Design of Compact LoRa Devices for Smart Building Applications

Sérgio I. Lopes[1,2](✉), Felisberto Pereira[3], José M. N. Vieira[3,4], Nuno B. Carvalho[3,4], and António Curado[1,5]

[1] Instituto Politécnico de Viana do Castelo, Viana do Castelo, Portugal
sil@estg.ipvc.pt
[2] Instituto de Telecomunicações, Aveiro, Portugal
[3] Instituto de Telecomunicações, Campus Universitário de Santiago, Aveiro, Portugal
[4] DETI, University of Aveiro, Campus Universitário de Santiago, Aveiro, Portugal
[5] CONSTRUCT LFC, Faculty of Engineering (FEUP), University of Porto, Porto, Portugal

Abstract. The use of smart devices in buildings is many times compromised by its form and size. Smart devices are composed of several components including sensors, boards, batteries, processing units, and antennas. However, the form and size of the smart devices are usually limited due to antenna restrictions. In this paper, we propose the architecture of a compact low-cost LoRa smart device designed for easy deployment in smart building applications. The proposed device architecture features a reduced size embedded antenna and an ultra-low-power microcontroller to interface several sensors and actuators. The results obtained have shown that the proposed design can be used for communication, between two compact LoRa devices, in line-of-sight for up to 4.2 km, in urban environments for up to 1.2 km and also for in-building communications for up to 152 m, without compromising the low-power features that LoRa supports.

Keywords: Green communications · LoRa · Smart buildings

1 Introduction

Green wireless communications are nowadays a hot topic in research that has been pushed by new ubiquitous applications in several application domains [1]. As a result, these communication systems have been designed for optimal spectrum efficiency and high transmission reliability [2]. Moreover, the need for energy efficiency with reduced environmental impact in radio communications increases the effort of reducing the communication cost and therefore, the power used for communications.

In [3], Buckman et. al. define a Smart Building as the harmonious integration of intelligent systems, control mechanisms, architecture and construction materials to operate as an entire building system, with adaptability at its core to enable

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continuous building improvement in terms of energy efficiency, longevity, comfort, and satisfaction. A central topic in the previous definition that is implicit and vital in the design of this type of systems is the selection of the communication technology, in order to enable a simple, non-invasive and transparent integration between the main elements of such systems.

In a smart building context, several sensors and actuators are deployed for data collection, reasoning, and building control. The lack of a widely accepted standard for low-power in-building communications opens a window of opportunity to use and adapt other standards with higher maturity levels that are already adopted by industry for long-range communications, e.g. SigFox or LoRa. Another common standard that has been very popular in this type of applications is Wi-Fi. Wi-Fi is a mature technology with a large ecosystem that is being integrated in several smart devices due to its easy deployment and simple integration with existing IP networks at an affordable price. However, the use of Wi-Fi faces two main drawbacks: (i) high power consumption that results in a reduced device autonomy and (ii) coverage bellow 40 m, making it difficult to perform effective in-building and inter-building communications.

Moreover, the use of smart devices in buildings is many times compromised by its form and size. Smart devices are composed of several components including sensors, boards, batteries, processing units, and antennas. However, the form and size of the smart devices are usually limited due to antenna restrictions.

Given this, in this work, we will evaluate the viability of using LoRa technology in the design of compact and ultra-low-power devices for smart building applications that demand reduced maintenance, i.e. battery operation over long periods of time (in the order of magnitude of the years) for in-building and inter-building connectivity. For this, we will focus on the design of a compact LoRa antenna with optimal performance without compromising the form and size of the smart sensor.

This paper is organized as follows. Firstly a discussion about the state-of-the-art in low-power wireless communication systems commonly used in smart building applications is undertaken. Secondly, the architecture of the proposed Smart device is introduced and its specification is presented. Thirdly the design and simulation of the LoRa embedded antenna are presented using a simplified model of the Printed Circuit Board (PCB) that includes its main components. Fourthly, real experiments are performed and the results are discussed. Lastly, final conclusions are undertaken and future work is pointed out.

