ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-WE3A001

RADIATION-TOLERANT MULTI-APPLICATION WIRELESS IoT PLATFORM FOR HARSH ENVIRONMENTS

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Abstract

The rise of the Internet of Things (IoT) has been a driving force behind the digital transformation of industries and innovation in consumer electronics, enabling real-time data collection, automation, and the creation of interconnected devices tailored to personalized user experiences. However, within the unique environment of particle accelerators, the adoption of wireless approaches is still in its early stages. Given this context, the primary objective of this study is to detail the efforts made in the development and implementation of a flexible IoT-based platform designed for remote monitoring and control within particle accelerators. Founded on the principles established by a previous radiation monitoring device at CERN, this platform stands out as a versatile hardware solution, having been pre-validated for radiation tolerance and energy efficiency. While it integrates seamlessly with CERN's existing LoRa Wireless network, it can also be configured for dedicated gateway setups or even operate in a stand-alone mode. The platform is designed to interface with a variety of sensors and conditioning circuits, representing a significant advancement in the evolution of monitoring and control systems.

INTRODUCTION

A particle accelerator is surrounded by a myriad of sensors and actuators, all functioning in perfect harmony. In this context, the concept of the Internet of Things (IoT) isn't new. At CERN, the devices that control and monitor these machines are usually called the "control system" [1]. Historically, this system has been deeply associated with cabled infrastructure, predominantly composed of "copper cables" and optical fibers [1]. The wireless IoT concept can be applied to a particle accelerator context but introduces new challenges, some of which were discussed and asserted in [2]. This showed the challenges of qualifying low-power components typical of IoT design, while in [3] the LPWAN solution that best suits the LHC environment was discussed and identified. This focused on the advantages and features that a stand-alone IoT wireless application could bring to the LHC.

As the operational dynamics of a particle accelerator evolve, so do its requirements. The instrumentation, therefore, must exhibit a similar adaptability. Given the expansive nature of these accelerators and their distributed instrumentation, each new requirement typically mandates the deployment of new systems, complete with their own power lines and communication cables. The methodology followed to develop such systems has ensured their high reliability and operational efficiency for years. However, when it comes to addressing simpler operational needs, conducting specific investigations, or undertaking cross-validations, this traditional approach becomes impractical. The labor intensive nature of such development and the cost implications of the associated cabling and integration often render such projects prohibitive.

The wireless IoT platform discussed in this study offers a new solution. It provides teams with a tool to address challenges that were once too difficult or expensive to tackle. This includes installation of monitoring devices for specific purposes in just a few hours, new installations in temporary experiments, and installations in remote locations or locations with high radioactivity. In this paper we talk about the hardware platform and its performance and characteristics. We also look at CERN's wireless network, focusing mainly on the LoRaWan network and its data publishing and collection architecture, and present how LoRaWan devices work in the CERN accelerators along with deployment strategies. The last part is dedicated to some examples of how this technology can be used.

CERN IOT HARDWARE PLATFORM

Developing a radiation-tolerant wireless hardware platform suitable in the accelerator context presents significant challenges. First, a deep understanding of radiation effects on electronics is necessary to properly select components and qualify them [4]. Achieving a balance between radiation resistance, power efficiency, and wireless capability requires a meticulous approach and rigorous validation. The design flow follows two paths: one purely electrical-performance driven and the other focused on radiation tolerance, driven by the radiation environment. The radiation qualification path has been discussed in other works [2] and will not be the focus of this paper.

Hardware Choices

To fulfill the requirements, several key criteria must be addressed in the design choices. First, to avoid the use of cables and exploit wireless powering, a design leading to extended battery life is essential. The choice of components is thus driven by these requirements and only components with low power features are selected. As depicted in Fig. 1, the platform is designed to be modular and consists of three units, the power supply board, the main board and the application sensor board. To meet the typical characteristics

