Performance of LoRaWAN Networks in Outdoor Scenarios

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Abstract—**The growing interest in Internet of Things (IoT) has facilitated the appearance of applications which use Low-Power Wide Area Networks (LPWAN). Networks based on the Long Range Wide Area Network (LoRaWAN) standard highlight among these. This paper presents a wide overview of this recent technology and some practical experiments. The developed LoRaWAN devices that compose the network as well as the server used to collect data are presented. Based on this testbed, some experiments are performed in two different scenarios to check the performance in terms of coverage, Signal-to-Noise Ratio (SNR) and Received Signal Strength Indicator (RSSI). Results show that LoRaWAN networks can be a useful solution to implement monitoring networks.**

Keywords-Internet of Things (IoT); LPWAN; LoRa; LoRaWAN; LoraServer: Highway; Rural; SNR; RSSI.

I. Introduction

The evolution of technologies and the ability to interconnect different devices have led to the existence of networks capable of communicating and acting together, creating what is known as Internet of Things (IoT) [1]. Thanks to sensors and actuators, it is possible to measure our environment and share data which, collected by platforms, allows the developers to create useful applications for the society [2]. The critical point in many scenarios resides in the energy consumption due to the batteries which feed these things. This is why so-called LPWAN technologies, which permit low power transmission, have been developed. In return, the transmission data rate is reduced (e.g., hundreds of kbps) but it is still enough for many IoT applications. Because of their standardization and the usage of non-licensed spectrum, these technologies have become serious competitors of solutions based on cellular networks, such as Long Term Evolution-Category M (LTE-M) or NarrowBand-IoT (NB-IoT) [3]. The most popular LPWAN technologies are Sigfox, LoRaWAN, Ingenu TPMA, and nWave. Their main characteristics and differences, assuming European parameters, are shown in Table I.

In this paper, we present the LoRaWAN technology and its main features to be considered for deploying this kind of networks. The paper also presents the devices we develop that compose our network and the server used to collect the data. Finally, practical experiments are carried out in two different scenarios to check the actual performance of this kind of networks.

TABLE I. Characteristics of LPWAN Technologies

Parameter	***Standard***			
	LoRa	***Sigfox***	***RPMA***	***nWave***
Frequency Band	868/915 MHz ISM	868/902 MHz ISM	2.4 GHz ISM	Sub-GHz ISM
Bandwidth	Ultra NB	8x125kHz Mod: CSS	1 MHz 40 channels	Ultra NB
Range	2-5k urban 15k rural	30-50k r. 1000k LoS	500k LoS	10k u. 20-30k r.

The remainder of this paper is organized as follows. Section II presents some related work. Fundamentals of the LoRaWAN standard are explained in Section III. Section IV depicts our LoRaWAN network prototype. Section V describes the performance evaluation experiments and results. Finally, Section V draws the main conclusions and future work.

II. Related Work

In this section, we present the related work on LoRa and LoRaWAN performance evaluations and LoRa implementations.

A performance analysis of the LoRa FABIAN network protocol stack for IoT, that employs protocols, such as CoAP, HTTP and DNS, was performed by Tara Petrić et al. in [4]. Authors evaluated the Packet Error Rate (PER), the Received Signal Strength Indicator (RSSI) and the Signal to Noise Ratio (SNR) of three LoRa stations deployed over Rennes, France. They highlighted the importance of the location and elevation of the antenna on the performance. Results showed frame losses of 3% under the best conditions. Authors concluded that SNR could be the best metric as RSSI did not present strong correlations.

A performance analysis of LoRa over critical noise conditions was performed by L. Angrisani et al. in [5]. For the transmitter, a LoRa STM32 Nucleo pack comprised of a SX1272 low-power RF shield and a NUCLEO-L073RZ board was utilized. The testbed utilized a master-slave configuration between the transmitter and receiver and employed LabView to perform the measurements. Results showed worse communication with larger bandwidth configurations. High SF (Spreading Factor) values achieve better performance. Finally, higher CR (Coding Rate) values obtained lower improvements in packet loss.

