



HAL
open science

Feasibility Study of a Radiation-Tolerant Wireless Extension for the CERN WorldFIP infrastructure

Antonio Scialdone, Rudy Ferraro, Salvatore Danzeca, Frederic Saigne, Jerome Boch, Luigi Dillo, Alessandro Masi

► To cite this version:

Antonio Scialdone, Rudy Ferraro, Salvatore Danzeca, Frederic Saigne, Jerome Boch, et al.. Feasibility Study of a Radiation-Tolerant Wireless Extension for the CERN WorldFIP infrastructure. 2024. hal-04715615

HAL Id: hal-04715615

<https://hal.science/hal-04715615v1>

Preprint submitted on 4 Oct 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

This is a self-archived version of an original article.
This reprint may differ from the original in pagination and typographic detail.

Title: Feasibility Study of a Radiation-Tolerant Wireless Extension for the CERN WorldFIP infrastructure

Author(s): A. Scialdone, R. Ferraro, S. Danzeca, F. Saigne, J. Boch, L. Dilillo, and A. Masi

Document version: Pre-print version (Final draft)

Please cite the original version:

A. Scialdone, R. Ferraro, S. Danzeca, F. Saigne, J. Boch, L. Dilillo, and A. Masi, "Feasibility Study of a Radiation-Tolerant Wireless Extension for the CERN WorldFIP infrastructure," Conference on Radiation Effects on Components and Systems (RADECS 2024), 2024.

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorized user.

Feasibility Study of a Radiation-Tolerant Wireless Extension for the CERN WorldFIP infrastructure

Antonio Scialdone, Rudy Ferraro, Salvatore Danzeca,
Frederic Saigne, Jerome Boch, Luigi Dilillo, and Alessandro Masi

Abstract

The article presents the development of a Wireless Physical Layer (PHY) designed to extend CERN's WorldFIP infrastructure, addressing the limitations of cabling within the LHC tunnel. This wireless PHY is based on a Software-Defined Radio (SDR) architecture that includes a Field-Programmable Gate Array (FPGA) and a fully configurable RF front-end. Both components are selected for their radiation tolerance to ensure reliable performance in the LHC's high-radiation environment. This solution allows for seamless integration into the existing WorldFIP network without the need for hardware upgrades, offering a flexible and scalable alternative to traditional cabling. The article details the design and implementation process of the PHY and evaluates its performance using actual CERN hardware. Additionally, the study examines the impact of radiation on the wireless link's performance and explores potential improvements to enhance the system's reliability within CERN's control architecture.

Index Terms

Field programmable gate arrays, Field buses, Software radio, Particle accelerators, Wireless communication

I. Introduction

At the European Organization for Nuclear Research (CERN), instruments for operating the Large Hadron Collider (LHC) are managed via a fieldbus network, that can guarantee real-time control between low-level instruments and higher-level applications. Various fieldbus types are employed at different hierarchical levels, each tailored to specific operational requirements. Within the LHC tunnel, radiation tolerance is critical due to exposure that can impact electronics. Communication links are susceptible to Total Ionizing Dose (TID), which degrades performance, and Single Event Effects (SEE), leading to data corruption or permanent link loss, thus affecting instrument availability. WorldFIP was chosen during the LHC commissioning for its excellent radiation tolerance [1] and is currently used for all slow control instruments in the LHC complex. It is CERN's most utilized fieldbus, with over 400 km of cables and more than 12,000 devices, including power converters, quench protection systems, cryogenic controls, beam instrumentation, and radiation monitoring. However, cable trays are nearing capacity, complicating new device installations. Additionally, custom-made, radiation-resistant cables are expensive. Thus, wireless solutions are being explored to reduce deployment costs and simplify installation and maintenance. Nonetheless, adopting wireless solutions at CERN is challenging. Unlike other industries, CERN's control equipment is custom-designed due to the lack of off-the-shelf solutions. Transitioning to a wireless protocol would necessitate redesigning systems and modifying the existing infrastructure, which is resource-intensive. Therefore, to address the short-term cabling issues, only wireless solutions that can be integrated without any hardware modifications can be considered at this moment.

In the past, many efforts were made to encapsulate wired fieldbus within traditional wireless standards and study how it impacts the real-time and reliability performance of the fieldbus. For instance, Willing [2] discussed the challenges for implementing PROFIBUS over the 802.11 Physical Layer (PHY). Using measurements such as packet loss and Bit Error Rate (BER) from an industrial environment [3], he showed that the real-time properties of the fieldbus were not satisfied anymore [4], proposing an alternative Medium Access Control (MAC) layer to improve the fieldbus performance [5]. In the R-Fieldbus [6] project, the authors evaluated how a custom radio repeater with the IEEE 802.11 can be used within a PROFIBUS network to handle multimedia content [7]. In [8] the authors analyze the performance of an alternative MAC protocol for wireless Controlled Area Network (CAN). Concerning WorldFIP instead, the timing requirements for providing a wireless extension without any modification to the protocol have been discussed [9], and a study for a custom gateway implementation to interfaces with distant sensors was carried out [10]. All these works emphasize the difficulties of encapsulating a wired protocol over a wireless medium. In fact, the wireless channel is more prone to errors due to channel outages and/or interference, which makes it difficult to keep the reliability and real-time requirements of a wired fieldbus [11], whose protocol does not take into account the unreliability of the wireless channel. Therefore, more recently there has been a growing interests towards wireless fieldbus such as WirelessHART [12] and ISA100.11a [13] which are built in purpose for dealing with a wireless medium. Nonetheless,

