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RnProbe: A LoRa-Enabled IoT Edge Device for Integrated Radon Risk Management

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ABSTRACT Radon is a naturally occurring radioactive gas that can easily accumulate in indoor environments. According to the World Health Organization (WHO), radon gas is the second largest risk factor associated with lung cancer, after tobacco smoking. People spend at least half their life inside buildings, which are becoming increasingly more hermetic due to the pursuit of high energy efficiency – an increase in ventilation rates tends to increase heat losses. In this context, energy efficiency and Indoor Air Quality (IAQ) concepts, if not studied in a balanced way, can move in opposite directions. The introduction of Internet of Things (IoT) technologies for continuous assessment of the IAQ can help to achieve an optimally integrated balance between them. This article focus on the specification and design of the RnProbe, an IoT Edge Device developed under the scope of the RnMonitor R&D project whose main objective was the specification and development of a Cyber-Physical System (CPS) for integrated Radon Risk Management in public buildings, such as schools, kindergartens, offices, and hospitals, that are restricted to regular occupancy schedules, so that policymakers and building managers can reduce public health risks associated with the exposure to this pollutant. The device collects, aggregates, and transmits up to the cloud, several indoor environmental parameters. When combined these measurements are used to perform specific mitigation actions in the building, to improve IAQ.

INDEX TERMS Sensor systems and applications, health and safety.

I. INTRODUCTION

Radon-222 is an inert gas produced in rocks and soil by the decay of uranium [1]. The gas is present in the outdoor air in small concentrations and penetrates buildings through its foundation joints, cracks in floors and walls, as well as through pipes and drains. Once inside the building, and particularly if the building is made of traditional construction materials with higher radon potential and has a basement or a semi-basement, the building envelope works as a retainer or buffer for Radon gas. If all the doors and windows are open, the gas ascends into the atmosphere and the concentrations inside and outside the building are similar. However, if the openings are all tightly closed, as it is usual in energy-efficient buildings, the indoor concentration will be considerably higher, potentially tens of thousands of times higher in some cases [2], [3].

A high level of gas concentration is directly correlated to lung cancer prevalence. International Commission on Radiological Protection (ICRP) [4] points out that among non-smokers the cancer risk increment was estimated at 0.4%, 0.5%, and 0.7% for exposition to radon concentrations of 0, 100, and 400 $Bq.m^{-3}$, respectively. In the case of lifelong smokers, the risk levels rise to 10%, 12%, and 16% for the same radon concentrations, respectively, according to Figure 1. The correlation between lung cancer and radon is also presented by Council [5]. In 2003, the United States Environmental Protection Agency (EPA) conducted a study

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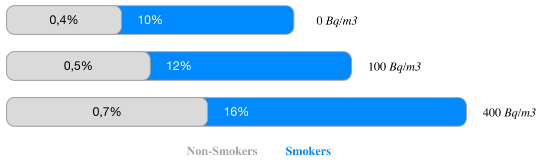


FIGURE 1. Lung cancer risk due to radon gas exposure in tobacco smokers and non-smokers. Data obtained from [4].

in which it was that out of a total of 157,400 lung cancer deaths in 1995, 13.4% were radon related [6]. These values are a bit lower in Europe, where it is estimated that the annual mortality from exposure to radon in buildings represents 9% of all deaths from lung-cancer [7].

It is important to emphasize that radon is particularly dangerous for buildings' occupants in scenarios of long periods of indoor exposure, such as is the case of people who both live and work in enclosed spaces subject to high radon levels. Occasional exposure is not particularly harmfully to humans, considering indoor environments with moderate radon exposure conditions. However, studies have shown that humans spend on average, 87% of their time in enclosed buildings and that human activities impact the timing, location, and degree of exposure to indoor pollutants [8]. Beyond the building industry, the mining industry is probably the most aware of radon-related problems, with multiple studies carried out to investigate the impact of long-term radon exposure [5], which activity in the air is expressed in becquerels per cubic meter of air ($Bq.m^{-3}$) or in picocuries per liter of air ($pCi.l^{-1}$). Here, the $Bq.m^{-3}$ nomenclature, however, there is a direct correspondence between units, since 1 $pCi.l^{-1}$ corresponds to 37 $Bq.m^{-3}$.

The last updated recommendations on protection against radon exposure published by World Health Organization (WHO) [1], express that, authorities should set a reference level in the range between 100 and 300 $Bq.m^{-3}$. However, and based on ICRP recommendations [9], national plans against radon should be more ambitious and must simultaneously address the objective of reducing the collective risk of the population, and the individual risk. To reduce the risk, policies should not only focus on reducing radon levels but also on linking this information with occupancy and other Indoor Air Quality (IAQ) parameters to ensure population safety. As indicated, radon is an inert gas formed by the radioactive decay of the element radium in rocks and soil, but although all rocks contain some uranium, most of them contain only a small amount. Volcanic rocks, like granites and dark shales, have higher uranium contents, therefore this means that zones with soils formed by these kinds of rock have higher radon levels [10]. Radon is colorless, odorless, and tasteless with a half-life of 3.8 days [5], [7]. In Portugal, the country where this work has been conducted, there is a large area of granite and orthogneisses as can be seen in Figure 2. Previous studies have shown that the Centre and the Northern regions of Portugal present high radon concentrations inside buildings [11]. According to the 2013/59/Euratom Directive [12]], transposed into Portuguese

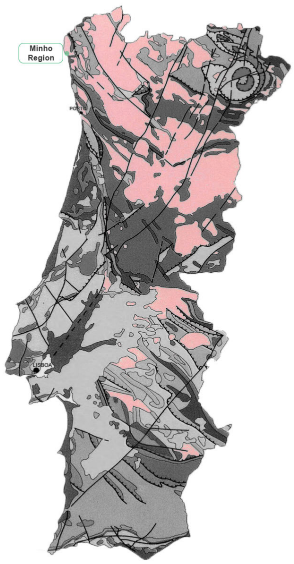


FIGURE 2. Portugal soil map, coloured zone represent granite and ortognaisses soil. Image adapted from [14].

legislation on December 3, 2018 [13], the exposure limit to radon gas concentration is 300 ($Bq.m^{-3}$). This legal limit is applied for housing, public buildings, and all workplaces, according to Article 145.

To comply with regulatory requirements, modern constructions are thermally isolated and provided with air conditioning systems, or other similar devices, designed to allow the maximum control of temperature and relative humidity inside buildings. However, and even though there are guidelines that safeguard IAQ [15], [16], this control is often made without fulfilling the minimum value for air change rates, and therefore completely neglects the good ventilation practices. The topic gained interest in recent years, and some works have evaluated the performance of traditional and some new types of ventilation systems to improve IAQ. Some recent studies have analyzed the effect of innovative ventilation concepts on the behavior of parameters like CO_2, indoor air temperature and relative humidity, and have studied its effect on the concentration of CO_2 and total volatile organic compounds (TVOC), relating it to occupancy, or outdoor air temperature [17], [18].

This research details the design and implementation of a Cyber-Physical System (CPS) architecture, which is part of the RnMonitor R&D project. In the RnMonitor project, an online monitoring infrastructure has been built allowing the implementation of a set of active mitigation strategies to control indoor radon gas in public buildings in the northern region of Portugal - the concept is presented in Fig. 3. To build this infrastructure, a network of Internet of Things (IoT) Edge devices capable of sensing radon gas concentration, atmospheric pressure, indoor air temperature, and relative humidity was implemented. Each IoT Edge device is equipped with two communications technologies (LoRa and Wi-Fi) ensuring that data is always transmitted. The device, named RnProbe, also performs edge computing,

