IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 11 August 2022, accepted 1 September 2022, date of publication 12 September 2022, date of current version 20 September 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3206030

RESEARCH ARTICLE

Coverage and Energy-Efficiency Experimental Test Performance for a Comparative Evaluation of Unlicensed LPWAN: LoRaWAN and SigFox

MANUEL PÉREZ[1], (Member, IEEE), FABIAN EDUARDO SIERRA-SÁNCHEZ[1], (Member, IEEE), FABIÁN CHAPARRO[1,2], DIEGO MÉNDEZ CHAVES[1], (Member, IEEE), CARLOS-IVAN PAEZ-RUEDA[1], (Senior Member, IEEE), GABRIEL PERILLA GALINDO[1], AND ARTURO FAJARDO[1], (Senior Member, IEEE)

[1]Department of Electronics Engineering, Pontificia Universidad Javeriana, Bogotá 110231, Colombia
[2]Department of Electronics Engineering, Universidad Santo Tomás, Tunja 150001, Colombia

Corresponding author: Manuel Pérez (manuel.perez@javeriana.edu.co)

This study was funded in part by the Gobernación de Boyacá through the 733 doctoral students call in 2015 and the 856 call for young researchers in 2019 from Colombia's Ministry of Science (MinCiencias). Furthermore, it was founded by the Pontificia Universidad Javeriana and the Colombian Ministry of Information and Communication Technologies (MinTIC) as part of the "Centro de Excelencia y Apropiación en Internet de las Cosas (CEA-IoT)" Grant ID: 7161.

ABSTRACT Low Power Wide Area Networks (LPWAN) have emerged as an attractive Internet of Things (IoT) communication option. When deploying a communication network to support IoT applications, large coverage and low power consumption are critical requirements. Despite the fact that existing LPWAN technology solutions promote IoT requirements such as long communication range, energy efficiency, scalability, and low cost, network performance is a major concern. With so many LPWAN technologies available, there is a growing interest in evaluating them. Recent works have presented various comparison studies of LPWAN technologies, but the majority of them have approached the analysis from the standpoint of comparing technical specifications rather than presenting measurement results obtained from network deployment scenarios. We argue that by proposing a comparative evaluation from an experimental standpoint, the comparison discussion is deepened. This paper proposes an experimental comparative evaluation of LoRaWAN and SigFox, two emerging LPWAN technologies operating in sub-GHz Industrial, Scientific, and Medical (ISM) frequency bands, based on coverage and energy-efficiency test performance. The experimental evaluation was proposed first by identifying coverage and energy-efficiency as the two most important design goals for LPWAN applications. Second, by proposing test performance to evaluate those goals, where extensive measurements were made in network deployments, and finally, by highlighting the main performance findings in both networks for comparison purposes. The results show that in a fair-weather test, LoRaWAN outperformed SigFox in terms of coverage, achieving a higher packet delivery rate (PDR $\gtrsim$ 80%), and having higher radio strength signal (RSSI $\gtrsim$ -110 dBm). Sigfox, on the other hand, shows better energy efficiency with 20% more sent messages under the same test conditions.

INDEX TERMS Internet of Things (IoT), wireless sensor networks (WSN), LoRaWAN, SigFox, LPWAN.

I. INTRODUCTION

Communication networks for the Internet of Things (IoT) have gained prominence since the introduction of the IoT paradigm. The International Telecommunications Union (ITU) formally proposed IoT in 2012 [1], [2]. IoT appears to be the most recent evolution of the Internet, which has progressed through five major milestones: First, one-on-one communication, also known as pre-Internet. Communications or content-Internet via the "www". Second, The

The associate editor coordinating the review of this manuscript and approving it for publication was Ghufran Ahmed.

services-Internet, or WEB 2.0. Third, The Social WEB, also known as the people-Internet, and finally, Machine to Machine (M2M), also known as the things-Internet, which maintains the same core concepts as the Internet of Things [3], [4], [5], [6], [7], [8], [9]. Identification, sensing, communication, computation, and semantics are IoT service elements. The primary goal of the Internet of Things is to collect data by connecting disparate objects, primarily through wireless communication technologies. Because IoT end-devices are inherently ubiquitous, devices should primarily operate with low power consumption because they are battery powered and are typically deployed in inaccessible or nomadic locations with no access to a constant power source. Second, end-devices must operate in large areas, which necessarily involves communication over long distances of a few kilometers in urban areas and tens of kilometers in rural areas. As a result, wireless connectivity is required for end-device network deployments. Finally, end-devices should be low-cost because massive deployment for multiple applications is desired, making it impractical to deploy them if end-devices are costly to manufacture and maintain.

There are numerous applications and service providers that use IoT technologies today. When using IoT technologies, common applications include remote control and telemetry, smart cities, health, and smart agriculture [10], [11], [12], [13], [14]. As previously stated, IoT devices are limited in terms of low cost, low power consumption, and ability to operate in remote areas. Because IoT networks are wireless, a variety of communication technologies have been developed to address this problem [15], [16], [17], [18], [19]. The IoT definition includes an additional dimension that involves connectivity for every object, at any time and at any moment [1]. As a result, depending on the communication range, IoT wireless networks employ a wide range of technologies, ranging from Wireless Personal Area Network (WPAN) technologies such as Bluetooth, Zig-bee, and Wireless Hart, which have coverage between 10 and 100 meters and are widely used in wearable applications such as patient health monitoring [20]. Wireless Local Area Network (WLAN) technologies such as IEEE 802.11a/b/g/n/ac/ah are also included, with radio coverage ranging from 100 to 1000 meters. IEEE 802.11-based technologies, also known as Wi-Fi, are important for enabling connectivity for smart home services. Due to its sensitivity to environmental dynamics, the Wi-Fi signal is now widely used for various sensing tasks other than communication, such as gesture recognition and fall detection [21]. Wireless Neighborhood Area Network (WNAN) uses technologies such as Wireless Smart Utility Network (WI-SUN), which is a forerunner of WPAN networks with IPV6 and coverage ranging from 3 to 10 kilometers [22]. Finally, Wireless Wide Area Networks (WWAN) include cellular mobile networks (2G/3G/4G) and Low Power Wide Area Networks (LPWAN) with Third Generation Partnership Project (3GPP) Releases 12 and 13 that include Long Term Evolution for Machines (LTE-M) and Narrow Band IoT (NB-IoT) in licensed spectrum and SigFox, LoRaWAN, Weightless, Ingenu, among others, in unlicensed and dynamic access spectrum [23], [24], [25]. LPWAN technologies have demonstrated long coverage ranges of 10 to 50 kilometers [11], [24], [26], [27], [28]. The numerous emerging solutions for long-range in IoT wireless networks with low power consumption have attracted the interest of standardization bodies such as the 3GPP and the IEEE Standard Committee. NB-IoT and the IEEE 802.11 standard, for example, developed common technologies that can be used in a variety of scenarios [29].

The works found in the literature have presented several comparative analysis of LPWAN technologies, but to the best of the knowledge of the authors, most of them have limited the evaluation and comparison only by defining a common framework with a systematic approach based on network features and requirements, without presenting measurement results obtained from network deployment scenarios [18], [30], [31], [32], [33]. It is always important to define a common framework when comparing technologies; however, additional questions arise in terms of how to measure performance and test the technologies in terms of the defined requirements. Only few papers have proposed an experimental evaluation of LPWAN technologies [34], [35], [36], [37], however, they have been oriented mostly to the exploration of a single technology and focused on one particular performance analysis. As for instance, the authors in [36] and [37] propose experimental evaluation set-ups of LoRaWAN networks for coverage performance in urban or rural scenarios. The work in [34], analyzes the scalabillity of a realistic SigFox communication model by generating SigFox traffic using Software Defined Radios. The work in [35] does include extensive measurement results of NB-IoT, SigFox, and LoRaWAN network deployments in the cities of Brno and Ostrava with plenty of Base Stations, however measurements results are oriented to propose enhancement of selected LPWAN radio propagation models in urban environment, without a comparison perspective.

This paper proposes an experimental comparative evaluation of LoRaWAN and SigFox in urban and rural scenarios based on coverage and energy-efficiency test performance, as illustrated in Fig. 1. LoRaWAN and SigFox are the most prominent LPWAN technologies operating in sub-GHz Industrial, Scientific, and Medical (ISM) frequency bands at 868MHz in Europe and 915MHz in North America. These two network technologies have been widely deployed in over 77 countries around the world, connecting billions of end-devices [38], [39]. The following are the main contributions of this work:

- An experimental comparison of LoRaWAN and SigFox, as well as a proposal for coverage and energy consumption test performance in both urban and rural scenarios.
- We present a technical description of the experiments conducted in urban and rural environments to obtain coverage and energy efficiency tests, demonstrating the practical performance of both networks.

