

# Performance Analysis of LoRa CSS Communication in Dense Foliage Environments

Paulo O. Mendes, Davi S. Timbó, Samuel do N. Arruda, Isabela A. Freire, Alberto Sampaio Lima, Francisco Helder Candido dos Santos Filho

**Abstract**—Communication in forest and dense foliage environments is challenging because vegetation obstructs the Fresnel zone, increases multipath propagation, and attenuates radio-frequency signals through leaves, trunks, and moisture. This paper evaluates the performance of LoRa Chirp Spread Spectrum (CSS) communication in a dense foliage scenario using Heltec V3 modules with Meshtastic firmware at 915 MHz. Field measurements were conducted under a line-of-sight baseline and under non-line-of-sight foliage obstruction, comparing 2 dBi and 5 dBi antennas when available. The analysis considers RSSI, SNR, and Packet Delivery Ratio (PDR). The results show that the LongSlow Meshtastic profile maintains connectivity under strong attenuation, with the 5 dBi antenna achieving 100% PDR at 220 m in dense foliage despite an average RSSI of -121.70 dBm and SNR of -6.58 dB.

**Keywords**—LoRa, CSS, Meshtastic, dense foliage, RSSI, SNR, packet delivery ratio.

## I. INTRODUCTION

The rapid growth of Internet of Things (IoT) applications has increased the demand for communication systems that are long range, low power, and robust in areas where conventional infrastructure is unavailable. In forested or densely vegetated regions, Wi-Fi and Bluetooth links are usually inadequate because their useful range and energy efficiency degrade quickly under obstruction. In these environments, communication channels are affected by severe path loss, scattering from biomass, ground reflections, and radio-frequency absorption associated with foliage and moisture. Low-Power Wide Area Network (LPWAN) technologies are therefore attractive for environmental monitoring, emergency tracking, and off-grid telemetry in areas with limited or no internet connectivity [1], [11], [12].

Among LPWAN technologies, Long Range (LoRa) is particularly relevant because it combines low power consumption with high receiver sensitivity. Its physical layer employs Chirp Spread Spectrum (CSS), in which information is encoded into linear frequency-modulated chirps. This modulation provides robustness against interference, Doppler effects, and multipath fading [1], [11], [12]. The Spreading Factor (SF) controls the trade-off between data rate and receiver sensitivity: higher SF values reduce throughput but increase link budget. The symbol rate ( $R_s$ ) is given by

$$R_s = \frac{BW}{2^{SF}} \quad [\text{chirps/s}], \quad (1)$$

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where  $BW$  is the channel bandwidth. This parameterization allows LoRa systems to prioritize coverage and reliability when the propagation environment is hostile.

Although LoRa has been widely investigated in urban, rural, and agricultural contexts, empirical evaluations in dense phytosociological environments are still limited. Recent studies have analyzed line-of-sight identification [2], LoRa propagation in Atlantic Forest areas [3], and path-loss models for composite environments [4]. However, many existing studies emphasize centralized LoRaWAN deployments or generic path-loss models, while fewer works evaluate peer-to-peer operation with Meshtastic firmware under completely obstructed Fresnel zones. This distinction is important because mesh-oriented systems may support search-and-rescue, ecological sensing, and field operations without gateways, cellular coverage, or permanent infrastructure.

This work evaluates LoRa CSS performance in the Matinha do Pici area of the Federal University of Ceará (UFC), Brazil. The study uses Heltec V3 modules operating at 915 MHz with the Meshtastic LongSlow profile. The experimental design compares a line-of-sight (LoS) baseline with a dense foliage non-line-of-sight (NLOS) scenario and analyzes RSSI, SNR, and PDR. When possible, the influence of antenna gain is also considered by comparing a standard 2 dBi antenna with a 5 dBi antenna. The main contribution is a practical field assessment showing that LoRa can sustain short text-message communication in dense vegetation, even when the received signal approaches the sensitivity limit of the transceiver.

## II. BACKGROUND AND RELATED WORK

The physical robustness of LoRa is directly associated with its CSS modulation, whose processing gain allows packet reception even at negative SNR values. The fundamentals of CSS modulation for LoRaWAN and the effects of parameters such as spreading factor, bandwidth, and coding rate on sensitivity, time on air, and link budget are discussed in [1], [11], [12]. These characteristics are central to forest and off-grid deployments, where the propagation channel is strongly affected by attenuation, scattering, diffraction, and multipath components produced by vegetation.

