Experimental Evaluation of LoRa RSSI Performance in Educational IoT Deployments

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Abstract. In this work LoRa RSSI performance under five critical parameters pertinent to educational IoT settings: distance variation, physical barriers, wireless interference, elevation, and multinode setups is presented. The results suggest that RSSI exhibits a logarithmic decay with distance, with a substantial decline beyond 100 m. The intensity of the signal is proportional to the density of the material with physical obstructions, with composite panels resulting in the highest attenuation. RSSI remains stable in spread-spectrum environments but appears to have moderate interference from Wi-Fi, Bluetooth, and additional LoRa transmissions, illustrating LoRa's resilience. Multi-node transmission has a minimal effect on RSSI, while elevation offers minimal enhancement. These results underscore the resilience of LoRa and offer valuable insights for the optimization of IoT deployments.

Keywords: LoRa · RSSI · wireless communication · network performance · environmental impact · IoT environmental

1 Introduction

The Internet of Things (IoT) has emerged as an essential foundation of technological advancement, its development through a multitude of sectors, including healthcare, agriculture, smart urban environments, and education. Within this technological framework, LoRa (Long Range) technology is particularly valued for its capacity to facilitate long-range communication while utilizing minimal power, rendering it exceptionally appropriate for environments characterized by

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hard constraints [17,22,26]. A variety of measurements can assess the functionality of a LoRa network, and RSSI (Received Signal Strength Indicator) is notably significant for its practical implications. It has a direct impact on the reliability of the connection, the distance the signal can cover, and the overall efficiency of the network [15,25].

Some research has already explored how LoRa RSSI performs in industrial and farming environments, especially under tough conditions like high humidity [11,16]. But when it comes to educational settings, there's still a noticeable gap. These places aren't simple to work with—they often involve tricky building layouts, lots of signal interference, and the need to keep wireless communication reliable over long distances, which makes them a unique challenge for IoT deployment. Current research predominantly emphasizes predictive modeling approaches, including neural networks, for estimating LoRa performance, rather than conducting thorough experimental assessments. Nevertheless, theoretical predictions alone inadequately address the complexities associated with real-world deployments, especially in the context of smart campus initiatives.

The present research empirically examines the behavior of LoRa RSSI in five key scenarios relevant to educational IoT networks: distance variations, physical barriers, wireless interference, elevation differences, and multi-node transmissions. This study presents a reproducible experimental framework that focuses solely on the empirical acquisition of RSSI data across diverse environmental and network contexts, in contrast to previous research that emphasizes performance estimation via machine learning methods. In this work, we draw from both theoretical foundations and practical fieldwork to better understand and improve the implementation of LoRa networks within educational environments. Rather than relying solely on simulations or models, our approach includes real-world testing and observation. The sections that follow describe in detail the methodology we used, how measurements were taken, and the analytical techniques applied to assess performance across different use cases.

2 Related Work

Multiple studies on LoRa networks have delved into core performance metrics, with a particular emphasis on RSSI characteristics, data transmission reliability, and system optimization across diverse operational environments, including industrial, agricultural, and urban contexts. One example is the study by [26], where machine learning was applied to improve RSSI prediction accuracy in industrial contexts. They found that working with real-world data actually led to better performance. Even so, many of these studies don't take into account the unique hurdles that schools and universities face. The mix of complicated building layouts, interference from other networks, and the need for reliable long-distance communication makes deploying IoT solutions in these settings far from straightforward. In a similar way, [2] examined propagation models in campus environments; although their focus remained mostly on outdoor spaces, they included important considerations such as indoor signal variability and multiple classroom designs. In [14], LoRa networks in subway systems revealed the

structural complexity and how it can lead to signal degradation, interference, and packet loss challenges that, don't fully reflect the realities of IoT used in educational buildings.

Additionally, in [1], Effective Signal Power (ESP) was suggested as a better option than RSSI to make networks more reliable in places with many changes, which could help educational IoT networks but hasn't been widely studied in this area. Other research efforts have focused on optimizing LoRa networks for high-density deployments, such as the work of [29], who analyzed the impact of transmission rates and large data packets on LoRa efficiency, emphasizing the need for optimized communication in applications like IoT enabled classrooms. In [4], the authors looked at how the height of transmission affects network performance, but their results are mostly relevant to suburban areas instead of indoor classrooms, where materials can weaken signals and there are other wireless networks nearby.

Most studies rely on predictive modeling or generalized propagation assessments without capturing the real-world deployment challenges in smart campuses. This study addresses these gaps by conducting a systematic experimental evaluation of LoRa RSSI under five key conditions: distance variation, physical obstructions, wireless interference, elevation, and multi-node transmissions.

3 Methodology

3.1 Experimental Setup

The study was carried out in the laboratory of the Instituto Tecnológico de Matamoros (ITM), this campus spreads over 22 ha and includes open fields, structures, and vegetated areas. This platform offered a controlled yet realistic setting for assessing IoT communication performance in various propagation conditions.

The testbed is comprising of six E220-900T22D LoRa modules from Ebyte, and was set up with one module assigned as the receiver and five as transmitters. The modules operate in the 915 MHz ISM band, and have a fixed transmission power of 22 dBm, a packet transmission period of 3 s, and a payload size of 32 bytes.

The spreading factor was analized, the bandwidth was setup for an adequate assessing performance across five experimental conditions: distance variation, obstacle interference, external radio interference, elevation impact, and multinode communication. RSSI value retrieval from the LoRa modules was done using the Ebyte E220 library and configuration parameters supplied by Mischianti's online documentation, hence guaranteeing consistency in RSSI readings throughout all tests. The experimental setups were designed to explore how environmental conditions and network-related variables impact the reliability and performance of LoRa communication in educational settings.