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LoRa servers have been implemented in order to be utilized for different types of applications. Jaeyoung So et al. implemented in [6] a LoRa server on OpenStack called LoRaCloud. Authors employed four virtual machines to implement the functions of LoRaCloud. These functions were the application server agent, the gateway agent, LoRa data and LoRa control. The gateway was implemented employing the SK-iM880A and the LoRa device was implemented with the 868 IoT station (Kerlink), using Semtech's HAL as software.

T. Hirata et al. presented in [7] a rice field management system employing LoRa servers. The servers were comprised of an AVR microcontroller, an SD card module, a LoRa module and a battery. The master was implemented utilizing a Raspberry Pi. Experiments were performed for seven days employing seven field servers. Results showed a power consumption of 75.36 mW per day providing the system with a 995-day continuous operation time.

Lastly, W. Zhao et al. implemented in [8] a smart irrigation system that utilized LoRa as the communication protocol. The system was comprised of a LoRa server for validation, description and data analysis, a cloud server for data storage and, as an interface between the applications and the LoRa server, the irrigation nodes and the gateway. Real experiments were performed measuring SNR and RSSI every 500 meters. Results showed that the SNR decreased 20 dBm and the RSSI presented a sharp decrease in the first kilometer. However, the SNR presented a slow decrease and RSSI remained stable in the last 7 km. Moreover, a communication distance of 8 km was achieved between node and gateway.

Other papers have studied performance analysis of LoRa or have used LoRa for diverse IoT systems. In this paper, we focus on the performance analysis of LoRaWAN with the implementation of TTN (The Things Network).

III. LoRaWAN Overview

This section presents some of the most important issues to be taken into account for deploying a LoRaWAN netwotk.

A. *LoRa Modulation*

LoRa® (Long Range) is a proprietary modulation of Semtech. It is based on CSS (Chirp Spread Spectrum) and aims at increasing the communication range while keeping the same low power characteristics of the FSK modulation. This modulation uses the full channel bandwidth to send signals, making a distinction between 'up-chirp' and 'down-chirp'. 'Up-chirp' refers to transmissions in which the frequency changes from the lowest to the highest value, and 'down-chirp' refers to the opposite situation. This technique allows LoRa to modulate its symbols in 'up-chirps' with a bandwidth of 125 kHz, 250 kHz or 500 kHz and with different Spreading Factors (SF) depending on the required data rate and channel conditions [9][10].

B. *LoRaWAN Networks*

The LoRaWAN standard, which is managed by the LoRa Alliance, defines a protocol architecture (specifying the Medium Access Control layer or MAC) and a system architecture. This standard allows devices to use either FSK or LoRa as modulations on the physical layer.

Regarding its architecture, it uses a star topology with a central device known as gateway. End- nodes communicate directly with the gateway through the radio interface. The gateway uses a normal network interface (e.g., Ethernet or Wi-Fi) to communicate with an application server through a network server. The usage of a star topology, instead of mesh network architecture, increases the lifetime of batteries, network capacity, security and quality of service (QoS), among other characteristics. In a mesh network, each node would act as an end-node and as a gateway (router) [11], which causes a greater number of hops and their corresponding packet forwarding, hence producing higher power consumption.

Nodes are not associated with specific gateways. Instead of this, any message received by a gateway will be forwarded to its network server, and these, in turn, will forward it to its application server.

Bi-directional communication between nodes and gateways are allowed by LoRaWAN. In particular, there are three classes of end-nodes named A, B and C [10]. Class A must be implemented by all the nodes, and all the classes are able to coexist in the same network. The characteristics of each class, whose transmission is depicted in Figure 1, are defined below:

- Class A: It is the class that consumes the lowest possible power. It is used in applications with unidirectional communication (from nodes to gateway), allowing a transmission in the downlink direction just after the node has finished its transmission. It is suitable for battery-based sensors.
- Class B: It is characterized by the possibility of opening extra reception windows at certain moments, in order to increase transmissions from the gateway to the nodes. For this reason, the consumption is higher than that of class A. This class is suitable for battery-powered actuators.
- Class C: The devices that implement this class are able to receive data from the gateway at any time (except when the device is transmitting). It is suitable for nodes connected to the electricity grid.

