



An autonomous IoT monitoring unit for radiological and nuclear emergency management

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Abstract Recent technological advancements have facilitated the deployment of distributed, cost-effective, and energy-efficient wireless sensor networks that are increasingly applied in various industrial and civil sectors, including the radiological and nuclear domains. In such a context, the role of radiation monitoring and early detection in ensuring the safety of both workers and the public during standard operations and in response to hazardous events is well recognized. In normal operations, a robust radiation monitoring framework is necessary to maintain compliance more easily with regulatory standards and prevent accidents or leaks from occurring. In response to hazardous events, early radiation detection is essential to the safety of emergency responders, citizens, and the environment. To this aim, this study introduces an autonomous device designed for enhanced radiological and nuclear emergency management capable of gamma rays and thermal neutrons detection. The unit features ultra-low power consumption, making it suitable for long-term placements in hard-to-reach or sensitive areas, and it employs long-range radio technology to ensure wireless and reliable data transmission over long distances, even in challenging environments. Its extended battery life, robust networking capabilities, and autonomous functionality make it suitable for continuous monitoring in critical areas such as nuclear power plants, urban radiation monitoring locations, post-disaster zones, and healthcare radiology units. Leveraging long-range radio technology ensures decentralized and secure monitoring without relying on local internet networks. This device addresses a critical need in radiological and nuclear emergency management, providing reliable measurements, longevity, and easy integration with existing networks and Internet-of-Things technologies.

1 Introduction

Radiological and nuclear activities require a careful balance of maintaining safety during routine operations while also being prepared to respond effectively to potential hazards. Reliable radiation monitoring and early detection play a central role in these efforts. Handling hazardous materials in these sectors introduces significant risks, including accidents, leaks, or intentional harm, which can have serious health, environmental, and socio-economic impacts. Consequently, adherence to strict safety measures and regulatory standards is necessary to manage these risks effectively. Continuous and accurate radiation monitoring is a key factor in detecting deviations from safe conditions during regular operations, ensuring that potential issues are identified promptly. In emergencies, early detection becomes even more important, as it enables timely evacuations, the implementation of protective measures, and coordinated responses that work to minimize exposure and associated health risks.

Various fixed and mobile radiation monitoring systems and analysis methods have been developed in recent years, utilizing both traditional and advanced technologies and approaches [1–6]. Conventional systems often rely on handheld inspection or wired connections for data transmission and centralized processing units for analysis. While these systems are reliable, effective, and standardized, particularly in stable, controlled environments such as nuclear facilities, they face significant limitations when deployed in other contexts, such as remote locations, rapidly changing environments, or scenarios requiring quick adaptation and response. These limitations include high installation and maintenance costs, limited flexibility in deployment, and delays in real-time data processing due to their centralized architecture [7–9].

The advent of the Internet of Things (IoT) and wireless sensor networks (WSNs) has introduced new possibilities for radiation monitoring. Communication technologies such as long-range radio (LoRa), NB-IoT, Zigbee, and SigFox have been increasingly applied in environmental monitoring, offering advantages like deployment flexibility, cost efficiency, and low power consumption

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[10–14]. These technologies enable the creation of inexpensive and distributed sensor networks capable of real-time data acquisition and long-range communication. These are particularly valuable in scenarios requiring rapid response and broad area coverage. Although several applications have demonstrated the potential of these technologies, challenges such as data security, scalability, and integration with existing systems still need to be partially or completely addressed [15–18].

Nevertheless, given these advancements and the challenges inherent in traditional systems, there is a clear need for solutions that can bridge the gap between the reliable but rigid traditional systems and the flexible, cost-effective modern technologies. The IoT-based radiation monitoring device presented in this paper is designed to address this need. By offering ultra-low power consumption, wireless connectivity, ease of deployment, low cost, potential disposability in case of contamination, and the capability to measure both gamma rays and neutrons, this device can serve as a complementary tool within existing radiation monitoring frameworks, particularly in situations where traditional systems face operational constraints, such as in remote locations or scenarios requiring rapid deployment. This study seeks to evaluate the technical performance of the device and its potential to enhance radiation safety and emergency preparedness.

The paper is structured as follows: Section 2 provides an overview of the key regulatory frameworks and existing solutions for radiation monitoring. Section 3 discusses the design and development of the IoT device, focusing on its technical specifications and the rationale behind key design choices. In Sect. 4, the performance of the device is evaluated through experimental testing, assessing its capabilities in measuring gamma rays and thermal neutrons under various conditions. Section 5 explores the improvements and developments. Finally, Sect. 6 concludes with an analysis of the implications of these findings for enhancing radiation safety and emergency response, offering insights into the practical applications of the technology.

2 Regulatory frameworks and compliance

Effective management of radiological and nuclear risks is guided by regulatory frameworks established by international and national bodies through comprehensive guidelines that provide standards for radiation monitoring and emergency response, turning principles into actionable solutions across different contexts.

The International Atomic Energy Agency (IAEA) sets global standards for radiation protection and emergency preparedness through a rich framework of guidelines and tools. Specifically, the General Safety Requirements (GSR) Part 3 mandates continuous radiation monitoring and the implementation of early warning systems [19]. Complementing this, the IAEA Safety Standards Series No. GSR Part 7 provides requirements for emergency preparedness to effectively detect and mitigate radiological threats [20].

To support practical implementation, IAEA-TECDOC-1092 offers guidance on environmental and source monitoring during emergencies, focusing on the technical and operational aspects [21]. In line with these standards, the IAEA also maintains specialized information management systems to facilitate international cooperation and data exchange. The EPR Information Management System (EPRIMS) [22] is a web-based tool that allows IAEA Member States to share information about their emergency preparedness and response (EPR) capabilities. The system's integration with the Power Reactor Information System (PRIS) further supports assessment and prognosis during potential emergencies [23]. Meanwhile, the International Radiation Monitoring Information System (IRMIS) [24] facilitates the reporting and visualization of large-scale environmental radiation monitoring data. IRMIS supports the implementation of the Convention on Early Notification of a Nuclear Accident by providing a platform for Member States and international organizations to share radiation data—additionally, the IAEA Safety Standards Series No. GSG-14 underscores the importance of real-time monitoring systems to ensure the timely dissemination of information to both the public and relevant authorities [25].