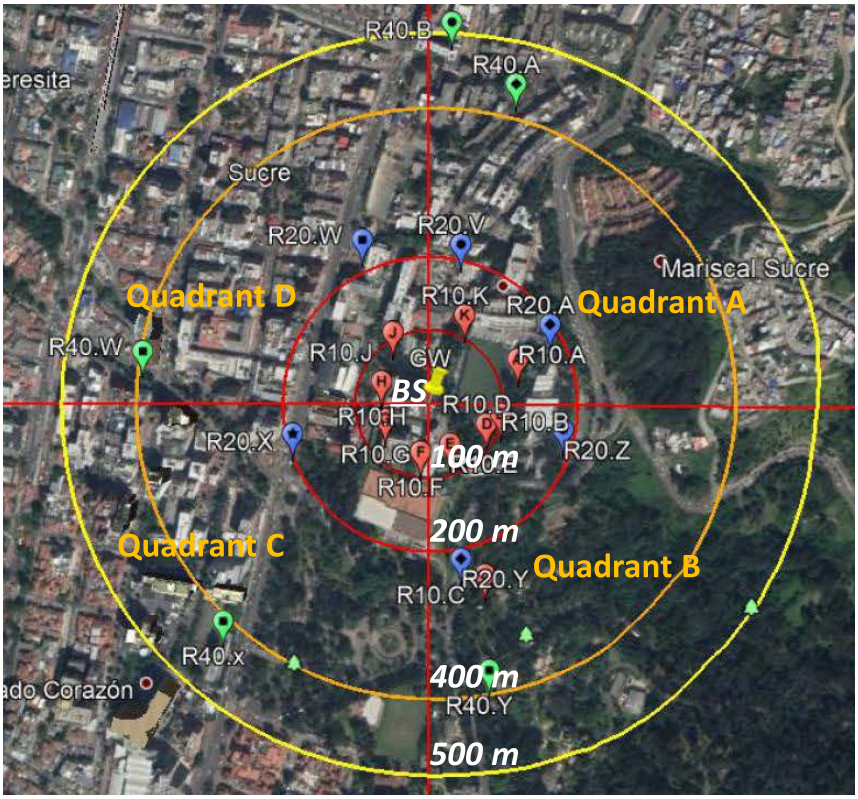

FIGURE 1. Experimental comparative evaluation of LoRaWAN and SigFox: Coverage and energy-efficiency.

- The analysis drawn from the comparative evaluation between SigFox and LoRaWAN that shows which of both network technologies perform better in terms of radio coverage and energy efficiency in urban scenarios.

This paper is structured as follows: Section II presents a review of recent works in the literature regarding survey, overview and evaluation of LPWAN technologies. Section III reviews the LPWAN network requirements, design goals and the criteria for the selection of coverage and energy-efficiency for the experimental evaluation proposed in this work. Section IV describes the main features of SigFox and LoRaWAN network technologies. Section V presents the LoRaWAN and SigFox configuration parameters of the network deployments and the description of the coverage and energy-efficiency experimental performance test in urban and rural scenarios. Section VI presents the analysis of the experimental results of this work. Finally, section VII concludes this paper giving the remarks and future perspectives.

II. RELATED WORK

With a wide range of emerging LPWAN technologies, there is a growing interest in evaluating and comparing network performance, particularly in unlicensed frequency bands. Several works have addressed the need for a common evaluation and comparison framework to gain real insights into LPWAN technologies, which can provide elements for determining which technology is best suited for a specific IoT scenario. In this regard, the overview and comparison of LPWAN solutions are only related with their technical specifications which in most of the cases lacks of a systematic analysis and in other cases lacks of experimental test performance proposal for network deployments in different scenarios. We argue that by proposing a comparative evaluation from the perspective of network and test performance, the comparison discussion is taken to the next level, yielding deeper insights into the network's performance. Following that, some related work is presented, starting with papers that cover a comparative analysis from a specifications standpoint, then moving on to those that follow a comparison based on simulation results, and finally presenting those that propose network deployment scenarios for technology evaluation.

Authors in [40] present a comparative study of LPWAN technologies, with a focus on unlicensed-based solutions. The authors include in their comparison study technologies such as Symphony Link and Ingenu RPMA as alternatives for LoRaWAN and SigFox, particularly in industrial environments and operating in the 2.4 GHz frequency band. In this case, the research is conducted from a technical standpoint, specifically by comparing the characteristics of each technology in each communication stack layer.

The work in [41] provides an overview and comparative study of SigFox, LoRaWAN, and NB-IoT. The comparison study is based on the definition of IoT factors such as QoS, deployment model, and cost. Despite the fact that the analysis

is interesting, the comparative framework lacks a systematic approach and insights into how to test the performance of IoT network technologies.

The work in [42] presents a survey article with a systematic analysis by defining the design goals and decisions of various commercially emerging LPWAN technologies. The authors examined six distinct design objectives and identified the design decisions required to achieve each objective. The system architecture and specifications of each LPWAN technology are presented, along with an outline of application use in various domains, with the goal of ultimately suggesting an appropriate LPWAN solution for each use case. Despite the fact that [42] proposes a comprehensive systematic review of LPWAN, evaluation and comparison are made solely through the identification and comparison of LPWAN design goals and specifications, with no reference to a experimental network deployment.

The research presented in [43] uses a systematic approach for identifying the key characteristics of IoT and machine to machine (M2M) applications, translating them into explicit requirements, and then deriving the associated LPWAN design considerations for SigFox, LoRaWAN, NB-IoT, and LTE-M. In this case, the set of design considerations is divided into two categories: expected and enhanced. Other aspects such as LPWAN architectural topology interconnection are also discussed. The comparison is also presented from the standpoint of technical specifications analysis, but without any evidence of experimental results derived from test performance.

Another work [44] has glanced at the coverage and capacity of SigFox, LoRaWAN, GPRS, and NB-IoT, based on simulated link loss models of end-devices in urban and rural scenarios taken from a real sub-1GHz cellular network grid in Denmark. The results are obtained by comparing the link budget of each technology with the link budget for computing the achievable data rate and time on air. Other network parameters, such as the probability of uplink random access collisions and download blocking, are also estimated; however, these results are based on simulation and do not include measurement results.

Finally, only a few works have proposed an evaluation from the standpoint of network deployment. For example, in [36], researchers tested the link quality and transmission performance of a LoRaWAN network using various modulation parameters such as the spreading factor (SF), coding rates (CR), and bandwidth for various radio propagation scenarios. The measurement locations are on a university campus, and the network performance metrics considered are the Received Signal Strength Indicator (RSSI) and Packet Delivery Rate (PDR). Despite the fact that the study is well-described and follows a well-structured methodology, the scope of the work is limited to one LPWAN technology (LoRaWAN), and the measurements are only in an urban scenario.

In addition, the authors in [37] presented an experimental evaluation of LoRaWAN for a wildlife monitoring application in a forest vegetation area. The PDR, RSSI, and Signal-to-Noise ratio (SNR) were tested as experimental network metrics for performance evaluation with different payload length, SF, and CR. The experimental evaluation is limited to LoRaWAN and is conducted in a forest environment, where they achieved a maximum communication range of 860 m with an SF of 12.

The authors of [34] presented a scalability analysis of the SigFox communication protocol under large-scale high-density conditions using a SigFox traffic generator implemented via Software Defined Radios (SDRs). When 360 orthogonal channels are available, the structural scalability obtained in the proposed scenario is approximately 100 sensor nodes. The experimental evaluation is limited to SigFox, and it is a lab experiment without network deployment.

Finally, the authors of [35] presented a case study for selecting accurate radio propagation models for Narrowband IoT (NB-IoT), LoRaWAN, and SigFox LPWAN technologies. Based on experimental measurements, they propose an improvement to selected propagation models. Despite the deployment of experimental network setups for extensive measurements, the goal of the paper is to cross-validate radio propagation models in two cities. In other words, their main contributions are aimed at providing a methodology for fine-tuning propagation models for LPWAN technologies based on experimental results, which falls outside the scope of an experimental comparative evaluation.

To summarize, none of the works found in the literature propose an experimental comparison evaluation of different LPWAN technologies based on network deployments. The related works in terms of compared LPWAN technologies, comparison perspective, performance analysis, and evaluation scenarios are summarized in Table 1.

III. LPWAN REQUIREMENT AND DESIGN GOALS

Many works have presented the goals, requirements, and features of LPWAN design [31], [32], [33], [42], [43]. They all agreed that LPWANs are the best network solution for large-scale IoT system deployments over large areas due to their energy-efficient working schemes, low-cost and low-complexity end-devices, low data rates, and high latency. Even though design considerations and requirements differ in some ways, they can be classified as general design goals or considerations. The authors of [43] defined application requirements based on LPWAN coverage, capacity, cost, low power operation, and enhanced characteristics. Coverage has been identified as being fundamental to almost all of the identified main applications, followed by low power operations primarily driven by the lack of electric power supply in remote locations, such as smart agriculture and farming, eHealth, life sciences, wearables, and smart environment applications [17], [28], [45], [46], [47], [48], [49], [50], [51].

Low power operation is highly valued in these applications. The work in [42] defined energy efficiency, long-range, load scalability, low-cost, interference management, and coexistence as design goals in LPWANs where design

TABLE 1. A summary of related work.

Ref.	LPWAN Technologies	Comparison perspective	Performance analysis	Evaluation scenario
[40]	LoRaWAN, SigFox, Ingenu RPMA, Symphony Link	Theoretical (specification)	-	Urban, Rural
[41]	LoRaWAN, SigFox, NB-IoT,	Theoretical (specification)	QoS, Battery Life, Scalability, Coverage, Deployment model, Cost	-
[42]	LoRaWAN, SigFox, Weightless-P, NB-Fi, DASH7, NB-IoT, LTE-M, EC-GSM	Theoretical (specification)	Energy Efficiency, Range, Scalability, Low Cost, Interference, Integration	-
[44]	SigFox, LoRaWAN, GPRS, NB-IoT	Simulation	Coverage, Capacity	Urban, Rural
[34][a]	SigFox	Experimental	Scalability	-
[35][b]	SigFox, LoRaWAN NB-IoT	Experimental	Coverage	Urban
[36]	LoRaWAN	Experimental	Coverage	Urban
[37]	LoRaWAN	Experimental	Coverage	Rural
This work	LoRaWAN SigFox	Experimental	Coverage, Energy Efficiency	Urban, Rural

[a]This work proposes an Open SigFox Stack Library integrated within SDR system for traffic generation of high density networks in laboratory.

