Evaluation of LoRaWAN Transmission Range for Wireless Sensor Networks in Riparian Forests

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ABSTRACT

Low power wide area networks (LPWAN) such as long range wide area networks (LoRaWAN), provide several advantages on monitoring systems development in forested environments due to its simple set-up, low cost, low power consumption, and wide coverage. Regarding the coverage area, the transmission in forested environments can be highly attenuated by foliage and must be defined to optimize the number of nodes. This paper discusses an empirical study of LoRa with LoRaWAN transmission range in riparian forests, based on path-loss modeling, using both received signal strength indicator (RSSI) and signal-to-noise-ratio (SNR). The measurements have been conducted in the riparian forest of three local rivers at urban, semi-urban, and rural environments located in the city of Cuenca, Ecuador. The measurement results found that there is a significant distribution difference among measurement places, a high correlation between two banks of the same river, a higher standard deviation in urban measurements and a larger coverage in rural areas.

KEYWORDS

LoRa; LoRaWAN; IoT; RSSI; SNR; path loss; forested; riverside; propagation; model; riparian

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1 INTRODUCTION

Program for water and soil management (PROMAS for its acronym in Spanish) monitors a wealth of environmental information regarding wind, rain, temperature, humidity, barometric pressure, and water level of rivers. For this purpose, around 130 remote weather stations have been deployed in a large area of Azuay, Cañar, and Chimborazo. PROMAS has two projects related to limnigraphic sensors. The first one is the early flood warning and the other is the flow prediction using neural networks [6].

Our research team is working on the design and implementation of a wireless network to gather the sensors information and transmit it to the PROMAS data center. The goal is to take advantage of wireless technologies to reduce the displacement of people in charge of downloading the data. Consequently, this will maximize the availability of limnigraphic information in an hour-based transmissions, reduce the risk of losing information, and minimize mobilization expenses that can be used for maintenance purposes.

LPWANs represent a new trend in the evolution of wireless communication technologies. This communication technology is able to connect and monitor high number of sensors, covering wide areas at low energy cost [2]. One of the newest approaches to this technology is long range (LoRa) [18]. LoRa gives all the LPWAN advantages, adding low device cost and easy deployment. LoRa-based wireless sensor networks (WSNs) are able to collect real time information such as temperature, rain, humidity, flow, and other weather factors. A clear application scenario for LoRa is forest environments.

LoRaWAN is a medium access control layer created by the LoRa Alliance. It uses the advantages of LoRa modulation to create networks, and it is focused on the Internet of Things (IoT) paradigm [21]. LoRaWAN uses a star topology where the nodes, collect the sensor information and send it to the gateways (GW). The GWs convert the data to the internet protocol (IP) and forward it to a remote application server via Internet. This architecture is shown in Fig. 1.

When any wireless network is designed, the main question that must be answered is the maximum distance between two nodes that still ensures a reliable wireless connection. Environmental vegetation plays a significant role in the fading phenomena in wireless

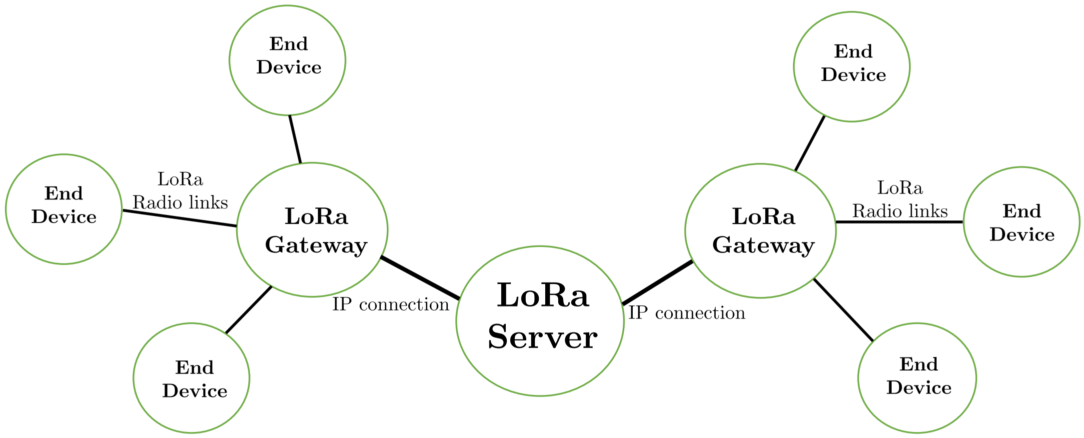

Figure 1: LoRaWAN Architecture [20]