In the European Union, the EURATOM framework governs radiation protection and safety, specifically through the Council Directive 2013/59/Euratom [26]. This directive establishes basic safety standards for protecting workers, the public, and the environment from the dangers of ionizing radiation. Among the key provisions of the directive is the requirement for member states to implement robust environmental radiation monitoring programs to provide real-time data on radiation levels, ensuring early detection of any anomalies and enabling timely reporting and intervention to protect public health.

In the USA, the Environmental Protection Agency (EPA) operates the RadNet system [27], a nationwide network designed to monitor environmental radiation levels in real time. RadNet consists of over 200 monitoring stations placed across all 50 states and US territories. These stations are equipped to continuously sample the air, precipitation, and drinking water for various forms of radiation, with a particular focus on detecting gamma radiation. The air monitors, which operate 24/7, send data to the EPA's National Analytical Radiation Environmental Laboratory (NAREL) [28], where the information is analyzed and made available to the public and government agencies through the EPA's online platform.

Several countries have established frameworks for radiation monitoring and emergency response. Japan's JAEA uses KURAMA-II [29] for radiation mapping and SPEEDI [30] for predictive modeling, both vital after Fukushima. Canada's CNSC emphasizes continuous monitoring through its REGDOC-2.10.1 framework [31], while China's NNSA operates a real-time, multi-level monitoring system [32]. France's Autorité de Sûreté Nucléaire [33] and the UK's Office for Nuclear Regulation [34] ensure compliance with international standards, and Brazil's ANSN maintains early warning systems for rapid radiation detection.

As a more detailed example, Italy's radiation monitoring infrastructure is a comprehensive and integrated system managed primarily by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale) [35] and ISIN (Ispettorato Nazionale per la

Sicurezza Nucleare e la Radioprotezione) [36], with support from regional environmental protection agencies (ARPA/APPA). The RESORAD network, managed by ISPRA, serves as the cornerstone of Italy's national monitoring efforts, continuously measuring environmental radioactivity across the country through a series of fixed stations.

In emergencies, the REMRAD network, overseen by ISIN, offers advanced capabilities for early detection and rapid response. This network is equipped with automated systems designed to detect even minimal levels of radioactivity, particularly in scenarios involving cross-border radiological events [37]. Additionally, the GAMMA network consists of around 60 monitoring stations distributed nationwide, focusing specifically on gamma radiation detection [38]. Complementing these national systems are the regional networks managed by ARPA/APPA, which provide localized monitoring, especially around sensitive sites like industrial areas.

Many other countries have established their radiation monitoring frameworks and installations tailored to their specific needs and regulatory environments. Although not detailed here, such frameworks collectively contribute to global radiological safety, demonstrating the diverse yet coordinated efforts made by nations around the world to protect public health and the environment from radiological hazards.

3 Monitoring network

As explored in Sect. 2, existing regulatory frameworks have established strong foundations for radiation monitoring. However, there remain areas where additional tools could enhance the effectiveness of these networks, particularly in terms of cost scalability, power efficiency, coverage in remote areas, easy deployment, and real-time responsiveness. While traditional systems are highly effective in many contexts, IoT systems may offer advantages in environments where deploying extensive infrastructure is challenging, or where additional, localized data is beneficial.

3.1 Overview of the architecture

In the IoT landscape, various wireless protocols have been developed to fulfill diverse communication requirements. While short- and medium-range protocols have their specific applications [39, 40], long-range protocols demonstrate exceptional performance when extensive and uninterrupted coverage is critical [41, 42]. Long-range protocols, such as LoRa (Long Range radio), or other widespread technologies like LTE and 5G, offer distinct advantages in scenarios like city-wide monitoring, vast natural environments, and remote infrastructure management.

For the development of the prototypes described in the present work, LoRa communication was chosen for its intrinsic advantages, including low power consumption, cost-effectiveness, extensive transmission range (both in line of sight and through obstructions, and up to 20 km in rural areas), networking capabilities, and data encryption. Its data rate, peaking at a few hundred kilobits per second (sub-GHz), is adequate for transmitting periodic small data packets, like radiation sensor readings [43, 44].

Unlike other wireless protocols often tied to specific service providers, LoRa's architecture easily allows for private network setups, giving organizations full control. This decentralized approach reduces reliance on continuous central or cloud connectivity, beneficial in areas with intermittent network access. Cost-effectively, both in terms of deployment and maintenance, LoRa is now employed in a wide range of industrial sectors, further solidifying its position as a prime choice also for radiation monitoring systems.