Recent Brazilian studies have also addressed LoRa performance under non-ideal propagation conditions. Intelligent identification of line-of-sight conditions in LoRaWAN networks is investigated in [2], emphasizing the importance of classifying the propagation path when interpreting link-quality indicators. LoRa propagation in an Atlantic Forest area is analyzed in [3], showing the relevance of empirical

measurements in vegetation environments. Path-loss behavior in composite environments is evaluated in [4], reinforcing that generic models may be insufficient when open areas, buildings, terrain variations, and vegetation coexist along the communication path.

Foliage-specific propagation studies indicate that vegetation structure and measurement geometry strongly influence LoRa links. Factors that affect LoRa propagation in foliage media, including the role of leaves, trunks, moisture, and obstruction depth, are discussed in [5]. In agricultural environments, direction-dependent path loss in orchards is shown in [6], which suggests that antenna orientation and vegetation alignment may significantly alter RSSI and SNR even for similar transmitter–receiver distances.

Mesh-oriented LoRa deployments complement these propagation studies by addressing operation without gateways or permanent infrastructure. The resilience of off-grid LoRa mesh networks using Meshtastic profiles in long-range scenarios is evaluated in [7], while a Meshtastic-based LoRa mesh system for smart campus applications is presented in [8]. These works support the relevance of evaluating peer-to-peer and mesh-capable LoRa systems in field conditions, especially for environmental monitoring, emergency communication, and campus-scale sensing. In this context, the present study contributes experimental results for Meshtastic LongSlow operation under dense foliage obstruction, focusing on RSSI, SNR, and PDR in a practical NLOS forest route.

### III. METHODOLOGY

The evaluation was conducted through field tests designed to quantify link quality under distinct propagation conditions. The hardware platform consisted of two Heltec WiFi LoRa 32 V3 nodes [9], based on the ESP32 microcontroller and the SX1262 LoRa transceiver. The nodes operated in the 915 MHz Industrial, Scientific, and Medical (ISM) band and were powered by portable battery banks to allow mobility during the measurements. The tests used the Meshtastic firmware and mobile application for device configuration, message transmission, GPS-assisted positioning, and real-time monitoring of telemetry indicators.

Meshtastic is an open-source firmware for decentralized, peer-to-peer, low-power mesh communication. It allows text messages and telemetry packets to be exchanged without cellular towers, Wi-Fi access points, or internet connectivity. In this work, Meshtastic was used not only as the communication layer but also as the data acquisition interface, since it reports RSSI and SNR for received packets. Distances between nodes were estimated using the GPS location associated with the connected mobile phones and were cross-checked with map-based distance measurements to reduce positioning uncertainty.

The experimental procedure evaluated communication robustness as a function of distance and environmental obstruction. First, a LoS baseline was established on the UFC Pici Campus along an open path with mild incidental obstacles such as parked vehicles, sparse trees, and small terrain variations. Measurements were collected at distances from 50 m to 500 m. This baseline was used to verify that the hardware and

firmware configuration behaved consistently before the dense foliage tests. Second, an NLOS scenario was conducted in the Matinha do Pici, where vegetation completely obstructed the visual path and the main Fresnel zone between transmitter and receiver. Measurements were recorded at 130 m and 220 m.

For each measurement point, the transmitter sent 20 text messages with an interval of 5 s between consecutive packets. The payload was a short standardized message of approximately 60 bytes. Link quality was evaluated using RSSI, SNR, and PDR. RSSI, measured in dBm, indicates the received signal power, while SNR, measured in dB, describes the relation between the useful signal and the noise level. The PDR was computed as

$$\text{PDR} = \frac{N_r}{N_t} \times 100\%, \quad (2)$$

where  $N_r$  is the number of successfully received packets and  $N_t$  is the number of transmitted packets. During all measurements, both antennas were kept approximately at chest height, around 1.30 m above the ground, to maintain a consistent deployment condition.

#### A. Line-of-Sight Scenario

The LoS test was performed at the UFC Pici Campus. The route connected the surroundings of the Telecommunications and Signal Processing Laboratory (LPTS) to the Institute of Culture and Art (ICA). The campus view and the measurement route are shown in Fig. 1 and Fig. 2, respectively. Although this scenario is referred to as LoS, it should be interpreted as a practical campus baseline rather than an ideal free-space experiment, because occasional vehicles, trees, and pedestrians could partially disturb the propagation path. This interpretation explains small fluctuations in PDR and signal level that do not follow a perfectly monotonic trend with distance.