2 Wireless Communication Technologies for Smart Buildings

When selecting a wireless communication technology for a smart building, four main criteria are commonly used: (i) cost; (ii) data rate; (iii) autonomy and (iv) communication range. Note that, when using these criteria, there is a strict and proportionally inverse relationship between data rate and autonomy and between communication range and autonomy, due to the increase in power consumption to communicate at higher bit rates or greater distances.

Given the scope of this paper, we will focus on low-power communication technologies. Table 1 compiles the five more promising standards that are being used in smart building applications, notably LoRa, Sigfox, NB-IoT, and Z-Wave. Note that, although the Wi-Fi technology was not designed for low-power applications, it has been included in this study, mainly due to its high maturity level and large ecosystem. The table includes the four main criteria introduced at the beginning of this section. The cost criterion has been estimated based on the average price of commercial off-the-shelf modules. Additionally, six technical criteria (modulation, bandwidth, frequency, etc.), have been added for a more effective comparison.

Table 1. Wireless technologies commonly used in smart buildings.

	LoRa[5]	SigFox[6]	NB-IoT [7]	Z-Wave[8]	Wi-Fi[9]
Cost	3–5€	2–5€	10–20€	8–12€	< 2€
Data Rate	<50 kbps	<100 bps	<200 kbps	<40 kbps	<300 Mbps
Autonomy	<10 years	<10 years	<10 years	<2 years	<10 days
Range (urban)	<5 km	<10 km	<1 km	<100 m	<40 m
Modulation	CSS	BPSK	QPSK	FSK	BPSK/QAM
Bandwidth	125/250 kHz	100 Hz	200 kHz	300 kHz	20/40 MHz
Frequency (EU)	868 MHz	868 MHz	LTE bands	868 MHz	2.4/5.0 GHz
Spectrum Cost	Free	Free	Very High	Free	Free
Max. msg/day	Unlimited	140(↑), 4(↓)	Unlimited	Unlimited	Unlimited
Max. payload	243 bytes	12(↑), 8(↓) bytes	1600 bytes	64 bytes	64 KB

LoRa technology combines long-range connectivity with a considerable increase of the battery lifetime at a low-cost using sub-GHz unlicensed spectrum. LoRa uses a Chirp Spread-Spectrum (CSS) modulation schema which results in a considerably higher resistance to noise, interference or jamming signals, and also presents known advantages in terms of multi-path fading and the Doppler effect [5]. Although it needs a specific infrastructure based on LoRa Gateways to connect the smart devices to the Internet, it is a good alternative to Wi-Fi when low-power devices need to be deployed inside a building.

Sigfox is a company with its own proprietary technology that was designed specifically for the IoT-era. It is a sub-GHz technology that takes advantage of ultra-low channel bandwidth in the communication process, offering a simple and very light protocol stack that imposes hard restrictions in the number and size of the messages exchanged [6], in a daily basis, cf. Table 1. The company has its own communication infrastructure, being its access offered as a paid service.

NB-IoT (Narrowband IoT) is an LTE-based synchronous protocol developed under the 3GPP (Third Generation Partnership Project), that has been designed to address the needs of very low data rate and low-power devices that need to connect to the Internet using standard mobile networks [7]. As major disadvantages, one can identify its high cost, not only the smart device cost but also the operational cost due to the use of licensed spectrum, which also compromises its ecosystem development.

Z-Wave is a wireless technology specifically designed for remote control and home automation applications. It is a low-power communication technology that works in the sub-GHz frequency range and was designed to operate in a source-routed mesh network topology, where each device is able to send and receive control messages through walls or floors taking advantage of intermediate devices to route around household obstacles or radio dead spots that might occur [8]. As major disadvantages, one can identify its intermediate cost, low range capabilities, and autonomy, when battery operation is considered, cf. Table 1.

