultural applications, including orchard irrigation management, nutrient optimization, disease detection, irrigation planning, and climate monitoring [9]. Figure 1 illustrates a schematic diagram of the wireless communication setup used in orchards for monitoring soil water content levels and controlling irrigation.

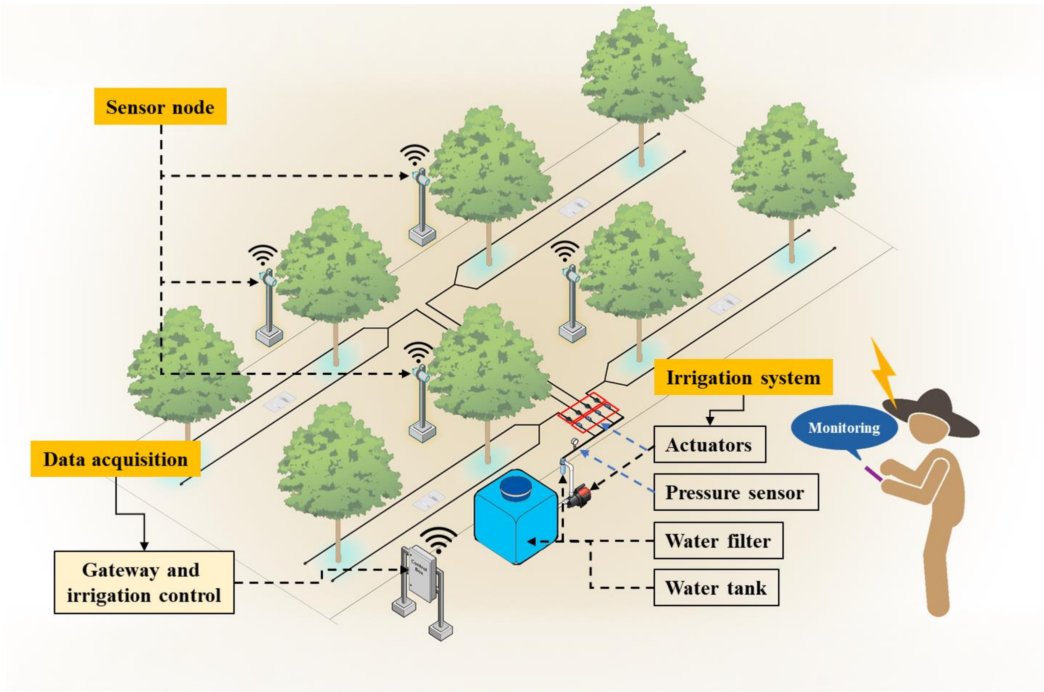

Figure 1. Schematic diagram of the system architecture of the LoRa-based irrigation considered in this study.

2.1. LoRa Transceiver Module and Sensor Node Fabrication

LoRa devices are subject to frequency restrictions imposed by different countries, which can potentially restrict the available options for LoRa modules [23]. In the Republic of Korea, the permissible frequency range for LoRa modules is between 920 and 923 MHz [23]. To conduct this experiment, a prototype sensor node was fabricated as an end node cable to transmit sensor data to a receiver gateway to monitor soil moisture levels from the orchard. Figure 2a illustrates the schematic diagram of the LoRa module interfacing with the MCU. A commercial microcontroller (model: Arduino Nano, Arduino, Ivrea, Italy) was used to interface with a transceiver module for processing sensor data, managing wireless communication between the sensor node and the receiver gateway, and setting all the parameters of the transceiver as shown in Figure 2b. To collect and transmit sensor data, a 9 V power supply was used to provide the necessary power for the system. A low-cost commercial LoRa transceiver module (model: RYLR896, Reyax Technology Co., Ltd., Taipei, Taiwan) was used as the wireless transmitter considering the permissible frequency range. The LoRa module used a Semtech SX1276 engine microchip to transmit the signals wirelessly. All settings of the LoRa module were set by the MCU using Attention Commands (AT) [24]. Table 1 shows the specifications of the LoRa module used in this study. To measure soil water content for irrigation control, a soil water content sensor (model TDR 310H, Acclima, Inc., Meridian, ID, USA) was integrated into the sensor node, as shown in Figure 2c.

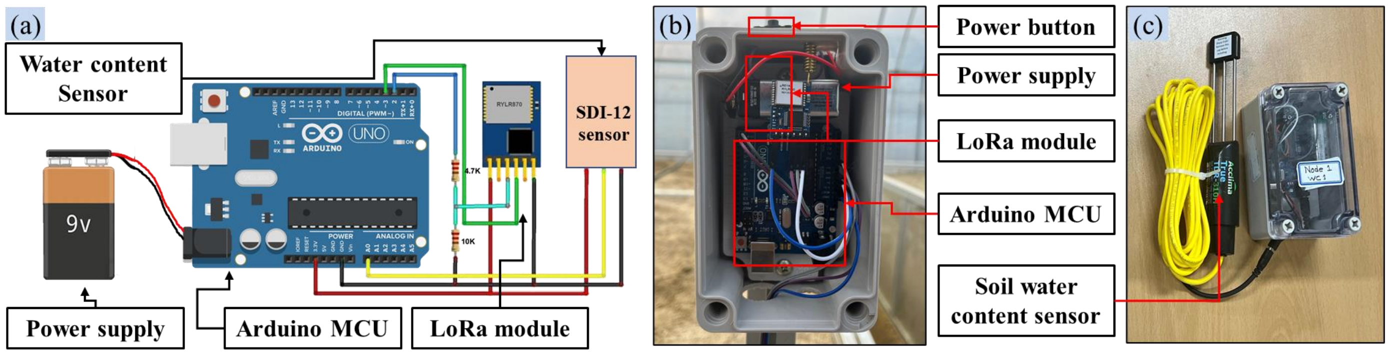

Figure 2. Sensor node fabrication: (**a**) schematic diagram of the LoRa module interface; (**b**) components of the sensor node; (**c**) soil water content sensor connection with the node.

Table 1. Specifications of the LoRa module used in this study.

Item	Specifications
Model	RYLR896
Frequency range	868/915 MHz
Frequency accuracy	±2 ppm
Transmission voltage	3.3 V
RF sensitivity	−148 dBm
Communication range	4–15 km
Transmit current	43 mA
Receive current	16.5 mA

LoRa is a physical layer technology within LPWANs, structured into four layers: end devices, gateways, network servers, and application servers, which employ a wireless modulation technique that provides an optimal balance between long-range communication, low power consumption, and secure data transmission [25–27]. However, this study focused solely on wireless data acquisition and the impact of orchard vegetation on the performance of LoRa-based sensor nodes, specifically examining the end device in this context. Figure 3 illustrates the basic architecture of a LoRa network.