Fig. 1: UFC Pici Campus, view from the Institute of Culture and Art (ICA).

The LoRa modules were configured using the Meshtastic LongSlow profile. This profile prioritizes range and robustness over data rate and is therefore appropriate for emergency or telemetry messages in obstructed areas. Table I summarizes the main physical-layer parameters.

TABLE I: LongSlow mode configuration parameters.

| Data Rate | SF / Symbols | Coding Rate | Bandwidth | Link Budget |
|-----------|--------------|-------------|-----------|-------------|
| 0.18 kbps | 12 / 4096    | 4/8         | 125 kHz   | 158.5 dB    |

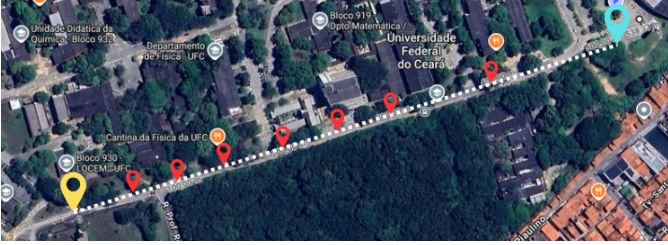


Fig. 2: LoS route at UFC Pici Campus, from LPTS to ICA, estimated using Google Maps.

### B. Dense Foliage Scenario

The dense foliage test was conducted near the Santo Anastácio Reservoir, inside the Matinha do Pici area of the UFC Pici Campus. This area covers approximately 79.5 hectares and includes vegetation formations associated with Cerrado, Caatinga, and Mata de Tabuleiro, a coastal phytophysognomy related to the Atlantic Forest. The area is classified as Seasonal Semideciduous Lowland Forest according to the Brazilian vegetation classification adopted by IBGE, as described in the environmental characterization of the ARIE Matinha do Pici [10]. Such diversity makes the site appropriate for propagation tests because it combines medium-density regions with localized high-density vegetation pockets.

To characterize the obstruction level, an approximate tree density estimate was considered using a sampled area of 2,000 m<sup>2</sup>. With 154 observed individuals in the sample, the density is estimated as

$$DA = \frac{N}{A} = \frac{154}{0.2} = 770 \text{ individuals/ha.} \quad (3)$$

This value indicates a medium-density forest region overall, although the specific communication path included sections with dense foliage and no direct visual contact between nodes. The routes used for the 130 m and 220 m measurements are shown in Fig. 3 and Fig. 4, respectively, while Fig. 5 illustrates the dense vegetation along the measurement path. Therefore, the dense foliage test should be interpreted as an NLOS experiment with strong biomass obstruction rather than a simple distance-extension test.

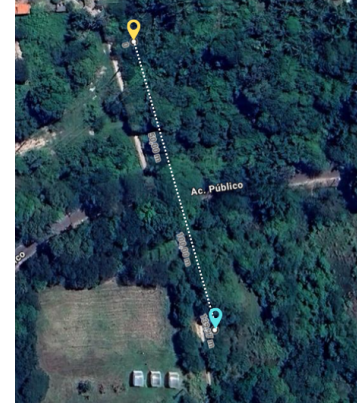


Fig. 3: Dense foliage route across Public Access to a point approximately 130 m away through Matinha do Pici.



Fig. 4: Dense foliage route from the Poultry Farming Laboratory to a point approximately 220 m away through Matinha do Pici.



Fig. 5: Dense vegetation observed along the Matinha do Pici measurement path.

## IV. RESULTS AND DISCUSSION

### A. Line-of-Sight Baseline Performance

Table II presents the LoS baseline results obtained with the 5 dBi antenna, while Fig. 6 illustrates the RSSI and SNR trends as a function of distance. The RSSI values remain relatively stable from 100 m to 300 m, ranging from -91.30 dBm to -96.15 dBm, and then decrease sharply at 400 m and 500 m. The SNR follows a similar tendency: it

remains positive up to 400 m but becomes strongly negative at 500 m. The PDR does not decrease monotonically with distance, which indicates that short-term environmental effects, partial obstruction, antenna orientation, and local interference influenced the measurements. In particular, the 100 m point produced only 50% PDR despite a positive SNR, suggesting a localized impairment during that set of transmissions rather than a range limitation.