Wi-Fi is a mature technology with a large ecosystem widely used in smart building applications. There are several suppliers of Wi-Fi modules, cf. Table 1, ready for smart device integration at an affordable price. Moreover, it is a technology easy to deploy and integrate with existing IP networks. However, it presents two major drawbacks, the first is related to its reduced autonomy an the second is related to a small in-building communication coverage.

Finally, and regarding QoS (Quality of Service), protocols that rely on ISM frequency bands, i.e. unlicensed spectra, are more susceptible to interference, multipath, and fading phenomena, which delivers lower QoS, when compared with protocols that use licensed spectrum, such as NB-IoT. Given this, NB-IoT is, therefore, more appropriate for applications that demand guaranteed QoS. In smart building applications, the devices used for sensing and actuation are mainly designed to achieve low cost and long battery lifetime, and not requiring high QoS demand or frequent communication, which places the LoRa technology in advantage when this type of application is considered [4].

3 Smart Device Architecture

Figure 1 illustrates a simplified block diagram of the proposed Smart Device architecture. It was specified to operate in two distinct modes: (i) Data Collection Unit (DCU) or (ii) Physical Actuation Unit (PAU). When configured as a DCU, it will be equipped with a set of sensors for data acquisition (e.g. CO_2, Relative Humidity, Temperature, Air Pressure, and Radon). These sensors will be connected to a low-power microcontroller using distinct interfacing methods (analog or digital). All the attached sensors will be digitally controlled using analog power switches that will enable a proper power management of the overall device. On the other hand, when configured to operate as a PAU, it will take advantage of two actuation possibilities: one for remote ON/OFF control and the second for remote PWM (Pulse Width Modulation) control, thus enabling the possibility to remotely control an electric motor for fine ventilation. The user interface will be based on a single push-button and an RGB led.

Several sensors have been interfaced to the microcontroller. To obtain a raw estimate of the CO_2 level, we opted for the low-cost SNS-MQ135 from Olimex. This is a resistive gas sensor that does not directly provide the CO_2 level, but it can be computed indirectly by software after a calibration process, being its

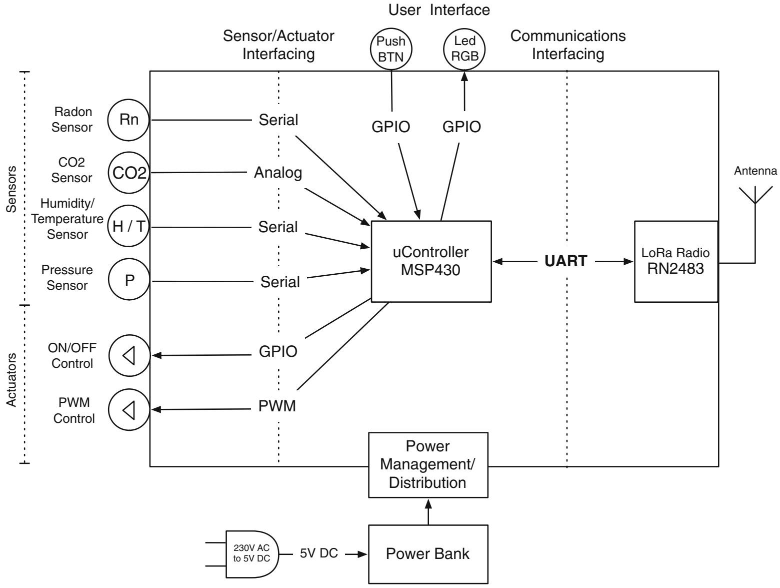

Fig. 1. Block diagram of the Compact LoRa Device.

precision highly dependent of this calibration process. The humidity and temperature are acquired using the HTS221 from STMicroelectronics, the maximum error for humidity is ± 3.5%rH and for temperature is ± 1°C. The MPL3115A2 from NXP Semiconductors is used for air pressure measurements with a maximum error of ± 0.4 kPa. Lastly, the PCB provides a serial connection to an external Radon gas sensor through a specific connector. The Radon sensor considered was the RD200M that measures the radon level after stabilized for 1 hour with a precision of ± 0.5 pCi/l. The RD200M needs to operate in a continuous mode consuming approximately 60 mA and it will be only attached for specific application cases.

