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Experimental Analysis of IoT Networks Based on LoRa/LoRaWAN under Indoor and Outdoor Environments: Performance and Limitations

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Abstract: Nowadays, Internet of Things (IoT) has multiple applications in different fields. This concept allows physical devices to connect to the internet in order to establish a strong infrastructure that facilitates many device control and monitoring tasks. Low Power Wide Area (LPWA) communication protocols become widely used for IoT networks because of their low power consumption and the broad range communication. LPWA enables devices to transmit small amounts of data in a long distance. Among LPWA protocols, LoRa technology gained a lot of interest recently from the research community and many companies. LoRa is a long range and low power wireless communication technology regulated by the LoRaWAN standard. It can be o good candidate to deploy node network where long distance and extended battery life is required. A LoRaWAN architecture is deployed in a star-of-stars topology and based on a systematic evaluation of a long-term operation of the network monitoring. This works describes experimental results of testing LoRa in indoor and outdoor environments to understand how it works, evaluate its performance, and limitations. As expected, results show that LoRa performs better outdoor. It is also interesting to note that elevating the gateway in order to have a free line of sight with the IoT node, or close to it, increases the signal quality received by the end-node devices, and consequently, longer distances can be achieved.

Keywords: Internet of Things, LPWAN, LoRa, LoRaWAN, TTN, cloud server.

1. INTRODUCTION

Nowadays, many companies are introducing solutions and services based on the Internet of Things (IoT). A typical IoT system is composed of nodes with an embedded micro-controller managing the specific action of the node (sensing, controlling,...) and data communication with a gateway; a gateway communicating with the nodes in the local network based on multiple communication protocols, and a server where the gateways are connected (through Ethernet, typically) and store node data or receive command to act on the nodes. IoT solutions are extending into new areas everyday, and several fields are already using this technology (industry, farming, house automation,...). For instance, in smart homes and buildings, intelligent security and thermostat systems are becoming popular. The industry sector has evidenced a big evolution thanks to the development of intelligent production systems where it is possible to create automation processes with real-time monitoring and control. These intelligent systems leads to the concept of smart industry, where the labor costs are reduced to generate more revenue. In the smart health area, health monitoring becomes easier with IoT solutions applied in this domain. Wearable IoT devices to extract vital measurements help hospitals to remotely monitor the health of their patients in real-time (Mishra and Rasool, 2019). IoT can also help to prevent ecological catastrophes by deploying warning systems based on toxic gases, water leak and temperature sensors (Lee et al., 2016). In the field of agriculture: temperature, humidity and other critical parameters such as pH and nutrition content can be measured and analyzed using IoT systems in order to optimize the yield. However, it is important to note that each application requires a different approach in the use of technologies for IoT device design and communication protocols used. For instance, in the case of agriculture, nodes must communicate in a long distance while having a long battery life. In this case, LPWAN represents a practical solution to provide cost-efficient IoT connectivity for small sensor nodes distributed over large areas.

Low Power Wide Area Networks (LPWAN) systems aim to overcome the challenges of IoT, thanks to the large communication range and low power consumption, as long as low bandwidth and non-critical communication is required (Raza et al., 2017). The data transfer rates provided by

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LPWAN are up to hundreds of bits per second, while the communication range is up to several kilometers. Battery life is a key factor for IoT systems, LPWAN promises a long life battery thanks to the low power consumption of LPWAN technologies. LPWAN have a single hop topology where end devices (nodes) communicate directly with gateways, but they can't communicate directly among them. Gateways act as bridges between LPWAN and a cloud server. The robust modulation techniques used in LPWAN allow sensor nodes to communicate with the gateway even under low Signal to Noise Ratio (SNR) and Received Signal Strength Indicator (RSSI) values. Several LPWAN technologies exist such as LoRa, SigFox, RPMA, NB-IOT, etc. LoRa technology has received a lot of interest from research recently. This technology is suitable for large-scale networks deployments in large environments, which can be covered by a single gateway with no need for any relays or handover, with low power, too (Atta, 2017).