communications [12]. The answer also depends on different technical parameters such as the transmitter power, receiver sensitivity, signal propagation and signal frequency [8]. Until now, there are studies reported in the literature about performance, scalability, indoor propagation, and range evaluation, but given that LoRa is a rather new technology, there are no reported measurements of propagation in riparian forest.

The contribution of this paper is to present the results of a 915 MHz ISM band, LoRa modulation riparian forest propagation measurement campaign. This is a typical limnigraphic measurement scenario. The main task is to capture channel statistics through received signal strength indicator (RSSI), signal-to-noise ratio (SNR), and packet error rate (PER) under different LoRaWAN available data rates (DR) at a height of under 2 m [19].

To the best of our knowledge, this is the first low antenna height LoRa measurement campaign conducted in a riparian forest. This collected data will be used to adjust a path loss model (P_L) to the specific measurement locations [14]. This study will help to a faster design and deployment of LoRa sensor networks, making it easier to calculate the useful coverage area of a LoRaWAN system.

2 BACKGROUND

2.1 LPWAN

The IoT ecosystem is broad, containing devices with data rates ranging from a few bps to Mbps. The coverage is also variable from a few centimeters to several kilometers. LPWAN is responsible for covering these needs in new applications that arise daily [3]. Although these networks must cover different needs, there are common requirements in the design of an LPWAN network. The main characteristics of an LPWAN network are:

- LPWAN requires a minimum energy consumption during operation. This because the limited capacity of batteries and its high cost.
- Cost is an important factor. Especially in the nodes, easy-to-install tools must be provided, and both the hardware and software should be low-cost.
- The level of activity depends on the specific application. However, the device must be able to wake up only when be needed to send information. This point would support the idea of star type architectures against mesh architectures.
- The network infrastructure must be easy to assemble. The addition of devices or the transfer to other countries must comply with international standards.
- The transferred information between the node and the final user must be safe.
- Nodes are not in motion in most of these applications, thus the channel remais almost constant.

2.2 LoRa

LoRa is a proprietary modulation scheme derived from the Chirp Spread Spectrum modulation (CSS). Its main objective is to improve sensitivity at the cost of a reduction in the data rate for a given bandwidth (BW). LoRa implements variable data rates, using orthogonal Spreading Factors (SF). It allows a compromise between the data rate and coverage, as well as optimizing the performance of the network with a constant bandwidth.

LoRa is a physical layer implementation and does not depend on higher layers implementations. This allows it to coexist with different network architectures. Some basic concepts about LoRa modulation and the advantages to develop an LPWAN network are presented [18].

In information theory, Shannon's Theorem - Hartley, defines the maximum rate at which the information can be transmitted on a communication channel with a specific bandwidth in presence of noise. From this well-known equation, it can be concluded that if it increases bandwidth, it can compensate the degradation of the SNR of the radio channel.

In Direct Sequence Spread Spectrum (DSSS), the transmitter carrier phase changes according to a code sequence. This process is achieved by multiplying the desired data signal with a spreading code, known as chip sequence. This chip sequence has a higher rate than the data signal, so widens the bandwidth of the original signal.

As a result, a reduction in the amount of interference occurs due to a processing gain. DSSS is widely used in communication applications. However, there are challenges when it is necessary to reduce the cost and energy consumption of devices with this technology.

LoRa modulation solves the DSSS problems by providing an alternative of lower cost and lower energy consumption. In LoRa modulation, the spread spectrum is achieved by generating a chirp signal that continuously varies in the frequency domain. An advantage of this method is that the timing and frequency variations between the transmitter and the receiver are equivalent, reducing the receiver complexity.