Regarding the power requirements and sensors specifications, we opted for an ultra-low-power microcontroller, i.e. the MSP430F247 from Texas Instruments. From the energetic point of view, the microcontroller consumes 270 μA in Active Mode at 1 MHz and just 0.3 μA in Standby Mode. In terms of digital and analog interfacing, it supports several serial communications protocols (UART, SPI, I^2C) and has multiple analog inputs that can be multiplexed to the input of an A/D module.

The Smart Device connectivity uses LoRa technology based on the RN2483 LoRa SoC (System-on-Chip), radio module manufactured by Microchip and designed to operate in Sub-GHz bands and therefore enabling long range, low power, and high network capacity [10]. The RN2483 LoRa SoC is equipped with a UART host interface for simple integration with a microcontroller via AT commands [10]. Its radio frontend can deliver to the antenna up to 14.0 dBm and presents a receiving input sensitivity of −148 dB.

The RN2483 LoRa SoC has no built-in antenna. The choice of an antenna involves the analyses of several aspects. For example, the direction of communication, the power gain required and the surrounding materials are some aspects that need to be considered in the antenna selection or design process. A list of requirements and a correct perception of the final application limitations is essential, especially in cases that include non-line-of-sight, such as in-building and inter-building communications.

3.1 Compact LoRa Antenna Design

The first aspect to be considered is the operating frequency. In Europe, LoRa operates in the 868 MHz ISM band. When using this ISM band the module operates with frequencies from 863 MHz to 870 MHz. The antenna should than be projected to operate in that frequency interval.

Furthermore, the smart device is supposed to operate inside buildings and, given the difficulty to predict the kind of environment that will be surrounding it, an omnidirectional radiation pattern should be considered. Nevertheless, it is also important to design the antenna having into account the metallic elements that are nearby, particularly in the PCB.

Given the necessity to design a small and compact device, all the metallic elements near the antenna, e.g. electronic components, microcontroller, and battery, must be carefully positioned. This proximity between parts may result in a great influence on the antenna performance and compromise the communication process. One possible solution is to use a commercial antenna. This approach has the advantage of achieving higher performance at a higher size and cost. Furthermore, a commercial antenna is not designed to be closer to metallic components and needs to be attached to the main board by means of a connector, which results in a lack of sturdiness and increased size. Another solution is to use a common monopole antenna. This type of antenna can be printed on the same board than the circuit and has an omnidirectional radiation pattern. However, this design is highly influenced by the surrounding environment and therefore not recommended for this application case.

In this work, we opted to use a Planar Inverted-F Antenna (PIFA), which is an alternative to the classic monopole antenna design. This design ensures more robustness regarding the surrounding environment without compromising the implementation and the omnidirectionality pattern. Besides the branch connected to the radiofrequency signal (RF), the PIFA also has a branch connected to the ground.

3.2 Simulation

The first step in the antenna design is to simulate the antenna based on its theoretical model. From this point, multiple adjustments in its dimensions are then made until the best results are achieved. This process is even more crucial when the antenna is close to a circuit or a ground plane, these elements have electrical characteristics that influence the antenna performance. More detailed information about the implications can be found in [11].

As we are focused on the design of a compact device, the PIFA antenna needs to be placed near the circuit, which can negatively impact the antenna performance. To mitigate this, the antenna was designed using the circuit presented in Figure 2 as the initial simulation model. The antenna was designed using the Computer Simulation Technology Studio Suite (CST Studio Suite).