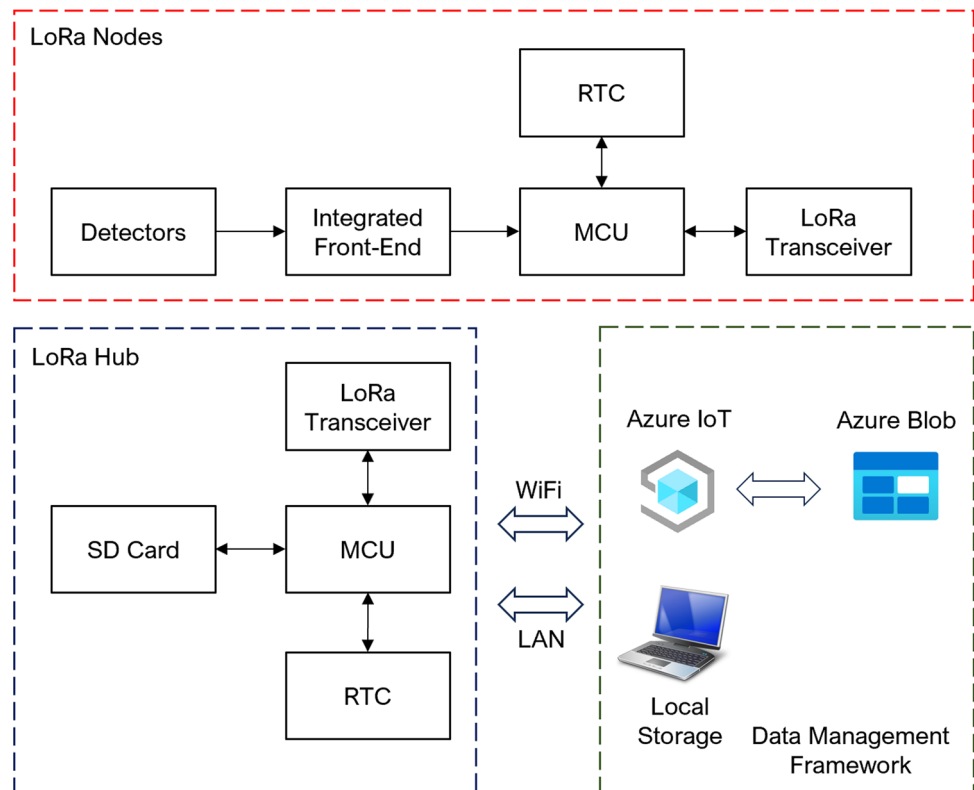
The WSN is architecturally delineated into three layers (Fig. 1):

- **LoRa Nodes:** characterized by a unique identifier within the network, are tasked to collect radiation data periodically or continuously. Designed with a focus on ultra-low power consumption and utilizing software optimization that cycles between active and deep-sleep states, these battery-powered nodes ensure prolonged operation with standard alkaline batteries. The gathered radiation data is automatically relayed to LoRa hubs, either directly or via repeaters if the situation demands.
- **LoRa Hubs:** they handle the LoRa traffic and forward data to local storage or an Azure IoT Central application via Wi-Fi through a Message Queuing Telemetry Transport (MQTT) broker. Additionally, they maintain synchronization across all nodes using acknowledgment radio payloads, mitigating the potential for data transmission collisions.
- **Data Management Framework:** implemented through an Azure IoT Central application, this platform allows for remote access and data processing. Metadata, defined in JSON format, details all the components of the network, including sensors, nodes, and hub configurations. Leveraging cloud storage capabilities ensures that end-users can access the sensor network remotely. Although this remote access necessitates internet connectivity, it is important to note that the network remains fully operational even in the absence of a connection.

3.2 LoRa node and detectors

The core design of each node uses an external, precision, temperature-compensated Real Time Clock (RTC) (DS3231SN#, Analog Devices) paired with a low-power microcontroller (MCU) (AVR64DD32, Microchip). For communication, a UART-interface LoRa transceiver (E220-900T22D, Ebyte) rooted in the LLCC68 from Semtech is deployed. These transceivers are equipped with a "wake on radio" functionality, beneficial for dynamic communication patterns where nodes can remain in low-power states until a specific

Fig. 1 Architecture of the proposed radiation monitoring WSN



radio signal is detected, optimizing power consumption, especially in scenarios with sporadic or event-driven data transmissions. It is notable that while UART-based LoRa transceivers cannot integrate into a LoRaWAN network, they present an advantageous balance of cost-effectiveness, reliability, and straightforward interfacing. Additionally, these devices offer the flexibility to adjust the transmission power up to +22 dBm and to vary the baud rate between a range of several hundred bps to multiple tens of kbps, allowing for customization of transmission distance, energy consumption, and data throughput.

The RTC directs the node's operations in alignment with specified monitoring parameters, such as defining detectors' integration windows or coordinating data transmissions. The nodes predominantly remain in a power-down state, conserving energy and ensuring several years of consistent operation without necessitating battery replacements. Data transmissions are organized using a combination of TDMA (Time-Division Multiple Access) and LBT (Listen Before Talk), synchronized with the onboard RTC. Despite the RTC's minimal drift, the clock is resynchronized after each transmission via an acknowledgment payload to minimize timing discrepancies and ensure consistent synchronization across the network. Additionally, a watchdog timer is implemented as well: if a system hang-up is detected, the current states are saved to non-volatile memory and subsequently recovered after a system reset.

Data about radiation levels are observed during specified measurement windows. These windows can be adjusted in both frequency and duration to optimize the device for power consumption, measurement granularity, and uncertainty considerations. The system consistently sends data after each measurement period. However, if an unusually elevated radiation activity level is identified, an alarm is activated, triggering an additional data transmission (Fig. 2).

Each node is configured to handle up to eight detectors simultaneously. For the task, low-power, off-the-shelf detectors were utilized, specifically designed for gamma rays and thermal neutrons (Fig. 3). For gamma-ray detection, BG51 detectors from Teviso, built upon an array of customized silicon PIN diodes, were selected. These detectors come with an integrated front-end that outputs TTL pulses, possess a 0.54-cm² active area, and are rated to detect gamma rays up to 2 MeV.

On the other hand, Domino v5.4 thermal neutron detectors were sourced from Radiation Detection Technologies and are based on a Microstructured Semiconductor Neutron Detector technology which combines a ⁶Li converter with 4 silicon diodes in a 4-cm² active area. They are radiation-hard and insensitive to gamma rays; moreover, they also come with an integrated front end that outputs TTL pulses and achieves up to 30% thermal neutron detection efficiency for sensing neutrons with energies up to 1 eV. A key modification introduced to both detector models was the provision of an open collector output, which enables daisy-chaining of detectors. Additionally, thanks to the low quiescent current draw (25 and 120 µA typical for gamma and neutron detectors respectively), by integrating a Schottky diode with a storage capacitor, the signal line was employed both for signal transmission and for direct power delivery to the sensors. This design simplifies the system's architecture and deployment, while also enhancing