Each LoRa module was connected to the ESP-WROOM-32 microcontroller, which comes equipped with a dual-core processor running at 240 MHz and has 520 KB of SRAM. Including a UART connection, for packet transmission, and

performed local data logging. Each configuration included a DS3231 RTC module linked to the ESP32. The module checked that the timestamps on sent and received packets were exactly the same by using correct Unix timestamps. To keep timing differences between devices to a minimum, some synchronization timestamps were sent out by a different reference node before each experiment.

The environmental parameters, including temperature, humidity, and potential interference sources, where recorded at the beginning of each experiment to reach their influence on signal performance. The receiver node was powered by a portable supply battery o make easy the measurements of the signal in various locations on campus to simulate different propagation conditions, including open fields, structural obstructions, and interference areas [15,17,25].

The Node-Red system was used for manage real-time data, and the MySQL Workbench was used for efficient database management. We kept track of several details during each test—like the experiment and node IDs, the exact timestamp, and the RSSI. Having that information on hand made it easier to follow what happened in each transmission and helped us make sense of the results later on. Figure 1 includes photos of both the transmitter and receiver modules used, plus some notes on how they were set up.

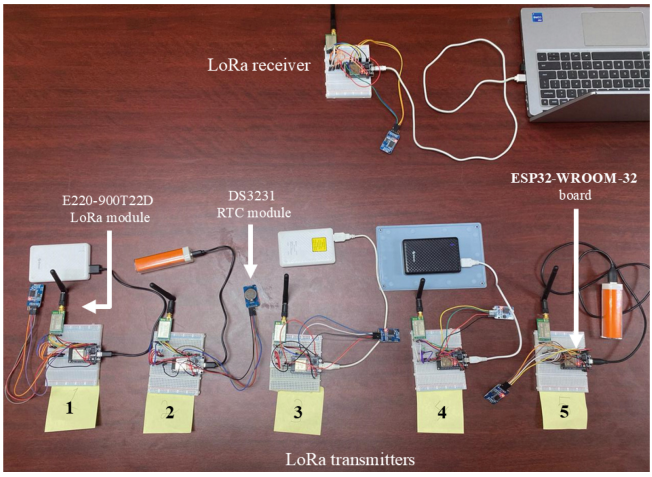

Fig. 1. Hardware components used in the experimental setup.

3.2 Experimental Scenarios

Each experiment was designed to analyze a specific factor of LoRa RSSI performance, ensuring controlled conditions to minimize external variables that affect the measurements.

EXP-01: Distance Variation in Line of Sight. This experiment evaluated the effect of distance on RSSI in an outdoor structured environment. The receiver was positioned in the main outdoor corridor of the ITM, while the transmitters were sequentially placed along the corridor at distances of 10 m, 50 m, and 100 m from the receiver to evaluate the impact of increasing separation on signal strength.

The receiver and transmitter nodes were placed on benches with a height of 70 cm to maintain a consistent elevation throughout the experiment, minimizing variations due to reflections and obstructions of the ground.

Data collection was made between 12:00 PM and 4:00 PM under environmental conditions of 28 °C and 97% humidity. During the experiment, the students was moving in the corridor, occasionally obstructing the transmission path, and it could affect the signal propagation due to human absorption and reflection effects.

Figure 2 provides a visual representation of the experimental setup, showing the placement of the receiver and transmitter devices at the specified distances.

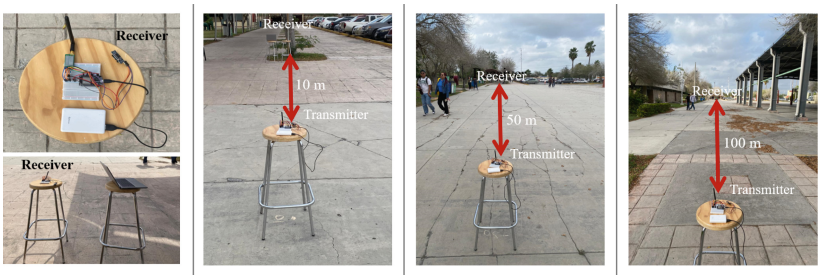

Fig. 2. Experimental setup for RSSI distance variation in outdoor corridor.

EXP-02: Obstructed Environments (Concrete, Glass/Metal, and Composite Material Panel). This experiment evaluated how RSSI is affected by different physical barriers in an indoor structured environment. The test consisted of four distinct scenarios:

1. Line-of-Sight (LoS) reference experiment. The transmitter and receiver were positioned 10 m apart in an unobstructed environment to establish a baseline measurement.
2. Concrete wall experiment. A 30 cm thick concrete wall was placed between the transmitter and receiver, which were positioned 5 m apart on opposite sides of the barrier, to assess signal attenuation through dense structural material.
3. Glass/Metal door experiment. The signal was transmitted through a double-leaf aluminum frame with large transparent glass panels, with the door remaining closed to evaluate its impact on RSSI. The transmitter and receiver were again placed 5 m apart on opposite sides.

4. Composite material panel experiment. A non-load-bearing partition made of an aluminum frame, polyurethane-based sponge panel, and fabric upholstery (10 cm thick) was used to assess attenuation caused by common office and classroom partition materials, with the devices positioned 5 m apart.

These four experimental conditions allowed for a comparative analysis of how different materials impact LoRa signal propagation, with the LoS scenario serving as a reference for evaluating attenuation levels in obstructed environments.

To ensure consistent elevation over all the experiments, the transmitter and receiver were placed on tables of different heights depending on the test. For tests 1, 2, and 3 (LoS reference, concrete wall, and glass/metal door tests), the devices were located on tables measuring 75.5 cm in height. These tests were conducted on the first day, with data collection taking place between 2:00 PM and 5:30 PM, under indoor environmental conditions of 8 °C and 94% humidity.