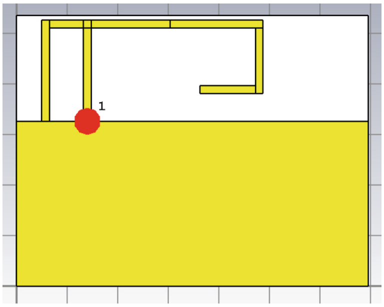

Fig. 2. Simulation model with groundplane and the PIFA antenna included.

In order to simplify the simulation process, the circuit has been imported to the simulator with a degree of abstraction, instead of representing all the circuit lines and components, the circuit was imported and converted to a ground plane. This abstraction does not compromise the results, since the metallic plane has the same influence represented by ground or lines, allowing a huge time-saving in the simulation.

Figure 3 illustrates the simulation results based on the S_{11} parameter. In green is represented the theoretical model and in red the optimized model after multiple adjustments. Note that, the S_{11} parameter represents the return loss, i.e. the reflected signal, and is directly related with the impedance mismatch from 50 ohms throughout the interconnection to the PIFA. In the frequency bands of interest, it is possible to observe an increase of performance of approximately 7.5 dB, between the theoretical and the optimized models.

The changes between the initial antenna and the optimized antenna are in terms of dimensions, the optimized antenna is more distant from the ground plane and the distance between branches are also different. Another important characteristic of the antenna is its omnidirectionality, cf. Fig. 4.

3.3 Field Experiments

The final circuit design and the assembled version can be seen in Fig. 5, where all relevant components can be observed, i.e. the PIFA antenna, the LoRa radio module, the microcontroller, sensors, and other passive components. The field

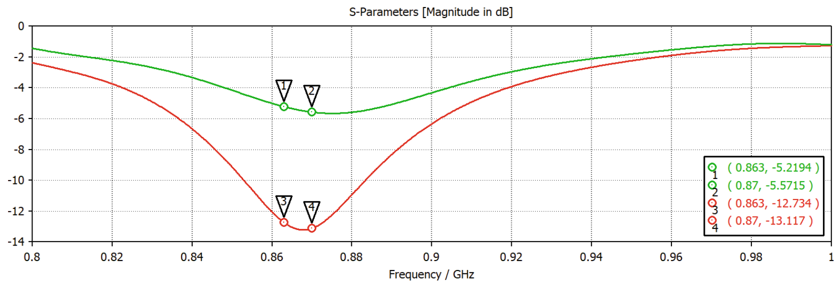

Fig. 3. S_{11}-parameter obtained after simulation. Green line represents the theoretical model and Red line represents the optimized model after multiple adjustments. (Color figure online)

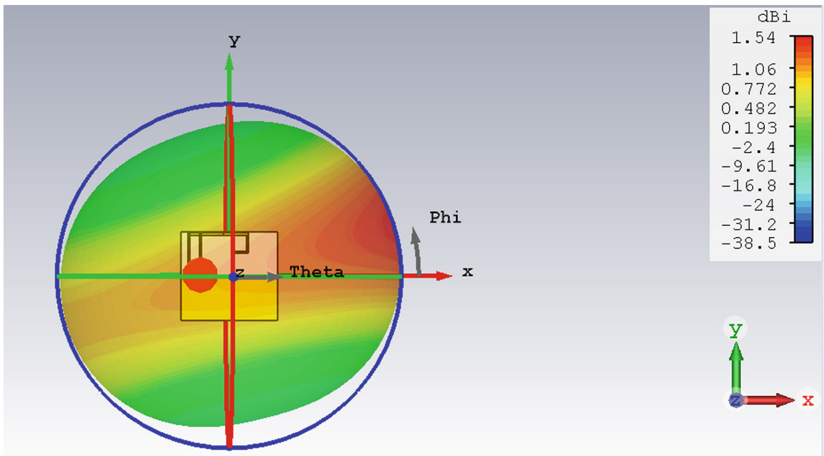

Fig. 4. Radiation diagram of the PIFA antenna using the PCB simplified model.

experiments were performed using two of these devices, one was configured as a transmitter and the other was configured as a receiver. The radio module used (RN2483) does not allow the measurement of any power indicator, such as the well-known RSSI, so the experiments were carried out to evaluate connectivity. The Printed Circuit Board dimensions are 91 × 69 mm.