[b]This work is oriented to the selection of propagation models for LPWAN technologies. Despite experimental network set-ups are deployed for extensive measurements, the goal of the paper is oriented to cross-validate radio propagation models in two cities.

decisions such as the operating frequency band (unlicensed or licensed), the carrier frequency, the frequency bandwidth, the modulation technique, the channel access method, the signal diversity technique, the duplexity, and the business model are classified based on their impact into the design goals. In this regard, range and power consumption are design goals where almost all proposed design decisions have a high impact on the operating process of LPWANs, demonstrating the significance of those requirements.

Our comparative study was proposed to evaluate LPWAN technologies on coverage and energy efficiency, which are primary design goals when deploying an LPWAN network. These two requirements are discussed further below.

A. COVERAGE

LPWAN are intended to work over long distances as wide-area networks, which means that their communication schemes must allow end-devices to efficiently deliver messages over a few kilometers in urban areas and tens of kilometers in rural areas. When compared to mobile cellular networks, the communication target of LPWAN is increased by 10-40 km in rural zones and 1-5 km in urban zones, with a link budget increase of +20 dB. Some applications may require connectivity in indoor environments, particularly underground and basement locations, which are generally difficult to access. In comparison to higher ISM frequency bands, LPWAN achieves long-range communications with robust and reliable characteristics by using Sub-GHz frequency bands. In any case, coverage must be evaluated not only from the perspective of the link budget, but also from the standpoint of the package delivery rate (PDR). We considered a target coverage of 5 km in urban areas and 10 km in rural areas, with a PDR of more than 90%.

B. ENERGY EFFICIENCY

Many IoT applications require end-devices to be ubiquitous; in particular, some applications require devices to be remotely located, so they must be battery powered and not rechargeable. As a result, low power consumption must be ensured through the use of low data rate modulation techniques. In this regard, the authors of [42] set a target battery lifetime of 10 years for end-devices. However, battery life is highly dependent on message sending rate, which is directly related to the type of IoT service, whether critical or massive.

IV. LPWAN TECHNOLOGIES

LPWAN network technologies used in IoT communications have unique characteristics such as limited packet size (e.g., 127 bytes), variable address length, and low bandwidth. Since 2007, the Internet Engineering Task Force (IETF) and the Six Low Wide Wide Pan Access Networks (6LoWPAN) groups have been working on the standard for mapping the required services in Internet Protocol version 6 (IPv6) over LPWAN networks. The standard specifies a Maximum Transmission Unit (MTU) that uses header compression to reduce transmission overhead caused by IoT requirements. LoRaWAN and SigFox are discussed further below.

A. LoRaWAN

LoRAWAN is a proprietary LPWAN technology based on the LoRa physical (PHY) layer that provides wide coverage whereas consuming low energy and transmitting low data rates. Semtech, IBM, Actility, and Microchip created LoRaWAN in North America. The LoRaWAN network is a single-hop network in which end-devices or motes connect directly to a LoRAWAN base station that acts as a gateway to the information server.

The LoRa PHY uses Chip Spread Spectrum (CSS) modulation. CSS is a Direct-sequence spread spectrum (DSSS) subcategory that uses controlled frequency diversity to recover data from weak signals, even near the noise level. CSS modulation was widely used in military communications due to its low transmission power requirements, resistance to channel

degradation, multi-path, fading, Doppler effect, and jamming interference [4], [11], [30], [52].

The Spreading Factor (SF), which can range from 7 to 12, is the quantity of transferred bits per symbol in CSS. The modulation of the signal is optimized by taking into account the number of symbols in chips of 2^{SF}, i.e., when the SF is set to 12, the symbol will contain 4096 chips, increasing the transmission time. The data rate decreases as the SF increases, while the transmission time, the end-device energy consumption, and the time delay all increase. The LoRa PHY is adaptable in its usage of radio spectrum by allowing the use of the same frequency with several SFs, enabling frequency orthogonality for multiple links to operate at once.

The SF is defined in (1), which is related with spread bandwidth B, the symbol rate R_s and the chirp duration $T = \frac{1}{R_s}$ through equation (2).

$$SF = \frac{chip\ rate}{symbol\ rate} \tag{1}$$

$$2^{SF} = \frac{B}{R_s} = BT \tag{2}$$

During a chirp period, the chirp may encode up to $SF = 12$ bits by changing the frequency-increasing ramp based on the 2^{SF} potential chip values. As a result, each chip code is created by shifting the chirp reference repeatedly [11].

A preamble of 10 raw up-chirps and 2 raw down-chirps is first transmitted to the receiver in order to estimate frequency, time offset, and time synchronization between transmitter and receiver. The receiver's decoder then calculates the offset of the coded symbols from the reference frequency after synchronization is complete. Gray indexing is employed to lower bit error rates (BER).

Equation (2) demonstrates that LoRaWAN may achieve a data throughput of up to 27 kbit/s by configuring a bandwidth of 500 kHz and an SF of 7. LoRaWAN provides the freedom to adjust the data rate and the frequency occupancy according to the transmission condition by altering the SF and the modulation bandwidth. When end devices are linked to the gateway over longer distances, a greater SF is typically employed, whereas smaller SF values are used over shorter distances. Frequency hopping patterns that are well-known to both the transmitter and the receiver are typically used for sending large amounts of data.

If Adaptive Data Rate (ADR) is enabled, a slave device, a type of end-device used in LoRaWAN, is led by a master device. In this context, the Medium Access Control (MAC) has the ability to regulate the SF, Bandwidth, and frequency band in order to regulate the output power of each node and increase the battery life and network capacity. This makes it easier to adjust the data rate, shorten transmission and reception times, and achieve higher data rates for specific applications. The Listen before Talk (LBT) protocol is used by a node to discover a free frequency sub-channel when it transmits.

In terms of radio frequency spectrum, LoRaWAN operates in the sub-1 GHz bands of 169, 433, 915 MHz in the United States and 868 MHz in Europe, particularly in the ISM unlicensed bands where duty-cycle constraints impose channel occupation restrictions [12]. This is a significant limitation for both LoRaWAN and networks using unlicensed frequencies. Therefore, the frequency channel selection must adhere to the maximum duty-cycle and implement pseudo-random channel-hopping at each transmission [53].

By utilizing a pseudo-random frequency hopping approach, an end-device is able to transmit at any time in any open sub-channel. When this occurs, the end devices operate at their highest bandwidth within the constraints of the duty cycle limitation. When the transmission power is greater than 20 dBm, the gateway administrator supports up to 10^4 end-devices. Forward Error Correction (FEC) is a method used by LoRaWAN to repair errors. The trade-off between coverage and message duration (i.e. Time over the Air - ToA) determines the data rate. High data rates not only increase the ToA but also carry additional data for interference protection.

In terms of energy consumption, authors in [27] has addressed the energy consumption of LoRaWAN end-devices for the evaluation of multi-hop bidirectional communication in a wide-area application. Results of their experimental set-up demonstrates a network coverage of 150 m with only 6 end-devices, achieving a potential node life-time of 2 years with batteries of 5400 mAh capacity, transmitting every 5s and reaching a reliability above the 80%.

In terms of network scalability, authors in [53] present a LoRAWAN network test-bed with a uniform distribution of end-devices, all connected with a network gateway. The estimated path loss is calculated with the Okumura-Hata model for urban cells, the average packet loss probability, and the sensitivity of transmitting end-devices with different SF. Results in [53] demonstrate that when the number of network nodes N is massively increased ($0 \leq N \leq 10000$) with low values of transmitting packets per second λ_p, the efficiency of the system is limited by the increased number of packet collisions. On the contrary situation, when high values of λ_p occur, the data rate is limited by the duty cycle.

In terms of network coverage, the signal-to-noise ratio and the maximum coverage distance of a LoRaWAN network can be computed by calculating the thermal noise level with the LoRaWAN modulation bandwidth (125 kHz $\leq B \leq$ 500 kHz) and the noise figure at the receiver. For instance, at 900 MHz with an uplink bandwidth of 500 kHz with an SF of 7, the link budget in free-space conditions and assuming the antenna gains balance roughly the Noise Figure, the signal-to-noise ratio SNR is given by (3).

$$SNR_{dB} = P_{Tx} + 95\,dB - 20\,log_{10}\left(\frac{R}{\lambda}\right) + CG_{dB} \tag{3}$$

where R is the distance in meters between the transmitter and receiver, λ is the free-space wavelength in meters and CG_{dB} is spreading coding gain, given by $2.5\,SF$ [11], [54]. Thus, considering an SNR threshold of 8 dB, a link margin of 4 dB and maximum transmission power of 14 dBm allowed by the

ETS regulation [55], [56], [57], the computed coverage range is ideally 23.6 km.