For experiment 4 (composite material panel), the transmitter and receiver were placed on a table measuring 75.8 cm in height to match the test conditions. This experiment was carried out on the second day, with measurements recorded between 5:30 PM and 6:30 PM, under an ambient temperature of 22 °C and 68% humidity.

Figure 3 illustrates the positioning of the transmitter and receiver for the four tested scenarios.

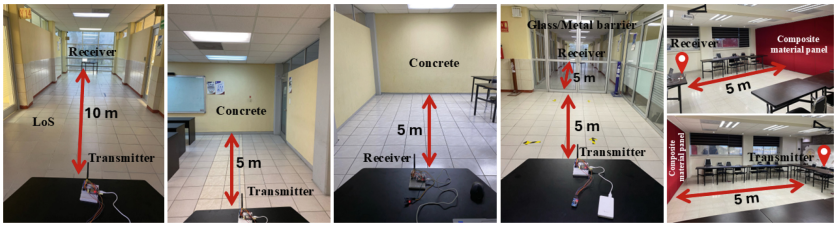

Fig. 3. Experimental setup for RSSI analysis with concrete, glass/metal, and composite panel obstructions.

EXP-03: Multi-source Wireless Interference (Wi-Fi, Bluetooth, and LoRa). This experiment evaluated LoRa performance in the presence of simultaneous wireless technologies, including Wi-Fi, Bluetooth, and an additional LoRa network. The tests were conducted in a library setting under two experimental conditions:

1. Baseline scenario: A single LoRa transmitter and receiver operated without interference from other wireless devices.

2. High-interference scenario: Forty students actively used laptops and smartphones connected to Wi-Fi, streamed music via Bluetooth, and an additional network of four LoRa transmitters operated simultaneously.

The experiments were carried out between 3:00 PM and 5:00 PM under indoor environmental conditions of 31 °C and 61% humidity. The LoRa transmitter and receiver were placed on tables measuring 77 cm in height to ensure consistent elevation across tests.

To ensure interference conditions, the devices were activated before RSSI measurements. Wi-Fi traffic was generated through instant messaging platforms, and Bluetooth interference was introduced by streaming music. The additional LoRa nodes transmitted at fixed intervals, synchronized with the primary LoRa transmitter, ensuring simultaneous operation during the RSSI measurement period.

Figure 4 illustrates the experimental setup for both scenarios, depicting the placement of the LoRa transmitter and receiver within the library environment and students using Wi-Fi and Bluetooth devices.

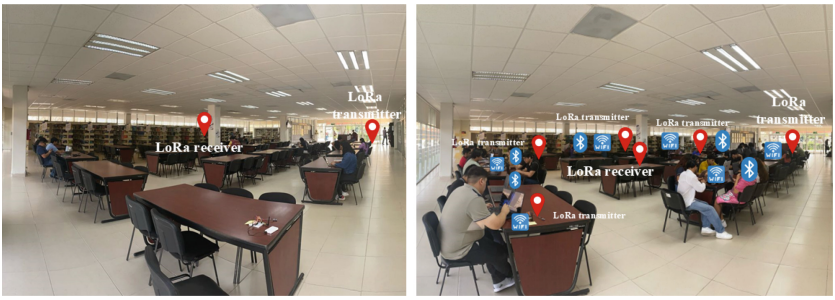

Fig. 4. Experimental setup for LoRa performance evaluation in a library environment under Wi-Fi, Bluetooth, and LoRa interference.

EXP-04: Elevation Variation and Multi-level Transmission. This experiment analyzed RSSI behavior at different heights in a multi-story educational environment. The receiver was positioned on the ground floor, placed directly on the floor in one of its corners. The transmitter was first placed on the second level at a height of 3.36 m and subsequently relocated to the third level at a height of 6.10 m.

Data collection was done between 4:00 PM and 6:00 PM under environmental conditions of 26 °C and 74% humidity. These measurements allowed for an assessment of how elevation differences impact signal strength, particularly in an outdoor multi-level setting where structural elements and height variations may influence LoRa signal propagation.

To ensure measurement consistency, the transmitter and receiver remained in a fixed orientation throughout the experiment. RSSI readings were recorded at predefined intervals of 3 s, maintaining uniform data collection.

Figure 5 represents the transmitter positions at different elevations, along with the receiver's position on the ground floor. Illustrates the vertical transmission path, offering insight into potential signal attenuation and structural interference effects.



Fig. 5. Vertical transmitter-receiver placement for multi-level RSSI evaluation.

EXP-05: LoRa RSSI Performance in a Multi-node Network Simulation. This experiment evaluated LoRa RSSI performance in a simulated multi-node network at Technological and Business Innovation Node (NITE). Two test conditions were analyzed to assess the impact of multiple concurrent transmitters on signal strength and network behavior:

1. Baseline scenario: A single LoRa transmitter and receiver operated in isolation, serving as a control condition.
2. Multi-node scenario: Four additional LoRa transmitters operated simultaneously, introducing potential interference and testing network scalability.

The experiments were made between 1:30 PM and 3:30 PM under indoor environmental conditions of 24 °C and 72% humidity. All LoRa devices were placed on tables measuring 75.5 cm in height to ensure consistent positioning across tests.

To prevent uncontrolled packet collisions, the LoRa transmitters were incorporated into the network in a staggered manner, ensuring that multiple nodes did not transmit simultaneously. All devices were operated with the default spread factor and bandwidth settings provided by the LoRa modules used in the experiments, ensuring consistency in RSSI comparisons.

The experimental setups, objectives, configurations, and execution times are summarized in Table 1.