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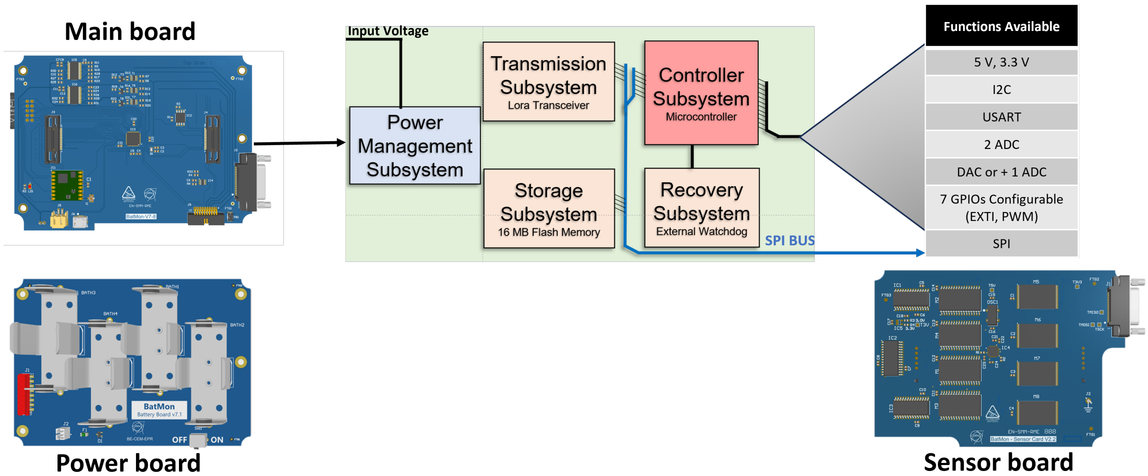

Figure 1: The different boards that compose the wireless IoT monitoring system. Pictured on the left, from top to bottom, are the sensor, main and power boards. A focus on the different subsystems that make up the mainboard is shown in the center. On the right are the different GPIO configurations available. Aside from the SPI lines, used by the mainboard for its functioning and not reconfigurable for other purposes, the other lines can be set according to the application need providing a great scalability to the system.

of IoT wireless devices the power board developed is a battery module that can accommodate up to 4 C-type batteries (Tadiran Lithium Inorganic Batteries), each with a capacity of 8.5 Ah, this makes it possible to extend the energy capacity of the system to 17 Ah. The batteries selected were non-rechargeable batteries to alleviate the safety issues associated with rechargeable batteries [5]. As visible from Fig. 1, the 4 batteries are organized in two parallel branches, each consisting of two batteries to provide a voltage of 5V that can be used by the sensor part. For less time-demanding applications, it is still possible to mount only two batteries. The batteries are connected to low quiescent current, linear voltage regulators (Power Management Subsystem in Fig. 1), avoiding the use of DC-DC converters, which are usually very sensitive in radiation environments [6]. The batteries and the regulated voltages are fed to a diagnostic circuitry which measures the discharge to allow a pro-active anticipation of a battery change and identifies other failure mechanisms when in operation. As can be noted from Fig. 1, the core of the design revolves around a microcontroller (MCU) that has demonstrated relative resilience to radiation. It is based on an ARM Cortex M0 architecture, which hosts advanced digital communication peripherals (SPI, I2C, UART, etc.) that facilitate interfacing with a diverse range of digital sensor conditioning electronics. By design, the main board, housing this MCU, gives the possibility to the user to read up to three analog signals (ranging from 0 to 3.3 V) coming from the sensorboard, achieving a sampling rate as high as 350 kSps. Other functionalities include the generation of signals via internal Digital to Analog Converters (DAC) and Pulse-Width Modulation (PWM) controllers, both of which are instrumental for producing excitation signals for various sensors and control applications. The three main protocols (Inter Integrated Circuit (I2C), Serial Peripheral Interface (SPI)

Table 1: Uptime of the mainboard as a function of the Measurement Period chosen. The time required to read the sensorboard will be application-dependent. In this example, a 5 s active period has been considered.

Measurement Period	Avg. Current [mA]	Lifetime 2 Batt. [Months]	Lifetime 4 Batt. [Months]
5 Minutes	0.29	41.18	82.36
1 Hour	0.12	102.16	204.33
1 Day	0.1	117.3	234.59

and Universal Synchronous/Asynchronous Receiver/Transmitter (USART)) are available through the independent line on the sensorboard and can be exploited to communicate with the digital sensors. The available functionalities that user applications can use are depicted in Fig. 1.