B. SigFox

For the first time, Hal R. Walker proposes the use of Very Minimum Shift Keying (VMSK) for compressing data transmission in a narrow band frequency in 2004. This modulation technique advances LPWAN networks but does not achieve the expected ultra-narrow bandwidth results. Later on, SigFox develops and patents Ultra Narrow Band (UNB) technology [11], [16], [58].

SigFox employs different uplink and downlink modulation schemes. For the uplink, Sigfox employs a binary data broadcast with a BPSK scheme at a low data rate *Rb* of approximately 100 bps on a channel bandwidth of 100 Hz. For the downlink, SigFox employs a GFSK scheme operating at 500 bps on a 600 Hz spectrum segment. SigFox is distinguished by multiple transmissions over frequency sub-channels with bandwidths of 100 Hz in a larger band of approximately 192 kHz in the ISM bands (868 MHz, 915 MHz). The benefits of UNB with BPSK are numerous; for example, it maintains a high throughput over longer distances than CSS [59]. One disadvantage of the Sigfox system is the requirement for a high precision oscillator to introduce an offset between the average frequency and the operation frequency at a specific time. A signal with a low bandwidth in UNB generally requires a high system sensitivity and then a higher transmitter oscillator precision [14].

The BPSK demodulation process employs a Fourier Fast Transform (FFT), which is applied to the received signal and then used in an adaptive detector to identify the spectral signature of the UNB signal [11], [16]. Each uplink message can be sent up to three times on different frequencies to improve reliability. The link is established when the base station responds on the same frequency, allowing the algorithm reception of the end-device to be simplified.

The associated MAC to UNB is Random Frequency and Time Division Multiple Access (RFTDMA). End-devices randomly access the wireless environment in the time - frequency domain. This corresponds to the Aloha access protocol without previously reviewing the channel occupancy. In contrast with classics Aloha transmissions, the carrier frequency has been chosen inside the working bandwidth within a continuous interval in contrast to a predefined discrete frequency set [4], [11], [59]. Because no medium sensing is required, RFTDMA reduces energy consumption, and time synchronization of end-devices.

The energy consumption of a SigFox end-device ranges between 20 mA and 70 mA. This characteristic is determined by the message size. It is critical to understand that when end-devices are idle, energy consumption can remain very low. End-devices can transmit up to 14 dBm in Europe and 21.7 dBm in America in the frequency bands where SigFox can operate. As a result, energy consumption can be adjusted to accommodate battery-powered IoT nodes while still allowing for long-distance transmissions.

Similar to a LoRaWAN deployment, when we have a data link with a line of sight (LoS), the signal-to-noise relation (SNR) is computed in this case, with the bandwidth occupation being much less due to the use of UNB modulation, which is 100 Hz. The noise floor is therefore set to $N_{dBm} = -154$ dBm $+NF_{dB}$. The signal-to-noise relation is given by (4) using the same considerations for free space as in the LoRaWAN network.

$$SNR_{dB} = P_{Tx} + 132\,\text{dB} - 20\,log_{10}\left(\frac{R}{\lambda}\right) \tag{4}$$

The received power must be $P_{Rx} \geq -140$ dBm with an end-device transmission power $P_{Tx} \geq 14$ dBm allowed by the ETS regulation [57], when taking the same SNR threshold as before of 8 dB and a link margin of 4 dB. This results in a coverage area of thousands of kilometers. In reality, authors in [11] reports a range of 63 km.

C. SUMMARY OF MAIN FEATURES OF LoRaWAN AND SigFox

With the goal of having comparison between LoRaWAN and SigFox, Table 2 summarizes the main specifications of both technologies.

V. LPWAN NETWORK DEPLOYMENTS AND TEST PERFORMANCE

LoRaWAN and SigFox were tested in both urban and rural scenarios in this study. The Received Signal Strength Indicator (RSSI) was used to test the communication range, as well as the Packet Delivery Rate (PDR) and energy efficiency of its end devices when transmitting in similar environments. The LoRaWAN network was deployed using a Multitech gateway, which can also function as a network server due to a pre-installed application called node-red, which allows direct interaction with received messages via javaScript. As end-devices, Pycom's LoPy/LoPy4 and SiPy modules were used and programmed in Python, with received messages stored in a SQL database. The configuration parameters of the network deployments are presented in Table 3.

A. URBAN SCENARIO

The tests for the urban scenario were conducted around our University campus, where the average building height is around 50 meters. A LoRaWAN and SigFox base station were installed on the terrace of our faculty building, approximately 30 meters above the floor level, in the test scenario. The measurements were taken at distances of 100, 200, 400, and 500 meters from the base stations in four quadrants (A, B, C, D) that covered all directions. Larger measurement distances were not considered in order to ensure comparable wireless channel conditions, primarily because the SigFox base station was part of a SigFox network deployment in the city, and thus other base stations located nearby could provide connectivity. Furthermore, more than four static end devices were tested sending uplink messages in each radio. Using both technologies, over 14000 uplink

TABLE 2. Summary of LoRaWAN and SigFox main technical features.

Feature	LoRaWAN	SigFox
Modulation	LoRa CSS/FSK	UNB GFSK(downlink)/ BPSK(uplink)
Frequency Band	Sub-GHz ISM: EU(433 MHz, 868 MHz), US(915 MHz), Asia(430 MHz)	Sub-GHz ISM: EU(868 MHz), US(920 MHz)
Channel bandwidth	125 kHz, 250 kHz, 500 kHz	100 Hz
Max. Data Rate	3-27 kbps (LoRa) 50 kbps (FSK)	100 bps (UL) 600 bps (DL)
Maximum Coupling Loss (MCL)	157 dB	162 dB
Sensitivity	-137 dBm	-129 dBm
Max. end-device Transmission Power	20 dBm	14 dBm
Coverage range	3-8 km (urban) 15-22 km (rural)	3-10 km (urban) 30-50 km (rural)
Messages/day	Unlimited	140
Payload size	2-255 bytes	12 bytes (UL) 8 bytes (DL)
MAC	ALOHA	ALOHA
End-devices/ Gateway	1k	1M
Topology	star of stars	star
Rx consumption	12 mA	12 mA
Tx consumption	42 mA	EU(42 mA) AU and South America(120 mA)
Coding rate	4/5 4/6 4/7 4/8	N/A
Encryption	AES-128	AES-128
Duty cycle	1%	1%
Proprietary aspects	PHY layer	PHY and MAC layers
Deployment model	Private and operator-based	Operator-based

messages were sent in total. Because the average height of the surrounding buildings in this scenario is 40 meters, significant link budget losses due to shadowing were anticipated. The test-bed in the urban scenario for both networks is outlined in Fig. 1, where the high building density around the base stations is clearly visible.

B. RURAL SCENARIO

The rural scenario tests were carried out in a rural area where the average building height is less than 10 meters, so low link budget losses were expected. Only a LoRaWAN base station was installed on a 30 meter high tower in this scenario, ensuring similar conditions of base station deployment in the urban scenario. The measurements were taken from 100 meters to 11 kilometers away from the base station, and over 11000 uplink messages were sent for analysis. Due to network operator restrictions, SigFox network deployment was not permitted. To ensure a fair performance comparison and analysis, only LoRaWAN results were obtained and compared with the case of an urban deployment of the same network. The test-bed in the rural scenario for a LoRaWAN network is shown in Fig. 2, where the low building density around the base station is clearly visible. It is also worth noting that quadrants B and C are primarily agricultural harvest areas.

TABLE 3. Network configuration parameters.

Configuration parameter	LoRaWAN	SigFox
Base Station	Multitech Conduit IP67 BS	Sigfox BS
Base Station Antenna	Outdoor $\lambda/2$ Omni-directional whip Antenna, Gain: 6 dBi, Height: 30 m	
End-device	Pycom LoPy/ LoPy4	Pycom SiPy
End-device Antenna	$\lambda/4$ Monopole Omni-directional Antenna, Gain: 2 dBi, Height: 1 m	
End-device Standby consumption	1 uA	0.5 uA
End-device Transmission power	14 dBm	
Operating Frequency Band	915 MHz	920 MHz
Modulation information	Bandwidth: 500 kHz SF: 7	Bandwidth: 100 Hz
MAC	ALOHA with Class A configuration	ALOHA
Uplink messages/ point [a]	250	240

[a]The criteria for determining the number of uplink sent messages at each point were determined based on the total measurements campaign time.

C. PERFORMANCE TEST

Different tests were designed for the performance evaluation of both networks in urban and rural scenarios, based on the main features, requirements, and design goals of the network considered in III.

1) COVERAGE TEST

The Received Signal Strength Indicator (RSSI) measurement of each uplink message from the various end-devices situated around the base stations for both urban and rural scenarios served as the foundation for the communication range test. Based on the RSSI of the received messages, the test's objective was to assess the radio coverage provided by the network's base station.

In order to calculate the packet delivery rate (PDR), the received message rates in both base stations were compared to the total amount of uplink messages sent from the end devices. This allowed to compare the two network technologies in the proposed urban scenario and demonstrated how a LoRaWAN network behaved in different radio environments in terms of packet losses.