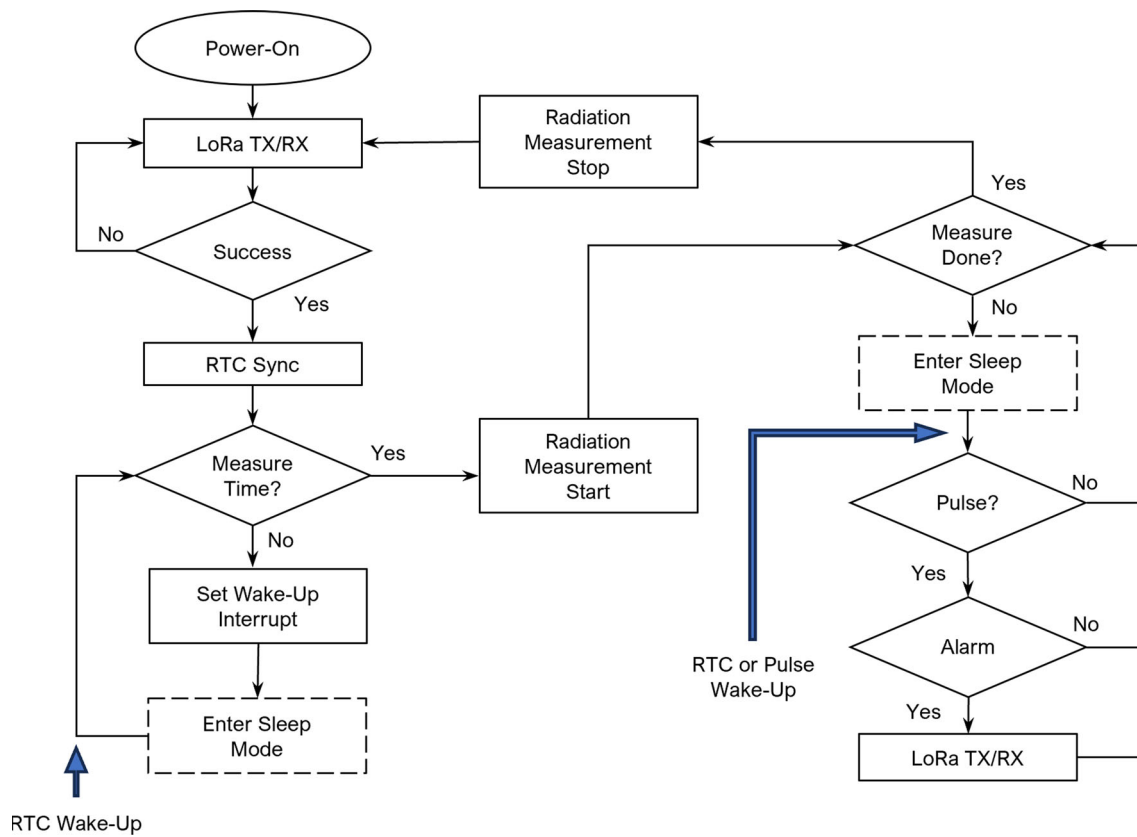
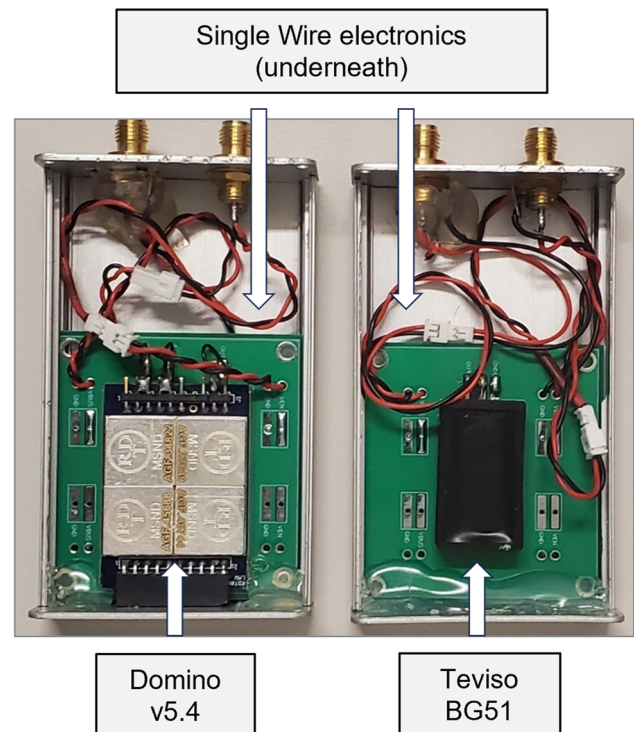


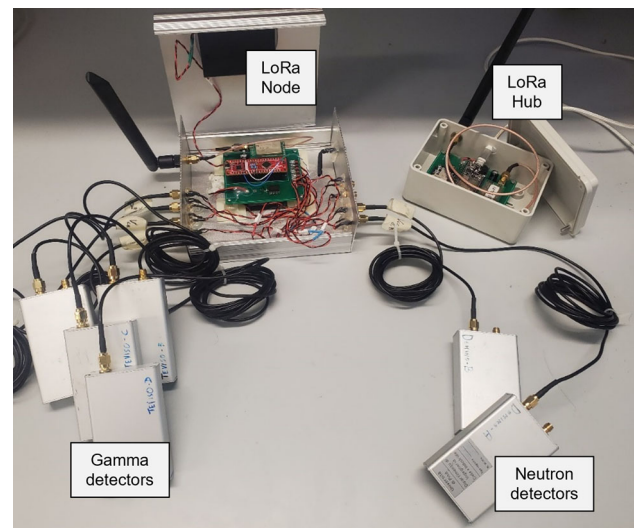
Fig. 2 Scheduling of the activities conducted by a sensorised LoRa node. Duration, frequency, and number of measurement windows are custom

Fig. 3 Solid-state detectors for thermal neutrons (Domino v5.4) and gamma rays (Teviso BG51)



detection efficiency if using more interconnected detectors at the cost of increased power consumption. Both gamma and neutron detectors were enclosed in aluminum enclosures to reduce potential susceptibility to EMI.