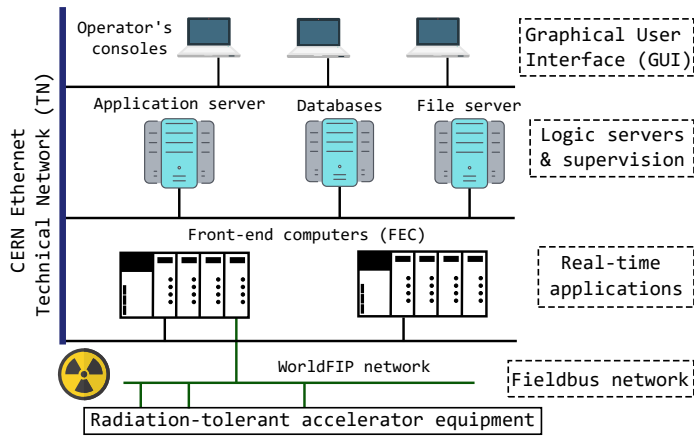


Fig. 1. Overview of the CERN control system. Operator consoles, servers, and real-time applications are connected via the CERN Ethernet Technical Network, while front-end computers (FEC) connect to radiation-tolerant accelerator equipment using the WorldFIP fieldbus network.

previous works did not consider radiation tolerance, which is the main requirement for the LHC tunnel. Past radiation tests on wireless transceivers, showed reduced performance, permanent failures and losses of configuration, which could lead to instruments unavailability in the case of a control network. The primary objective of this article is to develop a radiation-tolerant wireless link that encapsulates the WorldFIP fieldbus over a wireless channel, enabling the extension of the LHC control network without the need for hardware modifications. Focusing on radiation tolerance, the link leverages the flexibility and performance of Software-Defined Radios (SDRs), specifically incorporating an FPGA and RF transceiver selected for their resilience in high-radiation environments. The design of a repeater device that can integrate seamlessly with CERN WorldFIP network is discussed. The repeater implementation was experimentally validated using actual CERN hardware and software. The study assesses the radiation effects on the link's performance through proton irradiation testing of the wireless PHY, discussing the impact of radiation effects on the LHC control network.

II. CERN beam control system overview

The CERN control system [14] is the interface between the operators and the accelerator hardware. It allows the operator to remotely control and monitor instrumentation, i.e. configuring values, states, and reading their status. It is based on a 3-tier architecture, as shown in Figure 1. The top layer represents all those computers that the operators use to run high-level graphical applications. The middle tier is composed instead of embedded computers running the back-end for the high-level application of the first tier. The third layer instead comprises Front-End Computers (FECs), which are rack-mountable electronics enclosures containing a CPU, memory, and interfaces. Its main purpose is to perform the real-time control and acquisition of the accelerator equipment. All the layers, are connected to the database to store and retrieve data. Finally, the FEC communicates with the accelerator hardware through the WorldFIP fieldbus. The remaining of the article evaluates the feasibility of using wireless technologies at the lowest level of this architecture, i.e. between the FEC and the accelerator equipment, where a massive amount of cables is deployed. WorldFIP was chosen because the commercially available components used for its implementation showed a very good radiation tolerance. A WorldFIP device consisted of the FieldDrive chip and the MicroFIP ASIC. In particular, the first is a line driver chip necessary to interface a protocol component to a copper twisted pair through an insulating transformer. The second instead is an ASIC implementing the WorldFIP protocol. However, the industry dropped the support for the MicroFIP in favour of new technologies, which did not show as good radiation tolerance as the old one. For this reason, CERN decided to in-source the project and develop in-house replacement of the MicroFIP to ensure long-term support for the LHC. Conducting internal surveys to identify the essential functionalities of the WorldFIP protocol used at CERN, a decision was made to implement only the necessary subset, expediting the development process. Importantly, radiation tolerance was a primary focus from the very beginning. The outcome was nanoFIP, a radiation-tolerant WorldFIP agent [15], which is now the default interface solution used for slow-control instruments in the LHC.

A. The WorldFIP architecture

WorldFIP is based on a master/slave concept, where the master, namely the Bus Arbiter, grants bus access to the different slaves, the agents, according to a pre-configured table. The protocol offers cyclic communication, events (like alarms), and messages (such as configuration settings), which are achieved through exchange of periodic variables,

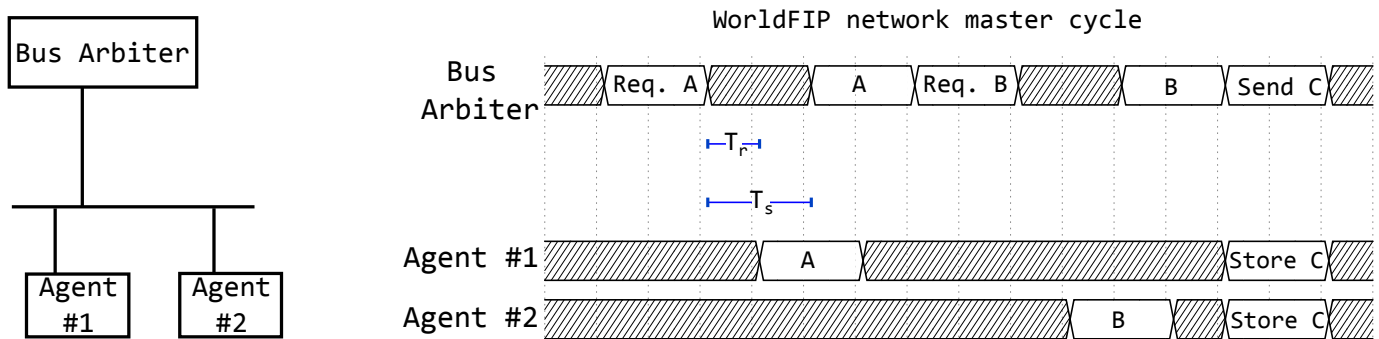


Fig. 2. Timing diagram for a WorldFIP network with a Bus Arbiter and two agents. Agent 1 and 2 are configured to produce variable A and B respectively, and to store variable C. All the agents receive the variable request, but only the producer of the variable replies.