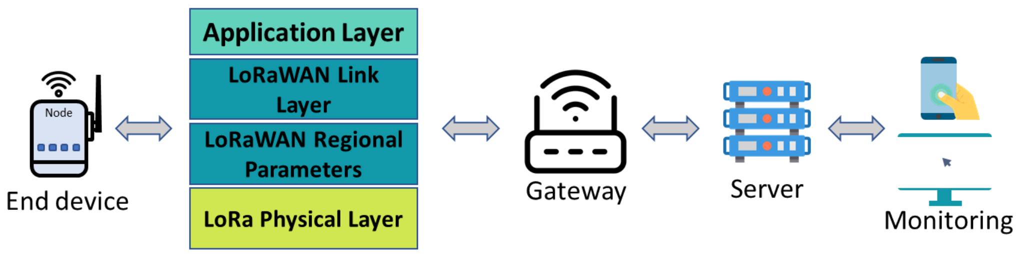

Figure 3. Architecture of a LoRa network layer (modified from [28]).

The configuration of LoRa can be adjusted by manipulating physical layer (PHY) settings, leading to variations in performance. The physical settings or parameters include the spreading factor (SF), bandwidth (BW), coding rate (CR), frequency (F), and antenna gain [20,29–31]. The SF in LoRa refers to the ratio between the number of data bits and chips, which are symbols used to transmit those bits. The SF can be calculated using Equation (1) [32] as follows:

$$SF = \log_2 n_{chirps} \quad (1)$$

where n_{chirp} is the number of chirps per symbol. A higher SF improves the signal-to-noise ratio (SNR), enhancing sensitivity and range. However, it also increases the packet airtime, which reduces data transmission rates. For the LoRa module used in this study, the SF values ranged from 7 to 12, each impacting the data rate accordingly. To conduct this study, three different SF values (8, 10, and 12) of the LoRa were considered, while other parameters were set to their default values. The SFs were selected to evaluate the LoRa's performance across a spectrum of configurations, balancing data rate and transmission range. SF8 represents higher data rates with a reduced range, while SF12 provides an extended range and greater resilience under challenging conditions, with SF10 balancing the two. These spreading factors were chosen to simulate practical configurations relevant to agricultural scenarios. While this study focused on SF8, SF10, and SF12, additional spreading factors such as SF7 or SF9 could offer further insights into the trade-offs between range and data rate. Table 2 summarizes all the parameters of the LoRa module used in this study.

Table 2. Parameters used to configure the LoRa module in this study.

Parameter	Value
Bandwidth	125 kHz
Spreading factor	8, 10, 12
Coding rate	1
Frequency	915 MHz
Antenna gain	1.2 dBi
Payload length	5 bytes

2.2. LoRa Metrics and Data Acquisition Procedures

The performance of the LoRa is commonly evaluated using metrics such as packet delivery ratio (PDR), received signal strength indicator (RSSI), and signal-to-noise ratio (SNR), as they are the most reliable indicators [33–37]. PDR is defined as the ratio of the number of packets successfully received to the total number of packets sent. PDR reflects wireless network reliability by measuring the ability to transmit desired data to the receiver at specified times with minimal delay and minimal packet loss [38]. It is often expressed as shown in Equation (2) [20,38]:

$$\mathrm{PDR} = \frac{\mathrm{D}}{\mathrm{T}} \tag{2}$$

where D is the number of packets successfully received, and T is the total number of packets sent.

The RSSI measures the power of the received radio signal and helps to assess the reliability of wireless communication. It provides insights into signal strength, contributing to a better understanding and improvement of LoRa networks. The RSSI can be calculated using Equation (3) [32] as follows:

$$\mathrm{RSSI} = -\left(10\mathrm{n}\log_{10}\mathrm{d} - \mathrm{A}\right) \tag{3}$$

where A represents the power received in dBm, d is the distance between the transmitter and receiver nodes (measured in meters), and n is the path loss of the environment exponent or loss parameter.

The SNR represents the relationship between the strength of the received signal and the noise floor, indicating the clarity or quality of the signal relative to background interference. A higher SNR generally implies a cleaner, more distinguishable signal, which is crucial for reliable data transmission. The SNR can be expressed in decibels (dB) and is calculated using the Equation (4) [39] as follows:

$$\mathrm{SNR} = 10\log_{10}\frac{P_{signal}}{P_{noise}} \quad (4)$$

where P_{signal} is the received power signal, and P_{noise} is the noise floor power.

The RSSI, SNR, and PDR were selected as primary metrics to evaluate the performance of the LoRa sensor node. The following metrics were chosen to provide a comprehensive assessment of network performance: signal strength was measured through the RSSI, signal clarity was assessed using the SNR, and data reliability was indicated by the PDR through packet success rates. A thorough evaluation of the sensor node effectiveness was achieved under non-vegetative and vegetative conditions in an orchard.

To establish wireless communication and collect all relevant LoRa metrics, a second LoRa transceiver with an Arduino MCU was connected to the existing irrigation system. This transceiver operated as a single-channel gateway, configured with the same network ID and parameters as the transmitter LoRa sensor node. All incoming data from the receiver node were stored as a comma-separated file (CSV) on the main MCU (model: Raspberry Pi 4B, Raspberry Pi Foundation, Cambridge, UK) of the irrigation system using a Python program. Figure 4 shows the interface and installation of the custom gateway within the data acquisition system.

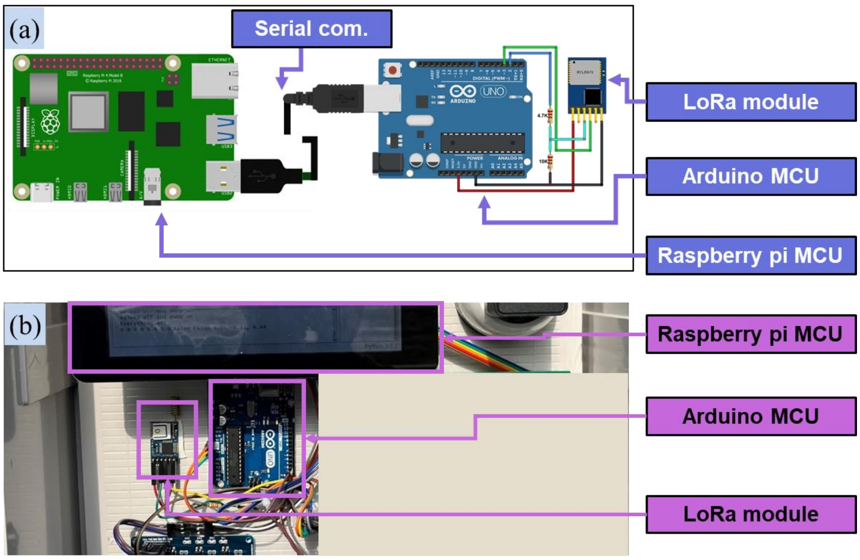

Figure 4. Data acquisition system: (**a**) schematic diagram of the LoRa module interface; (**b**) installation of the LoRa gateway receiver.