In the urban scenario, 11 static measurement points at various angles in the four quadrants were used for the first radio of 100 m, followed by four points at 200 m, 400 m, and 500 m. In the case of LoRaWAN, the Base Station (BS) intended to receive 250 messages from each end-device located at each point, whereas the SigFox BS was 80

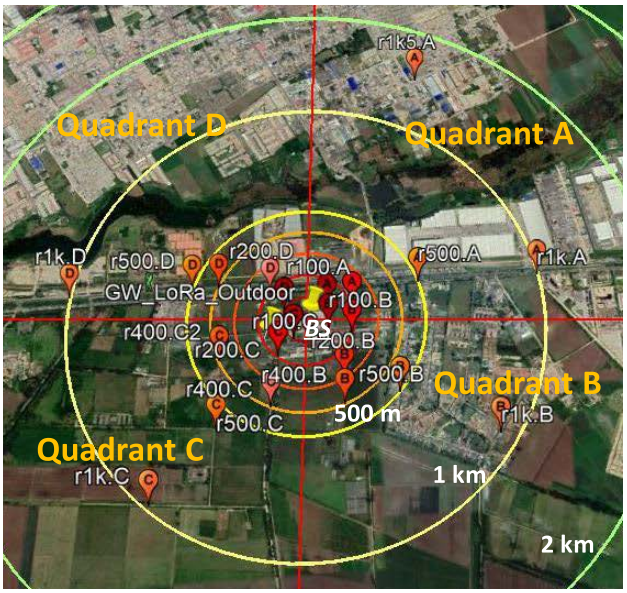

FIGURE 2. LoraWAN test-bed in a rural scenario.

messages from each end-device located at each point, with a total of 240 messages received after accounting for final re-transmissions. The specification defines the former SigFox re-transmission rate as each packet being simultaneously re-transmitted through three randomly selected communication channels at different time intervals. If a packet is not received despite the effort of simultaneous transmission via three SigFox channels, it is considered lost. The total number of messages received in SigFox could be validated using the network provider's backend. In total, over 14000 uplink messages were sent across both networks. The criteria for determining the number of uplink sent messages at each point were determined based on the total measurement campaign time. In this case, the campaign lasted two days during the same day hours and similar weather conditions, with each uplink message sent every four seconds for both LoRaWAN and SigFox end-devices at each point. The goal of the two-day campaign was to ensure fair conditions during the test by having similar channel conditions for both networks.

As previously stated, only LoRaWAN BS was installed in the rural scenario, and the measurements were oriented to obtain the performance metrics of an LPWAN network in two different scenarios. In this case, since building shadowing was less significant, each radio had only 4 static measurement points, one for each quadrant. Radii of 100 m, 300 m, 500 m, 1 km, 2 km, 3 km, 4 km, 5 km, 7 km, 9 km, and 11 km were chosen. A LoRaWAN end-device sent up to 250 uplink messages to each point, for a total of over 11000 messages sent for the study analysis. In this case, the campaign also lasted two days during the same day hours and weather conditions to ensure similar channel conditions.

Because all end-devices were GPS-enabled, each uplink message included the following information: the ID message, the ID end-device, the end-device position, the RSSI value, and the message's timestamp. The maximum transmission power was set to 0 dBm, and end-devices in the LoRaWAN network are activated via Over-The-Air Activation (OTAA), with the frequency plan AU915. Furthermore, the SF was set to 7 by default, with an uplink bandwidth of 500 kHz with an operating frequency in the band of 915 MHz.

2) ENERGY EFFICIENCY TEST

End-devices in LPWAN technologies like LoRaWAN and SigFox are typically in sleep mode whenever an application requires them to be, which minimizes the amount of energy consumed. The end-devices were configured to send the same message for this test. In this case, it was guaranteed that the message would be sent, regardless of whether the base station successfully received it. Every 30 seconds, messages are sent and registered until the battery in the device is completely depleted. Once the uplink message has been sent, each end device's voltage battery level will be measured throughout the process. For this test, an automatic data-logger based on an Arduino platform with an SD shield was integrated, where all time and measured data were saved. The implemented software of the data-logger stores the time stamp obtained from the microcontroller's Real Time Clock (RTC) and the ADC reading regarding the measured battery voltage.

Two 3.7 V Li-Polymer batteries with capacities of 4400 mAh and 1800 mAh were used for the test. In unidirectional transmission mode (Class A for LoRaWAN), with a payload of 12 bytes for each uplink message sent every 30 seconds, LoRaWAN and SigFox end-devices were configured. The re-transmission message rate of 3 was also considered in the case of SigFox. For statistical validation, the test was repeated several times.

VI. MEASUREMENT RESULTS AND COMPARATIVE ANALYSIS

The urban and rural scenarios described in section V were implemented. The outcomes and analysis of the proposed performance test are presented in the paragraphs that follow.

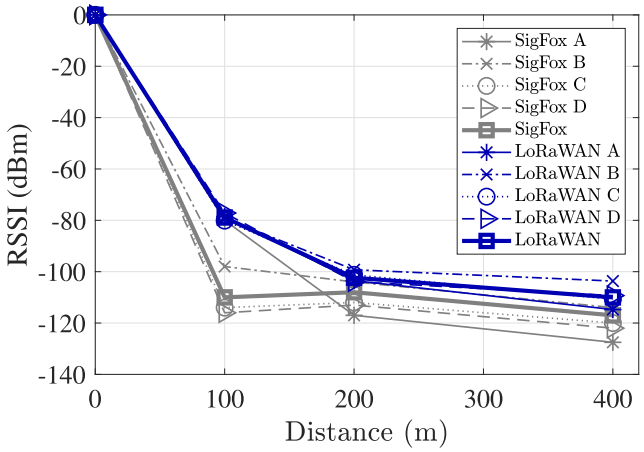

FIGURE 3. Average Received Signal Strength Indicator (RSSI) of uplink messages for LoRaWAN and SigFox in the urban scenario in quadrants A, B, C, and D. The average RSSI for all distances is also presented for both technologies.

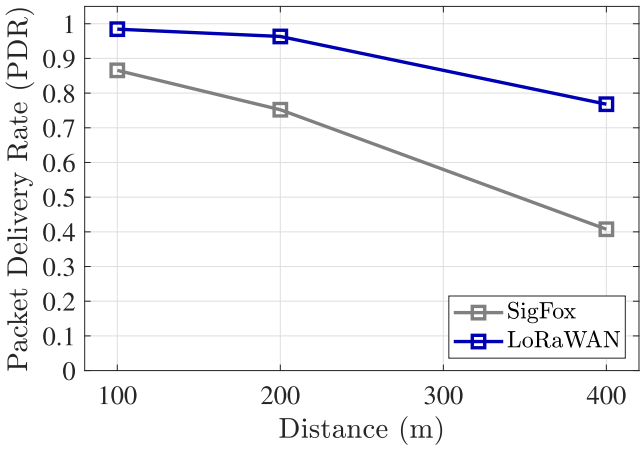

FIGURE 4. Packet Delivery Rate (PDR) for SigFox and LoRaWAN networks in the urban scenario.

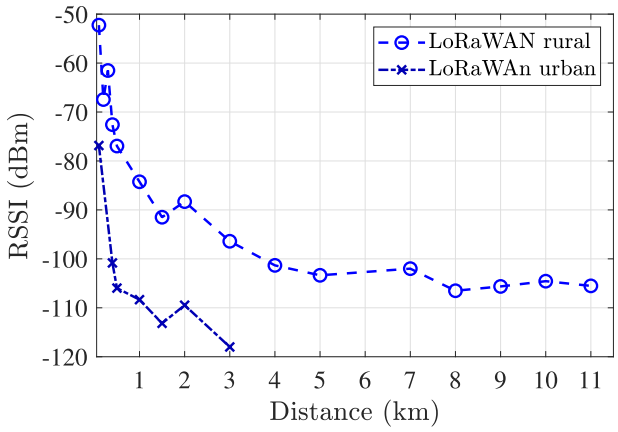

FIGURE 5. Average Received Signal Strength Indicator (RSSI) for LoRaWAN network in the urban and rural scenario.

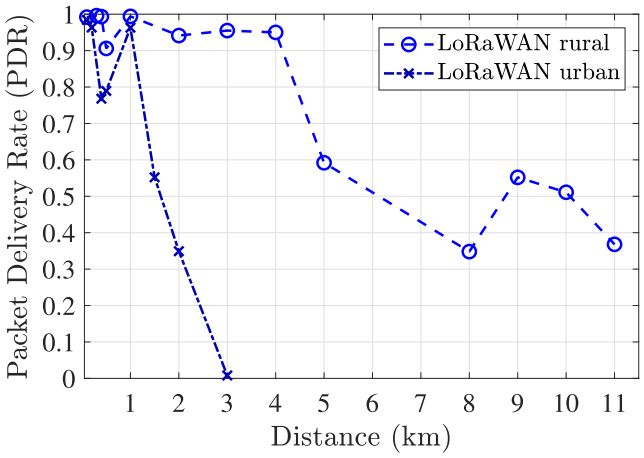

FIGURE 6. Packet Delivery ratio for LoRaWAN network in a urban and rural scenario.

A. COVERAGE TEST RESULTS

The measured RSSI values of the received messages in the BS for the 4 quadrants (A,B,C, and D) in the urban scenario are shown in Fig. 3. First, it is important to note that quadrants C and D have higher losses in both networks than quadrants A and B. This is highly likely because quadrants C and D are densely populated areas with high buildings (over 30 meters tall), which introduce additional shadowing losses. Quadrants A and B are primarily urban parks located on the mountainside, ensuring a better line of sight to the BS. Second, the LoRaWAN network exhibits greater robustness in terms of losses across the different quadrants, demonstrating that CSS modulation is resistant to multipath fading. The average RSSI for the two networks is also shown in Fig. 3, showing that SigFox consistently experiences higher losses than the LoRaWAN network. This fact is highly likely to occur due to the gain of the CSS modulation. While LoRaWAN performs better in terms of link budget, SigFox exhibits better noise sensitivity.