This chirp bandwidth is equivalent to the spectral signal bandwidth. The desired signal is widened with a chip and modulated on a chirp. The relationship between the desired data rate, the symbol rate and the chip rate for LoRa, is expressed by the Eq. (1).

$$R_b = SF \frac{\text{CodeRate}}{\frac{2^{SF}}{BW}} \text{bits/sec} \quad (1)$$

where:

- R_b = Bit rate of the modulation
- SF = Spreading factor $(7 - 12)$
- CR = Code rate $(1 - 4)$
- BW = Bandwidth (Hz)
- CodeRate = $4/(4 + CR)$

2.3 Transmission Parameters

LoRa devices can be configured using different Transmission Power (TP), Carrier Frequency (CF), Spreading Factor (SF), Bandwidth (BW) and Coding Rate (CR). This parameters are tuned to achieve the best connection performance and the lowest energy consumption.

The previous variables combination results in around 6720 possible configurations, which allows a user to completely adjust LoRa to the required application [4]. Next, a brief description of the mentioned parameters is presented [5]:

(1) **Transmission Power (TP)**: It can varies between −4 dBm and 20 dBm, but due to implementation limits, it can be adjusted from 2 dBm to 20 dBm. With transmission power of more than 17 dBm, only 1% of the duty cycle can be used.
(2) **Carrier Frequency (CF)**: It is the central frequency that can be varied in 61 Hz steps between 137 MHz and 1020 MHz, depending on the chip and the region of use.
(3) **Spreading Factor (SF)**: It is the ratio between the symbol rate and the chip rate. A higher SF not only increases the SNR, range and sensitivity, but also the air time of the packet. Each increase in the SF also reduces the transmission rate, doubling the duration of the transmission and the energy consumption. The SF can vary between 6 and 12, being useful for network separation since the SFs are orthogonal.
(4) **Bandwidth (BW)**: It is the frequency range in the transmission band. A higher BW gives a higher data rate (less airtime), but lower sensitivity for noise aggregation. A lower BW requires more precise crystals, that is, less parts per million (ppm). The data is sent at a chip rate equivalent to the BW. A BW of 125 kHz is equivalent to a chip rate of 125 kcps. A typical LoRa network operates at: 125 kHz, 250 kHz or 500 kHz.
(5) **Code Rate (CR)**: It is the Forward Error Correction rate (FEC) used by LoRa against interference. It can be configured with: 4/5, 4/6, 4/7 and 4/8. A larger CR offers more protection against noise, but increases the airtime. Transmitters with different CR can communicate since the CR is in the header of the packet that is always encoded at a 4/8 rate.

2.4 Key LoRa Modulation Properties

In the following we describe some key aspects that highlight LoRa and make it one of the best candidates for IoT applications [18]:

- **Scalable Bandwidth**: It can be used in narrow band frequency jumps and broadband direct sequence applications.
- **Low Energy Consumption**: Power output can be reduced compared to FSK, while keeping the same or better link budget.
- **High Robustness**: Due to its asynchronous nature, the LoRa signal is resistant to in-band and out-band interference.
- **Fade Resistant**: Thanks to the broadband chirp pulses, LoRa offers fading and multipath immunity, making it ideal for urban and suburban environments.
- **Doppler Resistant**: Doppler shift causes a small frequency shift in the LoRa pulse that introduces a non significant time axis shift of the baseband signal, making it immune to the Doppler effect.
- **Wide Coverage Capability**: Compared to FSK, maintaining the same transmission power, the link budget is higher in LoRa.
- **Enhanced Network Capability**: SemTech LoRa modulation employs orthogonal SFs that allow multiple propagation signals to be transmitted at the same time and on the same channel without substantial sensitivity degradation. The modulated signals with different SFs appear as noise to the target receiver and can be treated as such.