In this work we focus on measuring and evaluating LoRa technology and its communication protocol, LoRaWAN. We provide further insight over how the performance of a LoRa network can be affected by placement of the sensor nodes and we will evaluate the performance based on coverage (RSSI values), SNR values and packet received ratio. The LoRa network is tested in two environments: indoor and outdoor. This work is organised as follows: in Section 2 we give an overview about LoRa and LoRaWAN, and how it works; in Section 3 we discuss about related works; in section 4 we describe the setup and the environments where the performance measurements were done, and results of measurements are shown. Finally, section 5 concludes the paper, discussing the obtained results.

2. OVERVIEW OF LORA AND LORAWAN

LoRa is a long range and low power wireless technology that aims to increase battery lifetime of the devices, support a large number of connected devices, and improve the network robustness and capacity. As described in Fig. 1, LoRa technology consists of two layers: Physical and MAC. The physical layer is patented by Semtech (Haxhibeqiri et al., 2017a) and is based on Chirp Spread Spectrum (CSS), which affords high sensitivity for the receiver, in addition, the robustness against noise is increased thanks to the forward error correction messages used in this layer (Guibene et al., 2017). LoRaWAN is a MAC layer protocol and system architecture design and is standardized by the LoRa Alliance (Vangelista et al., 2015). LoRa technology uses unlicensed radio spectrum in the Industrial, Scientific and Medical band (ISM).

In Europe, LoRa uses the 863-870 MHz frequency band. It can operate in two sub-bands, one at 868 MHz and one at 867 MHz. The 868 MHz sub-band affords three LoRa channels of 125 kHz, while the 867 offers five channels of 125 kHz (Haxhibeqiri et al., 2017b). The LoRaWan duty cycle can be 0,1%, 1% or 10%. Regulations in Europe (ETSI, 2012) ask for adhering to a 1% duty cycle per sub-band. The duty cycle represents the delay between the successive frame sent by the device using the same channel. The payload of each transmission can be from 2 to 25 octets, while the data rate can achieve 50 Kbps, this rate varies based on the Spreading Factor (SF). The SF is given as a logarithm, in base 2, of the number of chips per symbol. A symbol is an instantaneous change in frequency, LoRa uses 6 different SF ranging from 7 to 12. If the SF is increased, the receiver sensitivity will increase, but the bit rate will decrease. The relationship between the bit rate, SF and the receiver sensitivity is given in table 1.

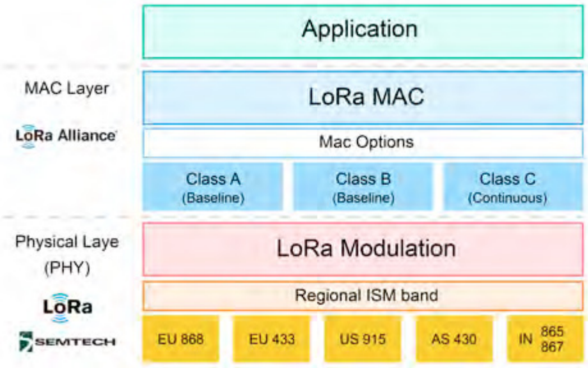

Fig. 1. LoRa technology protocol stack.

SF	Bit rate [kbps]	Rx sensitivity [dBm]
12	0,25	-137
11	0,44	-135
10	0,98	-133
9	1,7	-130
8	3,1	-129
7	5,4	-124

Table 1. Relationship between Spreading Factor (SF), Bit rate and receiver (Rx) sensitivity.

The LoRaWAN MAC layer provides the mechanism to enable the communication between LoRa devices and the LoRaWAN receiver gateway. LoRaWAN has a star topology architecture: the end-devices can not communicate one to another, they can only communicate with the receiver gateway. However, multiple gateways can be connected to a central LoRaWan server. In an IoT netowrk, an IoT node corresponds to an end-device.

LoRaWAN specifies three different classes of end-devices to address the various needs of applications:

- Class A: The end-devices support bidirectional communication. The class A device has a duty cycle of active/sleep interval, while the server remains active. The end-device sends an uplink packet and waits for a potential data reception within the specified intervals. Class A communication is always initiated by the end-device.
- Class B: The end-devices are synchronized to the network using periodic beacons. the class B device regulates its transmission windows and schedules receiver slots periodically. Therefore, the speed and cycle of data transmission are controlled by the server.
- Class C: The end-device can continuously receive, except when it transmits. It has almost no sleep time. Class C reduces latency, and is suitable for applications where continuous power is available.