A notable feature of the MCU is its low-power mode, which permits a minimal power consumption in the order of ~ 100 µA when in sleep mode and supports programmatic wake-up functionalities. The decision to employ a MCU over a more radiation-tolerant FPGA [8] was primarily driven by its energy efficiency and easy integrability for user application in terms of peripherals and code implementation. One of the peripherals present on the main board is a wireless LoRa transceiver. The transceiver is configured via software to be fully compliant with the LoRaWan network that, as demonstrated in [3], is the best choice for a particle accelerator environment. The firmware is designed to reduce the times of high consumption to only the times when the sensor is read, the measurement is saved, and the transmission is made. The reading frequency (measurement

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Table 2: Expected lifespan and sensitivity considering the radiation measured in various alcoves hosting control systems in the LHC during the 2018 run [7]. The evaluation is based on HEH sensitivity and TID duration [2].

Position LHC	Sensitivity [Reset/yr/Device]	Lifetime [yr]
ULs	$6.5{\cdot}10^{-4}$	$1.4{\cdot}10^{5}$
UJs	0.02	687.5
RRs (Tunnel)	0.19	25
P1L-Cell 17	0.27	63.95
P1L-Cell 11	3.12	9.16

period) can be configured via cable or remotely via downlink messages. As visible from Table 1, the measurement period basically determines the uptime of the system. When the wireless network is not available, the mainboard can use Flash memory storage to store all measurements, that can then be read when the device is physically accessible.

Radiation Tolerance

The platform's radiation tolerance ensures its robustness in high-radiation environments, while its modular design facilitates the integration of various sensors and modules. MCUs, along with other digital circuits, are susceptible to a spectrum of radiation effects when exposed to radiation. These can be broadly categorized into stochastic effects, commonly referred to as Single Event Effects (SEE), and cumulative effects [9, 10]. Cumulative effects progressively degrade device performance, eventually leading to device failure. On the other hand SEE are inherently transient and unpredictable, and can be manifest in both destructive and non-destructive forms. It is essential that components susceptible to destructive SEE are avoided, as a notable consequence of destructive SEE is elevated power consumption. It is therefore fundamental to comprehensively characterize components for destructive effects, to ensure their reliability in the anticipated operational environment. This principle is applicable not just to primary components like the MCU, but extends universally to all associated components.

All the active electronic components have therefore been tested and screened for destructive events in radiation facilities providing high energetic protons and/or mixed radiation fields [2, 11, 12]. While the IoT platform design exhibits resilience against destructive SEE, non-destructive or "soft" events remain a potential concern. Radiation testing was instrumental in evaluating the vulnerability of various devices, guiding our selection toward the least susceptible variant. Nonetheless, the residual risk of soft events necessitated the deployment of mitigation strategies. Software-based approaches have been developed to identify and counteract such events during the MCU's operational cycle, with several techniques being implemented [13]. Some hardware mitigation techniques have also been implemented, in particular, a voltage diagnostic circuit capable of detecting malfunctioning, and a supervisory circuit to detect when the microcontroller is unresponsive and restart it.

Table 2, assesses the lifespan of the device and the frequency of mitigation actions required to reduce radiation effects during platform operation, relative to the typical radiation environment found at the LHC.

WIRELESS NETWORK

This section presents the LoRaWAN implementation at the CERN Network and End-node level. The success of the implementation is demonstrated via a set of Key Performance Indicators (KPIs) extrapolated from the wireless IoT monitoring systems during their operation in the LHC.

LoRaWAN Network at CERN

Low Power Wide Area Networks (LPWAN) provide long range communication capability to low power devices in a cost-effective way. The price to pay is a lower data throughput than with traditional local or wide area networks such as Wi-Fi or cellular networks. CERN has deployed two parallel LPWAN networks covering both the surface of its campus and its underground facilities to support its need for battery-powered sensors. The first network, based on LTE-M, has been developed in collaboration with CERN's mobile network operator, while the second, a private LoRaWAN, was fully implemented by CERN. We will concentrate here on the latter. LoRaWAN is a media access control (MAC) protocol designed to allow wireless communication for battery-powered devices. The LoRaWAN protocols are defined by the LoRa Alliance and formalized via the LoRa Alliance technical specifications [14].