Fig. 4 Prototype of LoRa node and hub



3.3 LoRa hubs

Within the WSN, LoRa hubs receive data transmissions from nodes, transmits ACK payloads to ensure successful data reception, and resynchronizes the transmitting node's RTC addressing potential long-term drifts that could disrupt the precise timing of measurement and transmission activities. This is especially critical as transmissions follow a TDMA and LBT protocol with embedded retries for reliability. For robust data preservation, each hub incorporates an SD card, acting as non-volatile storage. Upon data reception, the information is committed to the SD card and simultaneously forwarded with an MQTT broker to the data management framework based on the Microsoft Azure platform using an Azure IoT Central application. The hubs are driven by ESP32 MCUs from Espressif with a firmware developed using the Microsoft Azure Libraries SDK for embedded-C.

In Fig. 4, the prototypes of the LoRa node and hub with attached detectors are shown.

The end-to-end system design ensures a smooth, automated flow from data collection to processing, transmission, and upload. Individualized dashboards can be created by configuring additional nodes as downstream devices and utilizing protocol or identity translation.

In our current setup, while the LoRa hubs offer flexibility and allow for custom protocol designs, commercial LoRa gateways, particularly those designed for LoRaWAN, could offer more robust, scalable solutions in certain environments. These gateways typically come equipped with integrated networking capabilities, advanced packet filtering, and support for multiple channels, making them better suited for larger, more complex deployments. Furthermore, commercial gateways often have built-in support for cloud integration and network management, which could streamline operations and provide additional features such as over-the-air updates and enhanced security protocols. However, for environments requiring more control over data flow and protocol design, our receiver-based approach remains viable, though we are aware of the potential benefits of transitioning to a commercial gateway solution in future iterations.

4 Results and discussion

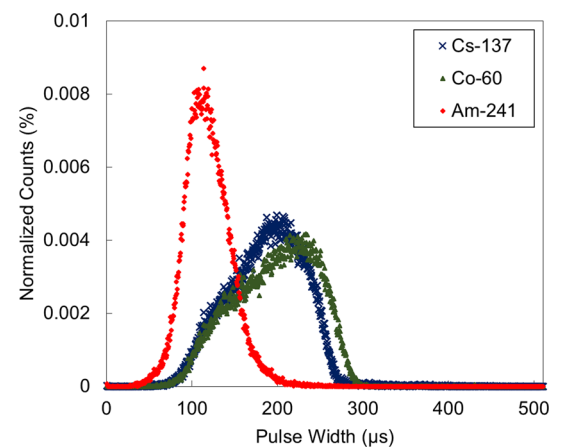
4.1 Gamma detectors' response

Two gamma-ray detectors of the BG51 series, designated as Gamma 1 and Gamma 2, underwent preliminary testing at the Joint Center for Military Studies and Applications (CISAM), San Piero a Grado, Italy, using point-like and calibrated Cs-137, Co-60, and Am-241 sources. The primary objective was to verify the sensitivity values provided by the manufacturer and assess the efficiency of the detectors. The detectors were mounted on wooden supports during testing and subjected to varying exposure durations and distances based on source availability. The experimental setup is depicted in Fig. 5, with detailed acquisition parameters and findings presented in Table 1.

In the process, an error margin of 5% was accounted for in the activity and calculated dose rates, in addition to considering the inherent uncertainties associated with counting statistics. The obtained results for Cs-137 align with the manufacturer's specifications. For Co-60, the sensitivity resulted lower than expected and may require further investigation. Moreover, for the lower-energy gamma rays from Am-241, it is suspected that an electronic cut-off threshold may be diminishing both the sensitivity and efficiency. The lack of sources with intermediate energies precluded an investigation at these energy levels. These findings indicate that a singular calibration factor might not accurately capture the detector's response across different energy spectrums. Specifically, the detector's

Fig. 5 Setup for the characterization of gamma detectors at CISAM**Table 1** Summary of the preliminary characterization of gamma detectors

Source	$dH^*(10)/dt$ ($\mu\text{Sv/h}$)	Exposure time (minutes)	Sensitivity ($\text{cpm}/\mu\text{Sv/h}$)	Efficiency (%)
Cs-137	5190	1	5.2 ± 0.3	0.179 ± 0.009
Co-60	3170	1	2.6 ± 0.3	0.155 ± 0.007
Am-241	37	10	1.4 ± 0.1	0.007 ± 0.001

Fig. 6 Results of the pulse width analysis to investigate a coarse form of gamma energy discrimination

capability to effectively detect very low-energy gamma rays is brought into question. As such, considering alternative detectors, like those based on scintillation, may be necessary.

While evaluating the response, the capabilities of a pulse width analysis approach to perform a coarse energy discrimination were also investigated. However, for high-energy gamma rays, the Compton effect is dominant in silicon, and the Time-over-Threshold (ToT) conversion behavior introduces significant nonlinearity (Fig. 6): pulse widths are not directly proportional to the actual gamma-ray energy, especially for higher energy pulses which appear condensed relative to the lower-energy ones. Although there is a potential for coarse energy discrimination through pulse width analysis, the combined effects of scattering and ToT nonlinearity make exact energy determination challenging. Thus, while pulse width measurements can provide some insight, they have clear limitations as a sole method for detailed energy discrimination in such detectors.

4.2 Thermal neutron detectors' response

Two thermal neutron detectors, designated as Neutron 1 and Neutron 2, underwent tests to investigate their response at the ETHERNES radionuclide source-based thermal neutron facility of the Polytechnic University of Milan. For this experiment, the detectors were exposed to a polyethylene-moderated (PE) Am-Be neutron source with an activity of $2.14 \times 10^6 \text{ s}^{-1}$, yielding a $437.4 \pm 14.0 \text{ n cm}^{-2} \text{ s}^{-1}$ thermal neutron fluence rate and $18.2 \pm 0.7 \mu\text{Sv/h}$ thermal ambient dose equivalent rate (Fig. 7). The counts registered by the detectors were collected over 35 min. The results from this evaluation are detailed in Table 2.