TABLE II: LoS baseline results using the 5 dBi antenna.

| Distance (m) | RSSI (dBm) | SNR (dB) | PDR  |
|--------------|------------|----------|------|
| 50           | -73.18     | 5.62     | 85%  |
| 100          | -91.30     | 5.40     | 50%  |
| 150          | -96.00     | 4.69     | 95%  |
| 200          | -90.40     | 5.58     | 100% |
| 250          | -93.42     | 5.11     | 95%  |
| 300          | -96.15     | 4.71     | 100% |
| 400          | -111.30    | 0.29     | 100% |
| 500          | -122.33    | -12.43   | 80%  |

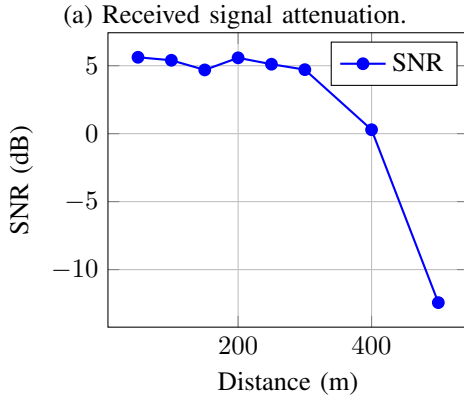
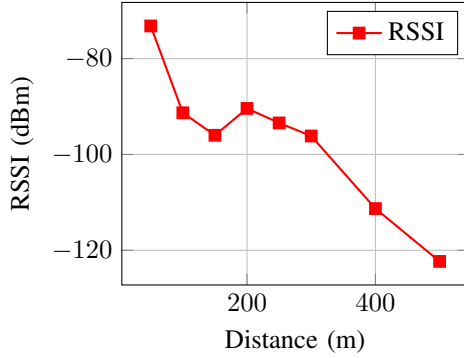
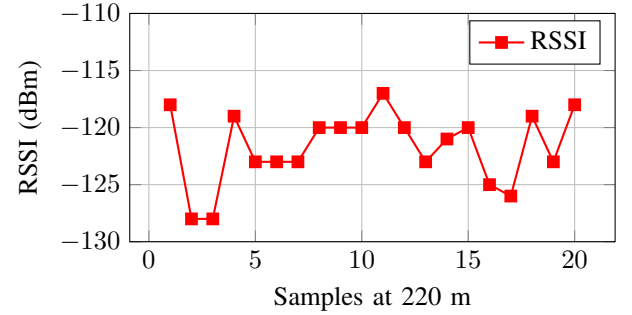


Fig. 6: LoS baseline metrics as a function of distance.

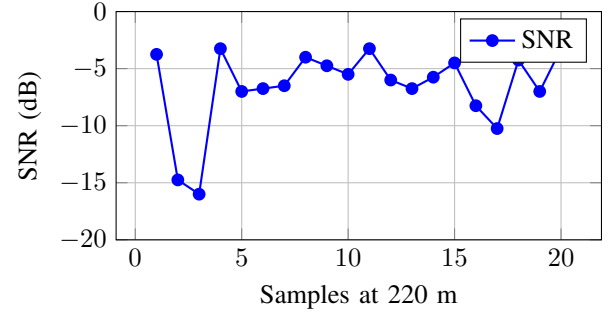
The 500 m point is the most relevant LoS stress condition because the average RSSI reached -122.33 dBm and the SNR dropped to -12.43 dB. Even under these conditions, 80% of the messages were decoded successfully. This result is consistent with the expected behavior of LoRa CSS at SF12, which can operate with negative SNR values due to processing gain. Therefore, the LoS baseline confirms that the hardware and firmware configuration can support communication close to the receiver sensitivity limit, although reliability becomes more sensitive to local propagation variations.

### B. Dense Foliage Performance

The dense foliage measurements show a clear degradation compared with the campus baseline. At 130 m, the 5 dBi antenna achieved an average RSSI of -108.09 dBm, average SNR of 2.68 dB, and 100% PDR. At 220 m, the average RSSI decreased to -121.70 dBm and the SNR became negative, reaching -6.58 dB. The packet-level RSSI and SNR variations at this distance are shown in Fig. 7. Despite this attenuation, all 20 transmitted packets were successfully received, resulting in 100% PDR. These results demonstrate that the LongSlow profile is suitable for low-throughput communication in obstructed forest paths when the objective is reliable delivery of short messages rather than high data rate.