The prototype presented in this paper will employ class A devices.

C. *LoRaWAN Security*

LoRaWAN uses two security layers characterized by protecting data at the link layer as well as at the application layer. As for the application layer, data is encrypted between the node and the application server, which implies end-to-end confidentiality. As for the link layer, a field (MIC), which allows guaranteeing data integrity between the node and the network server, is included. Figure 2 summarizes LoRaWAN security, which is explained below:

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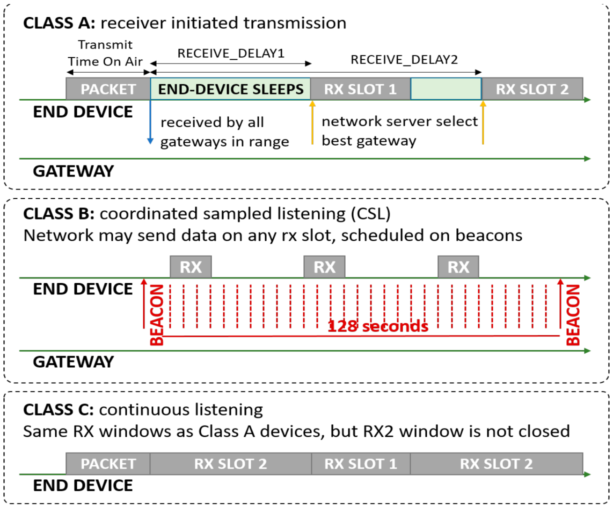

Figure 1. LoRaWAN Device Classes and Packet Transmission.

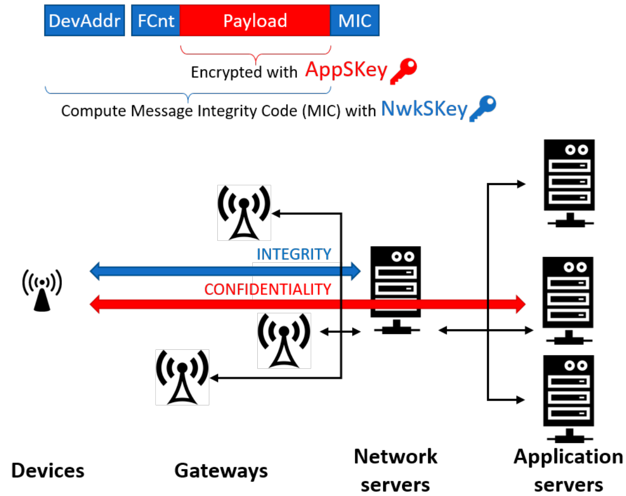

Figure 2. LoRaWAN Security.

- Authentication: A shared key is known by the node and the network, and it is used by AES-CMAC algorithms which are employed when a node joins the network. Two keys named AppSKey and NwkSKey, which are used for the data encryption and data integrity, are derived from the previous key.
- Integrity and confidentiality: The previous session keys are used for protecting all the traffic in a LoRaWAN network. Therefore, the NwkSKey is used for the end-to-end encryption between the node and the application server. Similarly, the AppSKey key is used to calculate a Message Integrity Code (MIC) in order to guarantee the integrity between the node and the network server. Finally, a sequence frame counter is included to prevent replay attacks.

There are two activation methods for initiating the connection: Over the Air Activation (OTAA) and Activation By Personalization (ABP). OTAA uses the parameters JoinEUI (Application ID), DevEUI (Device ID), NwkKey and AppKey (end-nodes specific keys). The previous session keys are obtained from these parameters. On the other hand, using ABP, these parameters must be previously personalized in both the node and the servers.