In the analysis, the errors margins derived from Monte Carlo simulations were factored into the thermal neutron fluence and the ambient dose equivalent rate. Inherent uncertainties from counting statistics were also incorporated. The results align with the manufacturer's specifications that cite a thermal neutron efficiency of up to 30% for thermal neutrons. Additionally, no significant discrepancy was observed between the two detectors.

Fig. 7 ETHERNES facility used for the characterization of neutron detectors at Polytechnic University of Milan

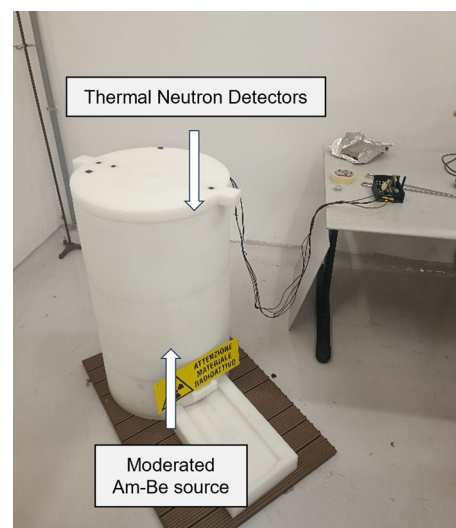


Table 2 Summary of the preliminary characterization of thermal neutron detectors

Detector	Sensitivity (cpm/ μ Sv/h)	Efficiency (%)
Domino v5.4 – A	757.9 ± 6.5	13.0 ± 0.4
Domino v5.4 – B	759.7 ± 6.5	13.1 ± 0.4

4.3 LoRa node performance assessment

Following the initial characterization, the performance of the sensorised LoRa node underwent evaluation at the Nuclear Measurement Laboratory (LNM) of the University of Pisa (Fig. 8). This evaluation was conducted to confirm the accuracy of the previously obtained detector characterization data. Additionally, the long-term reliability of the system was assessed, with particular attention to its consistent performance in routine functions like data gathering, data transmission, and alternating between active operational states and deep-sleep modes.

Fig. 8 Performance evaluation setup of the sensorised LoRa node at the LNM of the University of Pisa

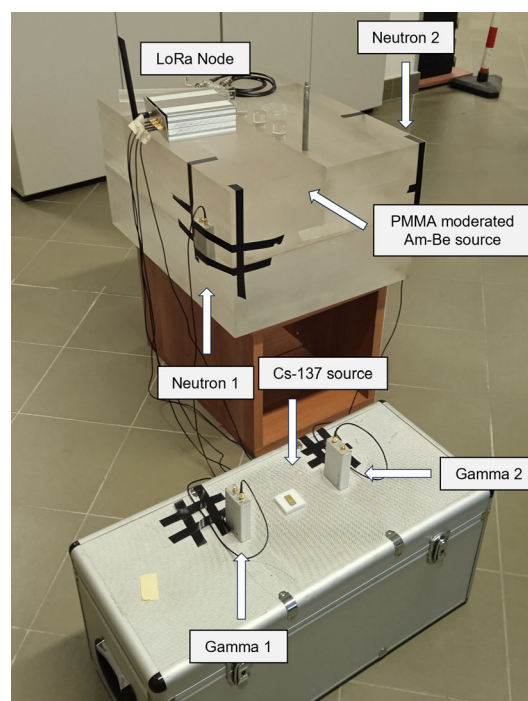


Fig. 9 Background radiation data collected for over 1 month by the LoRa node equipped with 2 gamma and 2 neutron detectors. Integration windows were set to 1 h with a repetition period of 6 h

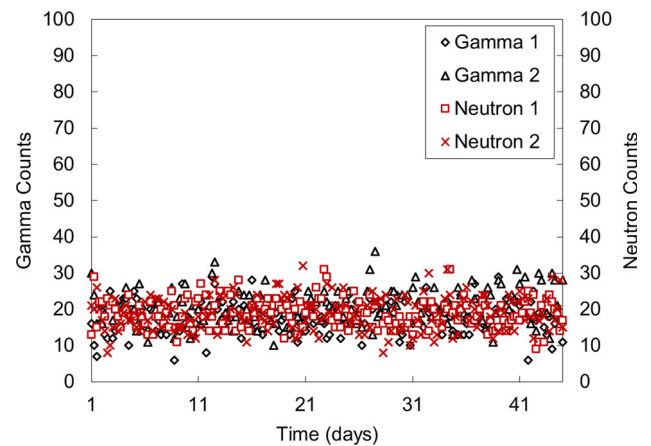


Fig. 10 Radiation data collected by the LoRa node in the presence of Cs-137 and PMMA moderated Am-Be sources. Integration windows were set to 1 h with a repetition period of 6 h

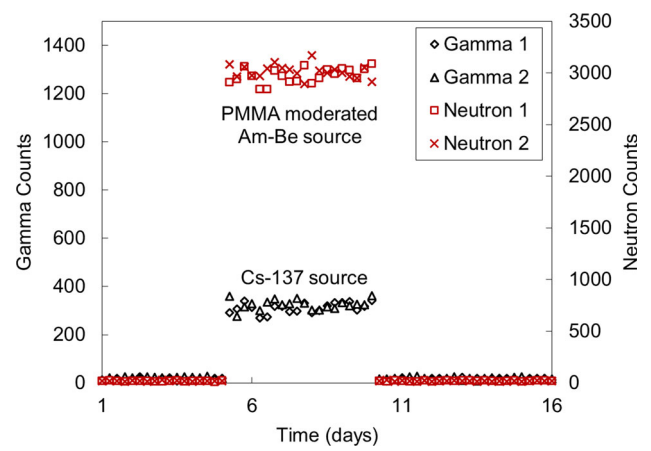


Table 3 Summary of the metrics computed for gamma and neutron detectors

Detector ID	MDCR (cpm)	MDFR ($\text{n cm}^{-2} \text{ min}^{-1}$)
Gamma 1	0.51	522.8 ± 26.5
Gamma 2	0.57	588.7 ± 29.2
Neutron 1	0.53	1.01 ± 0.03

During the evaluation process, the integration time window ΔT for all detectors was set to 1 h for all detectors, with a cycle repeating every 6 h. To aid in calculating metrics like the minimum detectable count rate (MDCR) and the minimum detectable fluence rate (MDFR), background radiation data spanning over a month was employed.