The LoraWAN network architecture is based on a star topology in which data transmitted by a node is typically received by multiple gateways, which relay those messages to a central network server (NS). The network server hosts the intelligence of the network. It handles the MAC layer, authenticates received frames, discards messages not belonging to the network, filters redundant received packets, performs security checks, schedules downlink messages, etc.

CERN has designed and deployed a LoRaWAN network [15] based on ChirpStack open-source Network Server. A private instance of ChirpStack is installed on premises so CERN can control the network, the device provisioning and the data flow.

A capacity and coverage study was performed to select the location of the gateways, to ensure geographical redundancy on the surface and to respect the duty cycle imposed by the regulators for downlink messages:

- LoRaWAN gateways have been installed on the roof of 15 CERN buildings to ensure the coverage of the campus ($60 km^2$).
- thanks to the existing radiating cable infrastructure, 46 extra gateways cover the injector chain, accelerators, adjacent tunnels, caverns, and experiments.

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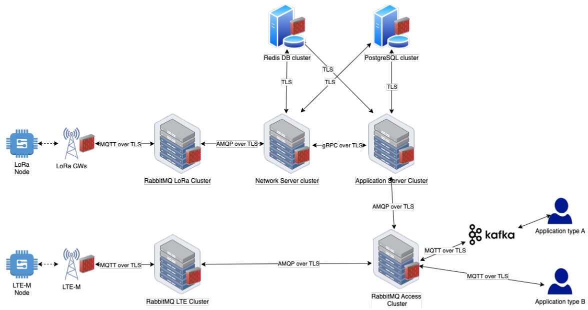

Figure 2: CERN LPWAN network architecture.

The LPWAN service, including the gateway software, is deployed, orchestrated, monitored, and maintained via CERN IT standard services. As shown in Fig. 2, all its components offer high availability:

- Three different RabbitMQ clusters handle the messaging among the different parts of the service. They have dedicated firewall rules and ACLs to isolate each part of the architecture.
- Two database clusters are used to run the LoRaWAN service: one hosting PostgreSQL and one hosting REDIS to store volatile information.
- A Chirsptack cluster has been designed by installing three parallel instances, each of them running both a network server and an application server exchanging data with each other. All instances connect to the same PostgreSQL and Redis database, enabling the duplication of messages and high-availability of the system.

LoRaWAN users can provision and control their devices autonomously via dedicated CLI, REST API and web tools.

They can consume the data produced by their sensors in two different ways depending on their integration needs. Either they can integrate their own systems via MQTT (CERN industrial control systems have integrated WinCC OA with the LPWAN networks in this way) or connect to Kafka as explained in one of the next sections.

LoraWan Implementation on Wireless IoT Platform

LoRaWAN-compliant end nodes are divided into 3 classes (A, B, and C), of which the latter two are extensions of the specifications of Class A devices [16]. Sensors implementing class A, as the IoT platform, are battery-powered and remain passive most of the time. After transmitting information (Uplink), the device opens two short receive windows (Rx) to receive downlink messages from the network. This class allows the opening of transmitting windows which are programmed with a defined delay. During Rx windows, if required by the user, it is possible to receive acknowledgments on the uplink (Confirmed Uplink) and customized downlink messages. The latter are messages transmitted by the Network Server (NS) and through the IoT platform. Firmware implementations are decoded and used to change the configuration or perform specific actions (e.g. GPIO control, enabling a peripherals, etc..). The Confirmed Uplink (CU) is usually used only as an acknoledgment for the Uplink reception, but on the wireless IoT platform is also used for two purposes: a) to detect the network unavailability or b) to detect a transceiver malfunction. In the first case, when the NS is reset due to any problem or update, previous connections to the network are lost and the devices must rejoin. The CU is used to assess the existence of a network link and to rejoin if necessary. The second case occurs when radiation effects affect the functionality of the transceiver. Since the possibility of detecting a failure of the transceiver on the IoT platform is not possible, the confirmed uplink is used to understand whether it is actually transmitting or not. Specifically, the confirmed uplink is requested every 3 transmissions. If a confirmation is received, this means that cases a) and b) are not occurring. Otherwise the device automatically restarts and rejoins the network re-estabilishing a trusted connection with the NS [13]. The procedure of failure recognition is depicted in Fig. 3. The reception of the customized downlink messages is independent of the CU messages and can coexist. The use of the customized downlink is reserved to reconfigure device functionalities such as a change of the transmission period, enabling peripherals, or configuring sensors. In compliance with LoRaWan, the IoT platform is capable of increasing the Spreading Factor (SF) during the joining period if the connection is not established. In case of non-compliance (beyond the maximum time a transmitter can be active within a specific time window) the transmission is delayed.