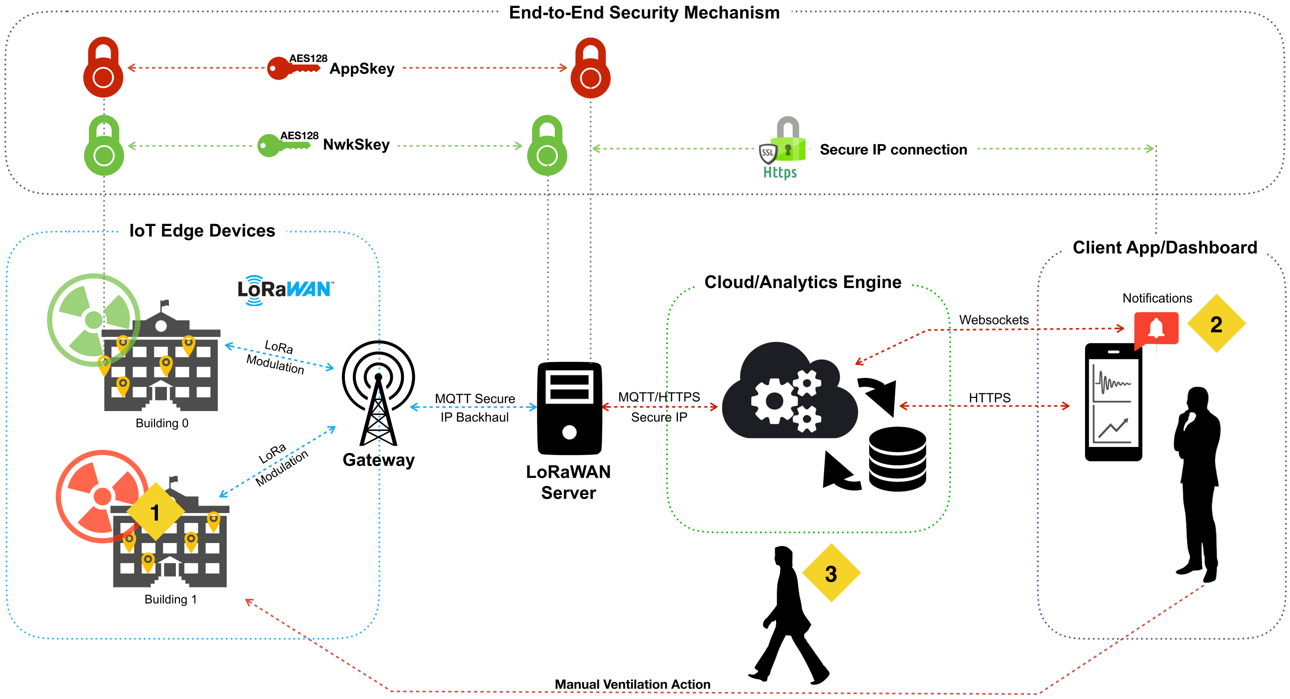


FIGURE 3. System architecture with end-to-end security mechanism and common use-case in three events: *Event 1)* a specific room of Building 1 has higher radon level; *Event 2)* an alarm notification is sent to the Building Administrator; *Event 3)* a manual ventilation action is carried out by the building administrator.

working as the first processing stage for the acquired data.

The paper is organized as follows: Section II presents the state-of-the-art regarding methods for testing for radon levels and also introduces relevant academic work for radon monitoring; Section III introduces and details the overall system architecture and its core security mechanisms; Section IV approaches all the topics regarding the IoT Edge device design and development; Section V describes the experimental validation procedures that have been carried out to validate the overall system architecture; Lastly, in Section VII the main conclusions of this work are introduced and future work guidelines presented.

II. STATE OF THE ART AND RELATED WORKS

This section considers the state-of-the-art and related work on radon detection and monitoring.

Regarding monitoring radon levels, there are two main types of radon gas detectors: passive and active. Passive detectors are inexpensive, not powered and the measurement principle is based on the integration of radon concentration over a certain period. Such measurements are useful to determine long-term exposures, i.e. monthly or annual average exposures. Data analysis is performed after exposure using special equipment normally available in specialized laboratories [19]. Active detectors need a power supply for operation and can operate continuously for short-term and long-term exposure. This type of detector is mainly designed to detect alpha radiation and can use one of three measurement techniques: ionization chambers, gross alpha counting, and alpha spectrometry.

Besides the distinction between passive and active, solutions for radon gas detection can also be divided into offline and online. In August 2016 Baskaran [19] presented a survey that compiles and compares several highly sensitive radon air probes. The RAD7 (Durridge, USA) performs offline measurements that may be downloaded to a computer using a USB or serial connection. However, for situations where it cannot be directly connected to a computer, it is possible to acquire a Bluetooth adaptor that delivers a 100-meter wireless range [20]. Having solutions for home and professional testing, Radon Scout Plus (SARAD, GmbH, Dresden, Germany) also presents offline solutions with visual alerts.

In addition to the natural radon concentration, some products like the RTM2200 also measure CO_2, temperature, relative humidity, and pressure [21]. Different from the previous commercial solutions, the work presented by Ashokkumar [22] introduces a scientific approach where the novelty is a substantial increase in the sensitivity. The work refers to a "portable on-line system" but does not provide any information about how this feature was implemented.

Even though the majority of radon monitoring systems work offline, some commercial products have online solutions. Airthings (Oslo, Norway) provides different radon monitoring systems that use Bluetooth and Airthings SmartLink (a proprietary long-range protocol) to transmit the acquired data and to make it available on the user personal device. The Bluetooth solution can be connected to any smartphone or computer while the proprietary protocol needs a second device working as a gateway and connected to an internet connection [23]. Another example of an innovative online radon probe is RStone™ from Radiansa (Girona, Spain) [24]. It is a portable, small-size, battery-powered, and easily programmable that delivers a complete set of information including instantaneous and average radon concentration, temperature, relative humidity, and pressure. Additionally, by using a proprietary accessory, i.e. RKey™, it is possible to perform wireless control of the device. The RadonEye and RadonEye+ from RadonFTLab (Seoul, South Korea) are two devices that ensure the continuous monitoring of radon concentration. The former uses Bluetooth, a Personal Area Network (PAN) technology usually used to communicate data at a short distance, notably with smartphones, and when not connected, the device stores the readings internally, which are then transmitted when a new connection is available. This is a major drawback since a smartphone with internet connectivity is required to stream data. The latter includes an additional Wi-Fi module, which makes it possible to connect to the internet through a Local Area Network (LAN), making data continuously available for more effective processing [25]. However, Wi-Fi presents two major drawbacks, the first is related to its high power consumption and the second is related to its small communication range (tens of meters) in indoor environments.

Possibly due to its novelty and multidisciplinary content, there is a lack of research that focuses explicitly on radon monitoring. The work presented by Blanco-Novoa *et al.* [26] uses the commercially available Safety Siren Pro Series 3 [27] and a low-cost System-on-Chip (SoC) as part of an integrated system. This measures radon, and transmits the collected data to the cloud using Wi-Fi, and uses a cloud platform to present time-series data to the end-user.

Another example of a radon monitoring solution with wireless capabilities is presented by Miles *et al.* [28]. The work details the monitoring process based on a custom silicon chip that detects the alpha particles produced by the decay of radon and uses a microcontroller with a built-in wireless transceiver to transmit multiple parameters to a backend application. More recently, Alvarellos *et al.* [29] published work focusing on the development of a secure low-cost radon monitoring system using Wi-Fi or Sigfox for communication. The solution measures radon concentration every 10 minutes and temperature, humidity, barometric pressure, and IAQ every 5 seconds. As it is a proprietary technology, to use Sigfox each device needs a subscription incurring in additional costs. The final results show the radon concentration in a specific location with the practical case of alerts and airflow control operated manually.

III. INTEGRATED RADON RISK MANAGEMENT

In the IoT era, low-cost and pervasive sensing can be an effective solution to manage radon risk exposure. Gray *et al.* [30], have found evidence that the reduction of radon exposure reduction has the potential to avoid 3.3% of the total number of lung cancer cases. Three main factors are affecting human exposure to radon gas: 1) source, 2) pathway (inhalation), and 3) receptor (smoker/non-smoker).

Of these three factors, the source factor is the only one that can be managed and controlled through technology. It is known that geology and climate make a significant contribution to high indoor radon levels. Additionally, the indoor environment, i.e. building construction materials and the available ventilation mechanisms (natural or mechanical) have a considerable impact on indoor radon levels. Another relevant topic regarding the source factor is the time duration of the exposure, which can be related to the occupancy by an individual of multiple buildings during the day, such as workplace/school/residence/etc. This exposure can be cumulatively computed if a risk analysis based on a dosimetric approach, as presented by Curado *et al.* [31], is considered.