IV. LoRaWAN Network Prototype

In this section, the implemented prototype is presented. This prototype will be used for the performance assessment in several scenarios.

The first components of a LoRaWAN network are the end-nodes and the gateway. The components are shown in Figure 3 and are described below:

- DIY multi-channel Raspberry Pi Gateway: the chosen gateway is composed of a Raspberry Pi 3 Model B, an IMST ic880A concentrator with a maximum transmission power of 20 dBm and an 868 MHz antenna with 2 dBi gain.
- End-Device: the used end-device is based on the development board 'WeMos D1 Mini', which uses the ESP8266 chip. A shield with the RN2483A chip (up to 14 dBm of TX power), which implements both the physical and the MAC layers of the LoRaWAN standard, is connected to the WeMos board. These are supplied by a external power bank.

As shown in Figure 4, the gateway is connected to a network server by an Ethernet, WiFi or 3G/4G connection. The most popular LoRaWAN network infrastructure is called The Things Network [12]. This infrastructure is an open and collaborative LoRaWAN network. There are also other network infrastructures which allow creating a private environment, such as the LoRa Server [13]. The main characteristics of those servers are described below.

A. *The Things Network (TTN)*

TTN is a community which offers open source software projects to its users to make possible the connectivity between different elements in a LoRaWAN network. One of its main strengths is the capability of connecting any LoRaWAN gateway to its network servers, so no extra infrastructure is required. In addition, it allows the configuration and data gathering through a simple but complete graphical user interface. Even if TTN offers a simple and scalable solution for servers, they are still external and therefore data is shared with the organization.

B. *LoRa Server*

LoRa Server (LS) project provides open-source components for building LoRaWAN networks. It provides the necessary and MIT licensed software components. Those are depicted in Figure 4, which shows the architecture of this project.

Packets are sent to the “LoRa Gateway Bridge”. This component could be installed both on the gateway and on the server environment, and it is in charge of the transformation of the packet-forwarder UDP protocol into messages over MQTT. The Broker will forward packets received by the Lora Gateway Server to the LoRa Server. This last component is in charge of the control and management of the network state as well as of the knowledge of active devices and their uplink/downlink frames.

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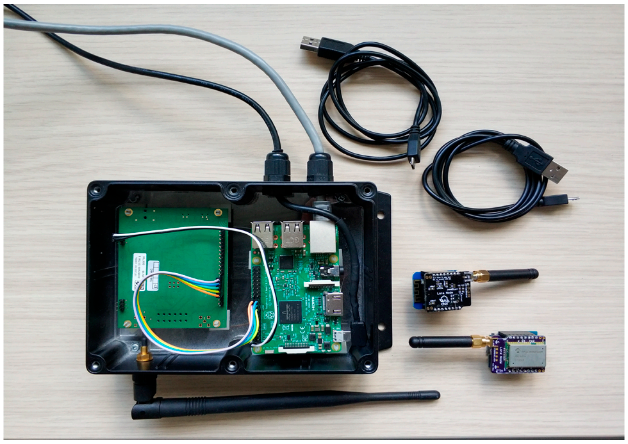

Figure 3. LoRaWAN Components: Gateway and End-node.

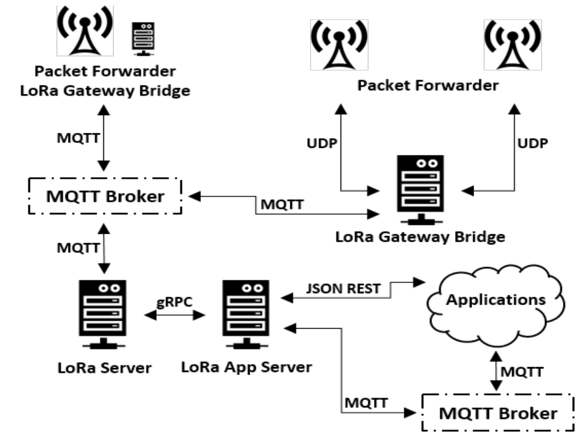

Figure 4. LoRa Server Architecture.