Wireless Performance of the IoT Platform in the LHC

The LoRaWan performance has been measured in various accelerator locations, such as experiments (Alice's cave), alcoves (ULs and TI), and near the beamline (Tunnel). These installations provided an excellent opportunity to evaluate the wireless performance of the device. Table 3 reports different KPIs related to the wireless IoT platform for different locations. The number of different packets transmitted is due to the different measurement periods used. Normally the devices use a period of 1 hour, but the P1-TI18 and P1 Tunnel installations used a shorter period (30 and 5 minutes respectively). On average the devices had a packet loss rate of 0.4 % with respect to the total number of packet sent. As it can be seen from Table 3 the device in P4R - Tunnel position has higher losses. The reason for this loss is mainly due a very low Received signal strength indicator (RSSI) usually this is the case when a device is positioned far or shielded from the antenna.

NETWORK ARCHITECTURE, LOGGING AND CONFIGURATION

The flow of data from the LoRaWAN service is captured through a fairly standard data streaming workflow centered around Apache Kafka technologies as depicted in Fig. 4 (at CERN this infrastructure is multi-purpose and used beyond IoT).

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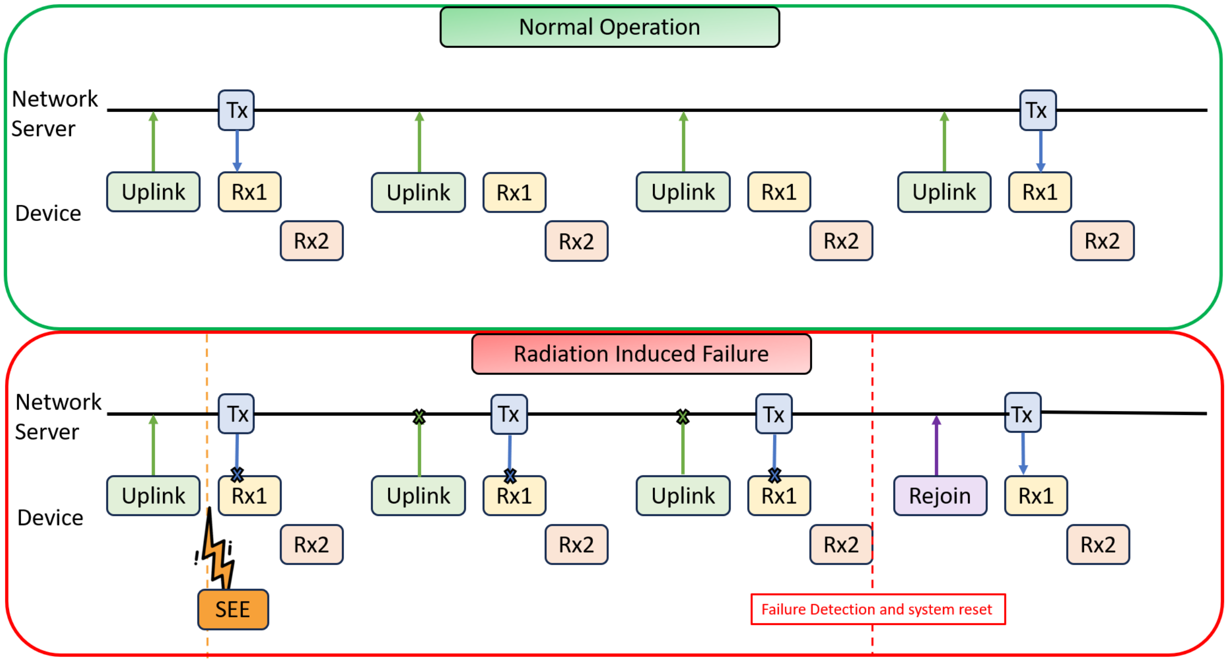

Figure 3: Flow Chart Diagram describing the working principle of the mitigation scheme used to detect induced failure or NS unavailability. Due to a radiation-induced failure in the LoRa transceiver (symbolized by a lightning bolt), the component is unable to perform any transmission operation. This failure is invisible to the MCU, which is still able to read the signature of the transceiver and control it via SPI. As a result of the failure and the missed transmissions, the uplink acknowledgement is never received by the end node (symbolized by an arrow ending in a cross). After three unsuccessful receptions, it resets and rejoins the network. In case of NS unavailability, the concept is the same with the only difference being that the device performs the uplink but never receives a confirmation from the NS.