At an individual/personal level, Radon Risk Management can focus on prevention. This can be done by performing radon testing to assess the effective risk that a specific individual or group of individuals are exposed to. A straightforward approach to manage risk is to consider it at the time of construction and ensure the building can deal with radon by itself. However, it may be difficult to perform the risk assessment in time due to the construction and architectural specificities of existing buildings [32].

Given this context, the development of technologies for integrated radon risk management is relevant not only for the technological challenges that arise from the balancing of building energy-efficiency and healthy indoor environments but also due to pertinence in the related societal challenges regarding radon risk communications and awareness among the population.

The following subsections introduce the RnMonitor platform concept and its core functionalities, as specified by Lopes *et al*. [33]. This takes advantage of the IoT Edge device presented in this article, to enable integrated radon risk management.

A. OVERALL SYSTEM ARCHITECTURE

Figure 3 illustrates the system conceptual architecture and the three core elements that depict a common use-case. In this example, several rooms in distinct buildings are equipped with IoT Edge devices that include long-range and low-power LoRaWAN connectivity. These devices are capable of acquiring a set of indoor environmental parameters (i.e. indoor radon concentration level, atmospheric pressure, temperature, relative humidity, and CO_2 concentration), and are responsible for its transmission up to the cloud for real-time processing and analysis. As a result, alerts can be automatically triggered to notify the responsible person to perform a manual ventilation action or to activate a ventilation mechanism, thus reducing the overall indoor radon gas concentration.

This conceptual architecture is divided into three main blocks:

1) **IoT Edge Device and LoRaWAN**: this block includes the IoT edge device, specifically designed in this work to acquire several indoor air parameters, namely: Radon gas concentration, CO_2, Relative Humidity, Temperature, and Air Pressure. Connectivity is guaranteed through Wi-Fi and LoRaWAN technologies. Each IoT device can work as a gateway, bridge, or edge, being one of these modes programmed at the time of installation. This choice is part of a coverage plan, designed to ensure that all measurements from all devices reach the Cloud/Analytics Engine. However, as it is a static configuration the nodes do not have the ability to reconfigure themselves. To help to deal with a device malfunction the network distribution was thought to have some redundancy, however, it was not possible to implement it in the whole system.
2) **Cloud/Analytics Engine:** this block is responsible for forwarding the data gathered by the IoT edge devices through a LoRaWAN network up to the cloud engine. It is also responsible for data storage, reasoning, and pre-processing, and also for providing all the system API's (e.g. RESTful and notification services). It was specified to compute a set of metrics and KPIs for distinct time periods: Real-Time (last hour), Very-Short-Term (last day), Short-Term (last 7 days), and Long-Term (last year), based on specific building occupancy profiles. More details on the cloud/analytics engine can be found in [34].
3) **Client App/Dashboard**: this block is responsible for data visualization and user interaction. It was specified to include a responsive Web-based App that includes real-time notifications. The application is map-centered which enables the establishment of native spatio-temporal relationships and trends between entities. By selecting a specific entity (building, room, or device), a customized dashboard is rendered, showing the relevant metrics and KPIs that were previously defined for radon management in a specific spatio-temporal context. This block is described in more detail in [34].

B. END-TO-END SECURITY MECHANISM

The architecture previously introduced has been designed having in mind three core security aspects: 1) confidentiality, 2) data integrity, and 3) authenticity. Confidentiality is relevant in this application since critical data must not be compromised or intercepted by non-authorized users that should not have access to identifiable data (e.g. building, room data) and that only authorized users (e.g. building managers or owners), will have access to the information. Finally, authenticity relies upon receiving data from an expected and authentic source, avoiding compromised communications that normally occurs as a result of false authentication.

In the designed architecture, cf. Fig. 3, end-to-end encryption in ensured by LoRaWAN communications between the IoT edge devices and the LoRaWAN Server, then a secure IP connection is guaranteed up to the Client App, using HTTPS.

The security mechanism implemented in LoRaWAN communications relies on AES cryptographic algorithms, which have been widely adopted for securing constrained networks and devices [35]–[37]. A critical point in the security of these types of architectures is related to the activation of the IoT edge devices. To circumvent this, LoRaWAN makes available two distinct methods for the activation of the IoT edge devices [38]: **i)** Over The Air Activation (OTAA) is the preferred and most secure way to connect with the LoRaWAN server. In this approach, the devices perform a join-procedure with the network, during which a dynamic device address is assigned and the security keys are negotiated with the device; **ii)** Activation by Personalization (ABP) is simpler since it skips the join procedure, but at the same time is less secure because the device address and the session keys are static and need to be hardcoded in the device which may be compromised by unauthorized access to the physical device, as will be detailed later in this document.

Security in LoRaWAN networks is guaranteed by three 128 bits AES keys, that can be described as follows [39]:

- **Application Key (AppKey)**: only known by the device and the application server. Dynamically activated devices with OTAA activation use the AppKey to derive the two session keys, i.e. Application Session Key (AppSKey) and Network Session Key (NwkSKey) during the activation procedure. In the case of static ABP activation, this key is meaningless.
- **Application Session Key (AppSKey)**: used for interaction between the end device and the Network Server and used for end-to-end encryption and decryption of the payload data in the current session. In the case of ABP activation, this key is hardcoded and doesn't change.
- **Network Session Key (NwkSKey)**: used for interaction between the end device and the Network Server in the current session. This key is used to validate the integrity of each message by applying the so-called MIC (Message Integrity Code) check using the AES-CMAC algorithm. The MIC can be seen as a checksum computed and attached in the end of the data payload by the sender. It is used for the detection of intentional message tampering. In the case of ABP activation, this key is hardcoded and doesn't change.

When operating, each LoRaWAN device is distinguished by a unique **AppKey** and a globally unique device identifier (**DevEUI**), being both used during the device authentication stage. After a device joins the LoRaWAN network, an **AppSKey** and a **NwkSKey** are generated. The **AppSKey** is kept private and the **NwkSKey** is shared with the network. Both keys are only used during the current session. These two session keys, **NwkSKey** and **AppSKey**, are unique per device and per session. The keys can be dynamically re-generated on every activation if the devices are using OTAA activation,

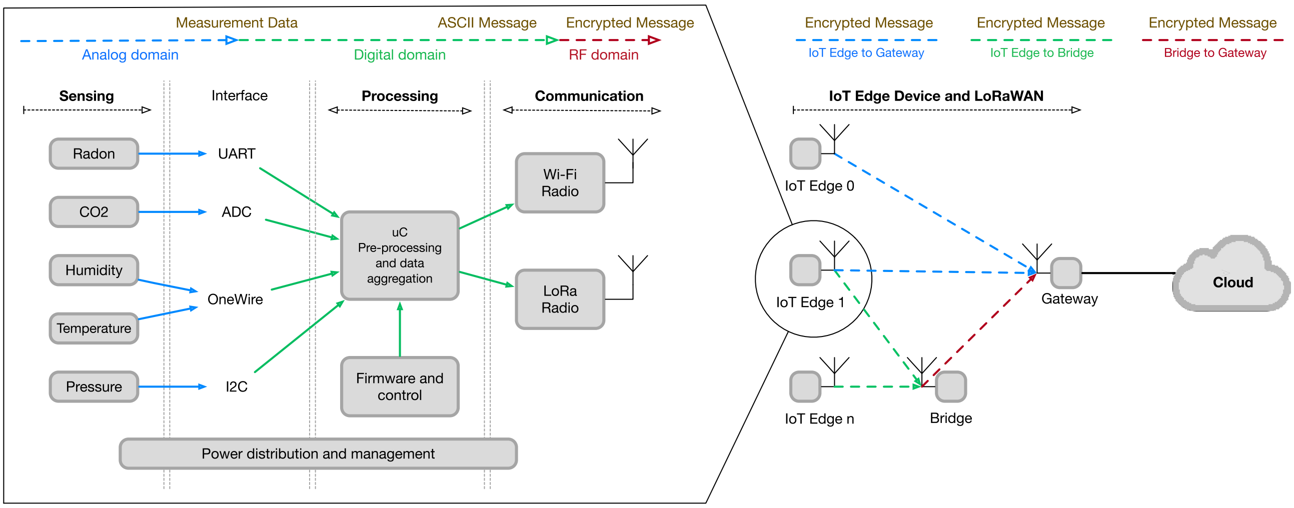


FIGURE 4. RnProbe IoT edge building blocks and LoRaWAN operation modes.

which increases the resilience of the security mechanism. Taking into account the arguments introduced before, in this work, we opted to use OTAA activation [38].