Lastly, LS project provides an application server called LoRa App Server, which allows the configuration of users, devices and applications by a graphical user-friendly interface. It is also responsible for handling of join-request and the handling and encryption of application payloads.

The main difference between both projects is the privacy. Using TTN you are able to create a collaborative network which allows you to use other gateways to reach your network and application server. However, if you are running a commercial solution and data is sensitive, you may create your own private solution with LoRa Server.

Although TTN has been used for the deployment done in this article, we have deployed a private environment using Ubuntu 16.08 Xenial EC2 instances of Amazon Web Services. This server will be used for future works.

V. RESULTS

This section shows the results of the network performance registered in our test bench. In order to evaluate the received signal strength by the nodes, an obstacle-free scenario and a coast rural scenario have been chosen.

A. Highway Scenario

The selected scenario is a road environment very similar to a highway (See Figure 5). It has three lanes in each side and also, pedestrian and bike lanes which lets us walk to take the measurements. Measurements have been taken while walking. The evaluated parameters have been the SNR, the RSSI, the packets loss ratio and the coverage of the end-device.

This road joins together the road named A-4006 on the north area of Granada with the street named *Camino Nuevo* at the entrance of Maracena. The route has approx. 3.3 km with 74 m of gradient. The gateway, whose location is in (37.2136373, -3.5951833) geographical point, is placed on a bridge which crosses the road as shown in Figure 5. It is almost a straight route without buildings or obstacles.

Figure 5. Gateway Placed.

Figure 6 shows the results obtained as a function of the distance, taking the gateway as reference point. The X axis of Figure 6a and 6b represents the distance from the end-device to the gateway. By performing an analysis of the results (Table II), it is possible to split them into four distance ranges. As shown, at 1000 m from the gateway, the average and maximum SNR values are 8.56 dB and 11 dB, respectively. In addition, Table II shows the 5 and 95 percentiles of the SNR, showing e.g., that 95% of the measurements are above 5.53 dB. The SNR decreases as the distance from the gateway increases. At 2.5 km, we can observe negative SNR values, which indicate that the noise level is higher than the received signal. Despite this, LoRa modulation robustness lets the gateway receive the packets correctly up to 3.3 km (see Figure 6c). It should be pointed out that the urban area of Maracena starts at this point, so the presence of buildings significantly reduces the SNR and the level of the RSSI.

Finally, Table II also shows the percentage of packet losses as a function of the distance to the gateway. As shown, the number of wrong packets received by the gateway increases as the distance to the gateway increases, being these losses more problematic for the last range (from 3 to 3.3 km).