a-periodic variables, and a-periodic messages respectively. However, the nanoFIP agent only supports cyclic communication through the exchange of periodic variables. The Bus Arbiter is configured at the beginning with a macro-cycle, which defines the order and the periodicity to scan each variable for all the agents. After configuration, it infinitely performs the same macrocycle until stopped. The protocol provides deterministic network communication because the time needed to updated any value is pre-determined. In fact, when the bus arbiter sends the request for a variable on the bus, the designated agent replies after a pre-configured time, namely turn-around time (t_r). On the other hand, the bus arbiter waits for a maximum pre-configured time, namely silence time (t_s), before proceeding with the next variable. The turnaround and silence time are fixed and depend on the bus speed. In the case under analysis, the bus speed is set at 1 Mbit/s, with a turnaround time of 14 μ s and a silence time of 150 μ s respectively. Figure 2 shows the macrocycle execution in a WorldFIP network with two agents and a Bus Arbiter. The two agents, #1 and #2, are configured to sample variable A and B respectively, and to read variable C. Thus, the bus arbiter is pre-configured with a macrocycle that scans variable A, B, and then sends variable C. Once finished, the macrocycle will restart and repeat indefinitely.

III. Challenges of Wireless Links in Radiation-Tolerant Fieldbus Systems

The feasibility study was conducted with two key constraints in mind. First, the proposed solution must be radiation-tolerant, as it will be exposed to the LHC's radiation environment. Second, it must integrate seamlessly with the existing infrastructure without requiring hardware modifications. Regarding radiation tolerance, electronics in the tunnel, including control infrastructure, are vulnerable to radiation effects, which can degrade communication performance. Various RF transceivers, such as LoRa, WirelessHART, and Zigbee, have shown performance degradation at different radiation dose levels [16]. For example, Zigbee transceivers failed at 640 Gy, while WirelessHART and ISA100.11 transceivers failed at 167 and 200 Gy, respectively. Another study reported that LoRa transceivers experienced communication loss and degraded functionality at various dose levels [17]. Furthermore, the Wireless IoT platform monitoring radiation at CERN encountered failures, including Single Event Effects (SEE) in LoRa transceivers [18]. These studies underscore the limitations of integrated transceivers, where failure sources are not easily identifiable or mitigated at lower levels, often leaving recovery methods as the only option, which may exceed acceptable thresholds for equipment control. In the LHC control network, such failures could lead to instrument unavailability, making a radiation-tolerant communication link essential. However, even radiation-tolerant standard solutions are unsuitable for this context. The physical layer of wireless standards such as WiFi and LoRa introduces additional delays (in milliseconds) that make it impossible to encapsulate the WorldFIP protocol. A WorldFIP repeater must enable variable exchange within the protocol's silence time [9]. For the CERN application, with a bus speed of 1 Mbit/s and a silence time of 150 microseconds, using certain wireless protocols becomes infeasible due to the excessive overhead introduced by the PHY, such as the 128-microsecond preamble required by IEEE 802.11 using Direct Sequence Spread Spectrum (DSSS). This overhead prevents timely information exchange within the WorldFIP silence period. A comprehensive review of wireless standards [11] revealed that traditional wireless protocols, due to PHY overhead, speed, and duty cycle limitations, cannot be used for repeater extensions without modifying the infrastructure. However, replacing WorldFIP entirely would be resource-intensive due to the large number of devices already deployed in the LHC. To address these constraints, an ad-hoc solution is needed that can integrate into the current infrastructure. One approach, called the gateway approach, involves adding a wireless-capable device to the bus arbiter, which manages distant WorldFIP agents independently. This architecture has been described in previous work [10]. The second approach, explored in this article, involves developing a custom wireless protocol that can encapsulate the WorldFIP standard

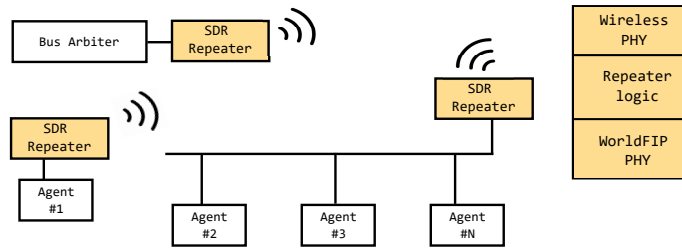


Fig. 3. WorldFIP network adopting SDR-repeaters.