2.3. Experimental Procedure and Performance Evaluation

To achieve the proposed objectives, two experimental sites were chosen, one under non-vegetative conditions at Chungnam National University, Daejeon, Republic of Korea (36°22′7.8″ N, 127°21′15.3″ E), and the second in a peach orchard under real vegetative conditions at the Rural Development Administration, Jeonju, Republic of Korea (35°49′29.7″ N, 127°1′32.5″ E). At the time of data collection on 5 July 2023, around 3 PM, the weather conditions were warm and clear. In Daejeon, the temperature was approximately 25.8 °C, with 60% humidity, a light northwest breeze of 5 mph, and no precipitation under mostly sunny skies. Similarly, in Jeonju, the temperature was 25.0 °C, with 60% humidity, a light northwest breeze of 5 mph, and no precipitation under mostly sunny skies. These stable weather conditions ensured that no significant external environmental variables, such as rain or strong winds, influenced the data transmission during the experiments.

A comprehensive evaluation was conducted to assess the performance of a LoRa sensor node over various distances ranging from 20 to 120 m, with intervals of approximately 20 m, under two distinct testing conditions: a clear, obstacle-free open field and a peach orchard. The experimental site was a peach orchard of the Cheonhongdo Baekdo variety, aged four years, with tree heights ranging from 3.12 to 4.36 m. The orchard's soil type was classified as silty loam, and the trees were planted in a two-main-branch structure (2-bonjuji) pattern. Unlike forests, which often feature irregularly spaced trees, varying heights, and denser vegetation, orchards provide a more uniform layout with systematic spacing. Data transmission occurred at a consistent interval of 20 s, with a total of 20 signals transmitted for each designated point. The data transmission code was developed to initiate operation upon activation of the power button of the sensor nodes, allowing it to transmit only for a specified duration before closing the transmission. Figure 5a illustrates the topographical characteristics of the open field conditions observed during the experiment performed in the absence of vegetation, while Figure 5b shows the topographical features of the orchard, characterized by dense vegetation. The terrain at location (a) exhibits a flat topography with no vegetation, whereas location (b) features a more varied terrain characterized by a higher density of plants, primarily consisting of apple and peach trees. The positioning of the gateway and the locations from which transmissions were initiated are shown in Figure 5. Table 3 provides the estimated linear distances between the various endpoints and gateway locations; however, for the purposes of this experiment, these approximate distances were considered as multiples of 20 m.

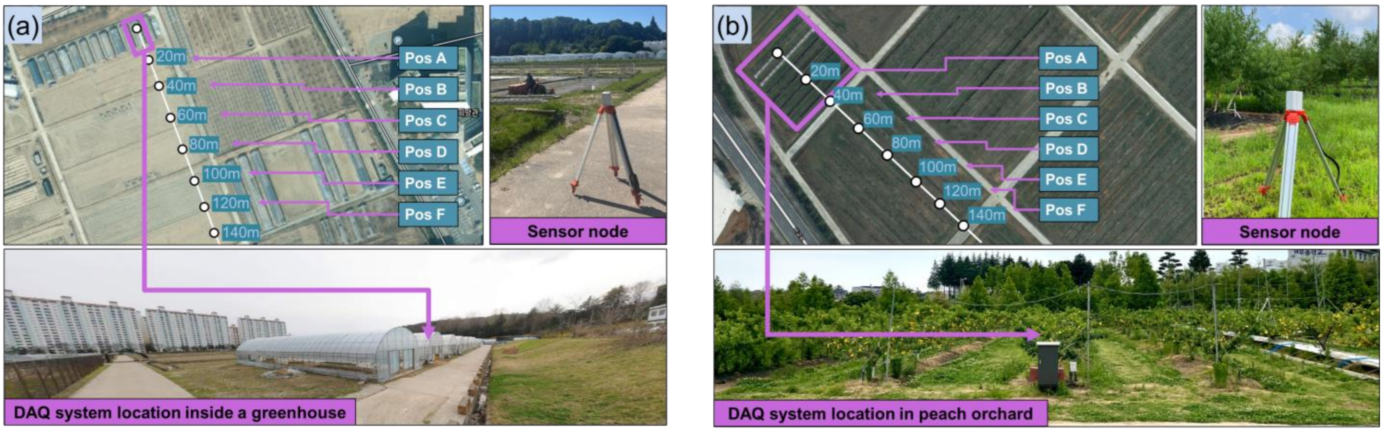

Figure 5. Data acquisition for performance evaluation: (**a**) test conducted without vegetation; (**b**) test conducted with vegetation.

Table 3. Estimated linear distances from the gateway to the sensor node during the tests.

Under Non-Vegetative Conditions		Under Vegetative Conditions	
Positions	**Distance (m)**	**Positions**	**Distance (m)**
Pos A	20	Pos A	20
Pos B	40	Pos B	40
Pos C	60	Pos C	60
Pos D	80	Pos D	80
Pos E	100	Pos E	100
Pos F	120	Pos F	120

Three SF values were set as SF8, SF10, and SF12, and the data were collected three times for each SF value at each position. All other parameters were set to default, including a transmission power of 20 dBm, a coding rate of 4/5, a bandwidth of 125 kHz, and a frequency of 915 MHz. The packet payload was set to 5 bytes, sufficient for soil moisture readings up to two decimal points. The PDR was calculated by dividing the number of packets successfully received by the gateway by the total number of packets sent upon arrival in the Python code. A PDR score of 1 represents a 100% success rate, indicating that all transmitted packets were successfully received, and a PDR value of 0 indicates a complete failure, where none of the transmitted packets reached the destination.

3. Results

3.1. Effects of SF on the PDR

After a transmission period exceeding six minutes, the PDR values were plotted in Figure 6 to assess the transmission performance. The PDR values for SF 8, 10, and 12 remained stable when the sensor node was tested under both non-vegetative and vegetative conditions at distances of 20, 40, 60, 80, 100, and 120 m. Variations in PDR values were observed when the sensor node transmitted signals in the orchard environment, likely due to the presence of vegetation. As shown in Figure 6a, across all SF values (SF8, SF10, and SF12), the gateway consistently received 100% of transmitted packets at all tested distances under non-vegetative conditions.