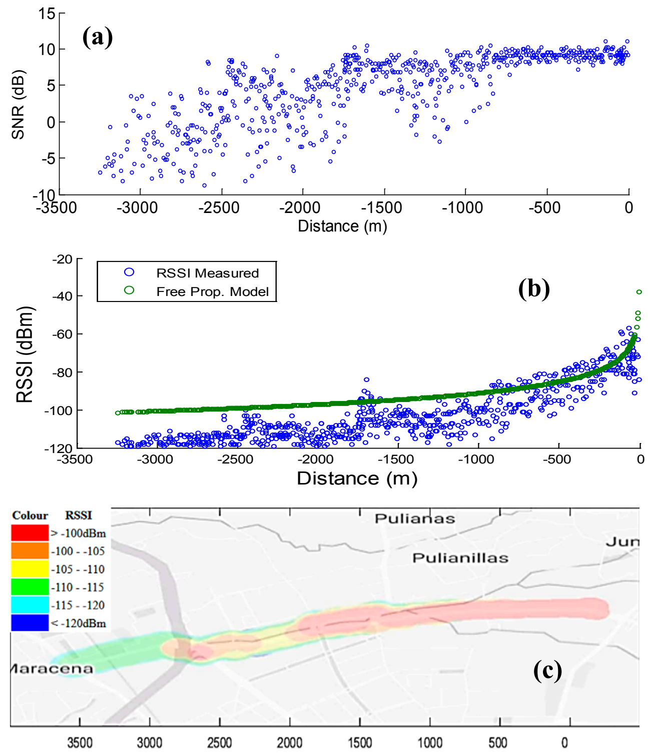

Figure 6. Measurement results of scenario 1. (a) SNR vs. Distance; (b) RSSI vs. Distance; (c) coverage map.

TABLE II. AVERAGE VALUES AND PERCENTILES IN SCENARIO 1

Dist. (km)	*Average Values, percentiles and packet loss in scenario 1*						
	SNR (dB)	*P5 (dB)*	*P95 (dB)*	*RSSI (dBm)*	*P5 (dBm)*	*P95 (dBm)*	*% of Packet Loss*
0-1	8.6	5.53	10.2	-89.4	-107	-68	4.72
1-2	4.82	-2	8.66	-108.3	-116	-99	9.84
2-3	-0.54	-7.33	6	-114.5	-118	-108	28.35
3-3.3	-5.14	-8.2	-0.5	-118.1	-119	-117	71.42

B. Coast Rural Scenario

In this case, the gateway with coordinates (38.932457, -0.099974) is placed on the terrace of a second floor house (~9m of height). The building is found at Oliva, a coast village of Valencia (Spain). The path followed and the coverage map is shown in Figure 7. The maximum measured distance is about 615 meters. As we can observe, this scenario has very different conditions. The scenario is composed by several small houses and the climate conditions are also different (higher humidity).

Taking the position of the gateway as the reference point, the measurements show the SNR (see Figure 8a) and RSSI (see Figure 8b) values as a function of the distance. It is remarkable how those values decrease with respect to the highway scenario. This is due to the presence of different obstacles like houses and vegetation. Table III summarizes the performance results. These results can be split into three distance sections. First one ranges from the first 200 meters and it includes the urban core. Considering the height of the gateway, there is practically direct vision with the end-node. The average SNR is 5 dB and the highest value is 8.2 dB.

According to the 5 percentile and Figure 8a, we observe that a 95% of the measurements are over 0.1 dB.