Table 1. Summary of the proposed experimental scenarios

Id	Objective	Details of the Configuration	Execution Time
EXP-01	Analyze RSSI based on varying distances.	**Distance Variation (Line of Sight)**. The receiver was placed in an open corridor. Transmitters were positioned at 10 m, 50 m, and 100 m distances in a clear line-of-sight (LoS) environment. Three distance conditions were tested.	135 min (3 tests × 45 min)
EXP-02	Evaluate RSSI degradation caused by obstacles.	**Obstructed Environments (Concrete, Glass/Metal, and Composite Material Panel)**. The receiver was placed indoors. Transmitters were placed 5 m away behind three types of barriers: concrete wall (30 cm thick), glass/metal door, and composite material panel (aluminum frame, polyurethane sponge, and fabric upholstery). A 10 m LoS reference test was also conducted.	180 min (4 tests × 45 min)
EXP-03	Measure RSSI under active interference.	**Multi-Source Wireless Interference (Wi-Fi, Bluetooth, LoRa)**. The receiver was placed in a library. Two scenarios were tested: (1) baseline (no interference), and (2) high interference with 40 students using Wi-Fi and Bluetooth devices, plus an additional LoRa network with four transmitters.	90 min (2 tests × 45 min)
EXP-04	Evaluate RSSI at different node heights.	**Elevation Variation and Multi-Level Transmission**. The receiver was on the ground floor. The transmitter was placed at 3.36 m (second level) and 6.10 m (third level) to evaluate the impact of height on signal propagation.	90 min (2 tests × 45 min)
EXP-05	Evaluate RSSI in a multi-node network.	**LoRa RSSI Performance in a Multi-Node Network Simulation**. Tests conducted at NITE with two conditions: (1) a single transmitter and receiver, and (2) a multi-node network with four additional transmitters operating simultaneously.	90 min (2 tests × 45 min)

4 Experimental Results

LoRa performance was tested under five conditions to analyze their effect on RSSI, offering practical insights for optimizing IoT use in education.

4.1 Results for EXP-01: Distance Variation in Line of Sight

The first experiment evaluated how RSSI degrades as the distance between the transmitter and receiver increases in a line-of-sight (LoS) scenario. The objective was to quantify signal attenuation over increasing separation and evaluates the feasibility of long-range LoRa communication in an open environment.

Figure 6 illustrates the variation of RSSI as a function of distance. The recorded values indicate a clear decline in signal strength as the transmitter-receiver separation increased.

The results show an expected inverse correlation between distance and RSSI, where signal strength weakened progressively as the separation increased. A decrease of approximately 24.25 dB in RSSI was observed when the distance increased from 10 m to 100 m, aligning with theoretical free-space path loss models. Specifically, at 10 m, the RSSI measured −67.27 dBm, whereas at 100 m, it dropped to −91.52 dBm, confirming significant signal attenuation.

Despite the open environment, RSSI fluctuations varied across different distances, with standard deviations of ±1.49 dB at 10 m, ±0.92 dB at 50 m, and ±0.49 dB at 100 m. At 10 m, RSSI exhibited the highest variability, likely due to small-scale multipath effects and sporadic student movement momentarily obstructing the line-of-sight (LoS) path. At 50 m, RSSI fluctuations were lower, suggesting reduced environmental influence, while occasional deviations were observed, potentially caused by transient obstructions. At 100 m, RSSI showed the lowest variability, indicating a relatively stable signal despite increased attenuation. The reduced fluctuations at longer distances suggest minimal external interference and a dominant free-space path loss effect.

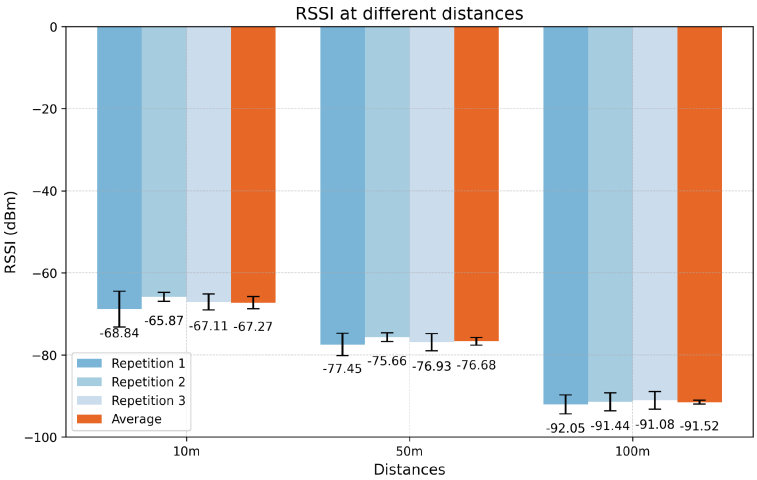

Fig. 6. RSSI attenuation as a function of distance in a Line-of-Sight environment.

These findings align with theoretical models predicting logarithmic signal attenuation over distance, as described in [3,13,19]. The results are consistent with the free-space path loss equation and empirical studies on signal degradation in LoRa networks [13,19]. The slight variability in RSSI measurements at intermediate distances suggests potential multi-path effects and environmental factors, which have been identified in prior studies analyzing RSSI fluctuations and their dependence on propagation conditions [3,19]. Despite the absence of major obstructions, the observed deviations may be influenced by uneven measurement distribution and minor reflections, factors previously discussed in path loss modeling research [3].

The results indicate that LoRa devices can maintain communication at moderate distances, but beyond 100 m, signal degradation is present. The importance of strategic node placement in large-scale IoT deployments to ensure optimal coverage and reliability in real-world environments.