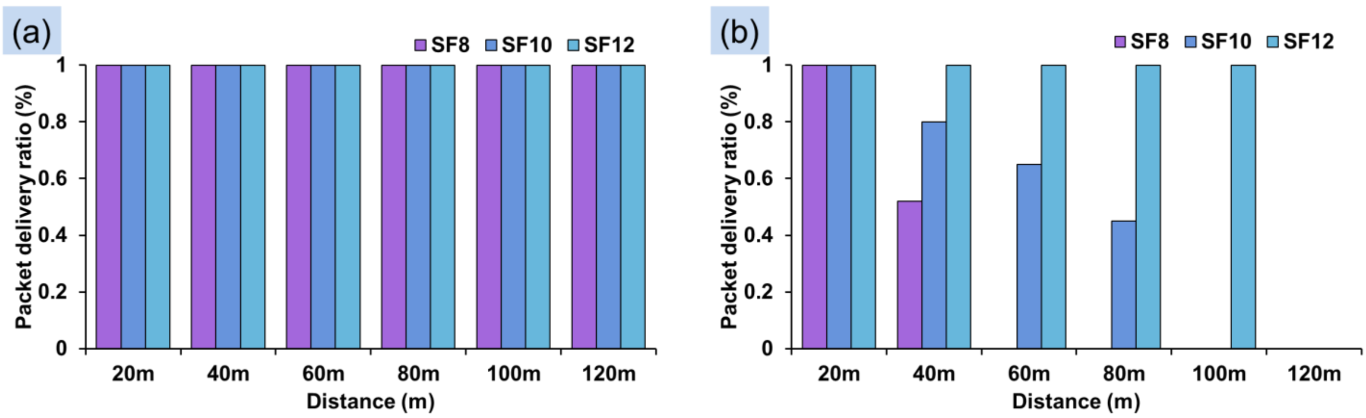

Figure 6. Effects of SF on the PDR: (**a**) test conducted under non-vegetative conditions; (**b**) test conducted under vegetative conditions.

In contrast, Figure 6b demonstrates that under vegetative conditions, the gateway consistently achieved a 100% packet reception rate with the SF12 configuration up to a maximum distance of 100 m, with the PDR dropping to 0 at 120 m. With SF10, the packet reception at 120 m was unsuccessful, though effective delivery rates were achieved at distances of 20, 60, and 80 m, with success rates of 100%, 80%, 65%, and 45%, respectively. For SF8, only positions A and B showed successful packet delivery rates of 100% and 52%, respectively. Although the specifications for the LoRa module indicate a transmission range of up to 15 km [40], field conditions demonstrated a significantly reduced PDR at much longer distances, with a notably low PDR observed at only 120 m with a maximum SF setting.

These data provide valuable insights for configuring LoRa-based systems to optimize reliability in orchards. Employing SF12 ensures stable communication in densely vegetated areas, albeit at the cost of increased power consumption. This trade-off underscores the importance of balancing battery life and transmission reliability when deploying sensors. The findings indicate that SF12 can consistently achieve reliable packet delivery up to 100 m in dense orchard environments, enabling effective monitoring of irrigation systems. However, the reduced PDR observed at 120 m under vegetative conditions underscores the necessity of deploying additional gateways to maintain reliable communication over longer distances. Strategically placing additional gateways ensures consistent packet delivery beyond 100 m, mitigating delays or inaccuracies in irrigation status reporting. This recommendation is particularly critical in orchards where extended coverage without compromising reliability is essential.

3.2. Effects of SF on the RSSI

Figure 7a displays the RSSI values recorded under non-vegetative conditions, while Figure 7b presents the RSSI values under vegetative conditions, highlighting the effects of different SF combinations in relation to distance and the presence of vegetation. During non-vegetative conditions (Figure 7a), the RSSI values exhibited a gradual decline with the increase in distance for all SF (SF8, SF10, and SF12). The maximum RSSI recorded was −50.6 dBm at a distance of 20 m for SF8, while the minimum observed was −103.56 dBm at a distance of 120 m for SF12.

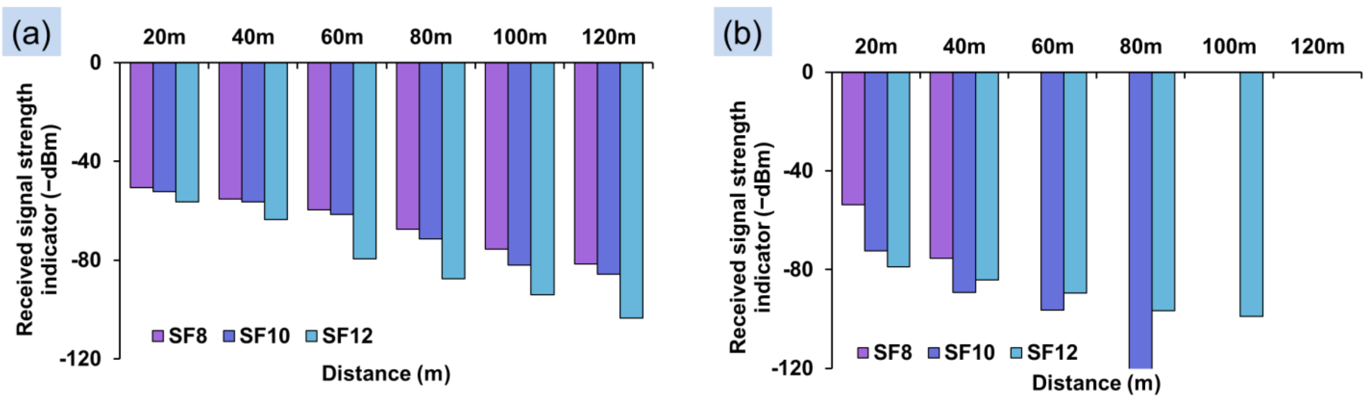

Figure 7. Effects of SF on the RSSI: (**a**) test conducted under non-vegetative conditions; (**b**) test conducted under vegetative conditions.

In contrast, the results presented in Figure 7b highlight the challenges posed under vegetative conditions, where the RSSI values showed significant degradation, reflecting the challenges posed by environmental obstructions. At distances of 20 and 40 m, the RSSI decreased approximately 40%, with SF8 dropping from −53.6 to −75.3 dBm. For SF12, however, the decrease between 20 m (−78.8 dBm) and 40 m (−84.2 dBm) was relatively minor. At distances of 60 and 80 m, the RSSI values were recorded at −89 and −96 dBm for SF10 and −85 and −90 dBm for SF12, respectively. At distances of 100 and 120 m, the RSSI values for SF8 and SF10 fell to 0, indicating a total signal loss, while RSSI values for SF12 remained detectable at 100 m (−98.98 dBm) but were absent at 120 m. The absence of RSSI values (0 dBm) suggests a potential signal loss or unsuccessful communication at these distances and specific SF, likely due to the influence of vegetation.