(a) Received signal variation at 220 m.



(b) SNR variation at 220 m.

Fig. 7: Packet-level RSSI and SNR samples in the dense foliage scenario.

TABLE III: Dense foliage results using the 5 dBi antenna.

| Distance (m) | RSSI (dBm) | SNR (dB) | PDR  |
|--------------|------------|----------|------|
| 130          | -108.09    | 2.68     | 100% |
| 220          | -121.70    | -6.58    | 100% |

The packet-level samples at 220 m also reveal that the link was not static. RSSI varied from approximately -117 dBm to -128 dBm, while SNR varied from -3.25 dB to -16.00 dB. This spread is expected in a dense foliage channel, where small movements, antenna orientation, vegetation geometry, and local scattering can modify the received field strength. The important observation is that packet decoding was preserved across the full sample set, indicating that the processing gain of SF12 compensated for instantaneous fades during the test.

### C. Coherence and Limitations of the Measurements

Some measurement trends require careful interpretation. First, the LoS baseline should not be described as an ideal unobstructed channel because the campus environment included mild obstacles; therefore, the lower PDR at 100 m is not necessarily inconsistent with the higher PDR at longer distances. It most likely reflects temporary local interference, antenna alignment, or partial obstruction during that specific point. Second, the dense foliage results currently provide complete averaged values for the 5 dBi antenna, while the text does not include a complete numeric table for the 2 dBi antenna. For this reason, the comparison with the 2 dBi antenna must be stated qualitatively unless additional measured values are inserted. Third, the 220 m dense foliage point and the 230 m figure description were standardized here as 220 m to match the table and route description.

These limitations do not invalidate the main conclusion, but they define the scope of the claims. The results support the feasibility of short-message LoRa communication through dense foliage at distances up to 220 m with the tested 5 dBi antenna and LongSlow profile. Broader generalization would require repeated campaigns, weather records, a larger number of packets, controlled antenna orientation, and parallel measurements with both antenna gains at every distance. Such additions would allow statistical confidence intervals and a more rigorous path-loss model for the local environment.

### V. CONCLUSIONS

This work evaluated the performance of LoRa CSS communication in a dense foliage environment using Heltec V3 modules, Meshtastic firmware, and the 915 MHz ISM band. The experiments compared a practical LoS campus baseline with an NLOS forest scenario in Matinha do Pici. The analysis considered RSSI, SNR, and PDR, emphasizing the feasibility of short text-message communication in areas without conventional network infrastructure.

The results show that vegetation imposes severe attenuation, but the Meshtastic LongSlow profile remains robust under strong obstruction. In the dense foliage scenario, the 5 dBi antenna maintained 100% PDR at 220 m, even with an average RSSI of -121.70 dBm and average SNR of -6.58 dB. The packet-level samples reached values as low as -128 dBm and -16.00 dB, yet the messages were still decoded. This behavior confirms the practical advantage of LoRa CSS for low-throughput communication in obstructed environments.

The LoS baseline also showed that the link can remain operational near the sensitivity limit, achieving 80% PDR at 500 m with RSSI of -122.33 dBm and SNR of -12.43 dB. However, the non-monotonic PDR observed at shorter distances indicates that local interference and partial obstruction can strongly affect packet delivery, even when average SNR appears favorable.

Overall, the study validates LoRa as a robust, low-power, and cost-effective alternative for off-grid communication in phytosociologically dense locations. The findings are relevant for environmental telemetry, remote sensor networks and campus-scale field monitoring in areas where traditional internet connectivity is unavailable.

Future work will extend the experimental campaign to denser forest routes, where the Fresnel zone is more severely obstructed and the foliage depth is greater than in the present measurements. Additional tests will include 10 dBi antennas to evaluate whether higher antenna gain can improve RSSI, SNR, and PDR under stronger vegetation attenuation. The comparison will be conducted against the 2 dBi and 5 dBi configurations to quantify the practical gain obtained in dense foliage scenarios.

Further measurements should also increase the number of packets per point, repeat tests under different weather and soil-moisture conditions, and include controlled antenna orientation. These additions will support statistical confidence intervals, a more detailed path-loss model for the local vegetation profile, and a better understanding of the effects of rainfall, canopy moisture, and multipath fading. Future experiments may also evaluate multi-hop Meshtastic routing and energy consumption under relay operation for longer off-grid deployments.

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