4.2 Results for EXP-02: Obstructed Environments

This experiment analyzed the impact of physical obstructions on LoRa signal strength by comparing RSSI values in four different propagation environments: free space, concrete wall, glass/metal door, and a composite material panel. The objective was to quantify the signal degradation caused by each barrier type and evaluate how different materials influence LoRa communication.

Figure 7 presents the measured RSSI values for each propagation environment, showing a clear reduction in signal strength as obstacles were introduced. In the free-space scenario, the average RSSI was −40.22 dBm, indicating minimal signal attenuation. When a concrete wall was introduced, the RSSI dropped to −51.96 dBm, representing an attenuation of 11.74 dB. The glass/metal door

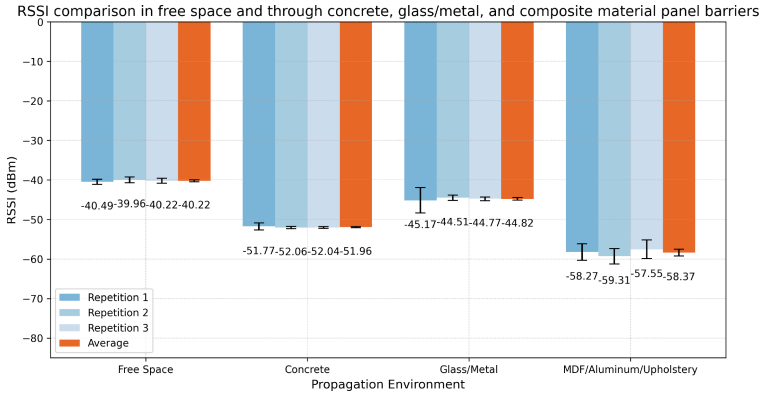

Fig. 7. RSSI variation across different propagation environments: free space, concrete, glass/metal, and composite material panel (aluminum frame, polyurethane sponge, and fabric upholstery).

caused a lower attenuation effect, with an average RSSI of −44.82 dBm, which is 4.60 dB weaker than free space but still higher than concrete. The composite material panel, consisting of an aluminum frame, polyurethane-based sponge panel, and fabric upholstery, exhibited the highest signal loss, with an average RSSI of −58.37 dBm, marking an attenuation of 18.15 dB relative to free space. These results confirm that denser and multi-layered materials cause greater signal degradation, reinforcing the importance of material-aware node deployment in indoor LoRa networks.

These results are consistent with established signal propagation behaviors, where denser materials introduce greater attenuation due to increased absorption and reflection effects. Concrete, with its high density and composition, led to significant RSSI reduction, aligning with prior empirical studies on LoRa signal degradation in urban environments [12]. The glass/metal barrier exhibited moderate attenuation, likely due to the partial penetration of glass, while the metal frame contributed to signal reflection and absorption [28]. The composite material panel resulted in the highest attenuation, suggesting that the combination of metallic elements, dense polyurethane padding, and fabric upholstery creates strong multi-path interference and absorption effects, severely impacting signal propagation [21,28]. These findings highlight the critical influence of material properties on LoRa communication and emphasize the importance of selecting optimal deployment locations in obstructed environments.

These results align with expected signal propagation behaviors, where denser materials introduce greater attenuation. Concrete, due to its higher density, led to significant RSSI reduction [12], while the glass/metal barrier showed moderate attenuation, likely because glass allows partial signal penetration while the metal frame contributes to reflections and absorption [28]. The composite material panel caused the highest attenuation, suggesting that the combination of metallic elements, dense polyurethane padding, and fabric covering creates

strong reflection and absorption effects, severely impacting signal propagation [21,28].

Overall, the findings confirm that LoRa communication is highly sensitive to physical obstructions, with denser and more complex materials leading to greater signal degradation. These insights highlight the importance of careful placement of LoRa nodes in indoor environments to minimize signal loss and ensure reliable connectivity.

4.3 Results for EXP-03: Multi-source Wireless Interference

This experiment evaluated the impact of simultaneous wireless interference from Wi-Fi, Bluetooth, and an additional LoRa network on RSSI performance. The objective was to determine whether the presence of multiple active communication technologies in the 915 MHz ISM band would cause significant signal degradation in LoRa transmissions. Two scenarios were tested: one without interference (baseline) and one with active interference sources.

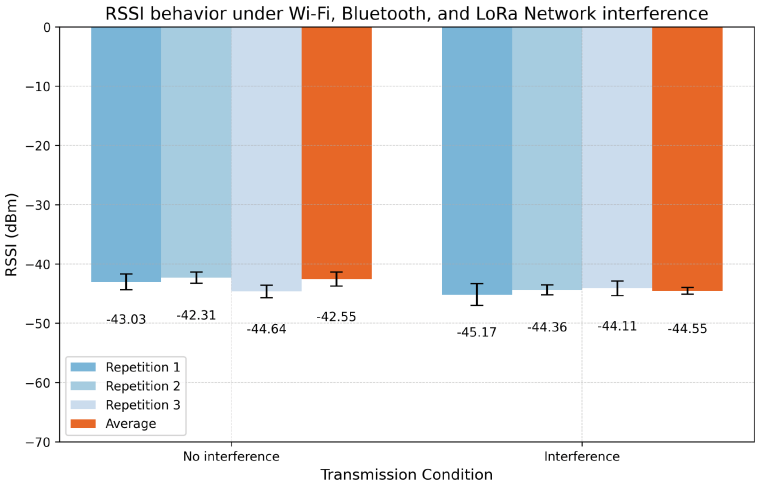

Fig. 8. RSSI behavior under Wi-Fi, Bluetooth, and LoRa network interference.