These findings suggest that higher SF settings should be prioritized in orchards with dense vegetation to ensure detectable signal levels, especially at critical distances. Additionally, the data emphasize the importance of strategically placing gateways closer to sensor nodes in heavily vegetated areas to mitigate signal attenuation. The pronounced RSSI degradation in vegetative conditions underscores the necessity of placing gateways within 40 m of nodes when using SF8. This approach is essential for maintaining detectable signal strength, preventing data loss, and ensuring efficient irrigation scheduling. While this recommendation is most applicable to scenarios prioritizing higher data rates with SF8, it underscores the broader need for tailored gateway placement strategies to address the unique challenges posed by dense vegetation.

3.3. Effects of SF on the SNR

Figure 8 illustrates the average SNR as a function of SF at distances from 20 to 120 m under both testing conditions. The experiments conducted at Pos 1 benefited from high-quality reception owing to their proximity to the gateway. All spreading factors not only influenced the SNR but also exhibited a gradual decrease with increasing distances under non-vegetative conditions, as illustrated in Figure 8a. The reduction in the SNR from 20 to 120 m was substantial, amounting to approximately 69.2% for SF8, 69.3% for SF10, and 70.3% for SF12. These findings highlight the pronounced impact of distance on signal quality, even in the absence of vegetation. The results also suggest that while all spreading factors experienced similar percentage reductions, SF12 maintained relatively higher absolute SNR values at longer distances, indicating better signal clarity compared to SF8 and SF10 under the same conditions.

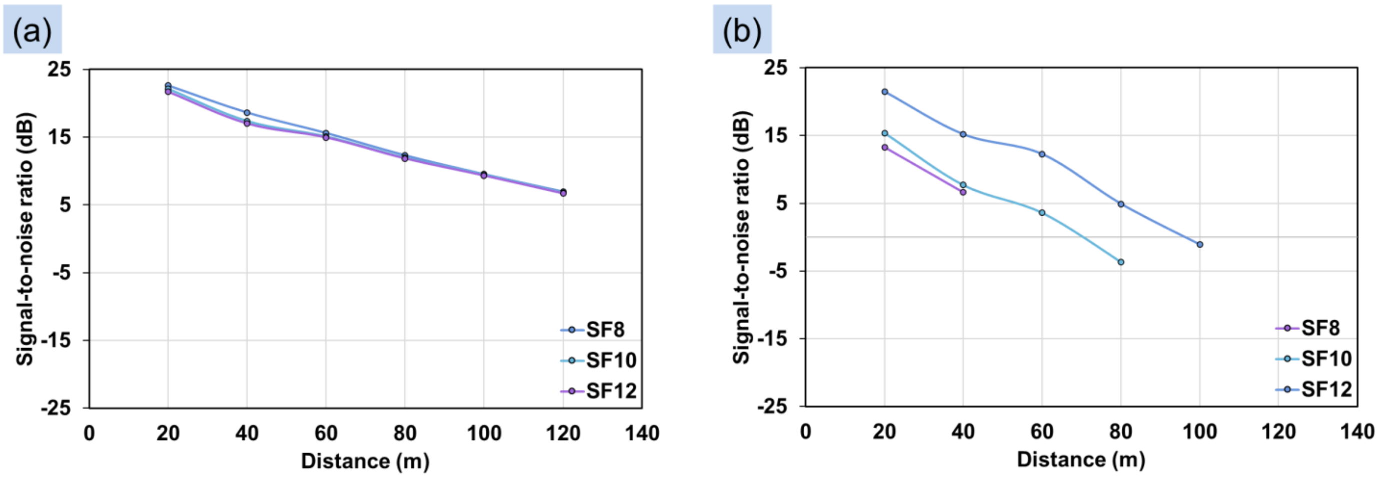

Figure 8. Effects of SF on the SNR: (**a**) test conducted under non-vegetative conditions; (**b**) test conducted under vegetative conditions.

Under vegetative conditions, the SNR exhibited a significant decrease compared to under non-vegetative conditions, emphasizing the impact of orchard trees on signal clarity shown in Figure 8b. The SNR values for SF8 became undetectable beyond a distance of 40 m, whereas they remained detectable at distances of 60 and 80 m for SF10 and SF12. At a distance of 100 m, the SNR value for SF12 was approximately −1.1 dB, while no SNR values were detected at a distance of 120 m for either SF8 or SF10 due to transmission failure. As the distance between the transmitter and receiver increased, the signal strength diminished due to path loss.

Maintaining positive SNR values is critical for ensuring successful transmission. Deploying sensors at SF12 enables communication over longer distances in orchards, supporting precise irrigation management. However, this requires careful power management to mitigate battery depletion. These findings provide valuable insights for optimizing sensor deployment and infrastructure upgrades, balancing costs with performance to enhance resource use in agriculture.

To provide a comprehensive comparison, Table 4 summarizes the PDR, RSSI, and SNR results under both vegetated and non-vegetated conditions across all tested distances and spreading factors.

Table 4. Comparative results of LoRa's performance under vegetated and non-vegetated conditions.

Distance (m)	Conditions	PDR			RSSI			SNR		
		SF8	SF10	SF12	SF8	SF10	SF12	SF8	SF10	SF12
20	Non-vegetated	1	1	1	−50.6	−52.16	−56.36	21.69	22.16	22.63
	Vegetated	1	1	1	−53.6	−72.3	−78.8	13.25	15.36	21.51
40	Non-vegetated	1	1	1	−55.3	−56.3	−63.54	17.01	17.39	18.65
	Vegetated	0.52	0.80	1	−75.3	−89.3	−84.2	6.65	7.69	15.21
60	Non-vegetated	1	1	1	−59.63	−61.45	−79.46	14.96	15.10	15.63
	Vegetated	MD	0.65	1	MD	−96.45	−89.46	MD	3.598	12.28
80	Non-vegetated	1	1	1	−67.51	−71.3	−87.63	11.85	11.95	12.34
	Vegetated	MD	0.45	1	MD	−120.3	−96.63	MD	−3.65	4.91
100	Non-vegetated	1	1	1	−75.64	−81.91	−93.98	9.33	9.45	9.55
	Vegetated	MD	MD	1	MD	MD	−98.98	MD	MD	−1.1
120	Non-vegetated	1	1	1	−81.56	−85.69	−103.56	6.69	6.75	6.98
	Vegetated	MD	MD	MD	MD	MD	MD	MD	MD	MD

MD indicates missing data.

