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

Pablo Avila-Campos ·
Fabian Astudillo-Salinas ·
Andres Vazquez-Rodas ·
Alcides Araujo

Abstract Low power wide area networks (LPWAN) such as long range wide area networks (LoRaWAN), provide several advantages to develop monitoring systems 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 located at urban, semi-urban and rural environments 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 a 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

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, 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

Universidad de Cuenca / Department of Electric, Electronics and Telecommunications
12 de Abril S/N, Cuenca-Ecuador
Tel.: +593-7-4051000
E-mail: {pablo.avila, fabian.astudillos, andres.vazquezr, alcides.araujo}@ucuenca.edu.ec

flow prediction using neural networks Felipe et al. (2013). The idea for the last one is to improve the model adding real time information. Currently, the researchers download the data directly at every sensor location.

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

LPWANs represent a new trend in the evolution of wireless telecommunications technologies. This communication technology is able to connect and monitor high number of sensors, covering wide areas at low energy cost Augustin et al. (2016). One of the newest approaches to this technology is long range (LoRa) Semtech (2015). LoRa gives all these LPWAN advantages, adding low device cost and easy deployment. These 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 aplication scenario for LoRa is forest environments. About 30% of the world's land surface is covered by forest, and more than 300 million people live in forest WWF (2016).

LoRaWAN, created by the LoRa Alliance, is a Medium Access Control layer that uses the advantages of LoRa modulation to create Networks and it is focused on the internet of things (IoT) paradigm Wixted et al. (2017). 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.
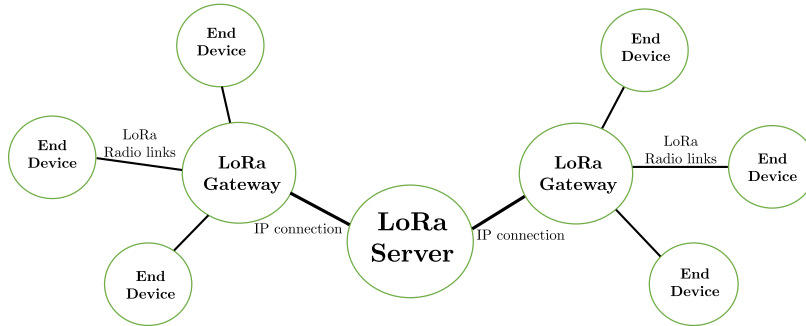

Fig. 1 LoRaWAN Architecture Vangelista et al. (2015)

When designing any wireless network, 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 communications Meng et al. (2008). The answer

also depends on different technical parameters such as the transmitter power, receiver sensitivity, signal propagation and signal frequency Harvanova and Krajcovic (2011). 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 kind of scenario is present when the limnigraphic stations are used. 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 Sornin et al. (2015).

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 Mikhaylov (2016). 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 Related Work

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

In Mikhaylov (2016), 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 Aref and Sikora (2014), 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 that they use of different payload length, transmission with the FSK modulation scheme, and the Fresnel zone is taken into account.

Another work, Wixted et al. (2017), 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 in not considered in the current work.

On the other hand, indoor measurements have been conducted in Gregora et al. (2016) and Petäjäjärvi and Mikhaylov (2016). In Gregora et al. (2016),

DR, SF, bandwidth and bit rate are fixed and RSSI is used to measure performance. In Petäjäjärvi and Mikhaylov (2016), 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.

3 Theoretical Background - 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. (1) Iswandi et al. (2017).

$$P_L(dB) = P_0(dBm) + 20 \, \log\left(\frac{d}{d_0}\right) + X_\theta \qquad (1)$$

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. (2) Rama Rao et al. (2012). 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.

$$L(dB) = A \, f^B d^C \qquad (2)$$

These models can be simplified into Eq. (3), as is proposed in Iswandi et al. (2017).

$$P_L(dB) = a + b \, \log(d) + X_\theta \qquad (3)$$

In this case, all the characteristics of Eq. (2) are expressed in Eq. (3). The exponential factor of distance is b, and the other are expressed by a. As in Eq. (1), the randomness of the received signal is expressed in X_θ. It is assumed that the error of fitting in (3) 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. (4).

$$\theta = \text{std}(P_L - \text{FittedCurve}) \qquad (4)$$

To calculate the P_L values from RSSI and SNR, Equation (5) is used according to Mikhaylov (2016).