3. RELATED WORK

The research community has already published many studies on different aspects of LPWAN technologies. The authors in (Cattani et al., 2017) show how variables such as weather conditions, temperature or humidity affect the performance of an LPWAN solution. For example, increasing the temperature by 10°C will reduce the RSSI by 1 dBm.

Oversaturation of the network is also another variable that can highly affect the Pattern Recognition Receptor (PPR), due to the high risk of packages collision if several end-devices are transmitting at the same time. The collision and packet loss analysis in a LoRaWAN network is described and simulated in (Ferré, 2017), together with their mathematical theory.

LoRa networks allows the public use of the neighboring gateways, which can cause interference. The authors in (Voigt et al., 2016) studied these interferences and showed that a directional antenna in presence of multiple gateways can be a solution to avoid this interference.

In order to avoid data collision, the duty cycle for EU bands is limited to 1%. The capacity limitations of LoRaWAN networks due to densification and duty cycle restriction are discussed and simulated in (Adelantado et al., 2017). In (Petäjäjärvi et al., 2017), the authors evaluate a LoRa network performance when end-node devices are mobile. Their results shows that, when the moving speed exceeds 40 km/h, the performance of communication is deteriorated, while the communication is relatively reliable for speeds below 25 km/h.

The network capacity is also studied in (Mikhaylov et al., 2016). The authors show that nodes near the gateway can send 2 kbit/s on average in uplink; this number decreases for an increased distance from the gateway, down to only 100 bit/s on average for far away nodes.

4. EXPERIMENTAL SETUP AND RESULTS

The experimental setup used in this study consists of a gateway, an end-node device and the cloud server of The Things Network (TTN). TTN is an initiative to build a worldwide open source infrastructure based on LoRaWan standards to facilitate a public IoT (Barro et al., 2019). The end-node used is ”WiMOD Demo Board” from IMST. The board includes a LoRa radio module iM880B already soldered; this module operates in the unlicensed 868 MHz band and combines a powerful Cortex M3 controller with the LoRa transceiver from Semtech (Fig. 2(a)). A temperature sensor and a potentiometer are implemeted in the board along with multiple inputs/outputs, and it's powered using 2 batteries AAA which make it portable. The gateway used is ”WiMOD LoRa Lite Gateway” from IMST, consisting of a Raspberry Pi and an iC880A connector (Fig. 2(b)).

The experimental test is conducted in indoor and outdoor environments. Fig. 3 shows the topology of LoRa network used: the end-node will send data to the gateway using LoRa modulation, the gateway will send the received data to the cloud server of TTN network via Ethernet.

In the experiments, Temperature and potentiometer values were sent using Cayenne Low Power Payload (LPP) that provides a convenient and easy way to send data over LPWAN networks such as LoRaWAN. The payload message structure consists of 8 bytes, 4 bytes for temperature information and 4 bytes for potentiometer. For each, the first byte is reserved for the channel, the second byte for the data type and the last two bytes contain the value. When a message is sent, The TTN server receive the message and it appears in real time in the web page.

All experiments were conducted using the following parameters for both devices (gateway and end-node) in indoor and outdoor environments:

- LoRa Class: Class A
- Bandwidth: 867.1–868.5 Mhz
- Channel size: 125 kHz
- Spreading Factor (SF): 12
- Coding Rate: fixed = 4/5
- Transmitting Power: 14 dBm

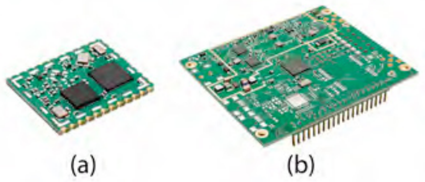

Fig. 2. (a): iM880B LoRa radio module for end-devices, (b): iC880A LoRa connector for the gateway.

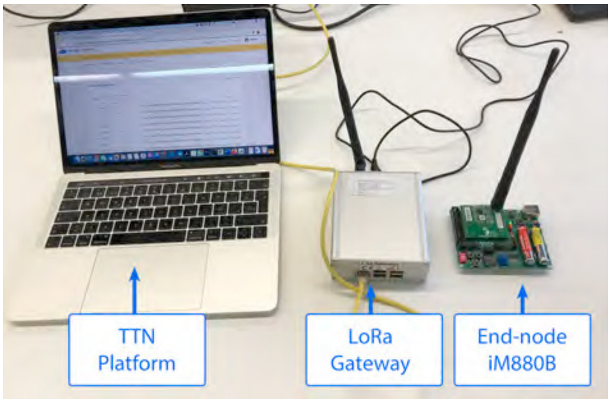

Fig. 3. Experimental setup used for the test: the end-node iM880B sends temperature values to the gateway, which sends the received values to the TTN platform. Data are consulted through TTN.