2.5 RSSI and SNR based Path Loss Model

In this section, we give a brief review of RSSI and SNR-based propagation models used in this study. Path Loss models are usually expressed in a logarithmic form as shown in Eq. (2) [9].

$$P_L(dB) = P_0(dBm) + 20 \ \log\left(\frac{d}{d_0}\right) + X_\theta \quad (2)$$

where d and d_0 are the transmission distance and reference distance respectively. P_0 is the power strength at d_0. X_θ is a random variable normally distributed with standard deviation θ.

Another widely used model is the exponential decay model, shown in Eq. (3) [17]. This equation shows that path loss is an exponential function with frequency f and distance d. This equation was proposed for cases were the antennas are located near to trees and thus the signal propagates through the trees. Weissberger and COST-235 models are modifications of this model to different forested environments.

$$L(dB) = A\ f^B d^C \quad (3)$$

These models can be simplified into Eq. (4), as is proposed in [9].

$$P_L(dB) = a + b \ \log(d) + X_\theta \quad (4)$$

In this case, all the characteristics of Eq. (3) are expressed in Eq. (4). The exponential factor of distance is b, and the other components are expressed by a. As in Eq. (2), the randomness of the received signal is expressed in X_θ. It is assumed that the error of fitting in Eq. (4) follows a normal distribution with zero mean and standard deviation (θ). In this work, the standard deviation is calculated between the fitted curve and the mean values of every measurement point as shown in Eq. (5).

$$\theta = \text{std}(P_L - \text{FittedCurve}) \quad (5)$$

To calculate the P_L values from RSSI and SNR, Eq. (6) is used according to [14].

$$P_L = |\text{RSSI}| + \text{SNR} + P_{\text{tx}} + G_{\text{rx}} \quad (6)$$

3 RELATED WORK

In this section, we briefly discuss some of the most important works related to propagation and coverage measurements, made with LoRa.

In [14], the authors present a study of performance and coverage that uses LoRa transceivers and RSSI as the main measurement variable to develop a path loss model. This work differs from our research mainly in two relevant aspects. First, this study is conducted in water and a coast environment. Second, they use European 868 MHz ISM band while we use American 915 MHz ISM band. This is because our study is conducted in Latin America allowing us to use different channels, and transmission power.

Another outdoor measurement based study is presented in [1], where the authors use PER and RSSI to estimate the performance of the system under two different tests. Authors evaluate the system under different payload length, bandwidth (BW), spreading factor (SF), and modulation schemes. The principal differences with our study are the use of different payload length, transmission with the FSK modulation scheme, and that the Fresnel zone is taken into account.

Another work, [21], presents a general evaluation of LoRa using multiple gateways; RSSI and ACKs to estimate the connection rate. A main aspect of the study is the reliability that was measured using long transmission periods. The study detected mobile network interference during certain hours that are not considered in the current work.

Indoor measurements have been conducted in [7] and [16]. In [7], DR, SF, bandwidth and bit rate are fixed and RSSI is used to measure performance. In [16], the study is more specific, the authors evaluated the performance of LoRa in health and wellbeing applications. The main difference is that we take into account an outside riparian environment of three rivers for measurements.

4 MATERIALS AND METHODS

This section presents a detailed description of the device parameters, environmental conditions and statistical tests used in the current work.

4.1 Equipment and Configuration

Propagation measurements are made at 915 MHz utilizing Microchip's Evaluation kit - 900. The Evaluation kit consists of a gateway working with the LoRa Semtech chip SX1301, two nodes that include light and temperature sensors with the RN2903. Transmission power, spreading factor, code rate and bandwidth are controlled by the LoRaWAN MAC protocol included [19]. The operation Data Rates (DR) can vary from 0 to 3 and the maximum power index of 5 gives a transmission power of 18.5 dBm. Technical modulation parameters are shown in Table 1. LoRaWAN DRs parameters are shown in Table 2.

For this experiment, we used one node transmitting 10 numerated messages transmitted with DR0, and 10 messages with DR3. The gateway is connected to a virtual server in a laptop to register the RSSI, SNR and the number of received messages at every transmission. Transmitter and receiver were located two meters above ground level. Physical configuration scheme is presented in Fig. 2. The implementation is available in [15].