The results of the Packet Delivery Rate (PDR) in the urban scenario are shown in Fig. 4. Both networks perform as expected, as PDR decreases with distance in both networks. In this regard, under test conditions, SigFox performed worse than LoRaWAN in the entire scenario, particularly at 400 meters, where the difference is notorious, with nearly twice the difference in the PDR. Furthermore, LoRAWAN performed better overall, with a decrease of approximately 22% from 100 to 400 meters, whereas SigFox decreased by approximately 46%.

When observing the RSSI in Fig. 3 and the PDR in Fig. 4, there is a difference of more than 20 dB in the RSSI between both networks at 100 meters, resulting in SigFox having a better sensitivity; however, this contrasts with the performance obtained in terms of PDR at the same distance, where SigFox can reach up to 86% while LoRaWAN can reach up to 98% of reliability. This trend does not hold for subsequent distances because RSSI values for both networks are closed; however, the PDR difference significantly increases. Under these conditions, the results show that LoRAWAN end-devices outperform SigFox end-devices in terms of interference.

The measured RSSI values of the received messages in the LoRaWAN BS in the rural scenario are shown in Fig. 5, where measurements were carried out until 11 km from the BS. In this context, the results were compared to RSSI measurements obtained with a similar LoRAWAN network deployment in an urban scenario with a distance from the BS of up to 3 km. In general, the results show that RSSI values are higher in the rural scenario than in the urban scenario, as expected. When calculating the link budget in the urban scenario, shadowing and fading effects are clearly visible when compared to the rural scenario, where wireless channels are much more dispersed. In fact, the communication range reach in the urban scenario was 3 km with a PDR of less than 1% and an RSSI of around -120 dBm based on PDR results in both scenarios shown in Fig. 6.

Other conclusions drawn from the results in Fig. 6 are related to the distance at which PDR decreases significantly for both scenarios; thus, in the urban scenario, PDR drops by 60% above 1 km, whereas in the rural scenario, this occurs above 4 km. After this distance, the reliability is nearly

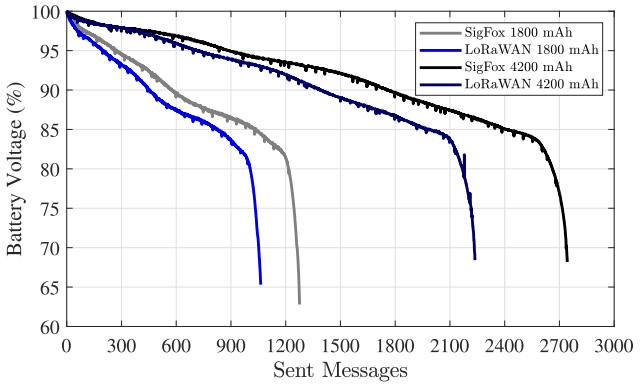

FIGURE 7. Battery discharge versus sent messages of a SigFox and LoRaWAN end-devices with 1800 mAh and 4200 mAh battery capacities.

maintained at around 50% in the rural scenario, whereas in the urban case, it drops rapidly and no uplink messages are received after 3 km. The aforementioned can also be seen in Fig. 5, where RSSI values drop to −110 dBm after 1 km. In contrast, all RSSI values in the rural scenario remain above −110 dBm.

Finally, drawing a general conclusion about the LoRaWAN network's communication range from the results, we discovered that, under test conditions, BS coverage can extend beyond 10 km, and it is highly likely that it can extend beyond 20 km as computed theoretically, while maintaining a PDR of around 40% in a rural setting with a wireless channel free of fading and shadowing effects. A different perspective is found in an urban scenario, where the communication range is less than 2 km under the same PDR conditions. Unfortunately, as previously stated, a SigFox network deployment in the rural scenario was not possible in this study; however, based on the RSSI values presented in Fig.3 and PDR values from Fig. 4, we can conclude that the performance of a SigFox network in a rural scenario would be similar up to 10 km while maintaining RSSI values above −110 dBm but with lower PDR values. However, by considering the UNB scheme modulation of SigFox in terms of noise interference, the network's performance will be maintained beyond 10 km from the BS. In contrast, LoRaWAN CSS modulation is less robust to noise level, and it is highly likely that PDR will decrease significantly above 10 km when RSSI levels fall below the noise level.

B. ENERGY EFFICIENCY TEST RESULTS

The results of the energy efficiency test are related to the battery discharge profiles of a LoRaWAN and SigFox end-devices in terms of the total number of uplink messages sent under similar transmission setups. Several tests were performed on both cases using batteries of varying capacities. In one of the performed tests, the results for LoRaWAN and SigFox end-devices powered with an 1800 mAh battery are presented in Fig. 7, where it is clearly shown how the battery discharge of the LoRaWAN end-device is faster than the SigFox end-device, in fact, this represents that, before the complete discharge of the battery, the total number of sent messages in the case of SigFox reached up to 1276 messages while LoRa reached 1060 messages. The results are similar in the test with a higher capacity battery (4200 mAh), which is also shown in Fig. 7, where the discharge profiles are maintained for both devices; the only difference with respect to the previous case is the total number of sent messages reached for each end-device, which was 2743 in the case of SigFox and 2237 in the case of LoRaWAN. Based on the previous findings, we can conclude that SigFox technology is more energy-efficient than LoRaWAN technology in general.

In general, the end devices in SigFox and LoRaWAN are in sleep or standby mode for the majority of the time, except when the application requires it, which reduces the amount of energy consumed. A LoRaWAN end device, on the other hand, consumes more power due to synchronous communication, as it invests in the transmission of some additional messages in order to connect with a BS.

VII. CONCLUSION

In this paper, we propose, for the first time, an experimental evaluation between LoRaWAN and SigFox, two representative LPWAN technologies that operate in unlicensed frequency bands. This was accomplished by first selecting coverage and energy consumption as the two most important design requirements in the network deployment for LPWAN applications based on criteria found in the literature by various authors. Then, performance test were proposed to evaluate coverage and energy efficiency which can be adapted for different LPWAN. Finally, in order to apply oriented performance tests with extensive measurements in different outdoor locations covering line and non-line of sight affected by different obstruction and multipath propagation environments, urban and rural scenarios were proposed for obtaining performance metrics for the analysis.

According to the findings of this comparative study, the achievable performance of LoRaWAN network technology can greatly vary depending on the deployment scenario, which can be reduced from more than 10 km to less than 3 kilometers with a reduction of Packet Delivery Rate (PDR) from more than 90% to less than 40%. Despite the fact that our results are consistent with the communication ranges stated in the specifications, it is evident that measured ranges are significantly shortened compared to the reported standard communication ranges for both technologies in an environment with obstructions over a distance of several kilometers.

In accordance with the measured RSSI of the signal, which in the case of LoRaWAN was higher than SigFox at least in 5 dB for all distances, our results also show that LoRaWAN outperforms SigFox in an urban environment in terms of coverage, obtaining higher PDR. The SigFox results, in contrast, clearly demonstrate a better energy efficiency operation that consistently reaches at least 20% more of sent messages. As a third design goal with a significant effect on the network's

performance, future work might examine the scalability of both networks.

ACKNOWLEDGMENT

The authors would like to thank the Electronics Department and the Laboratory of the Pontificia Universidad Javeriana, for providing the required resources to conduct this study.

REFERENCES

[1] *Overview of the Internet of Things*, document ITU-T-REC-Y.2060, Telecommunication Standardization Sector of ITU, Series Y: Global Information Infrastructure, Internet Protocol Aspects and Next-Generation Networks. Next Generation Networks—Frameworks and functional architecture models, ITU, 2012, pp. 1–22.

[2] K. E. Nolan, W. Guibene, and M. Y. Kelly, "An evaluation of low power wide area network technologies for the Internet of Things," in *Proc. Int. Wireless Commun. Mobile Comput. Conf. (IWCMC)*, Sep. 2016, pp. 439–444.

[3] R. Sanchez-Iborra and M.-D. Cano, "State of the art in LP-WAN solutions for industrial IoT services," *Sensors*, vol. 16, no. 5, p. 708, May 2016. [Online]. Available: https://www.mdpi.com/1424-8220/16/5/708

[4] L. Vangelista, A. Zanella, and M. Zorzi, "Long-range IoT technologies: The dawn of LoRa," in *Future Access Enablers for Ubiquitous and Intelligent Infrastructures*, V. Atanasovski and A. Leon-Garcia, Eds. Cham, Switzerland: Springer, 2015, pp. 51–58.

[5] J. Butler, E. Pietrosemoli, M. Zennaro, C. Fonda, S. Okay, and C. Aichele, *Wireless Networking in the Developing World*, 3rd ed. Copenhagen, Denmark: BookSprint, 2013. [Online]. Available: http://wndw.net/

[6] L. Krupka, L. Vojtech, and M. Neruda, "The issue of LPWAN technology coexistence in IoT environment," in *Proc. 17th Int. Conf. Mechatronics Mechatronika (ME)*, Dec. 2016, pp. 1–8.

[7] K. Benson, C. Fracchia, G. Wang, Q. Zhu, S. Almomen, J. Cohn, L. D'arcy, D. Hoffman, M. Makai, J. Stamatakis, and N. Venkatasubramanian, "SCALE: Safe community awareness and alerting leveraging the Internet of Things," *IEEE Commun. Mag.*, vol. 53, no. 12, pp. 27–34, Dec. 2015.