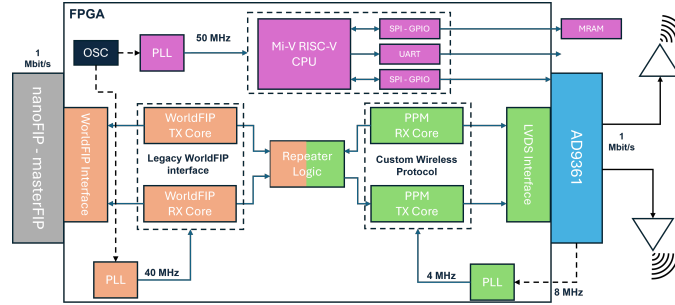


Fig. 4. FPGA-based implementation of the SDR-repeater.

and integrate seamlessly into the existing CERN WorldFIP infrastructure, known as the repeater approach. For this implementation, integrated transceivers were ruled out due to the timing and radiation tolerance challenges. Instead, a Software-Defined Radio (SDR) approach was chosen. A SDR is a re-configurable platform where most functionalities are implemented in programmable logic, such as FPGA, with the RF front-end handling only data transmission and reception. This approach offers significant flexibility, as wireless communication protocols can be updated without changing the hardware. In the LHC, where many devices are deployed, this flexibility is advantageous for future upgrades, as it saves costs by requiring only firmware updates instead of new hardware. Additionally, SDR allows the implementation of custom protocols in programmable logic and enables radiation mitigation techniques, which are not possible with traditional integrated RF transceivers that have fixed functionalities embedded in Application-Specific Integrated Circuits (ASICs). The rest of the article details the implementation of the repeater solution, its validation with real hardware, its radiation characterization, and the impact of radiation effects on the repeater within the CERN control system.

IV. Wireless-FIP PHY implementation

The proposed repeater is conceived as a plug-and-play solution that integrates into the network without any modifications to hardware/firmware/protocol of either the Bus Arbiter or agents. WorldFIP devices remain unaware of the SDR-repeater's presence due to the custom PHY developed to encapsulate the WorldFIP standard while adhering to protocol timing constraints. Figure 3 illustrates the architecture of the WorldFIP network using the SDR-based repeater. The repeater's hardware platform consists of the AD9361 RF Transceiver and the PolarFire FPGA. The RF Transceiver selected for this study, can be configured in the 70 MHz - 6 GHz range, with a maximum bandwidth of 56 MHz, and was previously evaluated under irradiation in a previous work [19]. The PolarFire FPGA instead is a flash-based FPGA which offers more robustness against SEE compared to those based on SRAM, and was previously qualified for use in the LHC environment [20]. The RF front-end transmits and receives raw data over RF, whereas most of the functionalities are implemented in the FPGA. Figure 4 shows an overview of the FPGA design, divided into three main domains: the WorldFIP interface, the custom wireless protocol, and the repeater logic itself. The WorldFIP interface, based on CERN-developed Hardware Description Language (HDL) cores, transmits and receives WorldFIP frames on the bus. Its main role is to interface with CERN WorldFIP hardware. The custom wireless protocol transmits and receives frames over the air using Pulse Position Modulation (PPM), ensuring transmission within the timing constraints imposed by WorldFIP. Its purpose is to exchange data between distant repeaters. Finally, the repeater logic interconnects the WorldFIP and the custom wireless protocol domain. In addition, the FPGA embeds a configuration unit made of the Mi-V RISC-V soft-CPU, a General Purpose Input/Output (GPIO) peripheral, a Serial Peripheral Interface (SPI) and a UART interface. In fact, given the complexity of the AD9361 and the amount of registers to be configured, C-based

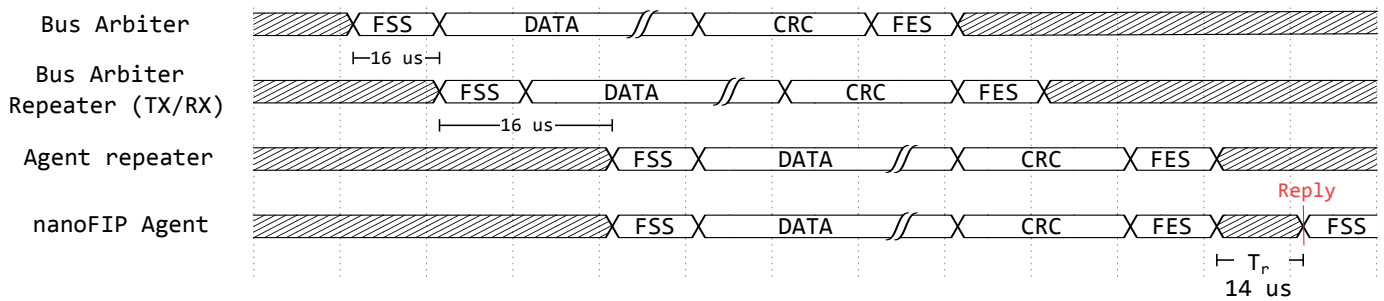


Fig. 5. Timing diagram for a WorldFIP transaction between Bus Arbiter and a nanoFIP agent using the repeater extension

drivers are provided by the manufacturer for its configuration. Hence, a soft-CPU was selected to run the application code necessary for the AD9361 configuration through GPIO and SPI. Such application code is stored in an external Magnetoresistive Random Access Memory (MRAM), which was qualified under radiation in the context of another work. Finally, the UART interface allows the communication to an host computer for debugging information.

The repeater's working principle is split into three phases: initialization, configuration and operation. On power-on, the design is initialized to a known state using a Power On Reset (POR) scheme. When the system exits from reset, the application code is copied from the external MRAM to the internal FPGA memory through a boot-loader, which is stored inside the PolarFire Non-Volatile Memory. Once the application is copied, the system enters into the configuration phase, hence the RISC-V CPU executes the application to configure the AD9361. Once configured, the repeater becomes operational, and WorldFIP devices can communicate through their corresponding repeaters.