Table 3: KPIs measured from IoT platforms for different LHC areas (Experiments, Alcoves, Tunnel). All the devices were configured to start joining from SF 10 and increasing it by one in case of three failed to join attempts. The devices joined most of the time with SF 10.

Position	Packet Transmit-ted	Packet Lost [%]	Avg. SNR [dB]	Avg. RSSI [dBm]
ALICE	2421	0.2	9.02	-89
P1 - TI18	5792	0.4	6.5	-100
P1 - UL16	2046	0	2.93	-112
P1L - Tunnel	2276	0.6	3.31	-112
P1R - Tunnel	2249	0.6	5.49	-107
P4L - Tunnel	2907	0.1	2.65	-98
P4R - Tunnel	2907	1.3	2.65	-117

The data from the IoT platform is collected from the LoRaWAN NS using MQTT and copied in Apache Kafka using Kafka Connect. A Kafka Streams application multiplexes this data in dedicated Kafka topics with different ACLs for authorization. A second pipeline takes over, validates and decodes the device payload into new decoded Kafka topics also using Kafka Streams. Once the data is decoded, Kafka Connect is used to transport these to relational databases (Oracle, Mysql, PostgreSQL), time-series databases (InfluxDB), or big data storage (Apache Hadoop HDFS).

Projects can tap into data in any part of the system, including reading directly from Kafka, from intermediate raw topics, decoded or can further enrich this data. Other projects can decide to connect their own applications to the final data stores, or simply use Grafana to create monitoring dashboards that target any of these data stores.

For the wireless IoT, the last described workflow is followed. Specifically, the MQTT messages are decoded via Kafka and stored in a dedicated InfluxDB database. In addition to the payload decoding, the available LoRa PKIs provided by the NS and associated with the specific packet are also captured from the MQTT messages.

The payload is fifty bytes in size, limited by the constraints of the CERN network. Twenty are used by the application to transmit control information (e.g. power rail or functionality monitoring), while the others are available to the user for custom implementation. If the packet size permits, these bytes can also be used to store previous measurements in order to cope with possible packet loss. This mechanism, already implemented in a non-radiation tolerant application based on Wireless IoT [17], improves the reliability of the application.

The Wireless IoT is directly connected to a customized Grafana interface where all measurements and PKIs are available. This interface is used to quickly verify the correct functionality of the system when it is installed in the accelerator.

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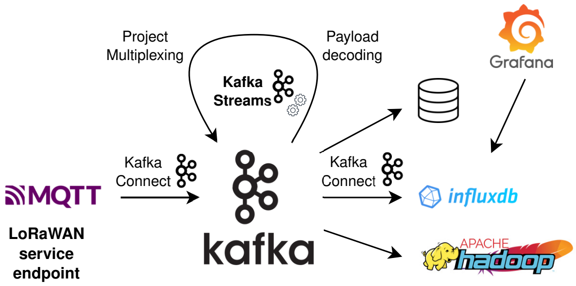

Figure 4: Block diagram of the technologies and architecture used for data transformation and streaming.

APPLICATION EXAMPLES

In this section, different application examples are described. These implementations are possible thanks to the great versatility and flexibility of the platform. As depicted in Fig. 5 we will focus on three example applications: temperature and humidity, equipment control and position.