4. Discussion

In this study, LoRa communication was tested under both non-vegetative and vegetative conditions for orchard irrigation management. Although this particular LoRa was designed for long-range communication, with a theoretical maximum coverage of 15 km [40], actual measurements in the orchard showed a much shorter range. The maximum effective range observed under vegetative conditions was 120 m at SF12. The results from non-vegetative test conditions were therefore presented for up to 120 m to align with the result range under vegetative conditions. A similar reduction in PDR performance was found in previous studies where the author of [20] reported a maximum PDR of only 21.66% within a 200 m range. Additionally, the authors of [41] presented theoretical findings, indicating a maximum transmission distance of 7 km in urban areas and 19 km in rural areas, as well as practical findings of 6.5 km in urban areas and 18.5 km in rural areas. The authors of [21] conducted experiments in urban, suburban, and forest environments using the 915 MHz frequency band, revealing that the presence of vegetation significantly affects communication performance, with LoRa SF12 achieving a maximum communication range of only 250 m in forested areas. The systematic planting pattern and uniform characteristics of peach orchards may result in less severe signal degradation compared to denser forest environments. The greater transmission distances observed in other studies may be attributed to the higher antenna gain values and specific field conditions encountered [17,41]. A lower antenna gain of 1.2 dBi resulted in shorter transmission distances, highlighting the influence of antenna specifications on signal range in this study.

To contextualize the findings, LoRa's performance was compared to ZigBee and Bluetooth, two commonly used technologies in agricultural applications. Table 5 provides a practical comparison of cost, range, power consumption, and suitability for orchard environments.

Table 5. Practical comparison between LoRa and other technologies.

Module	Approximate Cost Per	Theoretical Transmission Range	Practical Transmission Distance (Approximate)	Power Consumption	Data Rate	References
REYAX RYLR896 (used in this study)	USD 10–15	Up to 15 km	120 m in dense orchards	Low (battery life up to 10 years) 1.2 dBi	0.3–50 kbps	[40]
Semtech SX1276 LoRa shield	USD 20–25	Up to 15 km	200 m in tree farmland	Low 2 dBi	0.3–50 kbps	[20]
Semtech SX1276 MBED shield	USD 5–10	Up to 15 km	3 km in sub-urban areas	3 dBi	0.3–50 kbps	[22]
Microchip RN2483	USD 10–15	Up to 15 km	6.5 km in urban areas 18.5 km in rural areas	Low 5 dBi	0.3–50 kbps	[41]
XBee S2C	USD 19–49	Up to 1.6 km	40 m in indoor areas	2.1 dBi	20–250 kbps	[42]
Nordic nRF52840	USD 1–5	Up to 100 m	25 m in indoor areas	-	125 kbps–2 Mbps	[43]

The above analyses underscore the capabilities and limitations of LoRa technologies for agricultural applications, with a focus on orchard environments. The results indicate that LoRa outperforms ZigBee and Bluetooth in terms of range and suitability for orchard environments, making it the preferred technology for long-range agricultural applications. The LoRa utilized in this research demonstrated reliable performance in dense vegetation with a practical range of 120 m, making it a cost-effective and energy-efficient choice for small-to-medium-scale precision farming. However, the extended ranges achieved by other LoRa modules, such as the Microchip RN2483 (6.5 km in urban areas and 18.5 km in rural areas), highlight the critical role of antenna gain and design in improving coverage. Modules equipped with higher-gain antennas, such as the Microchip RN2483 with a 5 dBi antenna, outperform the used LoRa, which uses a 1.2 dBi antenna, in transmission distance. Future applications should consider higher-gain antennas and advanced modules to enhance coverage and reliability for large-scale agricultural deployments. Reduced sensor node density and enhanced connectivity can be achieved, especially in environments with dense vegetation.

This study highlights that while LoRa-based wireless sensor nodes demonstrate consistent packet delivery under non-vegetative conditions, the presence of vegetation significantly degrades transmission quality, resulting in substantially reduced PDR values, which can be further understood in the context of the RSSI. A communication drop was observed at RSSI levels below −135 dBm, as reported in [17]. In contrast to the findings in [44], this study further illustrates that the RSSI is less affected by the SF than the PDR. This result demonstrates that the presence of vegetation compromises the RSSI values in LoRa communication, highlighting that critical communication failures occur at distances beyond 100 m and that the SF has a lesser impact on the RSSI than on the PDR.

The results presented in Figure 8 revealed significant insights into the performance of the SNR under varying conditions and distances. The SNR values for SF12 remained detectable up to 100 m (−1.1 dB), while SF8 and SF10 experienced complete signal loss beyond 40 and 80 m, respectively. An SNR of −1.1 dB at 100 m for SF12 indicates poor signal quality, as values below 0 dB suggest that the signal strength is weaker than the noise level, potentially resulting in transmission failure [45]. This significant reduction in range is attributed to the challenge of the propagation conditions within the orchard environment. Despite using the more interference-resistant Chirp Spread Spectrum (CSS) modulation technique, LoRa remains sensitive to obstacles and reflective surfaces, which impact the performance of the signal transmission.

This study contributes to the growing body of research on LoRa communication by presenting a detailed experimental evaluation of performance in orchard environments under realistic conditions. Through systematic comparisons of vegetative and non-vegetative scenarios across varying distances and spreading factors, practical recommendations are offered for optimizing LoRa-based systems in agricultural applications. The emphasis on dense vegetation, a critical yet understudied factor in precision farming, establishes this work as a foundational contribution to the field. The findings address existing challenges in orchard management and provide a basis for future research into advanced configurations and complementary technologies, including NB-IoT and enhanced LoRaWAN protocols.

5. Conclusions

This study reveals the considerable impact of vegetation on LoRa communication performance in orchard environments, specifically for the wireless sensor networks used in irrigation management. Key metrics such as the PDR, RSSI, and SNR showed significant degradation in the presence of vegetation, with maximum transmission distances far below the theoretical range of LoRa. While SF12 proved resilient in maintaining packet delivery over 120 m under vegetative conditions, lower spreading factors were associated with higher transmission losses, underscoring the sensitivity of LoRa to environmental obstacles. Additionally, the RSSI values experienced up to a 40% reduction under vegetative conditions, indicating pronounced signal attenuation, while the SNR became undetectable for SF8 beyond 40 m.