[8] Z. D. R. Gnimpieba, A. Nait-Sidi-Moh, D. Durand, and J. Fortin, "Using Internet of Things technologies for a collaborative supply chain: Application to tracking of pallets and containers," *Proc. Comput. Sci.*, vol. 56, pp. 550–557, Jan. 2015. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1877050915017329

[9] A. Ali, G. A. Shah, and J. Arshad, "Energy efficient techniques for M2M communication: A survey," *J. Netw. Comput. Appl.*, vol. 68, pp. 42–55, Jun. 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1084804516300467

[10] M. Blackstock and R. Lea, "IoT interoperability: A hub-based approach," in *Proc. Int. Conf. Internet Things (IoT)*, Oct. 2014, pp. 79–84.

[11] C. Goursaud and J. M. Gorce, "Dedicated networks for IoT: PHY/MAC state of the art and challenges," *EAI Endorsed Trans. Internet Things*, vol. 1, no. 1, Oct. 2015, Art. no. 150597. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01231221

[12] M. Centenaro, L. Vangelista, A. Zanella, and M. Zorzi, "Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios," *IEEE Wireless Commun.*, vol. 23, no. 5, pp. 60–67, Oct. 2016.

[13] D. Chaves-Diéguez, A. Pellitero-Rivero, D. García-Coego, F. González-Castaño, P. Rodríguez-Hernández, Ó. Piñeiro-Gómez, F. Gil-Castiñeira, and E. Costa-Montenegro, "Providing IoT services in smart cities through dynamic augmented reality markers," *Sensors*, vol. 15, no. 7, pp. 16083–16104, Jul. 2015. [Online]. Available: https://www.mdpi.com/1424-8220/15/7/16083

[14] G. Margelis, R. Piechocki, D. Kaleshi, and P. Thomas, "Low throughput networks for the IoT: Lessons learned from industrial implementations," in *Proc. IEEE 2nd World Forum Internet Things (WF-IoT)*, Dec. 2015, pp. 181–186.

[15] O. Vermesan and P. Friess, *Internet of Things Applications: From Research and Innovation to Market Deployment* (River Publishers Series in Communications). Aalborg, Denmark: River publishers Aalborg, 2014. [Online]. Available: https://books.google.com.br/books?id=kw2doAEACAAJ

[16] X. Xiong, K. Zheng, R. Xu, W. Xiang, and P. Chatzimisios, "Low power wide area machine-to-machine networks: Key techniques and prototype," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 64–71, Sep. 2015.

[17] J. Petäjäjärvi, K. Mikhaylov, M. Hämäläinen, and J. Iinatti, "Evaluation of LoRa LPWAN technology for remote health and wellbeing monitoring," in *Proc. 10th Int. Symp. Med. Inf. Commun. Technol. (ISMICT)*, 2016, pp. 1–5.

[18] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[19] D. H. Kim, J. B. Park, J. H. Shin, and J. D. Kim, "Design and implementation of object tracking system based on LoRa," in *Proc. Int. Conf. Inf. Netw. (ICOIN)*, Jan. 2017, pp. 463–467.

[20] D. Metcalf, S. T. J. Milliard, M. Gomez, and M. Schwartz, "Wearables and the Internet of Things for health: Wearable, interconnected devices promise more efficient and comprehensive health care," *IEEE Pulse*, vol. 7, no. 5, pp. 35–39, Sep. 2016.

[21] H. Jiang, C. Cai, X. Ma, Y. Yang, and J. Liu, "Smart home based on WiFi sensing: A survey," *IEEE Access*, vol. 6, pp. 13317–13325, 2018.

[22] T. Junjalearnvong, T. Habara, R. Okumura, K. Mizutani, and H. Harada, "A dynamic routing protocol supporting mobile nodes in wi-SUN FAN systems," in *Proc. 20th Int. Symp. Wireless Pers. Multimedia Commun. (WPMC)*, Dec. 2017, pp. 325–331.

[23] D. Bankov, E. Khorov, and A. Lyakhov, "On the limits of LoRaWAN channel access," in *Proc. Int. Conf. Eng. Telecommun. (EnT)*, Nov. 2016, pp. 10–14.

[24] A. Ali, G. A. Shah, M. O. Farooq, and U. Ghani, "Technologies and challenges in developing machine-to-machine applications: A survey," *J. Netw. Comput. Appl.*, vol. 83, pp. 124–139, Apr. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1084804517300620

[25] (May 2015). Semtech. *LoRa Modulation Basics*. [Online]. Available: http://www.semtech.com/images/datasheet/an1200.22.pdf

[26] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2347–2376, 4th Quart., 2015.

[27] M. Bor, J. Vidler, and U. Roedig, "LoRa for the Internet of Things," in *Proc. Int. Conf. Embedded Wireless Syst. Netw.*, 2016, pp. 361–366.

[28] E. Borgia, "The Internet of Things vision: Key features, applications and open issues," *Comput. Commun.*, vol. 54, pp. 1–31, Dec. 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0140366414003168

[29] Z. Zelenika and T. Pusnik, "Reinventing telecom OSS toolkit as an IoT platform," in *Proc. Int. Symp. ELMAR*, Sep. 2016, pp. 21–26.

[30] V. A. Stan, R. S. Timnea, and R. A. Gheorghiu, "Overview of high reliable radio data infrastructures for public automation applications: Lora networks," in *Proc. 8th Int. Conf. Electron., Comput. Artif. Intell. (ECAI)*, Jun. 2016, pp. 1–4.

[31] J. P. S. Sundaram, W. Du, and Z. Zhao, "A survey on Lora networking: Research problems, current solutions, and open issues," *IEEE Commun. Surveys Tuts.*, vol. 22, no. 1, pp. 371–388, 2020.

[32] Y. Chen, Y. A. Sambo, O. Onireti, and M. A. Imran, "A survey on LPWAN-5G integration: Main challenges and potential solutions," *IEEE Access*, vol. 10, pp. 32132–32149, 2022.

[33] W. Ayoub, A. E. Samhat, F. Nouvel, M. Mroue, and J.-C. Prévotet, "Internet of mobile Things: Overview of LoRaWAN, DASH7, and NB-IoT in LPWANs standards and supported mobility," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1561–1581, 2nd Quart., 2019.

[34] A. Lavric, A. I. Petrariu, and V. Popa, "Long range SigFox communication protocol scalability analysis under large-scale, high-density conditions," *IEEE Access*, vol. 7, pp. 35816–35825, 2019.

[35] M. Stusek, D. Moltchanov, P. Masek, K. Mikhaylov, O. Zeman, M. Roubicek, Y. Koucheryavy, and J. Hosek, "Accuracy assessment and cross-validation of LPWAN propagation models in urban scenarios," *IEEE Access*, vol. 8, pp. 154625–154636, 2020.

[36] P. Kulkarni, Q. O. A. Hakim, and A. Lakas, "Experimental evaluation of a campus-deployed IoT network using LoRa," *IEEE Sensors J.*, vol. 20, no. 5, pp. 2803–2811, Mar. 2020.

[37] M. O. Ojo, D. Adami, and S. Giordano, "Experimental evaluation of a LoRa wildlife monitoring network in a forest vegetation area," *Future Internet*, vol. 13, no. 5, pp. 1–22, 2021. [Online]. Available: https://www.mdpi.com/1999-5903/13/5/115

[38] *SigFox Coverage Map*. Accessed: Nov. 18, 2021. [Online]. Available: https://www.sigfox.com/en/coverage