Figure 8 presents the measured RSSI values in both transmission conditions. In the no-interference scenario, the average RSSI was −42.55 dBm, with minor fluctuations between repetitions. When interference was introduced, the average RSSI decreased slightly to −44.55 dBm, representing a 2 dB drop in signal strength. This suggests that the presence of Wi-Fi, Bluetooth, and LoRa network transmissions introduced a moderate but measurable impact on LoRa signal reception.

The relatively small decrease in RSSI indicates that LoRa communication remains robust under moderate levels of interference from coexisting wireless

technologies. Previous studies have demonstrated LoRa's high resilience to co-channel interference, particularly against Bluetooth operating in the 2.4 GHz band, with its performance being highly dependent on system configuration [20].

Regarding Wi-Fi interference, research suggests that LoRa can experience communication failures when operating in the 2.4 GHz spectrum, but proposed solutions such as exploiting signal demodulation correlations have been effective in significantly reducing packet error rates [24]. Although the LoRa network in this experiment operates at 915 MHz, harmonics and sideband emissions from nearby Wi-Fi and Bluetooth transmissions could still contribute to minor disruptions in the LoRa spectrum [20,24].

Moreover, in-band interference from multiple LoRa nodes transmitting simultaneously is a challenge, as the network capacity is influenced by the number of end-devices and their transmission settings [10]. The presence of additional LoRa nodes in this experiment can introduce low levels of self-interference, affecting overall signal consistency. However, staggered transmission intervals were employed to minimize collisions, ensuring stable RSSI despite concurrent transmissions. Studies have shown that optimizing LoRa parameters can enhance signal robustness, even under interference conditions, with machine learning models being used to predict and adjust RSSI to improve network performance [26].

These findings support the notion that LoRa networks can coexist with other wireless technologies with minimal degradation in RSSI, reinforcing its suitability for dense communication environments. However, further research is needed to evaluate packet delivery rates and signal-to-noise ratios (SNRs) to comprehensively assess network performance under varying interference conditions.

4.4 Results for EXP-04: Elevation Variation

This experiment evaluated the impact of elevation variation on RSSI by comparing signal strength at two different transmission heights: first floor (ground level) and second floor (elevated position). The objective was to determine whether increased elevation improves signal stability and reception in an indoor environment.

Figure 9 presents the RSSI measurements recorded at both transmission positions. The experiment was conducted in an outdoor environment, where the transmitter was placed at two different elevations to evaluate the impact of height on RSSI stability. At ground level (first floor), the average RSSI was −63.12 dBm, with minor variations among repetitions. On the second floor, the average RSSI improved slightly to −61.40 dBm, representing an increase of approximately 1.72 dB in signal strength.

The relationship between transmission height and RSSI in outdoor environments is influenced by multiple factors, including signal propagation, environmental interference, and the physical setup of the communication system. Increasing the transmission height generally leads to improved RSSI due to reduced ground-level obstructions and lower signal absorption by surrounding structures. This effect is particularly relevant in outdoor settings, where line-of-sight (LoS) conditions can be more easily achieved, minimizing signal degradation [8,9].

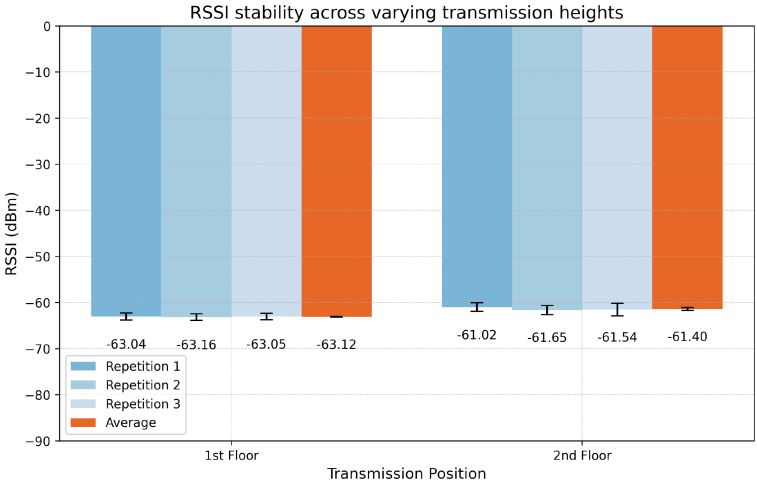

Fig. 9. RSSI stability across varying transmission heights.

A key factor contributing to improved RSSI at higher elevations is enhanced LoS visibility. The reduction of ground-level obstructions such as buildings and vegetation allows for a more stable communication link, decreasing attenuation and improving signal consistency [8,9]. Additionally, higher elevations reduce the likelihood of signal absorption and reflection by nearby structures, mitigating multipath fading and interference, which are common challenges in wireless communication [7].

Furthermore, research indicates that averaging RSSI over multiple heights can significantly reduce signal strength variation, improving localization precision in outdoor environments [18]. Implementing a height-only strategy has proven effective in stabilizing RSSI by minimizing the influence of ground-level interferences and reflections. Moreover, even small variations in transmission height can impact the path loss index, leading to measurable deviations in RSSI values. This further supports the idea that higher transmission heights help mitigate path loss effects, ensuring more stable and reliable LoRa communication in outdoor environments. Empirical path-loss models have shown that increasing transmission height improves signal coverage and reduces shading effects, which is essential for maintaining a stable connection in environments with varying topography and vegetation [4].

4.5 Results for EXP-05: Multi-node Network Performance

This experiment evaluated the impact of multinode LoRa transmission on RSSI performance by comparing two transmission conditions: a single transmitting node versus multiple transmitting nodes operating simultaneously. The objective was increase the network load, and concurrent transmissions introduced significant variations in signal strength, potentially affecting communication stability.