IV. IoT EDGE DESIGN AND IMPLEMENTATION

Here the design of the IoT Edge device is introduced and its implementation explained in detail. Finally, the RnProbe prototype is presented.

A. IoT EDGE SPECIFICATION

The RnProbe architecture is presented in Figure 4 and can be divided in three main blocks: 1) sensing, 2) processing and 3) communication. To better clarify each point, consider the following.

1) SENSING

The RnProbe works primarily as a data collection unit. It is equipped with sensors with digital interfaces that measure radon and CO_2 concentration, relative humidity, temperature, and atmospheric pressure. Radon is the main parameter of the whole architecture and its measurement must be accurate and constant. The CO_2 value is recorded to provide information about room occupancy, being more important in its variation with time than its absolute value. Relative humidity and temperature provide information about space's environmental conditions to assess thermal comfort. The atmospheric pressure is important to detect open windows or air circulation.

2) PROCESSING

The microcontroller is the processing unit that commands the monitoring and communication parts. It receives the measurement data from the sensors using different digital interfaces, performs some edge computing working as a first filter, and selects the best way to transmit the data.

It also has the responsibility of managing the system power consumption. When parts of the RnProbe are not in use, as it is the case of the radios when not receiving or transmitting data, the microcontroller force operation to low power modes. The same is true for the IoT Edge devices that have low power mode options and for the microcontroller itself, ensuring a minimized power consumption.

3) COMMUNICATION

Regarding communication, and to meet the dynamic Low-Power Wide-Area Network (LPWAN) requirement, each IoT edge needs to have both a Wi-Fi and a LoRa radio. The Wi-Fi module is the main way to communicate as it allows a direct connection between the RnProbe and the cloud. However, as the area of interest to monitor is spread over an area higher than 20 km (the cities of Viana do Castelo and Barcelos, Northern Portugal) it is not possible to ensure Wi-Fi for each device. This difficulty is overcome using LPWAN, or more precisely LoRa technology. Its spread spectrum modulation allows signal demodulation at -146 dBm which increases the communication distance up to some kilometers. To deploy this LoRa network it is important to plan the location of repeaters and gateways to cover the whole area. Besides having specific gateways to receive LoRa communications, the network should also have the capability to assume different tasks, creating a dynamic architecture, cf. Fig 4. According to this dynamic architecture, the RnProbe can operate in three different ways:

- **Gateway**: the RnProbe receives data through LoRa from other devices and uploads it to the cloud using the available Wi-Fi connection. Its measurements are directly transmitted to the cloud using the same connection;
- **Bridge**: the RnProbe receives data through LoRaWAN from other devices and re-transmits it using the same technology to a Gateway. Its data are also transmitted using LoRaWAN;
- **Edge**: in this mode the RnProbe operates in the physical endpoint, i.e. sensing or actuating, and transmits its

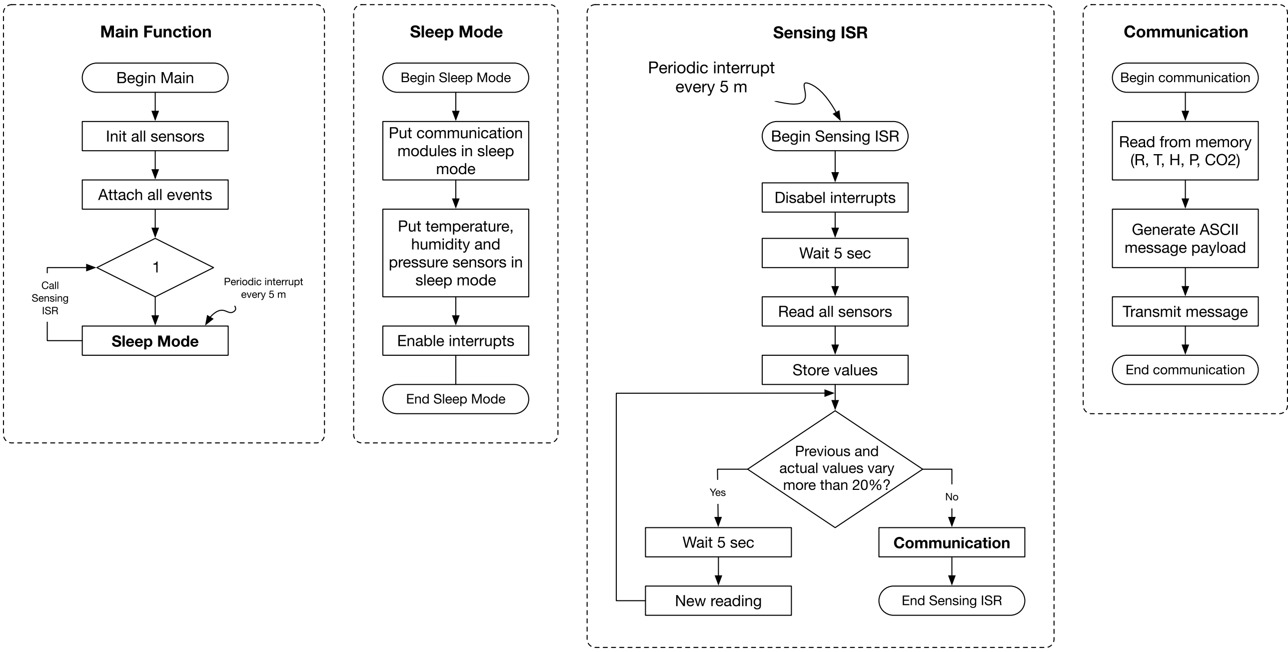


FIGURE 5. Embedded firmware flowcharts with the sensing interrupt service routine (ISR).

data to a Gateway using LoRaWAN, it does not receive anything from other devices;

B. HARDWARE DESIGN

Due to its accuracy of +/−10% and a measurement range up to 3700 $Bq.m^{-3}$ the RD200M from Radon FTLab was the sensor chosen to measure the radon levels. This sensor uses a Universal Asynchronous Receiver/Transmitter (UART) to receive commands and transmit data which facilitates communication with the microcontroller.

To provide data about the indoor CO_2 variations, and having in mind the low-cost requirement for the RnProbe, the MQ-135 gas sensor was used. The sensor does not directly measure CO_2 concentration but with its gas measurements, it is possible to detect CO_2. As explained, the CO_2 measurement does not need to be precise in its absolute value and hence this sensor is a valid solution. It provides information through its analog output.

The measurement of relative humidity and temperature is done using the DHT11 from Aosong. This low-cost sensor uses single-wire bi-directional communication with 16 bits to communicate with the microcontroller. The repeatability of the sensor is ±1% for relative humidity and ±2°C for temperature measurements.

The MPL3115A2 from NXP is the sensor chosen to provide data on pressure levels. The sensors operating range goes from 20 kPa to 110 kPa and uses an I^2C digital output interface to send its measurements to the microcontroller.

To provide LoRa communication the RN2483 from Microchip was used. This radio allows a transmission power of +14 dBm and has a receiver sensitivity of −146 dBm. The device communicates with the microcontroller using the UART protocol.

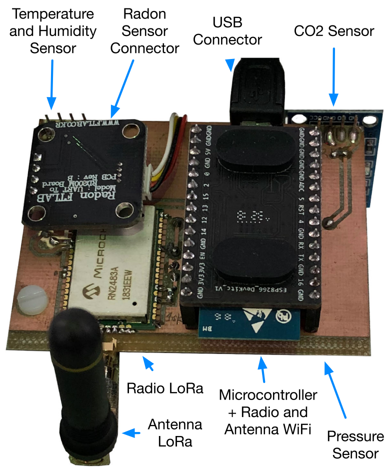


FIGURE 6. IoT edge hardware PCB.

Regarding the processing unit, a microcontroller with different communication modes was chosen, allowing it to receive data from the multiple sensors, with options for low power behavior and, for reasons of simplicity an integrated Wi-Fi radio. The ESP8266 from Espressif was the device selected.