These findings highlight the need for careful consideration of LoRa configurations and environmental factors in agricultural applications. The degradation in transmission quality has practical implications—unreliable communication could delay or misrepresent the irrigation status, leading to inefficient water use, higher operational costs, or even adverse effects on crop health. As a mitigation strategy, increasing the number of gateways to improve coverage, strategically positioning nodes within clearer line-of-sight paths, or utilizing higher-gain antennas could help offset these challenges. The optimal placement of gateways depends on the selected SF and its associated trade-offs. For SF12, additional gateways are necessary for distances beyond 100 m to maintain reliable communication. In contrast, SF8 requires gateways within 40 m to mitigate rapid RSSI degradation in densely vegetated areas. These tailored recommendations underscore the importance of adapting gateway placement to the specific requirements of each SF configuration. A potential cost–benefit relationship between the level of signal degradation and the required resource investments (e.g., additional gateways or denser node placement) is a valuable area for future exploration.

Future research could focus on enhancing transmission reliability in vegetative environments by testing different antenna types with the nodes, optimizing the number of nodes connected, using repeaters to extend coverage, exploring alternative LoRa settings such as spreading factors SF7 and SF9, or incorporating signal-processing techniques that could mitigate the adverse effects of vegetation on signal quality. Additionally, establishing a mathematical model to predict the relationship between transmission degradation and resource requirements could assist in designing cost-effective LoRa-based systems that balance coverage, reliability, and infrastructure costs in agriculture.

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References

1. Saqib, M.; Almohamad, T.A.; Mehmood, R.M. A Low-Cost Information Monitoring System for Smart Farming Applications. *Sensors* **2020**, *20*, 2367. [CrossRef] [PubMed]
2. Lee, H.C.; Banerjee, A.; Fang, Y.M.; Lee, B.J.; King, C.T. Design of a Multifunctional Wireless Sensor for Monitoring of Debris Flows. *IEEE Trans. Instrum. Meas.* **2010**, *59*, 2958–2967. [CrossRef]
3. Jiang, P.; Xia, H.B.; He, Z.Y.; Wang, Z.M. Design of a Water Environment Monitoring System Based on Wireless Sensor Networks. *Sensors* **2009**, *9*, 6411–6434. [CrossRef] [PubMed]
4. Alahi, M.E.E.; Xie, L.; Mukhopadhyay, S.; Burkitt, L. A Temperature Compensated Smart Nitrate-Sensor for Agricultural Industry. *IEEE Trans. Ind. Electron.* **2017**, *64*, 7333–7341. [CrossRef]
5. Alahi, M.E.E.; Xie, L.; Zia, A.I.; Mukhopadhyay, S.; Burkitt, L. Practical Nitrate Sensor Based on Electrochemical Impedance Measurement. In Proceedings of the 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings, Taipei, Taiwan, 23–26 May 2016; pp. 1–6.
6. Pu, F.L.; Wang, Z.L.; Du, C.; Zhang, W.C.; Chen, N.C. Semantic Integration of Wireless Sensor Networks Into Open Geospatial Consortium Sensor Observation Service to Access and Share Environmental Monitoring Systems. *IET Softw.* **2016**, *10*, 45–53. [CrossRef]
7. Lazarescu, M.T. Design of a WSN Platform for Long-Term Environmental Monitoring for IoT Applications. *IEEE J. Emerg. Sel. Top. Circuits Syst.* **2013**, *3*, 45–54. [CrossRef]
8. Lloret, J.; Sendra, S.; Garcia, L.; Jimenez, J.M. A Wireless Sensor Network Deployment for Soil Moisture Monitoring in Precision Agriculture. *Sensors* **2021**, *21*, 7243. [CrossRef] [PubMed]
9. Srbinovska, M.; Gavrovski, C.; Dimcev, V.; Krkoleva, A.; Borozan, V. Environmental Parameters Monitoring in Precision Agriculture Using Wireless Sensor Networks. *J. Clean. Prod.* **2015**, *88*, 297–307. [CrossRef]
10. Keshtgari, M.; Deljoo, A. A Wireless Sensor Network Solution for Precision Agriculture Based on Zigbee Technology. *Wirel. Sens. Netw.* **2011**, *4*, 25–30. [CrossRef]
11. Mackensen, E.; Lai, M.; Wendt, T.M. Bluetooth Low Energy (BLE) Based Wireless Sensors. In Proceedings of the 2012 IEEE Sensors Proceedings, Taipei, Taiwan, 38–31 October 2012; pp. 1854–1857.
12. Aliev, K.; Rugiano, F.; Pasero, E. Smartphone and Bluetooth Smart Sensor Usage in IoT Applications. *Sens. Transducers* **2016**, *201*, 27–34.
13. Ballerini, M.; Polonelli, T.; Brunelli, D.; Magno, M.; Benini, L. NB-IoT Versus LoRaWAN: An Experimental Evaluation for Industrial Applications. *IEEE Trans. Ind. Inform.* **2020**, *16*, 7802–7811. [CrossRef]
14. Santoshkumar; Udaykumar, R.Y. Development of WSN System for Precision Agriculture. In Proceedings of the 2015 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS), Coimbatore, India, 19–20 March 2015.
15. Fraga-Lamas, P.; Celaya-Echarri, M.; Lopez-Iturri, P.; Castedo, L.; Azpilicueta, L.; Aguirre, E.; Suárez-Albela, M.; Falcone, F.; Fernández-Caramés, T.M. Design and Experimental Validation of a LoRaWAN Fog Computing Based Architecture for IoT Enabled Smart Campus Applications. *Sensors* **2019**, *19*, 3287. [CrossRef]
16. Ali, Z.; Henna, S.; Akhunzada, A.; Raza, M.; Kim, S.W. Performance Evaluation of LoRaWAN for Green Internet of Things. *IEEE Access* **2019**, *7*, 164102–164112. [CrossRef]
17. Ojo, M.O.; Adami, D.; Giordano, S. Experimental Evaluation of a LoRa Wildlife Monitoring Network in a Forest Vegetation Area. *Future Internet* **2021**, *13*, 115. [CrossRef]
18. Froiz-Míguez, I.; Lopez-Iturri, P.; Fraga-Lamas, P.; Celaya-Echarri, M.; Blanco-Novoa, O.; Azpilicueta, L.; Falcone, F.; Fernández-Caramés, T.M. Design, Implementation, and Empirical Validation of an IoT Smart Irrigation System for Fog Computing Applications Based on LoRa and LoRaWAN Sensor Nodes. *Sensors* **2020**, *20*, 6865. [CrossRef]
19. Meng, Y.S.; Lee, Y.H.; Ng, B.C. Study of Propagation Loss Prediction in Forest Environment. *Prog. Electromagn. Res. B* **2009**, *17*, 117–133. [CrossRef]
20. Yim, D.; Chung, J.; Cho, Y.; Song, H.; Jin, D.; Kim, S.; Ko, S.; Smith, A.; Riegsecker, A. An Experimental LoRa Performance Evaluation in Tree Farm. In Proceedings of the 2018 IEEE Sensors Applications Symposium (SAS), Seoul, Republic of Korea, 12–14 March 2018; pp. 1–6.
21. Ferreira, A.E.; Ortiz, F.M.; Costa, L.H.M.K.; Foubert, B.; Amadou, I.; Mitton, N. A Study of the LoRa Signal Propagation in Forest, Urban, and Suburban Environments. *Ann. Telecommun.* **2020**, *75*, 333–351. [CrossRef]