$$P_L = |\text{RSSI}| + \text{SNR} + P_{\text{tx}} + G_{\text{rx}} \qquad (5)$$

4 Materials and Methods

This section presents a detailed description about 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 consist 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 Sornin et al. (2015). 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 Tab. 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 Pablo et al. (2017).
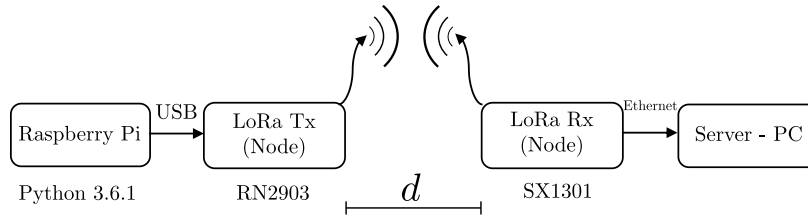

Fig. 2 Equipment Physical Configuration

Table 1 Equipment and Parameters of Transmission Microchip (2016)

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 Sornin et al. (2015)

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 in three different locations at 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 in covered with short grass. The third measurement were 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 were 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 Lee (1985). 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. Figure 3 shows the sampling points represented by circles and the receiver location represented by the star at the upper left of the map.

4.3 Statistical Analysis and Fitting

In first place, a correlation analysis was done using the Measurements 1 and 2 to prove the relationship between the RSSI values of a same river. An statistical analysis is done to prove the hypothesis that the urban, semi-urban and rural RSSI measurements follow different distributions. Kruskal-Wallis and Dunn tests are used to prove the hypothesis Mendenhall et al. (2010). 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. Figure 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.
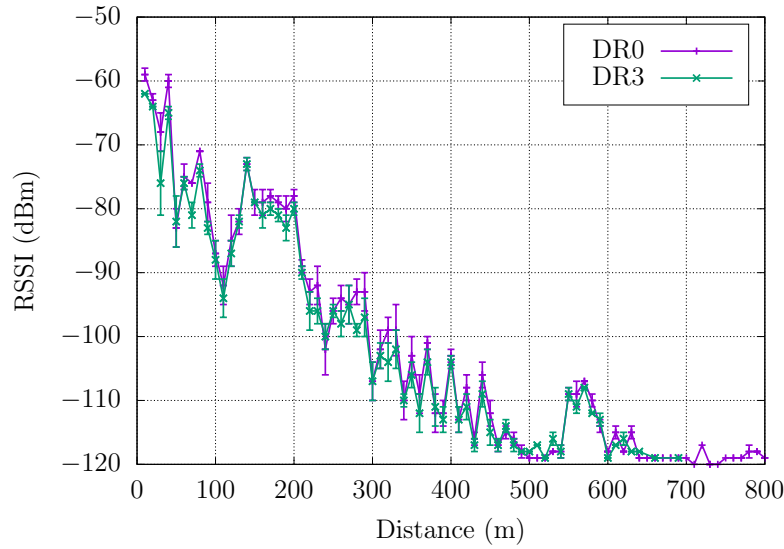
Fig. 3 Sampling location map - Measurement 1

Fig. 4 RSSI measurement 1 with DR0 and DR3

5 Results and Discussion

This section discusses and shows the results of measurements of LoRa transmission on different riparian forested environments. In 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
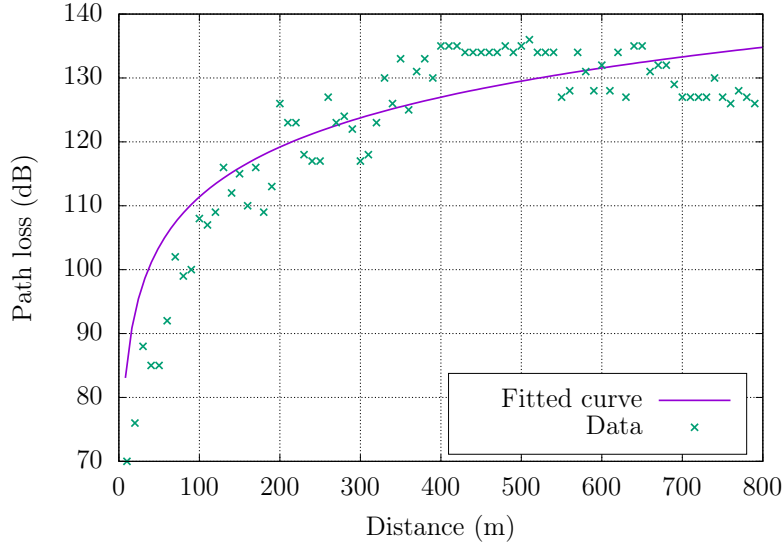
Fig. 5 P_L fitting in urban environment with minimum data rate

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 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. 5.2.