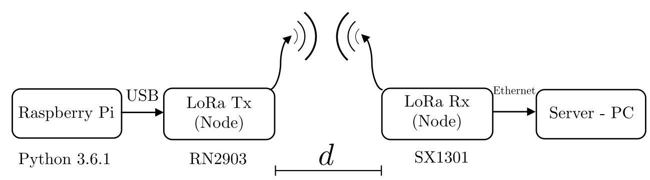

Figure 2: Equipment Physical Configuration

Table 1: Equipment and Parameters of Transmission [13]

Parameters/Equipment	Values/Description
Transmitter	RN2903
Receiver	SX1301
Antenna Gains	1.3 dBi
Modulation	LoRa
Spreading Factor	7 – 10
Bandwidth	125 kHz
Code Rate	4/5
Power Level	18.5 dBm

Table 2: Equipment Data Rates [19]

Data Rate	Configuration [SF/BW]	Bit Rate [bit/sec]
0	SF10/125 kHz	980
1	SF9/125 kHz	1760
2	SF8/125 kHz	3125
3	SF7/125 kHz	5470

4.2 Environment and Measurement Procedure

In this work, we carried out four measurements based on the previously mentioned PROMAS project using three different locations in the city of Cuenca, Ecuador. The first two measurements were made at the two riversides of Tomebamba river in an urban environment. This zone is characterized by different tree species of heights between 2 and 6 meters with irregular separations ranging from 4 to 6 meters. The ground is covered with short grass. The third measurement was done in one riverside of the Machángara river in a semi-urban zone of the same city. This place have mainly tree species of more than 5 meters in height, separations from 3 to 6 meters. The ground is covered by grass and rocks. The last measurement was done at a rural zone in the riverside of the Yanuncay River. In this zone, there are different trees species of heights between 1 to 6 meters with irregular separations from 1 to 4 meters. All rivers have a width of approximately 10 meters.

At each location, measurements were collected using a process called local average power, explained in [10]. According to this measurement procedure, one has to move a distance d of 20λ to 40λ in every measurement. Ten meters was selected in this study with the transmitter moving and the receiver (GW) fixed. As said before, at each point 20 packets were sent and registered by the receiver. Fig. 3 shows the sampling points represented by circles and the receiver location represented by the star at the upper left of the map.

Figure 3: Sampling location map - Measurement 1

4.3 Statistical Analysis and Fitting

In the first place, a correlation analysis was done using the Measurements 1 and 2 to prove the relationship between the RSSI values of the same river. A statistical analysis is done to reject the hypothesis that the urban, semi-urban and rural RSSI measurements follow the same distribution. Kruskal-Wallis and Dunn tests are used to prove the hypothesis [11]. DR0 and DR3 RSSI means measurements follow a similar distribution as shown in Fig. 4, for this reason, the tests were performed only with DR0.

This study focuses on generating a path loss model based on RSSI and SNR values. Fig. 5 shows the fitting result of the urban environment with the minimum data rate. The empirical model generated is useful to determine the number of required nodes in a riparian forested environment, that uses LoRaWAN and similar technologies.