Subsequently, a 140.4-kBq Cs-137-point-like source was used to expose the gamma-ray detectors stationed atop an unoccupied aluminum support, elevated 50 cm above the ground to mitigate scattering influences (Fig. 8). The detectors were positioned 10 cm away from the gamma-ray source, aligned with the mid-height of the detectors' active zone. A 1.1 GBq Am-Be neutron source, moderated with 25 cm of PMMA, was used to produce a measurable thermal neutrons fluence rate of $100 \pm 12 \text{ cm}^{-2} \text{ min}^{-1}$ in the air at 25 cm from the source itself. Thermal neutron detectors were positioned aside the PMMA moderator, 25 cm distant from the neutron source, and centered at the mid-height of the detectors' active region. The results of the analysis are shown in Fig. 9 and Fig. 10 and summarized in Table 3.

The sensitivity and efficiency values found for the detectors matched those from the previous characterization campaign, and they have not been reported. Moreover, the high efficiency of the Domino sensors enables a swift identification even of minimal thermal neutron contamination (an ambient dose equivalent rate of $0.01 \mu\text{Sv/h}$ can be reliably detected in a matter of seconds). In contrast, gamma detectors necessitate an extended integration time to obtain statistically significant results. For example, a $0.1 \mu\text{Sv/h}$ ambient dose equivalent rate can be reliably detected in 1 h, but this value roughly doubles if ΔT is reduced to 12.5 min. However, thanks to the neglectable power consumption, these detectors may be particularly well-suited for long-term monitoring of radioactive contamination or the rapid identification of high-activity radioactive sources.

Beyond its capacity for detecting ionizing radiation, the LoRa node was tested for power consumption, communication capabilities under non-line-of-sight (NLOS) conditions, and resilience to electromagnetic interference (EMI). To measure the average current consumption, the node was configured for daily measurements, utilizing 1-h integration windows, and incorporating both 2 gamma-

Table 4 Current consumption, communication capabilities, and resilience to EMI^aRSSI = Received Signal Strength Indicator

Average current draw (μA)	RSSI ^a (dBm)	EMI Susceptibility
15 (24-h period, 1-h windows)	143 dBm ($d = 250$ m, NLOS, + 5 dB antenna, + 22 dBm out, 2.4 kbps, 1.5 m height)	None (+ 30 dBm, 868 MHz, 2.4 GHz)

ray and 2 thermal neutron detectors. Deep-sleep current draw resulted in less than $1 \mu\text{A}$. The system's communicative reach in NLOS environments was evaluated by analyzing the Received Signal Strength Indicator (RSSI) up to 250 m, factoring in the obstruction of 3 buildings between the node and the hub. EMI sensitivity was probed by gathering data while + 30 dBm radio transceivers, operational at 868 MHz and 2.4 GHz bands, were active close to the LoRa nodes. The system's technical attributes are detailed in Table 4.

5 Further developments

5.1 Radiation hardness assessment

While the proposed IoT-based radiation monitoring devices offer significant advantages in terms of cost-effectiveness and deployment flexibility, their use in high-radiation environments requires careful consideration due to the susceptibility of certain components to radiation-induced degradation. For example, according to [18], components like microcontrollers, System on Chips (SoCs), and MOSFET-based circuits are particularly vulnerable, with the SoC used for the wireless transceiver ceasing functioning at around 0.46 kGy, while other critical components showing signs of degradation at higher doses, with failures occurring around 10 kGy. In other studies [45], it has been shown that electronic modules can tolerate radiation environments up to a total dose of approximately 0.3 kGy without performance degradation. However, beyond this threshold, these components tend to fail abruptly rather than gradually degrading, which is consistent with known characteristics of total ionizing dose effects, highlighting the need for enhanced shielding to ensure reliability in high-radiation environments.

These findings highlight the limitations of using standard commercial off-the-shelf (COTS) wireless components in high-radiation fields, where prolonged exposure can significantly impair performance or lead to complete failure. Therefore, the proposed IoT-based devices are more suitable for environments with lower radiation levels or for temporary deployment in high-radiation areas where long-term exposure is not required. Furthermore, the study suggests that while these devices may be effective for environmental monitoring, they should not replace traditional wired systems in critical areas like NPPs. Instead, they could serve as complementary tools, offering redundant data transmission channels or providing additional coverage in less critical zones.

To assess the platform's durability across various radioactive environments, a radiation hardness investigation is underway at the Bruno Guerrini Laboratory of the University of Pisa, Italy. This facility, equipped with calibrated high-activity gamma and fast neutron sources, is being used to conduct extensive long-term studies on the effects of radiation exposure to mixed fields on electronics following standardized methodologies [46], focusing on both cumulative effects, such as Total Ionizing Dose, and Single Event Effects, and to explore potential shielding solutions.

5.2 Impact on wireless signal propagation

Experimental studies conducted in high-radiation environments, such as in hot cells with gamma dose rates exceeding 100 Gy/h, revealed that electromagnetic waves can experience slight frequency shifts and signal power fluctuations. Although these effects do not completely disrupt wireless communication, they can introduce variability in signal quality, which may affect the reliability of data transmission in critical applications. For instance, frequency shifts of up to 400 kHz were observed under higher gamma dose rates, and power loss variations were noted, though no clear pattern emerged. These findings suggest that, while wireless systems can function under radiation, the presence of radiation can introduce uncertainties in signal integrity [47], highlighting the importance of cabled redundancy for critical operations.