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. 5.2.

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 are the same, as it is shown in Section 5.4.
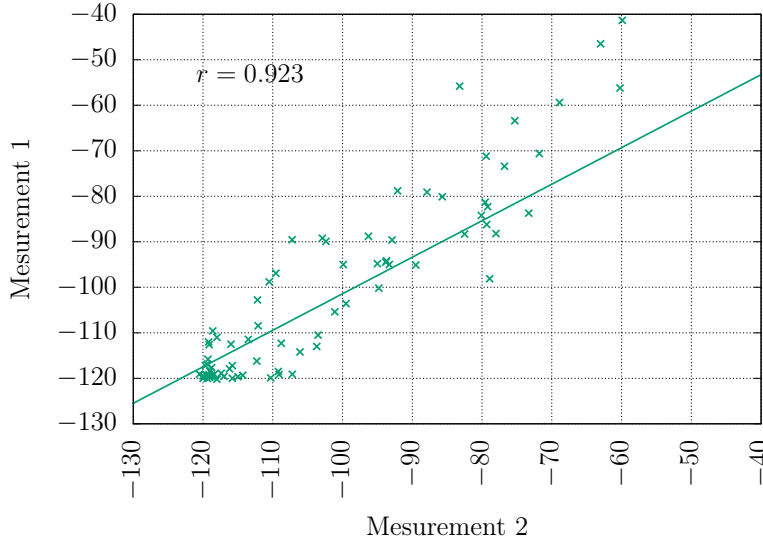

Fig. 6 RSSI values at Tomebamba river with DR0

– **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 Mendenhall et al. (2010).

Then, the Dunn test was performed to compare the environment combinations. These tests are focused on proving a hypothesis of equality of
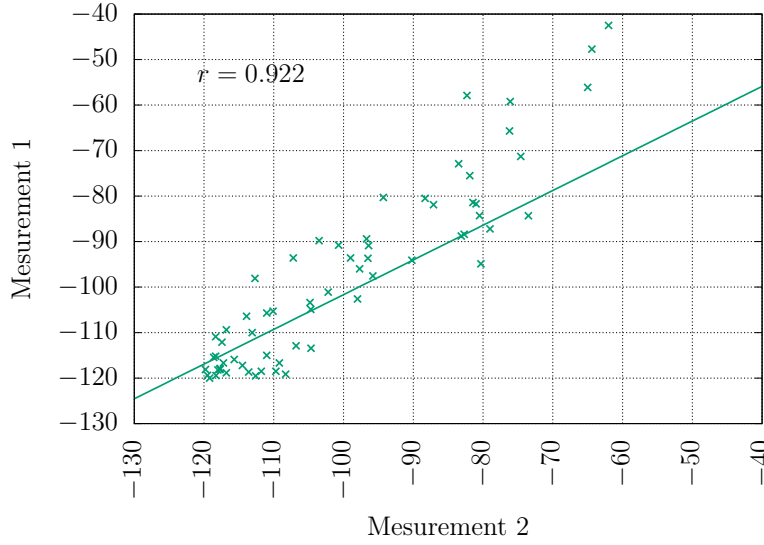
Fig. 7 RSSI values at Tomebamba river with DR3

distributions. Table 4 presents p-values of the test. P-values shows that there is not distribution relationship between rural with semi-urban and urban with semi-urban environments.

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, Equation (5) was used to calculate the path loss (P_L). The obtained values were fitted to Eq. (3). Finally, Equation (4) was used to calculate the standard deviation.

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

$$P_{L,DR0}(dB) = 59.53 + 11.26 \ \log(d) + X_\theta(\theta = 6.29) \qquad (6)$$
$$P_{L,DR3}(dB) = 53.38 + 12.98 \ \log(d) + X_\theta(\theta = 5.12) \qquad (7)$$

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. (8) and (9).

$$P_{L,DR0}(dB) = 44.96 + 13.39 \ \log(d) + X_\theta(\theta = 5.83) \qquad (8)$$
$$P_{L,DR3}(dB) = 26.24 + 17.49 \ \log(d) + X_\theta(\theta = 3.72) \qquad (9)$$

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. (10) and (11). The maximum coverage also improved to 1170 and 1100 meters for DR0 and DR3 respectively.

$$P_{L,DR0}(dB) = 61.55 + 10.7 \ \log(d) + X_\theta(\theta = 2.92) \qquad (10)$$
$$P_{L,DR3}(dB) = 62.74 + 10.67 \ \log(d) + X_\theta(\theta = 3.20) \qquad (11)$$