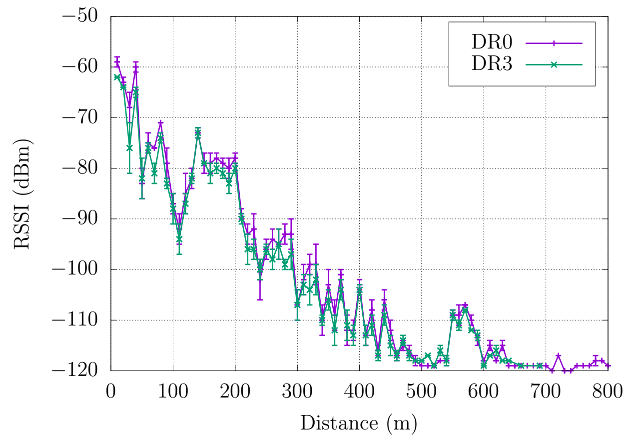

Figure 4: RSSI measurement 1 with DR0 and DR3

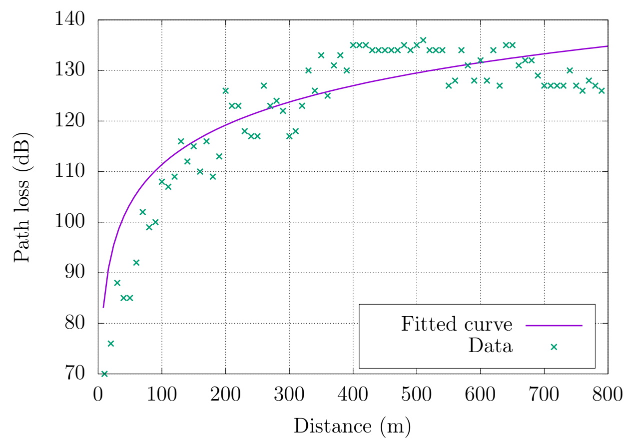

Figure 5: P_L fitting in urban environment with minimum data rate

5 RESULTS AND DISCUSSION

This section discusses and shows the measurement results of LoRa transmission on different riparian forested environments. In the first place, we show the correlation found between the riversides in the urban environment. Then the Kruskal-Wallis, Dunn tests and Path loss fitting results of DR0 and DR3 are presented. Finally, the variables of maximum coverage and standard deviation are compared between the different measurements.

5.1 Previous Measurements

To find the best number of messages to send at every sampling point, we did previous measurements of RSSI and SNR. Table 3 shows the standard deviations of RSSI for the different number of packets. Standard deviations show an expected tendency to decrease with the increase of sent messages. However, 10 packets were selected to send at every transmission point due to a low standard deviation variation of about 1 dBm.

Table 3: Standard deviation of RSSI with different number of packets

Test	Packets	RSSI Standard Deviation (dBm)
1	10	1.94
2	20	1.16
3	30	1.76
4	40	1.63
5	50	2.06
6	60	1.57
7	70	1.18
8	80	1.10
9	90	1.25
10	100	1.05

5.2 Statistical Analysis

In this section, we show the RSSI correlation analysis and Kruskal-Wallis and Dunn analysis results as described in Section 4.3.

- **Correlation Analysis:** It was carried out to know how correlated the RSSI measurements are between the two banks of the same river. In the case of measurements with the minimum data rate, a correlation value of 0.923 was obtained. Therefore, it is concluded that the correlation is high. This relationship is shown in Fig. 6.
  In the same way, in the case of RSSI measurements with the maximum data rate, a correlation coefficient of 0.922 was obtained, so it is concluded that there is a strong relationship between measurement 1 and measurement 2. This is shown in Fig. 7.
  The correlation value indicates that there is a strong relationship between the RSSI values. However, it does not mean that the LoRa coverage on the banks of the same river is the same, as it is shown in Section 5.4.

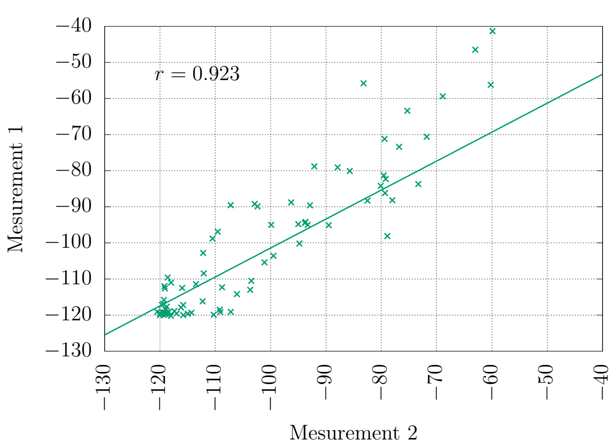

Figure 6: RSSI values at Tomebamba river with DR0

- **Distribution Comparison:** Two statistical tests were performed to determine the relationship between RSSI measurement distributions in the three selected environments. At first, the null hypothesis that the three environments had equal distributions was rejected using the Kruskal-Wallis test that resulted in a p-value of 0.01 [11].
  Then, the Dunn test was performed to compare the environment combinations. These tests are focused on proving a hypothesis of equality of distributions. Table 4 presents p-values of the test. P-values shows that there is not a distribution relationship between rural with semi-urban and urban with semi-urban environments.