Besides these elements, there are others like capacitors or heat dissipation areas that were included in the design process to ensure durability and correct operation of the whole system, which is presented in Figure 6.

C. EMBEDDED FIRMWARE DESIGN

As important as the hardware implementation is software development. Its role is to make sense of the hardware architecture and guarantee its operability. The first step to

TABLE 1. Message payload structure and byte budget.

Attribute	Value	Unit	Byte Budget	Description
ID=	001	-	6 bytes	Sensor Identifier
R=	1000	$Bq.m^{-3}$	6 bytes	Radon
C=	143	ppm	5 bytes	CO_2
T=	+23.5	^{o}C	7 bytes	Temperature
H=	63	%	4 bytes	Humidity
P=	102.074	kPa	9 bytes	Pressure

consider is to understand that all the physical quantities under measurement have the same required periodicity, in other words, this means that none of the sensors is supposed to have high variations in short periods and, due to that, it is possible to define a common reading period. This period was set to 5 minutes, which has into account the expected variations, allows the implementation of algorithms for error detection and correction. Using the communication protocols already mentioned, each sensor communicates its readings with the central unit that performs a verification to detect some wrong measurements. If the value varies more than $+/-20\%$ the central unit asks the sensor to repeat the measurement. The new value is again compared with previous readings - if the new value is consistent (variation below 20%) with the previous values it is considered as an accurate measurement, if it is not, it is considered a wrong measurement, and a warning is transmitted. The warning consists of a predefined value "FAULTY", which is impossible to be sent in a regular transmission. Additionally, if a specific device does not communicate with regularity, e.g. more than 30 minutes without communication, an alert is triggered towards the building manager, informing that the device is "OFFLINE". It is important to note that this process is performed at the edge intends to perform basic error detection. More complex actions to mitigate errors are implemented in the cloud structure where the computational power is available and easily scalable.

After interrogating each sensor, the central unit adds its measurement to a message which payload is encoded in ASCII format using pairs attribute/value delimited by the character '&', as follows:

```
ID=001&R=1000&C=1430&T=+23.5&H=63&P=102.074
```

In Table 1, the message format previously introduced is interpreted for each of the pair's attribute/value identified, including the corresponding unit value and the byte budget. Moreover, it can be observed that an upstream message will have a total byte budget of 37 bytes (31 attribute/value bytes plus 6 delimitation bytes). Considering the 5 minutes duty-cycle transmission, the daily average byte budget is 8928 byte which is a bit less the 10 kB/day that are imposed by the LoRaWAN standard for each device [40].

In this design, the edge is responsible for the temporal aggregation of the monitored parameters, always having in mind that the byte budget should be as low as possible

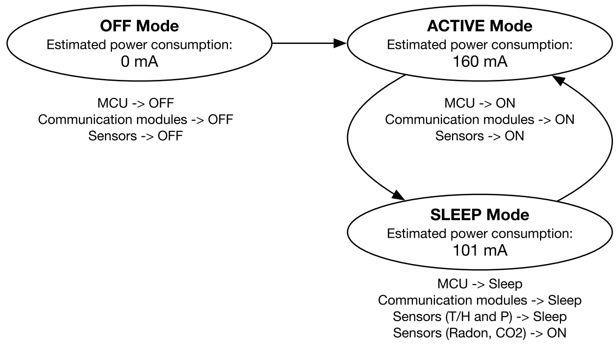


FIGURE 7. State diagram with the RnProbe operation modes.

to reduce the bandwidth occupied per probe in terms of LPWAN communications. The edge firmware was developed considering the characteristics of the distinct parameters, its sampling rate, and the transmission periods. The flowchart representing these routines can be visualized in Figure 5.

Besides the concerns regarding the bandwidth, the firmware was also designed to reduce its power consumption to the minimum. Temperature, relative humidity, and pressure readings do not require long warming up periods and, due to that, can be in sleep modes when not used. On the other hand, radon, and CO_2 sensors require stable energy conditions which means that they need to be always on. The communication modes and the microcontroller can also save energy if configured in their low power consumption modes. In this way, it is possible to define different operations modes for the RnProbe when it is operating as an edge or bridge device:

1) **OFF Mode** - all blocks are turned off, resulting in no energy consumption;
2) **ACTIVE Mode** - all blocks are turned on, resulting in an estimated current drain of 160 *mA*;
3) **SLEEP Mode** - the microcontroller, communication modules, temperature, humidity, and pressure sensors in sleep mode, and radon and CO_2 sensors are turned on, which results in an estimated current drain of 101 *mA*.

The state diagram that governs the operation of the IoT Edge device is illustrated in Figure 7.

When the RnProbe is operating as a gateway its power consumption can rise up to 330 *mA*, the WiFi radio 170 *mA*, and the LoRa radio approximately 39 *mA*.

D. RnProbe PROTOTYPE

The final circuit design and the assembled version of the prototype can be seen in Figure 8, where all relevant components can be observed, i.e. its Printed Circuit Board (PCB), the external LoRa antenna, the LoRa radio module, the microcontroller, sensors, and other passive components. The RnProbe prototype dimensions are 100 *mm* × 100 *mm* × 150 *mm*. The final dimensions of the prototype are largely conditioned by the dimension of the RD200M sensor. However, from a functional point of view,

FIGURE 8. RnProbe IoT Edge Prototype.

the size of the prototype does not compromise its installation and use in the buildings under monitoring.

V. EXPERIMENTAL VALIDATION

The experimental validation process was carried out for approval of the developed IoT edge device and its integration on the RnMonitor platform [33]. The experimental validation process was split into these three distinct stages:

A) **RnProbe Prototype Validation**: a set of four RnProbe prototypes were evaluated in the Lab, under a controlled environment, and compared with the reference device, a certified Airthings Plus Radon detector;

B) **LoRaWAN Connectivity Tests**: a set of tests were carried out to evaluate the connectivity of LoRaWAN communications in mixed environments (urban and rural) in the region of Viana do Castelo, Portugal;

C) **RnMonitor Platform Integration**: the four devices validated in stage B) were deployed in distinct compartments, with a regular occupation, for continuous online monitoring.

A. RnProbe PROTOTYPE VALIDATION

Figure 9a depicts the RnProbe experimental apparatus carried out in the L1.11 Lab at ESTG-IPVC and used for results validation during radon concentration assessment, which is the key parameter of the RnProbe. The IoT edge devices have been configured to acquire and transmit a set of measurements in periods of 5 minutes, i.e. 12 measurements per hour. The experimental validation procedure was performed continuously between 21/12/2019 and 06/01/2020 - a period where the Lab was not occupied due to the Christmas holidays, and therefore its indoor environment was stable. Figure 9b illustrates the radon concentration confidence error boundaries (gray) obtained statistically upon continuous data of four RnProbes with relation to the reference level (red) obtained with a certified Airthings Plus Radon detector. The average and maximum values of the continuous confidence error boundaries (i.e. standard deviation of a set of four measurements, one of each RnProbe) are 36 and 124 $Bq.m^{-3}$, respectively. The continuous confidence error obtained shows that the RnProbes are highly correlated, not only between each other but also with the reference device.