22. Augustin, A.; Yi, J.Z.; Clausen, T.; Townsley, W.M. A Study of LoRa: Long Range & Low Power Networks for the Internet of Things. *Sensors* **2016**, *16*, 1466. [CrossRef] [PubMed]
23. Network, T.T. Regional Limitations of RF Use in LoRaWAN. Available online: https://www.thethingsnetwork.org/docs/lorawan/regional-limitations-of-rf-use/ (accessed on 30 September 2024).
24. LTD, Reyax Technology Co. LoRa AT Command Guide. Available online: https://reyax.com/upload/products_download/download_file/LoRa-AT-Command-RYLR40x_RYLR89x_EN-8.pdf (accessed on 10 September 2024).
25. Jia, Y. LoRa-based WSNs Construction and Low-power Data Collection Strategy for Wetland Environmental Monitoring. *Wirel. Pers. Commun.* **2020**, *114*, 1533–1555. [CrossRef]
26. Sendra, S.; Parra, L.; Jimenez, J.M.; Garcia, L.; Lloret, J. LoRa-based Network for Water Quality Monitoring in Coastal Areas. *Mob. Netw. Appl.* **2023**, *28*, 65–81. [CrossRef]
27. Petäjäjärvi, J.; Mikhaylov, K.; Pettissalo, M.; Janhunen, J.; Iinatti, J. Performance of a Low-power Wide-area Network Based on LoRa Technology: Doppler Robustness, Scalability, and Coverage. *Int. J. Distrib. Sens. Netw.* **2017**, *13*, 1550147717699412. [CrossRef]
28. Lima, W.G.; Lopes, A.V.; Cardoso, C.M.; Araújo, J.P.; Neto, M.C.; Tostes, M.E.; Nascimento, A.A.; Rodriguez, M.; Barros, F.J. LoRa Technology Propagation Models for IoT Network Planning in the Amazon Regions. *Sensors* **2024**, *24*, 1621. [CrossRef] [PubMed]
29. Berto, R.; Napoletano, P.; Savi, M. A LoRa-based Mesh Network for Peer-to-peer Long-range Communication. *Sensors* **2021**, *21*, 4314. [CrossRef] [PubMed]
30. Goldoni, E.; Prando, L.; Vizziello, A.; Savazzi, P.; Gamba, P. Experimental Data Set Analysis of RSSI-based Indoor and Outdoor Localization in LoRa Networks. *Internet Technol. Lett.* **2019**, *2*, 75. [CrossRef]
31. Shilpa, B.; Gupta, H.P.; Jha, R.K.; Hashmi, S.S. LoRa Interference Issues and Solution Approaches in Dense IoT Networks: A Review. *Telecommun. Syst.* **2024**, *87*, 517–539. [CrossRef]
32. Udomchaipitak, T.; Boonnam, N.; Puttinaovarat, S. An Experimental Study of RSSI for LoRa Technology in Different Bandwidths. In Proceedings of the 2022 37th International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC), Phuket, Thailand, 5–8 July 2022; pp. 728–731.
33. Myagmardulam, B.; Miura, R.; Ono, F.; Kagawa, T.; Shan, L.; Nakayama, T.; Kojima, F.; Choijil, B. Performance Evaluation of LoRa 920 MHz Frequency Band in a Hilly Forested Area. *Electronics* **2021**, *10*, 502. [CrossRef]
34. Moradbeikie, A.; Zare, M.; Keshavarz, A.; Lopes, S.I. RSSI-based LoRaWAN Dataset Collected in a Dynamic and Harsh Industrial Environment with High Humidity. *Data Brief.* **2024**, *53*, 110120. [CrossRef]
35. Budi, B.; Machdi, A.R. Distance Testing on Point to Point Communication with Lora Based on RSSI and Log Normal Shadowing Model. *J. Energy Electr. Eng.* **2024**, *5*, 89–93.
36. Khan, M.A.A.; Ma, H.; Aamir, S.M.; Baris, C.A. Experimental Comparison of SNR and RSSI for LoRa-ESL Based on Machine Clustering and Arithmetic Distribution. In Proceedings of the 10th International Symposium on Computational Intelligence and Industrial Applications (ISCIIA2022), Beijing, China, 23–25 September 2022.
37. Liang, R.B.; Zhao, L.; Wang, P. Performance Evaluations of LoRa Wireless Communication in Building Environments. *Sensors* **2020**, *20*, 3828. [CrossRef] [PubMed]
38. Jang, W.-S.; Healy, W.M. Wireless Sensor Network Performance Metrics for Building Applications. *Energy Build.* **2010**, *42*, 862–868. [CrossRef]
39. Documentation, L. SNR. Available online: https://lora.readthedocs.io/en/latest/#snr (accessed on 30 September 2024).
40. LTD, Reyax Technology Co. Rylr896. Available online: https://reyax.com/products/rylr896/ (accessed on 10 September 2024).
41. Sanchez-Iborra, R.; Sanchez-Gomez, J.; Ballesta-Viñas, J.; Cano, M.D.; Skarmeta, A.F. Performance Evaluation of LoRa Considering Scenario Conditions. *Sensors* **2018**, *18*, 772. [CrossRef]
42. Haque, K.F.; Abdelgawad, A.; Yelamarthi, K. Comprehensive Performance Analysis of Zigbee Communication: An Experimental Approach with XBee S2C Module. *Sensors* **2022**, *22*, 3245. [CrossRef] [PubMed]
43. Pancham, J.; Millham, R.; Fong, S.J. Analysis of Bluetooth Low Energy Detection Range Improvements for Indoor Environments. *Comput. Sci.* **2018**, *10862*, 598–609.
44. Luomala, J.; Hakala, I. Effects of Temperature and Humidity on Radio Signal Strength in Outdoor Wireless Sensor Networks. *Acsis-Ann. Comput. Sci.* **2015**, *5*, 1247–1255.
45. TechTarget. Signal-to-Noise Ratio (S/N or SNR). Available online: https://www.techtarget.com/searchnetworking/definition/signal-to-noise-ratio (accessed on 15 September 2024).