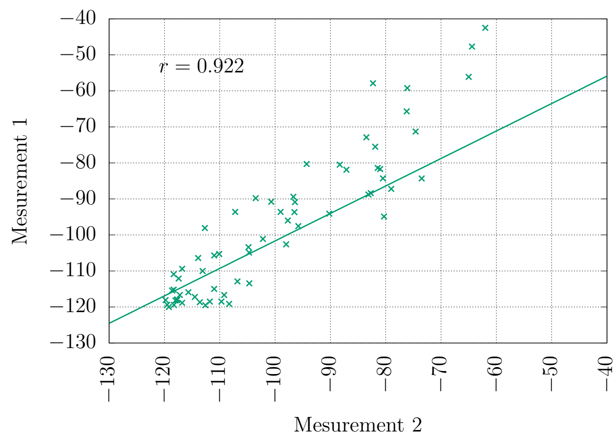

Figure 7: RSSI values at Tomebamba river with DR3

Table 4: P-values of Dunn test

P-value	Rural	Semi-urban
Semi-urban	0.0010	
Urban	0.3788	0.0100

5.3 Path Loss Fitting

With RSSI and SNR mean values, Eq. (6) was used to calculate the path loss (P_L). The obtained values were fitted to Eq. (4). Finally, Eq. (5) was used to calculate the standard deviation.

(1) Propagation on Urban Environment (Measurement 1): Fig. 4 shows the RSSI measurements with DR0 and DR3. Using RSSI and SNR data, path loss is modeled and expressed in Eq. (7) and Eq. (8) for DR0 and DR3 respectively. Eq. (8) shows less standard deviation and greater range, as shown in Tables 5 and 6. The lowest standard deviation may be because DR3 has fewer samples to adjust by its lower *SF*.

$$P_{L,DR0}(dB) = 59.53 + 11.26\ \log(d) + X_\theta(\theta = 6.29) \quad (7)$$

$$P_{L,DR3}(dB) = 53.38 + 12.98\ \log(d) + X_\theta(\theta = 5.12) \quad (8)$$

(2) Propagation on Urban Environment (Measurement 2): Compared with measurement 1, lower standard deviations are observed in DR0 and DR3, in addition to greater coverage, this is due to the topographic characteristics of the place that

are similar to those of Measurement 1 but are not the same. The logarithmic fittings are observed in Eqs. (9) and (10).

$$P_{L,DR0}(dB) = 44.96 + 13.39\ \log(d) + X_\theta(\theta = 5.83) \quad (9)$$
$$P_{L,DR3}(dB) = 26.24 + 17.49\ \log(d) + X_\theta(\theta = 3.72) \quad (10)$$

(3) Propagation on Semi-Urban Environment (Measurement 3): The third measurement was performed in a semi-urban environment. Standard deviations are lower compared to the urban measurements due to the lower number of obstacles in the environment. This is shown in the Eqs. (11) and (12). The maximum coverage also improved to 1170 and 1100 meters for DR0 and DR3 respectively.

$$P_{L,DR0}(dB) = 61.55 + 10.7\ \log(d) + X_\theta(\theta = 2.92) \quad (11)$$
$$P_{L,DR3}(dB) = 62.74 + 10.67\ \log(d) + X_\theta(\theta = 3.20) \quad (12)$$

(4) Propagation on Rural Environment (Measurement 4): The last measurement was taken in a rural setting. In this case, the obstacles were mainly trees and shrubs beside the own topography of the place. The transmission range is the best since 1600 and 1500 meters were reached for DR0 and DR3 respectively. The logarithmic fittings are observed in Eqs. (13) and (14).

$$P_{L,DR0}(dB) = 55.36 + 11.27\ \log(d) + X_\theta(\theta = 3.73) \quad (13)$$
$$P_{L,DR3}(dB) = 61.13 + 10.55\ \log(d) + X_\theta(\theta = 3.88) \quad (14)$$

5.4 Comparison of Fittings

This section summarizes the comparison of the four measurements performed. The results show that the urban environment is the one that would need a greater number of nodes to build a network with LoRaWAN technology.