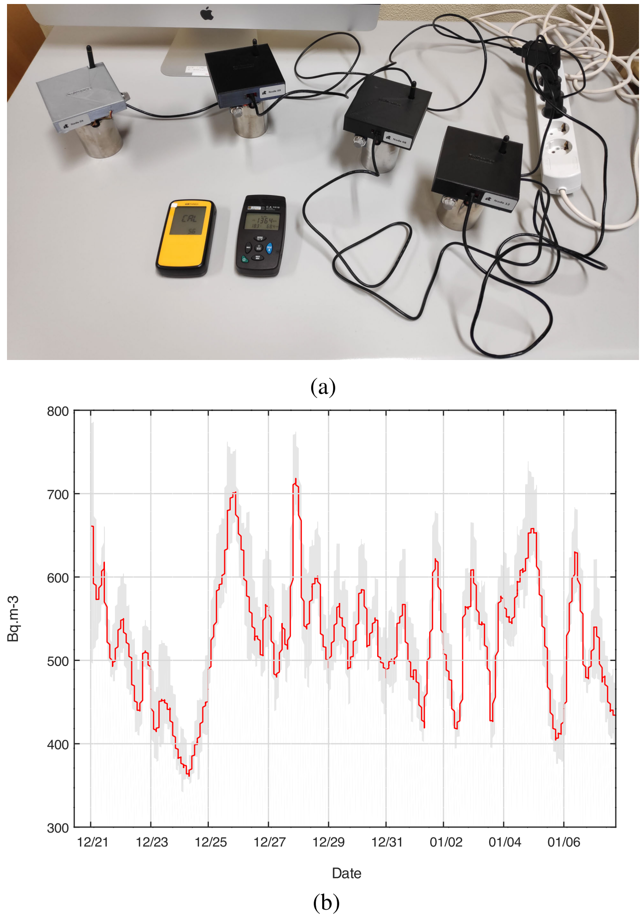


FIGURE 9. RnProbe validation. a) Experimental apparatus in the L1.11 Lab; b) Radon concentration continuous confidence error boundaries (gray) obtained statistically upon data of four RnProbes with relation to a reference value (red) obtained by a calibrated Airthings radon detector. Data was obtained continuously over a period of two weeks.

TABLE 2. Global stats obtained in the validation period.

	D03	D07	D09	D12	Reference
Arith. Mean ($Bq.m^{-3}$)	537	534	477	550	509
Stand. Dev. ($Bq.m^{-3}$)	72	79	66	80	112

Another relevant analysis is related to the global period in which the experiment was undertaken. Table 2 depicts the global statistical results obtained for the validation period of two weeks based on the arithmetic mean average and its corresponding standard deviation, showing consistent results for short-term periods of 2 weeks.

The final RnProbe, which was previously presented in Figure 8, is the main output of this project. At the time of writing, 15 IoT edges are collecting and transmitting data in the cities of Viana do Castelo and Barcelos,

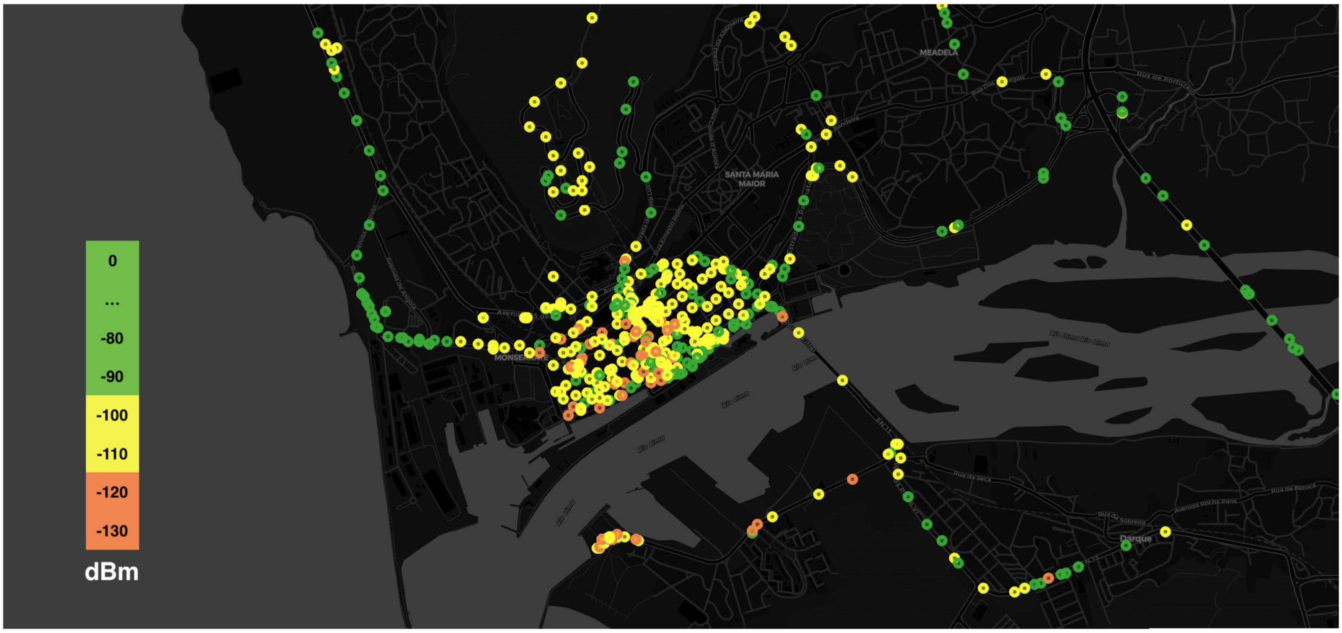


FIGURE 10. LoRaWAN connectivity tests in mixed environments, i.e. urban and rural.

Northern Portugal. The first set of devices have been working for two months.

B. LoRaWAN CONNECTIVITY TESTS

The first tests using LoRa communication were done before the RnProbe was ready, the goal of the test was to evaluate the installation of the LPWAN in the real scenario. The field test scenario was implemented at Viana do Castelo, the city in the North of Portugal where this work was conducted. To implement the field test, a LoRa gateway was positioned in the city's highest point and an IoT Edge device equipped with GPS and LoRa communications was moving in mixed environments, i.e. urban and rural. The result map, with the communications performed and Received Signal Strength Indicator (RSSI) information is presented in Figure 10.

The radio module used (RN2483) does not allow the measurement of any power indicator, such as the RSSI, so experiments carried out to evaluate connectivity were made by using the ARF8123A LoRaWAN field test device from Adenius, operating in the EU863-870 MHz frequency band. This experiment shows that LoRa technology is effective for communications in mixed environments on an urban and rural scale, being an optimal solution for the target application.

C. RnMonitor PLATFORM INTEGRATION

Figure 11 depicts the map-centered client application. The map changes its zoom and centroid based on the polygons that the user is managing. The map presents two types of layers, i.e. sensors and polygons, that are represented by a specific color associated with a previously computed Radon Risk Indicator (RRI). By selecting a specific sensor (represented by a dot) or compartment (represented by a polygon), in the map, a dashboard with three plots is automatically rendered

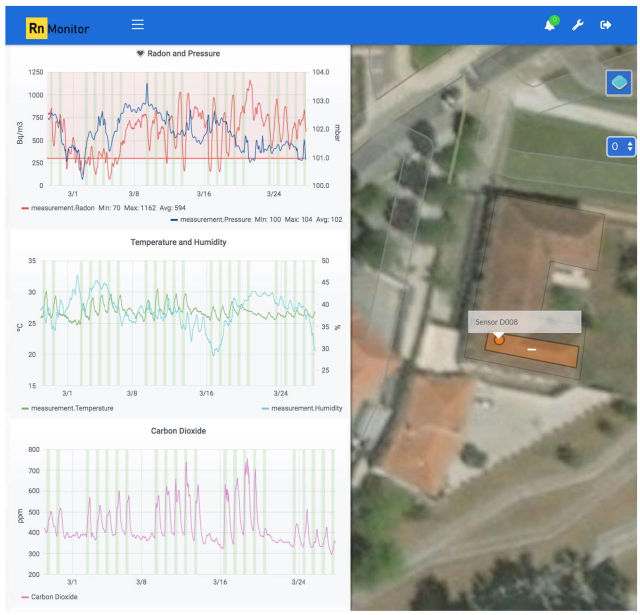


FIGURE 11. Example of the RnMonitor platform dashboard.

with time-series data corresponding to the last 30 days. In the first plot, the radon concentration (red) and the atmospheric pressure (dark blue) are both presented and the horizontal red line represents the 300 $Bq.m^{-3}$ action level, as defined in [12]. The second plot depicts the indoor air temperature (dark green) and its corresponding relative humidity (light blue). Its behavior in rooms with manual ventilation is known, cf. [41], [42], with the temperature increasing during the day and relative humidity increasing during the night. The third plot gives the CO_2 concentration, where it is possible to observe the effectiveness of indirect measurements. Each

TABLE 3. Statistical results and RRI computed with reference to the last day of acquired data.