[39] *LoRaWAN Coverage Map*. Accessed: Nov. 18, 2021. [Online]. Available: https://lora-alliance.org
[40] J. P. Queralta, T. N. Gia, Z. Zou, H. Tenhunen, and T. Westerlund, "Comparative study of LPWAN technologies on unlicensed bands for M2M communication in the IoT: Beyond LoRa and LoRaWAN," *Proc. Comput. Sci.*, vol. 155, pp. 343–350, Jan. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1877050919309639
[41] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "Overview of cellular LPWAN technologies for IoT deployment: Sigfox, LoRaWAN, and NB-IoT," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshops (PerCom Workshops)*, Mar. 2018, pp. 197–202.
[42] B. Buurman, J. Kamruzzaman, G. Karmakar, and S. Islam, "Low-power wide-area networks: Design goals, architecture, suitability to use cases and research challenges," *IEEE Access*, vol. 8, pp. 17179–17220, 2020.
[43] B. S. Chaudhari, M. Zennaro, and S. Borkar, "LPWAN technologies: Emerging application characteristics, requirements, and design considerations," *Future Internet*, vol. 12, no. 3, p. 46, Mar. 2020. [Online]. Available: https://www.mdpi.com/1999-5903/12/3/46
[44] B. Vejlgaard, M. Lauridsen, H. Nguyen, I. Z. Kovacs, P. Mogensen, and M. Sorensen, "Coverage and capacity analysis of sigfox, LoRa, GPRS, and NB-IoT," in *Proc. IEEE 85th Veh. Technol. Conf. (VTC Spring)*, Jun. 2017, pp. 1–5.
[45] H. Taleb, A. Nasser, G. Andrieux, N. Charara, and E. M. Cruz, "Energy consumption improvement of a healthcare monitoring system: Application to LoRaWAN," *IEEE Sensors J.*, vol. 22, no. 7, pp. 7288–7299, Apr. 2022.
[46] K.-H. Tseng, M.-Y. Chung, L.-H. Chen, and Y.-W. Huang, "Implementation of composite LPWAN on the slope disaster prevention monitoring system," *IEEE Sensors J.*, vol. 22, no. 3, pp. 2658–2671, Feb. 2022.
[47] E. Osorio-de-la-Rosa, J. Vazquez-Castillo, A. Castillo-Atoche, J. Heredia-Lozano, A. Castillo-Atoche, G. Becerra-Nunez, and R. Barbosa, "Arrays of plant microbial fuel cells for implementing self-sustainable wireless sensor networks," *IEEE Sensors J.*, vol. 21, no. 2, pp. 1965–1974, Jan. 2021.
[48] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "Smart grid technologies: Communication technologies and standards," *IEEE Trans. Ind. Informat.*, vol. 7, no. 4, pp. 529–539, Nov. 2011.
[49] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)*, Standard 802.15.4–2011 (Revision IEEE Std 802.15.4–2006), IEEE, 2011, pp. 1–314.
[50] M. Kirsche and M. Schnurbusch, "A new IEEE 802.15.4 simulation model for OMNeT++/INET," 2014, *arXiv:1409.1177*.
[51] C. T. Kone, A. Hafid, and M. Boushaba, "Performance management of IEEE 802.15.4 wireless sensor network for precision agriculture," *IEEE Sensors J.*, vol. 15, no. 10, pp. 5734–5747, Oct. 2015.
[52] M. Aref and A. Sikora, "Free space range measurements with Semtech LoRa technology," in *Proc. 2nd Int. Symp. Wireless Syst. Conf. Intell. Data Acquisition Adv. Comput. Syst.*, Sep. 2014, pp. 19–23.
[53] F. Adelantado, X. Vilajosana, P. Tuset-Peiro, B. Martinez, J. Melia-Segui, and T. Watteyne, "Understanding the limits of LoRaWAN," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 34–40, Sep. 2017.
[54] (2017). LoRa Alliance Technical Committee. *LoRaWAN 1.1 Specification*. [Online]. Available: https://lora-alliance.org/resource_hub/lorawan-specification-v1-1/
[55] *Low Throughput Networks (LTN); Protocol and Interfaces*, Standard ETSI GS LTN 003, 2014, pp. 1–24.
[56] *Low Throughput Networks (LTN); Functional Architecture*, Standard ETSI GS LTN 002, 2014, pp. 1–20.
[57] *Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Short Range Devices (SRD); Radio Equipment to be Used in the 25 MHz to 1 000 MHz Frequency Range With Power Levels Ranging up to 500 mW; Part 1: Technical Characteristic*, Standard EN 300 220–1—V2.4.1, 2012, pp. 1–73.
[58] D. Lachartre, F. Dehmas, C. Bernier, C. Fourtet, L. Ouvry, F. Lepin, E. Mercier, S. Hamard, L. Zirphile, S. Thuries, and F. Chaix, "7.5 A TCXO-less 100 Hz-minimum-bandwidth transceiver for ultra-narrow-band sub-GHz IoT cellular networks," in *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, Feb. 2017, pp. 134–135.
[59] B. Reynders, W. Meert, and S. Pollin, "Range and coexistence analysis of long range unlicensed communication," in *Proc. 23rd Int. Conf. Telecommun. (ICT)*, May 2016, pp. 1–6.

MANUEL PÉREZ (Member, IEEE) received the M.Sc. degree in electronics engineering with a focus on wireless communications and the Ph.D. degree in electronics and communications engineering from the Politecnico di Torino, Italy, in 2009 and 2013, respectively, and the double B.E. degree in electronics engineering from Pontificia Universidad Javeriana, Bogotá, Colombia, and the Politecnico di Torino.

From 2009 to 2013, he was a Research Assistant with the iXem Laboratories, Politecnico di Torino, and the Laboratorio di Antenne e Compatibilita Elettromagnetica (LACE), Istituto Superiore Mario Boella (ISMB), Turin, Italy. He is currently an Associate Professor with the Electronics Department, Pontificia Universidad Javeriana. He has also collaborated with the Centro de Excelencia y Apropiación en Internet de las Cosas (CEA-IoT) as the Team Director, in the areas of wearables, smart cities, and safety, working in several I+D+i projects. His research interests include applied electromagnetics, computational electromagnetics (CEM), antenna design, radar, the IoT, and electromagnetic compatibility (EMC).

FABIAN EDUARDO SIERRA-SÁNCHEZ (Member, IEEE) was born in Bogotá, Colombia, in August 1993. He received the B.S. degree in electronics engineering from Sergio Arboleda University, Colombia, in 2016, and the M.Sc. degree in electronics engineering from Pontificia Universidad Javeriana, Colombia, in 2021. His employment experiences include telecommunication companies, oil & gas industry in Colombia. From 2019 to 2020, he was a Researcher recognized by the 812 Program of the Ministry of Science and Technology (MinCiencias) of Colombia. He is currently working as a Cloud Cybersecurity Specialist. His research interest includes the evaluation of low-power wide-area network for Internet of Things applications.

FABIÁN CHAPARRO was born in Duitama, Boyacá, Colombia, in 1983. He received the joint B.S. degree in electronics engineering from Universidad Santo Tomás, Tunja, in 2005 and 2013, respectively, and the M.Sc. degree in telematics from Universidad Autónoma, Bucaramanga. He is currently pursuing the Ph.D. degree in engineering with Pontificia Universidad Javeriana, Bogotá. From 2005 to 2008, he worked with the Instituto Nacional Penitenciario y Carcelario—INPEC and the Empresa de Telecomunicaciones de Bogotá—ETB, Colombia. He has been working as a Professor with the Electronics Engineering Department, Universidad Santo Tomás, Tunja, Colombia, since 2008. His research interests include telecommunications networks, networking infrastructure, bandwidth requirement estimation, and the Internet of Things with applications in agricultural environments.

DIEGO MÉNDEZ CHAVES (Member, IEEE) received the B.E. degree in electronics engineering from Universidad Nacional, Bogotá, Colombia, in 2005, the M.E. degree from the Universidad de Los Andes, Bogotá, in 2009, and the M.Sc. and Ph.D. degrees in computer science from the University of South Florida, Tampa, FL, USA, in 2011 and 2012, respectively. He is currently an Associate Professor with the Department of Electronics Engineering, Pontificia Universidad Javeriana, Bogotá. His research interests include the Internet of Things (IoT), embedded systems, wireless sensor networks, participatory sensing, digital systems design, operating systems, and high-level systems design.

CARLOS-IVAN PAEZ-RUEDA (Senior Member, IEEE) was born in Cúcuta, Colombia, in March 1973. He received the B.S. degree in electronics engineering from Pontificia Universidad Javeriana, Colombia, in 1997, the M.Sc. degree from the Universidad de los Andes, Colombia, in 2002, and the Graduate (Specialist) degree in research and education from Universidad Sergio Arboleda, Colombia, in 2004. He is currently pursuing the Ph.D. degree in engineering with the Universidad de los Andes, Colombia, in 2017.

His employment experience include several telecommunication companies in Colombia. Since 2006, he has been a Professor with the Electronics Department, Pontificia Universidad Javeriana. His working field include simulation models and optimization algorithms for telecommunications, computational electromagnetics (CEM), and design of passive radio frequency devices.

GABRIEL PERILLA GALINDO was born in Bogotá, Colombia, in 1955. He received the B.E. degree in electronics engineering and the M.Sc. degree (Hons.) from Pontificia Universidad Javeriana, Colombia, in 1979 and 2008, respectively, and the master's degree in photovoltaic solar energy from the Universidad Politécnica de Valencia, Spain, in 2010. Since 1977, he has been working in the academy, leading courses that address the theoretical aspects and practical applications of electrical circuits, power electronics, electrical energy conversion, and renewable energy. He has been working as an Assistant Professor with Pontificia Universidad Javeriana, since 1977. He has been an Associate Professor with the Universidad Nacional de Colombia, since 2001, and as a Special Professor with the Escuela Colombiana de Ingeniería Julio Garavito, since 2008.

ARTURO FAJARDO (Senior Member, IEEE) received the Graduate degree in electronic engineering from Pontificia Universidad Javeriana (PUJ), Colombia, in 2002, the master's degree in electronic engineering, in 2008, and the Ph.D. degree in electrical engineering from the Federal University of Santa Catarina, Brazil, in 2018.

From 2002 to 2003, he was the Director-Head of the Information Technology Office at the customs user's ombudsman attached to the Colombian National Tax and Customs Directorate (DIAN). He worked as a Junior Researcher with the PUJ's Research Group of Control Systems, Power Electronics, and Management of Technological Innovation in Electronics, from 2003 to 2008. He has been a Professor with the Department of Electronics and a Researcher with the PUJ Telecommunications Research Group, since 2006. He led the development of PUJ's networking and telecommunications program, in 2020. His current research interests include power-efficient RF circuits for body area networks, wireless power transfer, indoor solar panel modeling, DC/DC converter modeling, and wireless instrumentation electronics.

Dr. Fajardo's awards and honors include the Best Paper of the Power and Energy Track of the IEEE-ANDESCON 2020, the Lucent Technologies Undergraduate Fellowship, and the COLCIENCIAS Ph.D. Scholarship.