4.1 Indoor Environment

The first experiment was done at the School of Engineering ETSE in University of Valencia. The school is situated in the city of Bujassot (Spain), with a constructed area of 33,248 m^2. with five 5 blocks:

(0) Administration and secretary.
(1) Department of Computing.
(2) Department of Telematics Engineering.
(3) Department of Electronic Engineering.
(4) Department of Chemical Engineering.

The block 0 consists of 3 levels, while the other blocks have 4 levels (Fig. 4(a)). In this experiment, we placed the LoRa gateway (receiver) inside our laboratory situated in the Electronic Engineering Department (Block 3, level 2) while the location of the end-node LoRa device (transceiver) was changed to take several measurements in different locations. Fig. 4(b) shows the school plan and the location of the gateway (red point) and the measurement locations (blue points).

For each block, the measurements between the end-node and the gateway are repeated in the same location but a different level. A total of 15 messages are sent from each transmit location and a payload value is measured. Each message contains the following information: time when it is received, base station EUI (identification number), end-node device EUI, encrypted and decrypted payload, frequency, data rate spreading factor and bandwidth, Received Signal Strength (RSSI) and Signal to Noise Ratio (SNR). The RSSI is the receiver signal power in milliwatts and measured in dBm represents how well the receiver can "hear" a signal from the transceiver. The closer to 0 the better the signal is.

SNR is the ratio between the received power signal and the noise floor power level. The noise floor is an area of all unwanted interfering signal sources which can corrupt the transmitted signal and therefore re-transmissions will occur. Positive SNR means that received signal operates above noise floor, while negative SNR means that the received signal operates below noise floor. Normally the noise floor is the physical limit of sensitivity, however LoRa works below the noise level (RSSI below SNR). Typical LoRa SNR values are between -20dB and +10dB. A value closer to +10dB means the receiver signal is less corrupted. LoRa can demodulate signals which are -7.5 dB to -20dB blow the noise floor.

The percentage of the received packets (RP) was calculated in each location as described in (1), where NACK denotes the number of packets which Acknowledgement signal received, and NAP denotes the number of all transmitted packets.

$$RP[\%] = 100 \times \frac{NACK}{NAP} \tag{1}$$

Table 2, table 3 and table 4 represent the average RSSI, the average SNR and the percentage of received packets (RP), respectively, measured in each floor for all the blocks.

	Floor 0	**Floor 1**	**Floor 2**	**Floor 3**
Block 0	-121	-120	-113	—
Block 1	-110	-109	-105	-114
Block 2	-92	-90	-87	-106
Block 3	-87	-69	-42	-81
Block 4	-93	-100	-94	-112

Table 2. Average RSSI [dBm] measured in each level, for each of the five blocks in the building.

The average RSSI and the average SNR are represented in Fig. 5 as a function of distance where the gateway is situated (gateway location is the origin, i.e. 0 m). There is no interference with other LoRa gateways in the school zone, thus, the influence of interference was not evaluated.