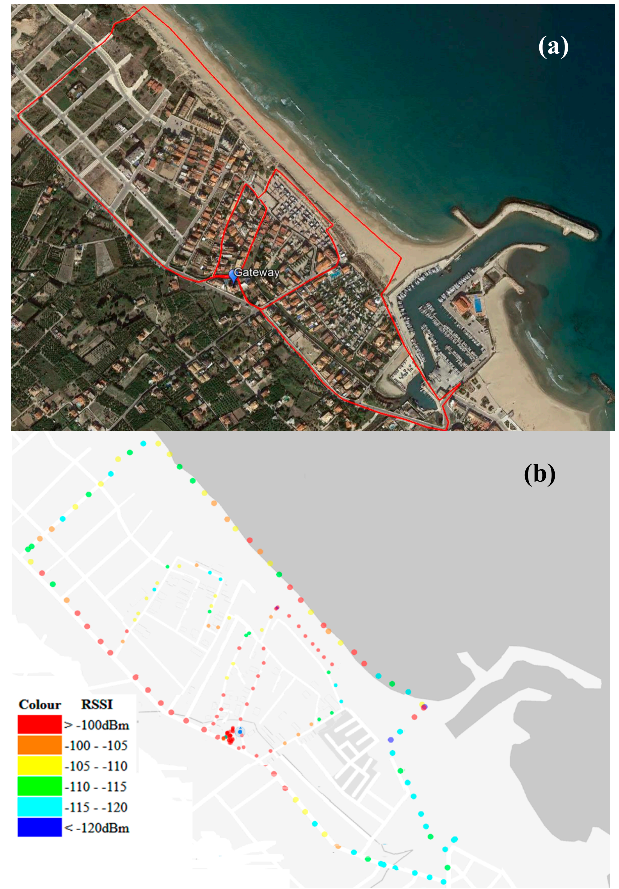

Figure 7. Oliva Map Coverage. (a) aerial map;(b) TTN map results

TABLE III. AVERAGE VALUES AND PERCENTILES IN SCENARIO 2

Dist. (km)	**Average values, percentiles, and packet loss in scenario 2**						
	SNR (dB)	*P5 (dB)*	*P95 (dB)*	*RSSI (dBm)*	*P5 (dBm)*	*P95 (dBm)*	*% of Packet Loss*
0-0.2	4.97	0.1	7.5	-85.77	-111.1	-61.9	50
0.2-0.4	2.75	-7.78	6.8	-105.31	-122.3	-87	48
0.4-0.6	0.52	-9.88	6.39	-112.15	-120	-101	57

The rest has a negative SNR value due to the non-direct vision with the gateway. The second section ranges from 200 to 400 meters. In this area, we find the beach (in front of the gateway), a nautical port (right) and houses with empty parcels (left). As we can see, SNR and RSSI values start to decrease because of the distance and the different nature of the environment. The average RSSI decreases by 20 dBm, which implies that the strength of the signal worsens considerably.

Last section ranges from 400 to 615 meters approximately. The majority of those measurements are taken in the left area of the gateway. This part includes empty parcels so the measurements improve with respect to the total of measurements in the second area.

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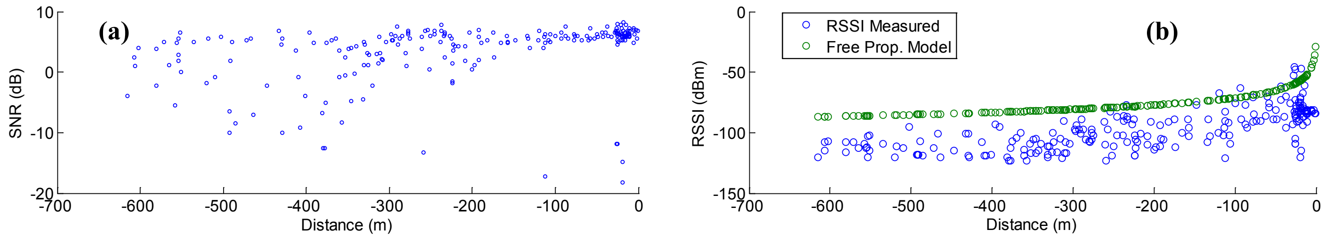

Figure 8. Measurement results of scenario 2. (a) SNR vs. Distance; (b) RSSI vs. Distance.

As shown in Table III, the average SNR is still positive and the 95% of the SNR measurements is over and above -9.8 dB, two points lower than in the second area. Even so, the 95% of the RSSI measurements are two points better than in the previous section. Regarding the percentage of packet losses, the RSSI and SNR are more affected by the presence of buildings, reaching values of 57% for distances of 600 m.

VI. CONCLUSIONS

The aroused interest in LoRaWAN networks and the lack of practical experimental studies have generated the need of deploying these networks in several scenarios to get valuable information regarding aspects of maximum coverage and network performance. This article has presented the main characteristics of the LoRaWAN architecture and how these networks work, including as well, a real experimental study performed in two different scenarios. From the analysis of the results, we can conclude that a LoRa network based on our devices could be cover a distance higher than 3 km, in free-obstacle scenarios, since our gateway is still capable of receive packets correctly. Thus, LoRa networks would be an interesting solution for getting data in scenarios, such as crops or rural areas where we want to cover a very large area. As future work, we would like to test new networks and application servers which allow us to deploy completely private environments. The different power options will be also measured. Finally, we will perform real experiments in urban and indoor environments in order to compare the LoRa performance in several scenarios, such as agricultural holdings [14].

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