A. Repeater implementation

The repeater is implemented through an external device, the SDR, which connects to the Bus Arbiter and the nanoFIP agents using the connector currently used for the WorldFIP bus. The repeater logic is fully implemented in the FPGA. It is composed of the WorldFIP PHY and a custom Wireless PHY, which are interconnected through a bridge logic. The first is necessary to communicate with the Bus Arbiter and the agents through WorldFIP, whereas the second is necessary to communicate over the air. The Wireless PHY is kept as simple as possible and it is specifically tailored to the application. It introduces a preamble of only 8 μs, and data is modulated using Pulse Position Modulation at 1 Mbit/s. Modulated data is then transferred to the RF Transceiver which proceeds with the D/A conversion and then the up-conversion to RF frequency. The repeater logic, on the transmitter side, implements the following behaviour:

- 1) The repeater uses the Frame Start Sequence (FSS) delimiter available in the WorldFIP frame to start the transmission of the radio packet by sending the preamble. In the meanwhile, incoming data is buffered
- 2) Once the preamble is sent, the repeater keeps sending all the bytes received from the WorldFIP PHY. Data is sent as it is, without any modification
- 3) The repeater uses the Frame End Sequence (FES) delimiter of the WorldFIP frame to start the transmission of an End Of Packet (EOP)

The repeater logic on the receiver side implements the following behaviour:

- 1) The repeater detects the radio preamble and starts the transmission of the FSS on the WorldFIP bus. In the meanwhile, incoming radio data is buffered
- 2) Once the FSS is sent, the repeater keeps sending all the data received from the air on the WorldFIP bus. Data is already formatted according to the WorldFIP protocol, so no modification are necessary.
- 3) The repeater detects the EOP and starts the transmission of the FES

An example of variable exchange using this implementation is shown in Fig. 5, with the related overhead introduced by each step of the repeater logic. The diagram shows only the delays between the Bus Arbiter and the agent, but they must be considered in the opposite direction too. Thus, the total overhead is 78 μs, where 32 μs are introduced by the Wireless PHY, 32 μs are due to the WorldFIP PHY implemented in the repeater necessary to detect a FIP frame, and 14 μs are due to the turnaround time.

B. Repeater validation

The aforementioned solution has been implemented in hardware, and an experimental evaluation was carried out in the laboratory using the test bench shown in Figure 6. The setup includes a pre-configured Bus Arbiter and a nanoFIP agent, the RadMON [21], which is the radiation monitoring system of the LHC tunnel. The Bus Arbiter is configured with a 2 seconds macrocycle. In particular, it is designed to poll 32 different agents. For each agent, it requests

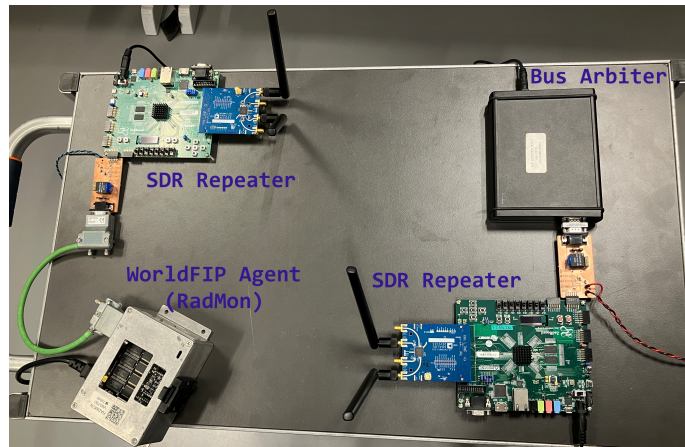


Fig. 6. Test setup overview which includes a nanoFIP agent (the RadMON) and the Bus Arbiter.

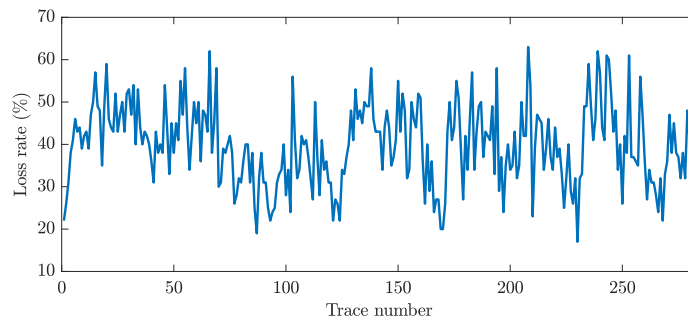


Fig. 7. Loss rate for the variable updates with a measurement of 16.5 hours

three variables, and sends one configuration variable. Once all the agents are polled, the rest of the macrocycle is filled with synchronization variables addressed to all agents. Both the Bus arbiter and the agent, were connected to the corresponding SDR-repeater working in the 2.4 GHz ISM band. Only for this evaluation purposes, the repeater was implemented using the AMD-Xilinx Zynq-7000 SoC. The SoC includes an ARM-Cortex CPU, namely Processing System (PS), and a programmable logic (PL). The PL implements the wireless and the WorldFIP PHYs, together with the repeater logic described before. The PS instead runs the application code necessary for the configuration of the AD9361 only. Figure 7 reports the results for a measurement of 16.5 hours using a single agent, even though the proposed solution is independent from the number of agents used. The measurement is divided into traces, where each trace contains 100 updates correctly registered from the Bus Arbiter. The figure reports the percentage of missing updates per each trace. It can be seen that the percentage varies over time, with traces showing less than 20% of updates missing and other with more than 50%. The losses can be related to missed packets and bit errors. A packet can be missed because the repeater fails to acquire bit synchronization, which can be due to the use of the short preamble and the absence of any training sequence. This may happen on both repeaters. In the case of the agent repeater, it will not detect any request, therefore it will not send any variable update. On the other hand, when the agent detects the request and sends the update, it may be missed by the bus arbiter repeater. Bit errors instead are caused by data corruption over the wireless channel, which cannot be corrected since no error correction code is implemented in the Wireless PHY. Whenever a radio packet is detected, the repeater starts the WorldFIP transmission towards either the agent or the arbiter. However, in case of errors, the checksum computed by the WorldFIP MAC will be wrong, causing the request/update to be discarded. Figure 8 shows the distribution of the time between the logged variable updates during the entire measurement. It can be seen that most of the periods are packet-loss free or with short-period of loss-packets, but also long periods (more than 40 seconds) without any variable update were observed. The performance may be influenced by several factors. Firstly, the PPM modulation utilized in this evaluation is highly susceptible to multi-path interference, resulting in the receiver's signal containing echoes of the transmitted signal, potentially leading to decoding failures and packet loss. Additionally, the SDR repeater's high-transmission rate exacerbate these issues. In fact the Bus Arbiter is configured with a 2-seconds macrocycle that scans 32 agents and is then filled with synchronization variables, resulting in a high-transmission rate for the SDR-repeater. Secondly, the