- **Measurements with the Minimum Data Rate:** Fig. 8 shows a comparison of the path losses for the measured environments. It can be observed that the rural environment has the largest range. In the same way, it also can be observed that the Measurement 1, corresponding to the urban environment decays faster, as expected.
  The Measurement 3, corresponding to the semi-urban environment has the lowest standard deviation. This indicates that it fits the best to the data and presents less shadowing as shown in Table 5.

Table 5: Propagation characteristics comparison with DR0

Parameter	**Measurement**			
	Urban 1	**Urban 2**	**Semiurban**	**Rural**
Max. Distance (m)	800.00	950.00	1170.00	1600.00
Standard Deviation (dB)	6.29	5.83	2.92	3.73

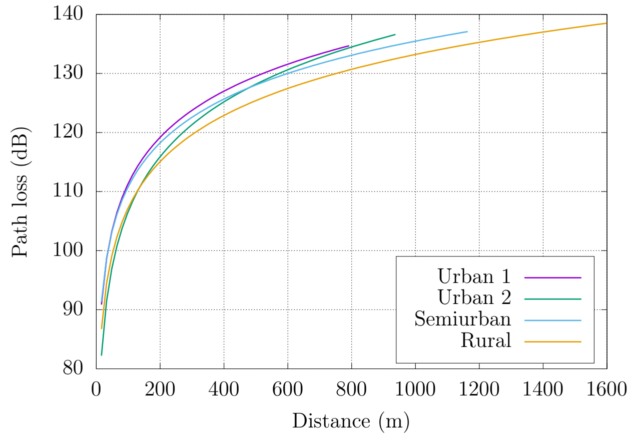

Figure 8: P_L fitted models with DR0

- **Measurements with Maximum Data Rate:** The results obtained in the measurements with DR3 are very similar to those obtained with DR0 with the difference that the coverage is lower in all the measurements. The results are shown in Fig. 9 and Table 6.

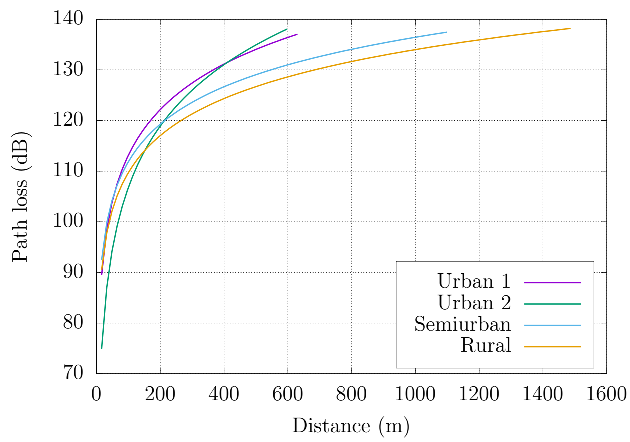

Figure 9: P_L fitted models with DR3

Table 6: Propagation characteristics comparison with DR3

Parameter	**Measurement**			
	Urban 1	**Urban** 2	**Semiurban**	**Rural**
Max. Distance (m)	640.00	600.00	1100.00	1500.00
Standard Deviation (dB)	5.12	5.72	3.20	3.88

6 CONCLUSION AND FUTURE WORK

The transmission performance of LoRaWAN has been empirically evaluated by measuring RSSI and SNR in different riparian forested environments. The measurements found that the transmission range depends strongly on the environment. The high correlation between RSSI measurements between the two banks shows a strong relationship between them. DR0 and DR3 present the same attenuation but DR0 presents a larger range in all the measurements. Correlation Standard deviation decreases in semi-urban and rural environments due to fewer obstacles. For delivering the measurements results, the path loss characteristics have been expressed as logarithmic models.

Future work will vary the transmitter and receiver antennas height to improve transmission range. Scalability in forested environments have not been proved and could present challenges to the transmission with this technology.

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