5.3 Certification for safety-critical applications

Another important aspect to allow the deployment of IoT-based radiation monitoring systems is their certification for safety-critical environments through adherence to a set of stringent international standards governing the system's design, functionality, and reliability. The IEC 61226 [8] categorizes functions and classifies systems based on their safety significance, which in turn dictates the level of design and testing rigor required for each system component. Building on this, IEC 61513 [9] establishes general requirements for designing instrumentation and control systems critical to safety, emphasizing the need for redundancy, fault tolerance, and reliable operation under all conditions, including those during and after accidents.

In terms of software and hardware, IEC 60880 [48] and IEC 62138 [49] provide guidelines for developing and validating software in safety-critical systems. Complementing this, IEC 60987 [50] focuses on the hardware design requirements, stressing the need for reliability and robustness, particularly in harsh nuclear environments.

Data communication and cybersecurity are key areas of focus, with IEC 61500 [51] addressing secure data transmission, particularly for systems performing Category A functions. To address the ever-present threat of cyberattacks, IAEA Nuclear Security Series No. 17 [52], along with IEC 62645 [53] and IEC 62859 [54], establish cybersecurity requirements tailored for nuclear facilities, focusing on protecting digital systems from cyber threats such as man-in-the-middle (MitM) and denial-of-service (DoS) attacks. Additionally, STUK Guide YVL A.12 [55] and NRC DI&C-ISG-04 [56] offer further guidance on handling cybersecurity and communication issues in control rooms including encryption, intrusion detection systems (IDS), and network segmentation.

Electromagnetic compatibility (EMC) and EMI are also important factors in the certification process. EMC testing is mandated by IEC 62003 [57] to ensure that the IoT system does not cause or suffer from interference with other safety-critical equipment. Furthermore, the establishment of exclusion zones, as outlined by NRC RG 1.180 [58] and SSG-39 [59], serves as an additional safeguard by physically separating wireless devices from sensitive I&C equipment to prevent EMI/RFI interference.

Based on the standards and guidelines discussed, the steps that would be needed to certify the proposed IoT-based radiation monitoring system are the following:

- System classification according to IEC 61226. This classification will guide the necessary design and testing rigor.
- Architectural design by IEC 61513, focusing on redundancy and fault tolerance. For example, ensure that critical communication links have backup channels to maintain functionality during failures.
- Development and testing of hardware and software following IEC 60880, IEC 62138, and IEC 60987 standards. For instance, conduct tests that simulate radiation exposure to verify that components maintain integrity and software functionality.
- Ensure secure communication as required by IEC 61500. Additional cybersecurity measures should follow the guidelines provided in IEC 62645, IEC 62859, STUK YVL A.12, and NRC DI&C-ISG-04 to protect against cyber threats.
- Perform testing and validation of the system, ensuring that it meets the requirements outlined in IAEA SSG-39.
- Conduct EMC and EMI testing by IEC 62003 to ensure that the IoT-based system is resilient to electromagnetic disturbances and does not interfere with critical safety functions within the nuclear facility.
- Validation of the entire system against the requirements outlined in IAEA SSG- 39.

6 Conclusions

In this paper, an innovative IoT device, engineered for autonomous radiation monitoring and detection, has been designed, developed, and characterized. The platform, leveraging LoRa technology for communication, can measure both gamma rays and thermal neutrons, offering reliable data collection capabilities while mitigating challenges associated with traditional wired systems. The device's ultra-low power consumption, combined with its wireless interface integration, ensures efficient communication and prolonged operation, making it ideal for long-term monitoring without the associated risks of human exposure.

Current regulatory requirements focus on robust, wired systems, but the flexibility, scalability, and rapid deployment needs of modern monitoring demands are not fully addressed by traditional approaches. Our device tries to bridge this gap by offering a cost-effective, easy deployable, long-range wireless solution that coexist with existing monitoring systems while providing enhanced mobility, scalability, and real-time data collection in high-risk or remote areas.

In the development and characterization stages, gamma detectors underwent preliminary utilizing calibrated Cs-137, Co-60, and Am-241 sources, to verify the sensitivity values provided by the manufacturers and evaluate the overall efficiency of the detectors. Subsequently, thermal neutron detectors were characterized exposing them to a PE-moderated Am-Be neutron source.

After the initial characterization, the LoRa node's efficacy was studied to confirm the findings from the detectors' previous characterization and, secondly, to ascertain the system's long-term reliability. Emphasis was placed on the node's consistent performance in scheduled operations, including routine data acquisition, seamless data transmission, and its transition capabilities between active and deep-sleep operational modes. The high efficiency of the thermal neutron detectors facilitates prompt detection of even minimal thermal neutron contamination; in contrast, the gamma detectors, despite their lower sensitivity, are especially adept for extended monitoring of radioactive contamination thanks to the minimal power consumption, or for quick identification of highly active radioactive sources.

In addition to its ionizing radiation detection capabilities, the LoRa node underwent evaluations focusing on power usage, communication effectiveness in NLOS scenarios, and robustness against EMI. The comprehensive and successful testing underscored the system's versatility, reliability, and adaptability in various operational environments.

Ongoing efforts are focused on investigating the radiation hardness of the device to ensure optimal performance in variable radiation exposure environments. While the system's current performance meets the expected requirements for routine monitoring, further enhancements are being considered to make the device more resilient to the certification challenges posed by safety-critical applications in high-radiation fields.

Nevertheless, the adoption of WSN for radiation monitoring amplifies both routine and emergency operational effectiveness, reinforcing safety protocols and considerably reducing risks to human operators. This highlights the important role of IoT technologies in delivering pertinent information to stakeholders in a timely and efficient manner, solidifying their position in contemporary nuclear safety practices.

Author contribution Andrea Chierici did conceptualization, methodology, software, formal analysis, investigation, data curation, writing—original draft, and visualization. Riccardo Ciolini done methodology, software, formal analysis, investigation, data curation, writing—review & editing, and visualization. Debora Siqueira Nascimento contributed to methodology, formal analysis, investigation, data curation, writing—review & editing. Francesco d’Errico was involved in project administration, supervision, investigation, data curation, writing—review & editing, and funding acquisition.

Data Availability Statement Data have been stored locally, so there is no data repository available to the public at this time. The manuscript has associated data in a data repository.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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