		Case Study I	Case Study II
Total Average Radon Concentration		**397** $Bq.m^{-3}$	**59** $Bq.m^{-3}$
Total Average Radon Concentration in the Occupancy Period		**383** $Bq.m^{-3}$	**38** $Bq.m^{-3}$
RRI (Average Radon Concentration in the Occupancy Period) (**Level 1** , **Level 2** , **Level 3** , **Level 4**)	VST (last day)	Level 3 (**674** $Bq.m^{-3}$)	Level 1 (**39** $Bq.m^{-3}$)
	ST (last week)	Level 3 (**495** $Bq.m^{-3}$)	Level 1 (**25** $Bq.m^{-3}$)
	LT (all data)	Level 3 (**383** $Bq.m^{-3}$)	Level 1 (**38** $Bq.m^{-3}$)

time the compartment is occupied, the CO_2 level increases and starts decreasing once the compartment is empty. In all plots presented in the dashboard, the compartment occupancy is identified by the periods represented by the vertical green bars.

The RRI is computed each day for each compartment in the map using the data available in the last 24h. On the other hand, real-time data is used to trigger notification alerts to a specific sensor/polygon owner, to promote ventilation actions. The RRI was specified based on a dosimetric approach, cf. [31], which considers the building occupancy profile with a regular occupancy period of 8 hours, and is divided into four levels:

1) **Level 1 [Safe]**: average radon concentration in the occupancy period bellow 100 $Bq.m^{-3}$;
2) **Level 2 [Warning]**: average radon concentration in the occupancy period between 100 and 300 $Bq.m^{-3}$;
3) **Level 3 [Alert]**: average radon concentration in the occupancy period between 300 and 2000 $Bq.m^{-3}$;
4) **Level 4 [Critical]**: average radon concentration in the occupancy period above 2000 $Bq.m^{-3}$.

and can be computed for distinct periods: Real-Time (last hour), Very-Short-Term (last day), Short-Term (last 7 days), and Long-Term (all data available) with reference to the last day of acquired data.

VI. RESULTS

In this section, the results of two case studies are presented. Two distinct laboratories of the School of Technology and Management of the Polytechnic Institute of Viana do Castelo, i.e. L1.11 and L3.5 have been continuously monitored using the IoT edge in parallel with the RnMonitor Platform [34]. L1.11 is situated on the ground floor and L3.5 is located on the third floor of the building. The former was analyzed during the period between 01/10/2019 and 10/31/2019 and the later during the period between 01/11/2019 and 30/11/2019. Both laboratories are regularly occupied on working days between 9:00 am and 5:00 pm. Since the occupancy of the building under study is normally restricted to a regular schedule, the computation of the RRI was performed using only the data obtained when the building is occupied.

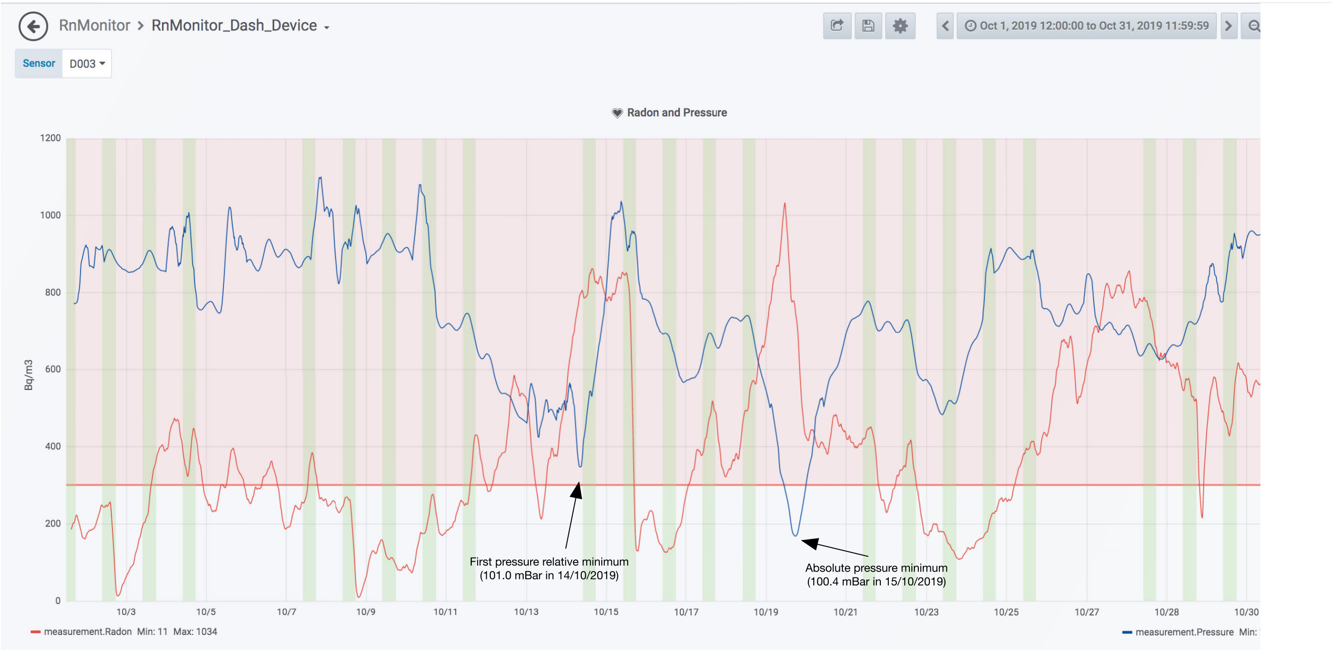
The analysis of the results will focus on the radon concentration, the crucial aspect of this work. The approach followed in this analysis considers only the data collected for the specific occupation profile defined before, i.e. working days between 9:00 am till 5:00 pm, which are identified in the dashboard plots, cf. Fig. 12a and Fig. 12b as vertical green bars.

Table 3 compiles the statistical results obtained for both case studies. Additionally, a time series plot with the radon gas concentration and the indoor atmospheric pressure is presented for each case study, and given its known correlation within an enclosed space [43], in this section, we opted to focus the results analysis on these parameters.

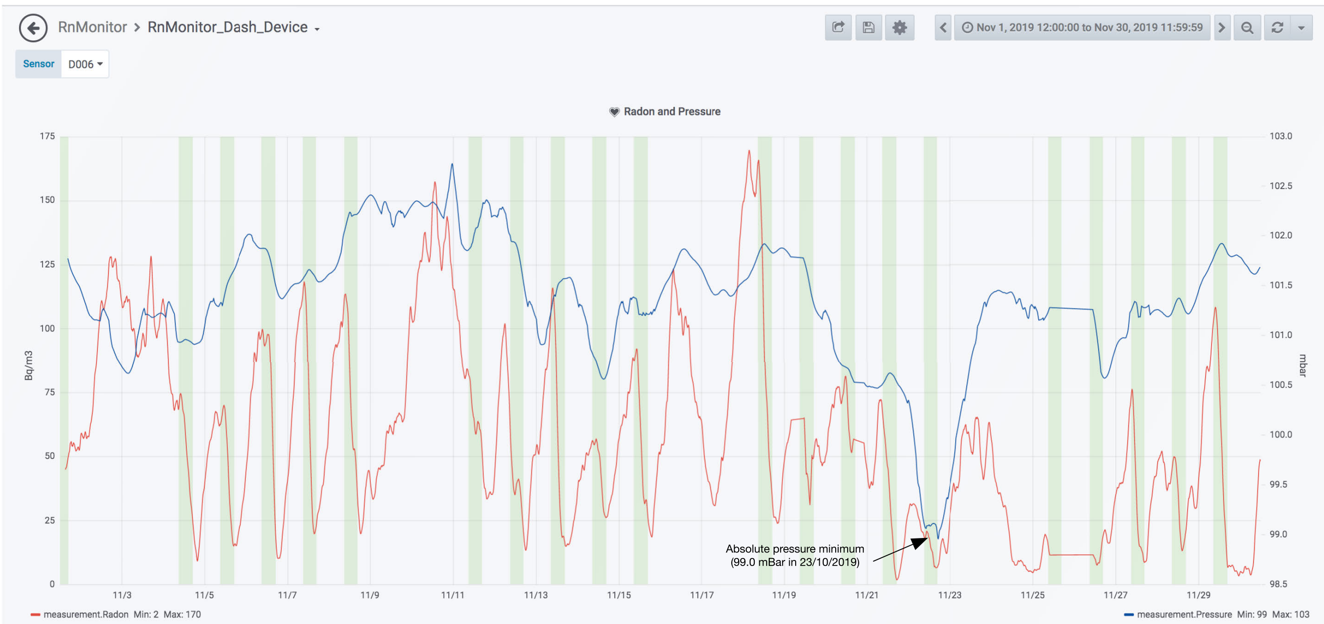
A. CASE STUDY I: L1.11

Figure 12a illustrates the time series plot related to the IoT Edge device D003 which is associated with the L1.11 laboratory, located on the ground floor. Therefore, the correlation between indoor radon concentration and atmospheric pressure within an enclosed space built upon the ground level in direct contact with the foundation soil, as presented in Figure 12a, can be interpreted as follows:

1) The inverse correlation between indoor atmospheric pressure and the indoor air radon concentration results from the difference between the pressure in the subsoil and the pressure in the indoor space. Higher values in indoor atmospheric pressure prevent the migration of radon from the building subsoil to the indoor air space. In this case, the radon concentration measured by the IoT edge device reaches its minimum value at the same time as the pressure reaches its maximum. This relation is known [44] and can be used to reduce the indoor radon concentration by using fan pressurization mechanisms to pump air into the room increasing the indoor atmospheric pressure [44]. During the period under analysis, no active ventilation mechanisms have been used in the compartment, only ventilation actions performed by the occupants.
2) On the other hand, when the indoor atmospheric pressure reaches its minimum, it enables the radon gas to migrate from the subsoil into the room air, showing a tendency to reach equilibrium. This inflow of radon gas into the compartment is shown in Figure 12a when the indoor atmospheric pressure reaches the first relative minimum (101.0 mBar in 14/10/2019) and the absolute minimum (100.4 mBar in 19/10/2019).
3) The radon gas concentration dynamics changes daily with a lag caused by the time necessary to transport the radon gas from the subsoil to the indoor air of the compartment.



(a) Indoor atmospheric pressure (blue) and indoor radon concentration (red) between 01/10/2019 and 31/10/2019 in the Lab L1.11.



(b) Indoor atmospheric pressure (blue) and indoor radon concentration (red) between 01/11/2019 and 30/11/2019 in the Lab L3.5.

FIGURE 12. Relation between indoor atmospheric pressure (blue) and indoor radon concentration (red) over one month for two compartments in two distinct floors of the ESTG-IPVC building. The horizontal red line represents the 300 $Bq.m^{-3}$ action level introduced in the 2013/59/Euratom Directive. The compartment is regularly occupied on working days between 9h00 am and 5h00 pm (vertical green bars).

B. CASE STUDY II: L3.5

Figure 12b illustrates the time series plot related to the IoT Edge device D006 which is associated with the L3.5 laboratory. In this case, the compartment is located in an upper floor, and not in direct contact with the subsoil. Data obtained can be interpreted as follows:

1) There is a direct relationship between the indoor atmospheric pressure and the indoor air radon concentration, in opposition to what was found for L1.11. In this case, given the fact that the L3.5 laboratory is placed on the third floor, lower radon levels have been found. In contrast, regarding this specific case, the indoor

atmospheric pressure and the indoor radon concentration are directly correlated which does not accentuate the migration of radon gas from the lower level floors to the upper floor, where the compartment under analysis is located. During the period under analysis, no mechanical ventilation devices have been used in the compartment, only natural ventilation performed by the occupants i.e. opening and closing windows and doors.

2) In this case, the radon level measured by the IoT edge device is always below the Euratom action level of 300 $Bq.m^{-3}$ [45], reaching its minimum value at the same time that the indoor atmospheric pressure reaches its minimum, i.e. between 21/11/2019 and 23/11/2019. This direct relation between both variables arises in periods of high occupancy of the laboratory, when reinforced ventilation actions are performed by the occupants, such as regular windows opening or doors movement.
3) The radon gas concentration changes daily showing a direct relation with the laboratory occupancy periods (vertical green bars). For example, at weekends, when the laboratory is closed and not occupied, it is possible to observe a considerable increase in indoor radon levels. Additionally, it is also possible to observe a daily dynamic change with time lags caused by the daily occupancy related activities.

From the two case studies, it is possible to validate the RnProbe correct operation. The radon and atmospheric pressure measurements present an expected relation allowing the detection of some events, e.g. room occupancy. Besides that, the configurable LoRaWAN communication also proved to be a solution for a city-scale implementation. Both aspects are advances in the state-of-the-art of radon monitoring.

VII. CONCLUSION

Despite not being well known by the general population, the regular exposure to high radon gas concentration in indoor environments can cause serious health hazards to those who work and live inside buildings. In this sense, Radon Risk Management is a crucial step to effectively manage radon concentration inside buildings and consequently minimize the health risk that people restricted to a regular schedule are exposed to.

This work focuses on the design and implementation of the RnProbe, an IoT Edge Device developed for integrated radon risk management in regularly occupied buildings. The device collects, aggregates, and transmits several indoor environmental parameters, which after being combined with the building occupancy, are used to trigger specific ventilation actions. The conceptual and technical solution presented in this article has shown a high potential for Radon Risk Management, and at the time of writing, there are 15 IoT Edge Devices installed and operating in several public buildings in Viana do Castelo and Barcelos, cities located in the Minho region, North of Portugal. Radon testing is normally performed statistically by sampling, which means that we should test compartments with higher radon potential. In specific problematic situations, radon testing may be extended to several additional compartments in the same building. However, this is not the rule, it is the exception. In this case, the number of devices is directly related to the number of compartments that need to be tested, with more prevalence at the floor level or below floor level, such as buried basements. This research can be highly relevant not only by the technological challenges that arise from the balancing of the building energy-efficiency and healthy indoor environments but also due to pertinence in the related societal challenges regarding radon risk communications and awareness among the population.

The use of a simple and intuitive scale for radon risk assessment based on the previously introduced RRI has also high potential, not only in terms of risk communication but also for the increase of awareness regarding effective exposure, when considering a dosimetric approach in risk assessment.

A set of good practices or recommendations will be outlined for compartments which are classified in one of the four risk classes, according to average radon concentration level, during the occupancy period: for Level 1 (safe) it is encouraged to "keep up the good work" — i.e., the occupants must continue ventilating the spaces as usual. No extra remediation measures are needed since the airflow rates seem to be adequate to keep the occupants in a safe mode. Regarding Level 2 (warning) some additional remediation measures are advised, mainly by improving the room air renovation, implementing a daily schedule for opening windows to promote air circulation for a predefined period of time, or to install an extraction fan, by adopting a mechanical ventilation strategy.

In what concerns Level 3 (alert), the occupants are strongly encouraged to take steps to remediate the problem, mainly by adopting some combined measures which imply the application of mitigation methods to reduce indoor radon concentrations, which should rely on two solutions: dilution and/or pressure change, achieved by the installation of a pressure-modifying sump, generally in conjunction with an extraction fan, and install, if possible, natural under-floor ventilation, in the case of suspended flooring, or by the construction of a passive sump below the level of the ground floor. The installation of a radon-proof membrane across the entire ground level of the room is advised, if possible. Finally, for Level 4 (critical), the approach must be to empty the room. In fact, the risk regarding people's occupation is relevant, and the safe strategy must involve vacating the room. That does not mean the compartment cannot be visited for technical purposes, or simply to work as a storeroom or a utility room, but for sure it is not adequate for people's occupation during long periods of time.

From a technical point of view the RnProbe has two big advantages: i) a dynamic communication system that allows each device to assume an edge, bridge, or gateway configuration; and ii) additional sensors to acquire complementary data which are important to estimate different hazard levels, e.g. pressure or CO_2. Regarding the main challenges; it was important to learn from radon specialists the radon behavior to design a solution that fits the problem; it was crucial to add robustness to the system to ensure it does not suffer any damage during the transport and installation process; and, it was also needed to properly fix the RnProbes so people would not move them and create instabilities on the measurements.

Future work will encompass two main goals: the first is to include a better approach for occupancy detection which has already some developments in a parallel work [46]; the second is the development of an integrated automatic ventilation system which would act after a balanced decision considering the building occupancy, its energy-efficiency, and the radon concentration.

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