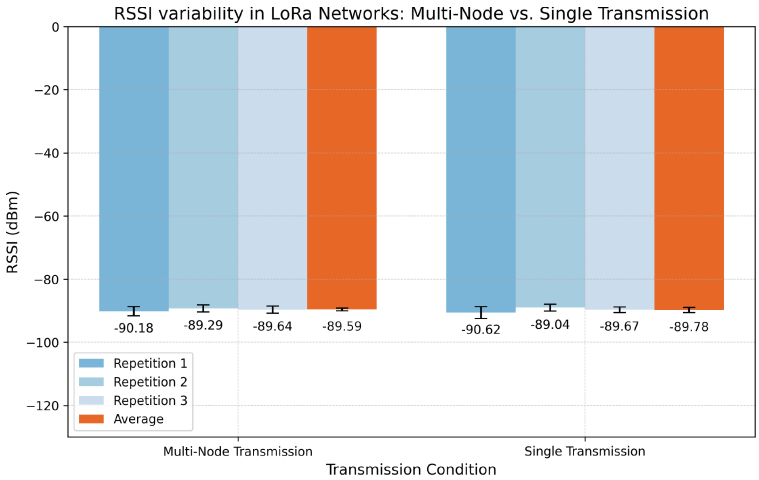

Fig. 10. RSSI variability in LoRa networks: Multi-node vs. single transmission.

Figure 10 presents the measured RSSI values under both transmission conditions. In the multi-node scenario, the average RSSI was −89.59 dBm, while in the single transmission scenario, the average RSSI was −89.78 dBm. The difference of 0.19 dB between the two conditions is minimal, it suggests that simultaneous transmissions from multiple LoRa nodes had a negligible impact on overall signal strength.

The relatively stable RSSI values across both scenarios indicate that LoRa communication is resistant to network congestion in terms of received signal power, a claim supported by multiple studies on LoRa's robustness under varying network conditions [5,6]. The small variations in RSSI observed in this experiment can be attributed to adaptive transmission schemes, which mitigate interference by dynamically adjusting transmission parameters such as spreading factor and transmission power. This adaptability, enabled by LoRa's Adaptive Data Rate (ADR) mechanism, helps maintain stable communication quality even in congested networks [23,27].

LoRa's strong anti-interference capability further contributes to signal stability, as it allows communication to remain reliable despite external sources of interference such as Wi-Fi networks. Studies have shown that techniques leveraging signal demodulation correlations significantly reduce packet error rates, reinforcing the stability of RSSI values across different network conditions [24]. Additionally, empirical research comparing simulated and real-world RSSI data confirms that LoRa networks maintain consistent signal strength across various deployment environments, highlighting their resilience to network congestion [5,6].

Furthermore, dynamic configuration techniques within enhanced ADR algorithms have been shown to improve packet delivery rates while reducing in-band interference, ensuring that transmission timing among nodes is efficiently

distributed [23,27]. Emerging machine learning models for RSSI prediction and transmission optimization further support LoRa's ability to adapt to environmental variations, contributing to consistent signal reception strength despite fluctuating network conditions [26].

While network contention can influence other performance metrics such as packet delivery ratio and latency, LoRa's network efficiency and capacity to manage multiple end-devices ensure that signal reception strength remains largely unaffected [10]. Although RSSI is known to be sensitive to environmental factors, research confirms that LoRa networks can sustain reasonable signal levels across different environments, reinforcing their resilience in congested scenarios [5].

These findings support the conclusion that LoRa networks can maintain stable RSSI values under increased network load, ensuring reliable communication even in dense IoT deployments. However, while signal reception remains stable, other network performance aspects, such as latency and packet loss, may still require further optimization to maximize overall efficiency in congested environments.

5 Conclusion and Future Work

This study examined LoRa signal strength (RSSI) through five applied experiments in an educational IoT setting. As expected, signal quality diminished with distance, and physical obstacles—especially dense materials—caused notable attenuation. Interference from other wireless technologies showed minimal disruption, and changes in elevation had only a minor effect. Even under simultaneous activity from multiple nodes, the system remained stable, suggesting that LoRa can reliably support more dynamic configurations. These observations mark the starting point of a larger effort focused on designing adaptable IoT networks for real-world use in academic environments.

At this stage, the analysis was based solely on RSSI. Future phases will expand the evaluation by incorporating additional metrics such as Signal-to-Noise Ratio (SNR), Packet Error Rate (PER), and Effective Signal Power (ESP). Although the current implementation does not yet include full data transmission or network interconnection, its modular architecture was conceived with scalability in mind. It is worth noting that three of the five experiments were conducted indoors, including those involving signal obstruction and interference. Further tests across varied building types and indoor layouts will be necessary to broaden the relevance and reliability of the findings.