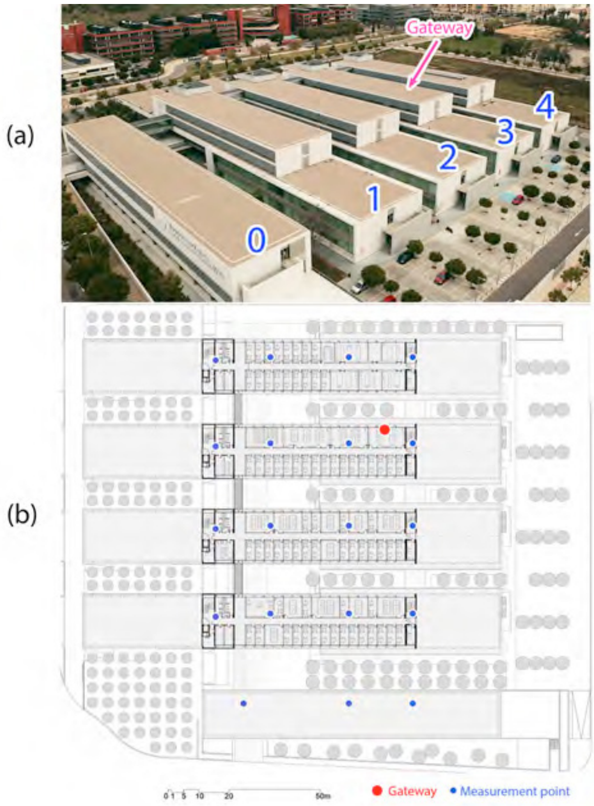

Fig. 4. The school of Engineering plan where experimental measurements where done. (a): Aerial photograph showing the 5 blocks, (b): Plan of the school, showing the measurement locations where the end-node was located in each floor (blue points) and the LoRa gateway location (red point).

	Floor 0	**Floor 1**	**Floor 2**	**Floor 3**
Block 0	-3	-9	-8.5	–
Block 1	-1.5	-6	-9.5	-11
Block 2	8	3	-6.5	-4
Block 3	7.9	9.4	8	8.9
Block 4	3.5	-1.5	-7	-6.4

Table 3. Average SNR [dBm] measured in each level, for each of the five blocks in the building.

	Floor 0	**Floor 1**	**Floor 2**	**Floor 3**
Block 0	6	6	13	—
Block 1	40	40	87	53
Block 2	87	100	100	93
Block 3	100	100	100	100
Block 4	87	100	100	100

Table 4. Received packets ratio [%] each level, for each of the five blocks in the building.

The experimental results show that inside Block 3 where the gateway is located, the end-node could send 100% of packets from each floor. In other blocks, as the distance increases, the RSSI starts to decrease, the first packets loss is observed at 40 m (Block 2 and 4). At 75 m (Block 1) we lost more than 50% of packets. After 90 m (block 0) more than 90% of packets are lost. These data show that this environment has a big impact on SNR and eventually, on RSSI as well. However, SNR does not obey a similar structure as we lost packets at an average of -3 dBm, while

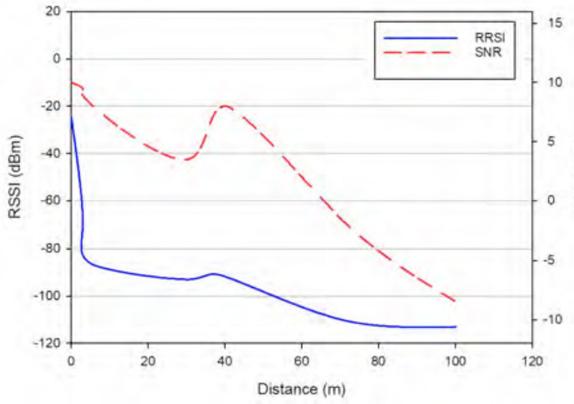

Fig. 5. RSSI and SNR as function of distance in an indoor environment with multiple walls and objects between the gateway and the end-node.

other packets can be received without problems with -9,5 dBm.

The LoRa signal covered most of the locations in the school building, except Block 0. The gateway is situated inside the laboratory, thus it is surrounded by walls made of solid cement, plasterboard and metal. The big density of the materials used in this building prevents a good propagation of the LoRa radio waves when both end-node and gateway are indoor.

4.2 Outdoor Environment

A second test was conducted in the center of Valencia city, Spain. As shown in Fig. 6, the LoRa gateway receiver was placed in the balcony of an apartment, in the 10^{th} floor, with an altitude of 40 m, approximately. The gateway is powered and connected to the Internet.

Fig. 6. LoRa Gateway experimental setup for outdoor measurements in a highly populated area.

The end-node device was moved along nearby streets and measurements in several locations with different distances were taken. Fig. 7 represents a screenshot from situation map, showing the location of the LoRa gateway and the different measurement positions (P1 to P11).

From each transmit location, 15 messages were exchanged between the end-node and the gateway. Each message contains the same information as in the case of indoor

Fig. 7. P1 to P11 represent the measurement locations. The gateway location is represented by the green location icon.

experiment: time when it is received, base station EUI (identification number), end-node device EUI, encrypted and decrypted payload, frequency, data rate spreading factor and bandwidth, Received Signal Strength (RSSI) and Signal to Noise Ratio (SNR).