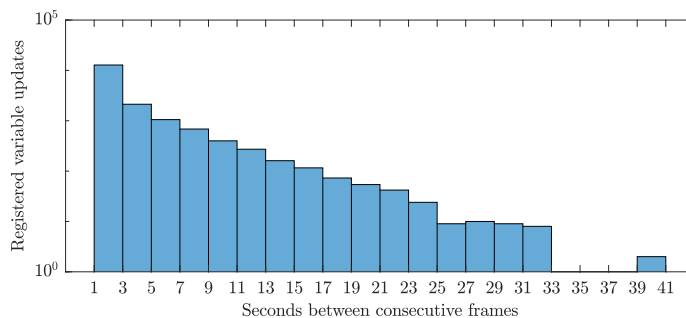


Fig. 8. Distribution of the variable updates period on logarithm scale.

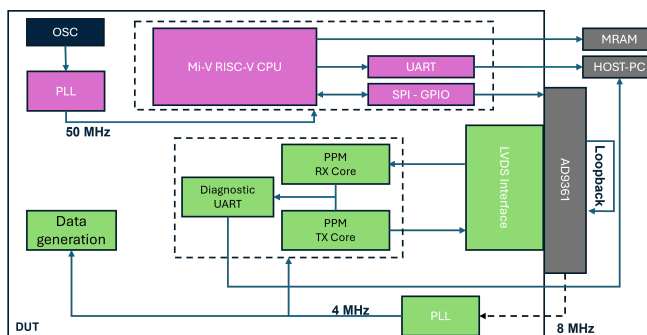


Fig. 9. Overview of test setup used during irradiation.

synchronization phase presents challenges due to the transmitter and receiver operating on different clocks. Decoding is based on consecutive pulses, making the receiver algorithm highly sensitive to signal variations. Additionally, the short preamble may not be sufficient to guarantee packet decoding. Therefore, different solution may be adopted to improve the performance, such as additional signal processing normally used in wireless communication systems, i.e. channel equalization, error correction codes. Nonetheless, they may introduce delays that conflicts with the WorldFIP timing constraints, necessitating alternative approaches, like the gateway approach [10].

V. Radiation test methodology

Radiation tests were conducted on a reduced version of the repeater platform, which comprised the custom wireless core, the RISC-V subsystem, and the RF interface. The WorldFIP domain, along with its associated hardware, was excluded from these tests, as it had already undergone radiation qualification. This exclusion allowed for an evaluation of the radiation effects on the wireless components alone. The design was implemented on the PolarFire MPF300 FPGA, mounted on a custom radiation-tolerant board [22]. The AD9361 was mounted on the FMCOMMS3 board, an evaluation kit for the AD9361. Both the wireless transmitter and receiver were implemented on the FPGA. Data was generated internally, with packets of fixed payload sent at predefined intervals. Data was transmitted through the RF interface, with an internal loop-back enabled to send the data back to the FPGA, where it was decoded by the receiver. A custom UART module was used to report diagnostic information to the host-PC. Figure 9 presents a schematic of the test setup.

Various designs were evaluated to assess their impact on link reliability. Alongside the standard design, a version using Triple Module Redundancy (TMR) at the register level was tested, implemented using the primitive available in the FPGA tool. Another version without the System Controller was also tested. The System Controller, a utility in the PolarFire FPGA that provides additional functionalities such as data security, was excluded in one design because, according to user manuals, it could cause unintended resets under irradiation. This exclusion allowed for assessing the impact of this utility on link reliability. Table I summarizes the various designs tested. For all designs, different metrics were evaluated using diagnostic information, including the number of incorrect packets, communication link loss, and crashes of the wireless core and of the RISC-V subsystem. The errors were distinguishable due to the diagnostic features added to the design, which increased the observability of failure types. For CPU crashes, an UART peripheral monitors the execution of application code on the RISC-V subsystem during the operational phase. A CPU crash is indicated by a complete loss of communication. However, since the RISC-V subsystem is separate from the rest of

TABLE I
Characteristics of the designs under test

Design name	TMR	System controller
RT-PPM1	No	Yes
RT-PPM2	No	No
RT-PPM3	Yes	Yes
RT-PPM4	Yes	No

TABLE II
Number of events and fluence reached for each design under test using a proton flux of $3.80 \cdot 10^8 \text{ p/cm}^2/\text{s}$