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References

1. Abdelghany, A., Uguen, B., Moy, C., Lemur, D.: On superior reliability of effective signal power versus RSSI in LoRaWAN. Wirel. Netw. **27**(12), 4545–4560 (2021)
2. Anisah, N., K.A., Basri, S.: Experimental results of LoRa network radio propagation modeling in campus area. J. Wirel. Commun. Netw. **29**(3), 235–245 (2023)
3. Azevedo, J.A., Mendonça, F.: A critical review of the propagation models employed in LoRa systems. Sensors **24**(12), 3877 (2024)
4. Batalha, I.d.S., et al.: Large-scale modeling and analysis of uplink and downlink channels for LoRa technology in suburban environments. IEEE Internet Things J. **9**(23), 24477–24491 (2022)
5. Boonsong, W., Inthasuth, T., Kannan, U.: The quality of RF signal communication performance of LoRa-RSSI analysis based on various environments tests (2023)
6. Dinev, D., Haka, A., Aleksieva, V., Valchanov, H.: Analysis of LoRa RSSI data using simulations and real devices. In: 2023 18th Conference on Electrical Machines, Drives and Power Systems (ELMA), pp. 1–4. IEEE (2023)
7. Dong, Q., et al.: Study of RSSI accuracy for outdoor sensor localization. J. Circuits Syst. Comput. **31**(06), 2250115 (2022)
8. Dong, Q., Zhu, F., Cai, Y., Fang, L., Lu, M.: Analysis of RSSI feasibility for sensor positioning in exterior environment. In: 2021 Wireless Telecommunications Symposium (WTS), pp. 1–7. IEEE (2021)
9. Gao, J., Liu, Z., Guo, L., Hu, S., Zhong, Z., Nan, Z.: Design and analysis of outdoor multipath measurement system. In: 2024 Photonics & Electromagnetics Research Symposium (PIERS), pp. 1–6. IEEE (2024)
10. Gkotsiopoulos, P., Zorbas, D., Douligeris, C.: Performance determinants in LoRa networks: a literature review. IEEE Commun. Surv. Tutor. **23**(3), 1721–1758 (2021)
11. Irianto, K.D.: Performance evaluation of LoRa in farm irrigation system with internet of things. Kinet. Game Technol. Inf. Syst. Comput. Netw. Comput. Electron. Control **4**(1), 81–90 (2022)
12. Jörke, P., Böcker, S., Liedmann, F., Wietfeld, C.: Urban channel models for smart city IoT-networks based on empirical measurements of LoRa-links at 433 and 868 mhz. In: 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 1–6. IEEE (2017)
13. Karttunen, A., Molisch, A.F., Wang, R., Hur, S., Zhang, J., Park, J.: Distance dependence of path loss models with weighted fitting. In: 2016 IEEE International Conference on Communications (ICC), pp. 1–6. IEEE (2016)
14. Liu, J., et al.: Measurement and analysis of LoRa transmission performance in subway station. IEEE Trans. Wirel. Commun. **21**(7), 5201–5210 (2022)
15. Lopez, J., Kim, M., Nakamura, H.: Performance evaluation of LoRa communications in harsh industrial environments. Sens. Actuators, A **320**, 210–225 (2024)
16. 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 **53**, 110120 (2024)
17. Nguyen, P., Zhang, L., Singh, Y.: Performance evaluation and comprehensive analysis of LoRa network planning for IoT deployment scenarios. J. IoT Appl. **12**(4), 320–335 (2023)
18. Obeidat, H., Al-Sadoon, M., Zebiri, C., Obeidat, O., Elfergani, I., Abd-Alhameed, R.: Reduction of the received signal strength variation with distance using averaging over multiple heights and frequencies. Telecommun. Syst. **86**(1), 201–211 (2024)

19. Onykiienko, Y., Popovych, P., Yaroshenko, R., Mitsukova, A., Beldyagina, A., Makarenko, Y.: Using RSSI data for LoRa network path loss modeling. In: 2022 IEEE 41st International Conference on Electronics and Nanotechnology (ELNANO), pp. 576–580. IEEE (2022)
20. Polak, L., Paul, F., Simka, M., Zedka, R., Kufa, J., Sotner, R.: On the interference between LoRa and bluetooth in the 2.4 ghz unlicensed band. In: 2022 32nd International Conference Radioelektronika (RADIOELEKTRONIKA), pp. 1–4. IEEE (2022)
21. Ren, Y., Liu, L., Li, C., Cao, Z., Chen, S.: Is LoRaWAN really wide? Fine-grained LoRa link-level measurement in an urban environment. In: 2022 IEEE 30th International Conference on Network Protocols (ICNP), pp. 1–12. IEEE (2022)
22. Rifki, M.I., Ikhwan, A., Muhammad, F.: Performance evaluation of RSSI prediction methods in wireless communication networks. ZERO Jurnal Sains Matematika dan Terapan **8**(1), 14–25 (2024)
23. Sanou, F.d., Hamadoun, T., Yelemou, T.: Dynamic adaptation of the modulation in a LoRa channel according to the link quality. In: 2024 IEEE Multi-conference on Natural and Engineering Sciences for Sahel's Sustainable Development (MNE3SD), pp. 1–8. IEEE (2024)
24. Shao, C., Tsukamoto, K., Ma, Y.W.: Toward resilient LoRa communication under Wi-Fi interference. In: 2024 International Conference on Consumer Electronics-Taiwan (ICCE-Taiwan), pp. 249–250. IEEE (2024)
25. Syed Taha, S.N., Abu Talip, M.S., Mohamad, M., Azizul Hasan, Z.H., Tengku Mohmed Noor Izam, T.F.: Evaluation of LoRa network performance for water quality monitoring systems. Appl. Sci. **14**(16), 7136 (2024)
26. Tabaa, M., Hachimi, H., et al.: RSSI prediction for improved LoRa communications performance. In: 2024 IEEE 12th International Symposium on Signal, Image, Video and Communications (ISIVC), pp. 1–7. IEEE (2024)
27. Wang, H., Zhao, B., Liu, X., Pan, R., Pang, S., Song, J.: An adaptive data rate algorithm for power-constrained end devices in long range networks. Mathematics **12**(21), 3371 (2024)
28. Wu, Z., Shen, Q., Wang, J.: Researching on signal transmission performance of LoRa technology in urban environment. In: 2023 IEEE 12th Data Driven Control and Learning Systems Conference (DDCLS), pp. 1056–1061. IEEE (2023)
29. Zhang, Z., Zhang, B., Zhang, X.: Performance research of LoRa at high transmission rate. J. Phys: Conf. Ser. **1544**, 012177 (2020)