Line-of-sight and urban environment connectivity were evaluated based on two field experiments, cf. Fig. 6. In both cases, one device was configured as a transmitter with an output power of 14 dBm and the second device was configured to operate as a receiver (sensitivity of −143 dBm). In both experiments, the receiver was placed in the roof of a building (blue marker). In the first experiment the transmitter was placed in line-of-sight situations (red markers), and in the second experiment, the transmitter was placed inside a car that was moving in an urban environment (green markers). The two devices presented successful

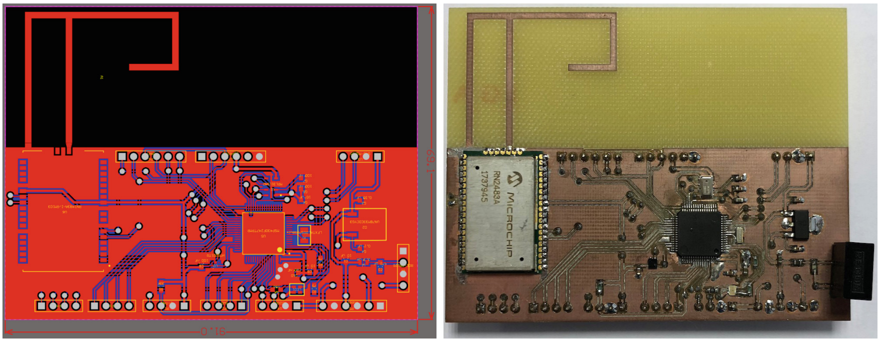

Fig. 5. PCB design with antenna and assembled version.

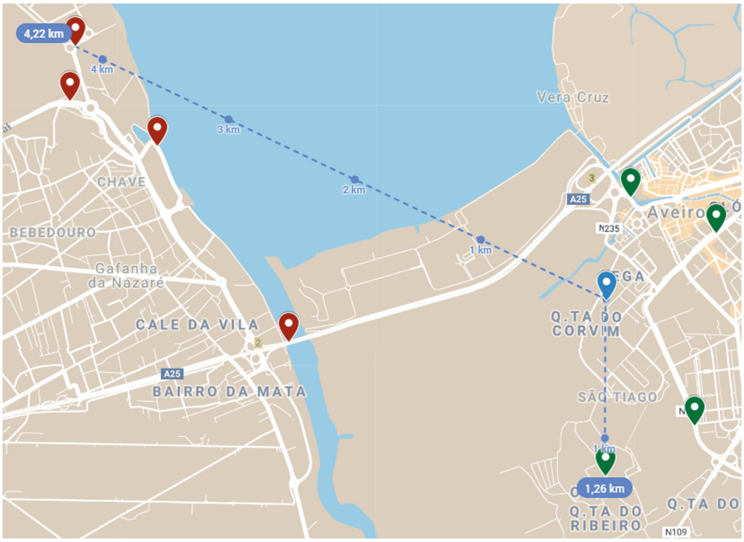

Fig. 6. Successful connectivity obtained for Line-of-sight (experiment 1) and urban environment (experiment 2) communications. (Color figure online)

communications up to distances of 4.2 km and 1.2 km, for the first and second experiment, respectively.

Indoor connectivity was evaluated based on two additional experiments, one to evaluate the in-building connectivity and other to evaluate the inter-building connectivity with neighbor buildings, cf. Fig. 7. In both experiments, the receiver was placed inside a building (blue marker) at the underground level. In the third experiment the transmitter was placed in distinct positions inside the same building at the same level in non-line-of-sight situations (green markers), and in the fourth experiment, the transmitter was placed in two distinct neighbor buildings (red markers) at upper levels. The longest distance that the devices were able to communicate in this environment was 152 m.