Error signature	RT-PPM1		RT-PPM2		RT-PPM3		RT-PPM4	
	Events	Fluence [p/cm^2]	Events	Fluence [p/cm^2]	Events	Fluence [p/cm^2]	Events	Fluence [p/cm^2]
SEFI	16	$4.28 \cdot 10^{11}$	8	$2.61 \cdot 10^{11}$	27	$5.43 \cdot 10^{11}$	18	$3.11 \cdot 10^{11}$
CPU crash	16	$7.91 \cdot 10^{10}$	2	$1.23 \cdot 10^{10}$	23	$1.40 \cdot 10^{11}$	18	$1.07 \cdot 10^{11}$
Corrupted communication	18	$4.13 \cdot 10^{11}$	13	$2.11 \cdot 10^{11}$	38	$4.95 \cdot 10^{11}$	5	$2.56 \cdot 10^{11}$
Wireless Core crash	6	$3.60 \cdot 10^{11}$	4	$3.62 \cdot 10^{10}$	12	$1.64 \cdot 10^{11}$	13	$9.32 \cdot 10^{10}$

the FPGA logic, the test can continue. Communication errors, on the other hand, involve lost or corrupted packets in the wireless receiver. Due to the loop-back, these errors are caused by issues within the transmitter or receiver, not the wireless channel. For instance, a SEU might prevent the receiver logic from detecting a packet, or an SEU might corrupt the packet payload, resulting in an incorrect packet. Without error correction codes, to maintain WorldFIP timing compliance, a corrupted packet is treated the same as a lost packet, leading to a communication error on the WorldFIP bus. An FPGA crash was identified when the diagnostic UART module, connected to the PPM entities, reported a halt in the algorithm. In this case, the number of transmitted and received packets remained constant until the system was restarted. Additionally, a radiation-induced reset, indicated as a Single Event Functional Interrupt (SEFI), was observed. This reset was identifiable by two main indicators: the diagnostic UART module sending an initial message when the system exits reset, and the RISC-V subsystem returning to the initialization stage, triggering the boot-loader execution.

VI. Radiation test results

The device has been tested under the 200 MeV proton beam at the Paul Scherrer Institute (PSI), Villigen, Switzerland. Table II reports the different error signatures observed during the test for each design, together with the number of events observed and the fluence reached. The cross-sections with the 95% confidence interval for the different error signatures are shown in Fig. 10. Regarding the CPU crash, the cross-sections across different designs are relatively similar, indicating that TMR did not impact its reliability. This is reasonable because the application code executed by the CPU is stored in internal FPGA memory resources. Therefore, if the application code is corrupted, the CPU execution will stop. Since the memory was unprotected in all designs, the similar cross-sections are likely due to the corruption of the application code. For the Wireless Core crashes, the two versions with TMR show higher cross-sections compared

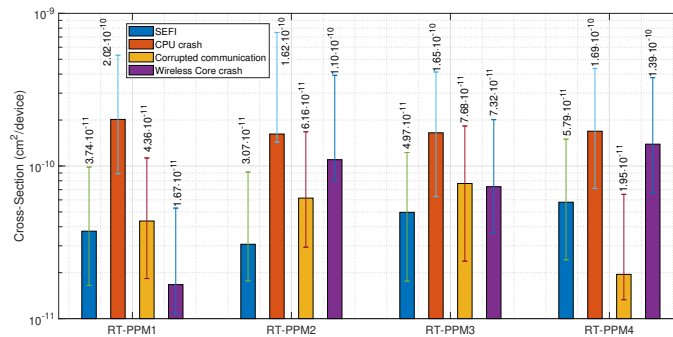


Fig. 10. Proton cross-sections of the error signatures observed during irradiation for the various designs under test

to the standard version. This may indicate that using TMR introduces additional logic that increases potential points of failure in the FPGA design. Regarding corrupted communications, the versions with and without TMR (RT-PPM1 and RT-PPM3, respectively) show that the TMR version has a higher cross-section. However, since TMR is implemented at the register level, errors might be due to combinatorial logic propagating through logic elements. Nevertheless, using TMR in combination with a disabled system controller shows a 4x reduction in the cross-section compared to the version with the system controller. Finally, for SEFI, all designs exhibited a SEFI cross-section of the same order of magnitude, with the TMR designs showing a slightly higher cross-section. Despite the user manual suggesting this could cause unintended resets, experimental data indicates that disabling the system controller may not improve the SEFI cross-section. As for TID effects, during this experiment, only the FPGA was exposed to radiation, hence no degradation on the link performance were expected given that the PolarFire had already demonstrated its robustness against TID up to 5 kGy [20]. Nonetheless, the designs have been tested on the same FPGA, which cumulated a total of 1 kGy of dose without any degradation.

VII. Discussion

Different considerations can be made regarding the feasibility of the repeater approach and the radiation response of the wireless PHY. Experimental validation using real hardware shows that while timing constraints can be met, link reliability is highly dependent on the Wireless PHY, potentially limiting its suitability for certain applications. Adjustments, like increasing silence time to enable longer preambles or acknowledgment packets, could improve reliability. However, relaxing timing constraints may reduce the variable consumption rate. For instance, the FGCLite system requires a variable consumption rate of 20 ms [23], which could be achieved with this adjustment. However, more critical systems may demand higher consumption rates, which may not be feasible under this modification. Additionally, the link reliability's impact should be evaluated for each application. For example, CERN's Radiation Monitoring system (RadMon) [21] has a variable consumption rate of 1 variable/second, and since it's a monitoring application, real-time is not required. Therefore, this approach could fully meet the application's needs. In contrast, the gateway approach [10] eases the constraints on the wireless PHY by decoupling wireless communication from the WorldFIP protocol. This allows the implementation of common wireless communication techniques, such as error correction codes, packet re-transmission, and longer training sequences, to address the wireless channel's unreliability. However, a challenge remains in ensuring that variable updates stay synchronized with the WorldFIP macro-cycle, which is essential to maintaining the protocol's deterministic nature, crucial for LHC operations. Furthermore, hardware complexity increases since a new device—the gateway—must be deployed and configured for each Bus Arbiter.