Temperature Humidity

Environmental monitoring, specifically temperature and humidity sensing, is pivotal in applications involving electronics and sensors. These environmental factors can skew sensor readings, necessitating calibration and compensation algorithms. In particle accelerators, numerous precision sensors, ranging from survey instruments to beam intercepting devices, are influenced by these conditions. Moreover, temperature and humidity are primary factors affecting electronic reliability. Monitoring these parameters ensures that the operating conditions align with reliability calculations, preventing potential equipment failures. For example, tracking conditions within equipment racks or near specific boards is crucial for system performance. In scenarios where radiation shielding is employed localized temperature measurements become essential to ensure the shielding doesn't inadvertently elevate temperatures beyond design limits. To address these needs, we've introduced a temperature and humidity (TH) sensor board integrated with our wireless IoT platform. This TH board is designed with Radiation Hardness Assurance in mind, utilizing components resilient to radiation. It can measure temperatures ranging from -23.61 to 75.33 °C and relative humidity from 5% to 95 % , making it apt for the aforementioned applications. The temperature measurement is done with a PT100 in a bridge configuration while the humidity is measured with a capacitive humidity sensor (proven to be rad-hard) and a readout circuit using an oscillator. The advantages of this implementation is its low power consumption as the setting time is very small and the readout circuitry can be shut down when the device is in sleep mode and placed in active mode only when the measurements are carried out. This can be re-used for other analog sensors.

Control Application: Increased Reliability With On-Off Switching

Digital control, particularly through Input Output (IO) boards, is essential in applications where remote system

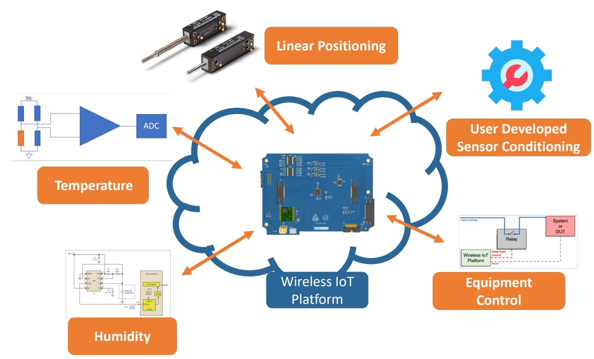

Figure 5: A summary of the current applications that can be exploited by the Wireless IoT is provided. The ability for the user to develop their own sensor conditioning board opens the way to an unlimited number of possible applications.

management is required. Such boards enable control of electronic systems, allowing the toggling of power states or initiating system restarts. In the context of particle accelerators such digital IO board can facilitate remote interventions, allowing system resets or power cycling, and serving as a mitigation strategy against radiation-induced failures. To cater for these needs, we've developed a digital IO board integrated with our wireless IoT platform. This board is designed with a focus on resilience, ensuring it remains operational even in high-radiation environments. The IO application has been used to remotely control a commercial router under radiation testing, with the IoT platform resetting the router in case of malfunction. This showed that thanks to its radiation tolerance such a system is capable of increasing the reliability and the availability of other systems during operation.

Position Sensing

Analog position sensing, in particular using potentiometers, is often used in applications requiring precise position feedback and control. Such boards are adept at translating the variable resistance of potentiometers into meaningful data, representing positions or movements of various machine elements. An analog sensing board, interfaced with potentiometers, can provide independent or redundant readouts of these positions, ensuring that the machinery operates within desired parameters and offering a backup measurement system in case primary sensors fail. To cater to these and other similar needs, we've developed an analog sensing board integrated with our platform. This board is designed to measure the resistance from a single potentiometer, translating it into wireless uplink messages. The board can be adapted to linear and rotating potentiometers and the range of potentiometer measured resistances can be changed with a resistance change on the board allowing a wide range of sensor integration.

CONCLUSIONS

In this work, we have presented the development of a general-purpose radiation-tolerant IoT platform, designed specifically for the challenging environment of CERN's

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Large Hadron Collider (LHC). The component selection and testing procedures have ensured that the platform remains reliable during many years of operation even when exposed to an intense radiation environment. The introduction of the LoRaWAN network at CERN is an innovative approach to monitor various systems without the need for cables. The measured wireless performance has underscored the network's reliability and robustness. Moreover, the utilization of the Apache Kafka technology for data transformation and streaming has effectively streamlined data management, enabling easy monitoring and control. The applications detailed in this work, from environmental monitoring to machine element positioning and control, are just a few examples of what the IoT platform is capable of. They are proof of the versatility and adaptability of the system to perform in challenging conditions. As technology and research needs continue to evolve, we anticipate many more innovative applications for this device, further demonstrating its potential for wireless monitoring in particle physics environments.

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