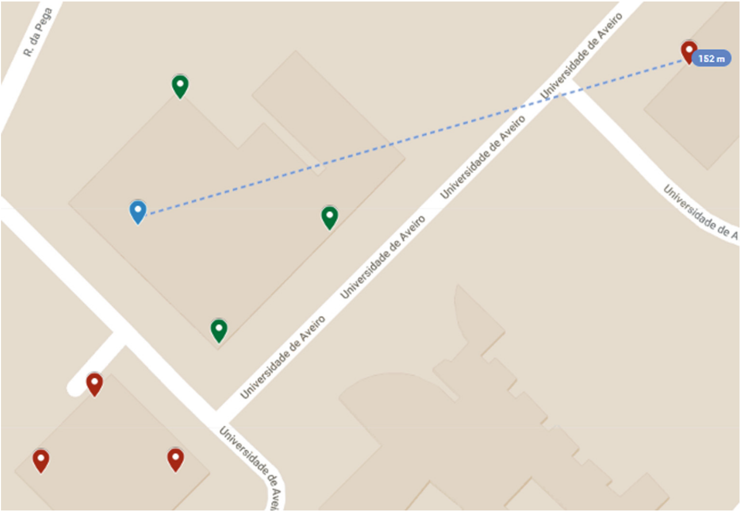

Fig. 7. Successful connectivity obtained for in-building (experiment 3) and inter-building (experiment 4) communications. (Color figure online)

Regarding the power consumption the device can be separated into three distinct modes: (1) Transmission mode - happens when a communication is performed and consumes approximately 39.2 mA; (2) Sensing mode - occurs when the sensors are acquiring data, the consumption depends on the sensor, being 40.2 mA for measuring CO_2, 280.6 μA for Temperature/Humidity and 542.1 uA for air pressure; (3) Sleep mode - when the device is not performing any task, consuming 9.4 μA.

Considering that the device performs one set of measurements per hour, i.e. sensing mode, and it takes around one second to do the job, the consumption in this mode is around 11.1 μA. Furthermore, and considering that the device transmits hourly with a transmission period of approximately one second, the consumption in the transmission mode is approximately 10.9 μA. In the remaining time, i.e. 3596 seconds per hour, the device is in Sleep mode consuming 9.4 μA. Adding these values we can estimate the overall average consumption of the device, i.e. 31.4 μA. Taking into account that the device can be powered by a CR2477 coin cell (that has a power capacity of 1000 mAh), and if we consider the profile of operation previously introduced, the device can operate for a period of approximately 3 years and 7 months. This power budget does not include the RD200M Radon sensor due to its power needs. In applications that demand Radon monitoring, the smart device must be continuously connected to the public power grid or powered by an alternative energy source, e.g. photovoltaic panel.

4 Conclusions and Future Work

Regarding the antenna design, it was proved that it is crucial to integrate the antenna design with the circuit in order to obtain an optimized performance. The results obtained have shown that the proposed design can be used for communication, between two compact LoRa devices, in line-of-sight for up to 4.2 km, in urban environments for up to 1.2 km and also for in-building communications for up to 152 m, without compromising the low-power features that LoRa supports.

Major advantages of the proposed design, when compared with other common approaches include: (i) flat design; (ii) PCB can be placed in a closed box, e.g. waterproof box not requiring any aperture; (iii) low-cost design; (iv) no external connectors required for antenna; (v) easy manufacturing (printed together with the circuit) and (vi) design can be optimized for the application under interest.

As future work, it is expected to minimize the presented circuit and to create forms and dimensions that could ensure and easy deployment in buildings. In that case, the antenna should be re-designed having into account the new materials and limitations.

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