Location	Distance[m]	RSSI[dBm]	SNR[dBm]	RP[%]
P1	50	-45	9	100
P2	120	-80	3.5	100
P3	205	-76	-1.5	100
P4	295	-89	-7	93
P5	415	-94	1.5	100
P6	553	-101	0.2	87
P7	578	-108	-3.2	93
P8	641	-113	-7.8	53
P9	718	-105	-4	66
P10	756	-110	-10	40
P11	803	-112	-7	33

Table 5. Distance, RSSI, SNR and Received packets ratio (RP) for each outdoor location.

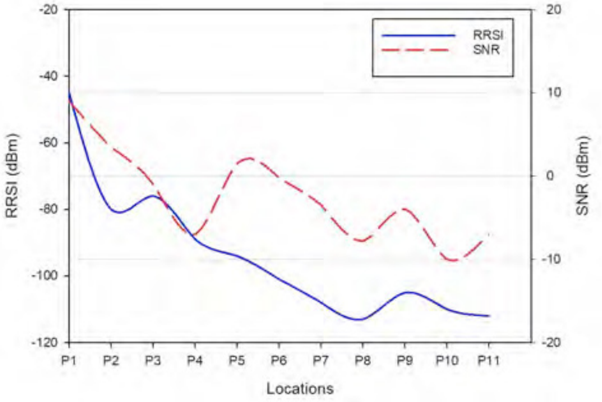

Fig. 8. Outdoor RSSI and SNR as function of distance.

Table 5 shows the results obtained. It represents the distance between the measurement locations and the LoRa gateway, the RSSI and SNR of each location, and the percentage of the received packets RP.

As we can see in Fig. 8, the RSSI decreases as the distance increases. The first packets loss was noticed at position P4 (295 m); however, at position P5 (415 m), all the packets sent arrived successfully. At position P6 (553 m) packet loss was common and the RSSI decreased under -90 dBm. Despite of that, SNR does not follow a similar trend as we could send 100% of packets at an average of -1.5 dBm. At an average of 0.2 dBm, only 87% of packets were received. Location P4 had poor transmission characteristics compared to P7 even that P4 is closer to the gateway, that is due to many factors such as the absorption, refraction, diffraction and scattering which degrade negatively the signal strength of connectivity.

5. CONCLUSION

In this paper, we evaluated the performance of a LoRa network and we analyse how the limitation set by the performance affect the indoor and urban outdoor environments. In the first experiment, we can notice that the signal quality is getting worse significantly as the measurement point is far from the floor where the LoRa gateway was located. In this environment, reaching three blocks far from the gateway was impossible due to the high amount of noise quantity of dense materials forming the building walls, windows, etc. Inside the block where the gateway was situated, we succeeded to send 100% of packets in all the levels. Thus, for small buildings, a LoRa network can work perfectly. Furthermore, it is useful to evaluate the blocking effects before deploying a LoRa network inside a building in order to get appropriate placements for the LoRa sensor nodes with better signal coverage.

The second experiment showed that in an open space, the signal keeps a good quality for longer distances. Even with the existence of many buildings in the area, we noticed that the connection between the two devices can be established up to 800 m. Elevating the gateway to a point with a free line of sight or close to it increases the signal quality, and consequently, longer distances can be achieved, as in the case of a rural area. The deployment of LoRa gateways in a high place as a radio tower can prevent obstructions and thus, the signal can reach distances of several kilometers. In some cases, where elevating the LoRa gateway is impossible, the solution is to use several LoRa gateways. Concerning indoor environments, we could verify that a LoRa-based IoT network can be deployed if distances between the gateway and nodes do not exceed 70 meters.

From the previous experiments, we can notice that we started to lose packets when the signal exceeds the threshold of -120 dBm. However, SNR seems to have less impact on sending packets using LoRa modulation, as we could receive packets at an average of -9,5 dBm without problems. The obtained results show that LoRa technology can be used for several applications that do not require sending a huge amount of data continuously, both outdoor and indoor. In addition, LoRaWan protocol helps users around the world to have a shared infrastructure allowing them to share data in large distances. This results will help us in our future works related to the development of smart and reliable IoT networks.

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