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 besides 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. (12) and (13).

$$P_{L,DR0}(dB) = 55.36 + 11.27 \ \log(d) + X_\theta(\theta = 3.73) \qquad (12)$$
$$P_{L,DR3}(dB) = 61.13 + 10.55 \ \log(d) + X_\theta(\theta = 3.88) \qquad (13)$$

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:** Figure 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
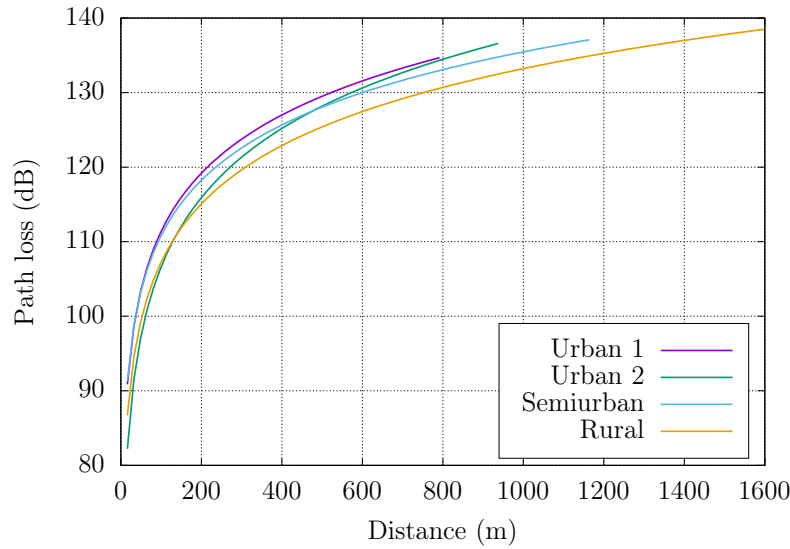
Fig. 8 P_L fitted models with DR0

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 is the one with the lowest standard deviation. This indicates that it was the one that best fit the data and in which there was less shadowing as shown in the 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

– **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.

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
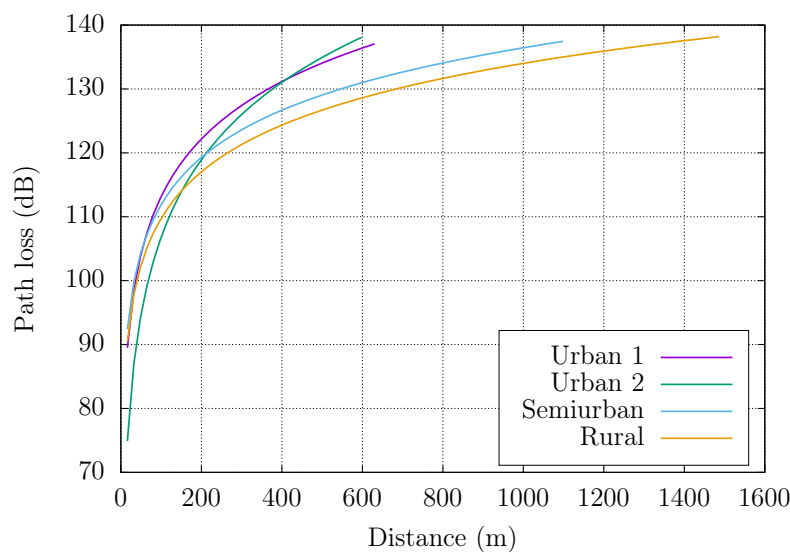
Fig. 9 P_L fitted models with DR3

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

measurements found that 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 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.

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

Availability of data and materials

Not applicable

Competing interests

The authors declare that they have no competing interests.

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Authors contribution

PA designed the idea, performed the experiments, processed the data and partially written the manuscript. FA and AV verified the experiments and results, analyzed and interpreted the data and completed the writing of the manuscript. AA gave valuable suggestions on the structuring of the paper and assisted in the revising and proofreading. All authors read and agreed the manuscript.

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Abbreviations

BW: Bandwidth; DR: Data rate; GW: Gateway; IoT: Internet of things; IP: Internet protocol; LPWAN: Low power wide area networks; LoRa: Long range; Packet error rate (PER); PROMAS (spanish abbreviation): Program for Water and Soil Management; RSSI: Received signal strength indicator; SF: Spreading factor; SNR: Signal-to-noise-ratio; Wireless sensor network (WSN).

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