As for radiation effects, the Wireless PHY reliability becomes crucial, as the instruments would be unusable if the wireless link were unavailable. As demonstrated by the experimental results, the PolarFire FPGA suffers from SEFI, causing an unintended reset of the system. This kind of event has already been observed in past experiments, where the PolarFire System controller was not disabled [20]. Nonetheless, even though the user manual suggests suspending the system controller for critical application, the results show that it does not resolve the SEFI issue. However, after the reset, the system automatically recovers its functionality thanks to the bootloader which reloads the application from the external MRAM and reconfigures the RF Transceiver. Therefore, in the context of the control system, this will induce only a temporary downtime, which in the current implementation lasts around 4 seconds. Moreover, in addition to the failures concerning the FPGA gateway, other parts of the systems are susceptible to SEE as well. In particular, during the evaluation of the AD9361 [19] various types of SEE were detected, and solutions have been proposed for real-time operation. Notably, configuration losses occurred but could be recovered by re-configuring the device in real-time without losing the link, while permanent failures necessitated a reset via a dedicated pin. These events exhibited a cross-section in the order of 10^{-12} . Moreover, while the boot-loader can help mitigate the link-losses due to the SEFI occurring in the PolarFire FPGA, it cannot mitigate those occurring because of the AD9361. Therefore, it is fundamental to monitor the link functionalities, i.e. using a watchdog, and to issue reconfiguration of the device in case a configuration loss occurred. Therefore, the main event causing link loss is represented by the PolarFire SEFI, which is however only a temporary link loss. By considering the upper limit SEFI cross-section, the availability of the communication link can be computed for the different areas of the LHC accelerator. Table III reports the approximate number of instruments installed in various LHC areas using WorldFIP and the expected annual failure rate based on the upper limit cross-section of RT-PPM1. The annual fluence considered corresponds to the fluence expected during the HL-LHC phase [24]. For calculation purposes, it is considered that all the nodes will make use of this wireless extension. As it can be seen, in all the areas, including the DS with the highest failure rate, there is a link availability of 99%, computed over an entire LHC run, from April to October. Even though these are very good results that show the feasibility of using such solution in a radiation environment, further radiation tests are being prepared to investigate the source of the SEFI and to reduce the uncertainty on the cross-section to an acceptable level. Moreover, SEFIs could be addressed by switching to a different flash-based FPGA, such as the SmartFusion2, which is immune to this issue.

TABLE III
Link availability across the LHC

LHC Area	Annual fluence [p/cm ²]	Communication nodes	Upper Limit Annual failure rate	Link availability
DS	5×10^{10}	~600	3.05	> 0.99
ARC	1×10^9	~9000	0.06	> 0.99
UJ	5×10^9	~400	0.31	> 0.99
RR	3×10^9	~2000	0.18	> 0.99

However, the SmartFusion2 has a shorter lifetime of 650 Gy and loses programmability after 70 Gy [20], unlike the PolarFire FPGA, which has a significantly higher threshold. For what concern the system lifetime instead, in addition to the PolarFire, the other components of the repeater architecture were evaluated in various experiments. The AD9361 RF transceiver was evaluated in a past experiment involving real data transmission under radiation [19], showing no notable performance degradation up to an absorbed dose of 500 Gy. The MRAM instead, was recently tested in the context of another work at CERN up to 3 kGy, also without showing any degradation. Considering these results, the components represents ideal candidates for operation in the LHC accelerator complex.

VIII. Conclusion

This article explored the feasibility of extending CERN's existing WorldFIP infrastructure using wireless technology. A radiation-tolerant repeater extension, based on SDR, was designed and evaluated. Testing with real CERN hardware confirmed the solution's viability, though its performance is affected by the choice of custom Wireless PHY, potentially limiting its suitability for some applications unless the protocol's timing constraints are relaxed. In terms of radiation tolerance, the repeater is built around the PolarFire FPGA and the AD9361, which are radiation-tolerant components. While SEFIs in the PolarFire FPGA caused temporary link loss, this issue was mitigated by the boot-loader recovery system. The link availability, in high-fluence areas of the LHC exceeds 99%, and the system's resilience to high radiation doses, make the wireless solution suitable for long-term use in the harsh environments of the LHC. However, further radiation testing is required to reduce uncertainties in SEFI cross-sections, or alternative FPGA options, like the SmartFusion2, could be considered despite their limitations in terms of TID.

References

- [1] T. Wijnands and C. Pignard, "Radiation tolerance of the WorldFIP fieldbus interface," CERN, Tech. Rep., 2006. [Online]. Available: <https://cds.cern.ch/record/977425>
- [2] A. Willig, "Analysis of the PROFIBUS Token Passing Protocol over Wireless Links," in *Industrial Electronics, 2002. ISIE 2002. Proceedings of the 2002 IEEE International Symposium on*, vol. 1, DOI 10.1109/ISIE.2002.1026040, pp. 56–60 vol.1, 2002.
- [3] A. Willig, M. Kubisch, C. Hoene, and A. Wolisz, "Measurements of a Wireless Link in an Industrial Environment using an IEEE 802.11-compliant Physical Layer," *IEEE Transactions on Industrial Electronics*, vol. 49, DOI 10.1109/TIE.2002.804974, no. 6, pp. 1265–1282, 2002.
- [4] A. Willig and A. Wolisz, "Ring Stability of the PROFIBUS Token-passing Protocol over Error-prone Links," *IEEE Transactions on Industrial Electronics*, vol. 48, DOI 10.1109/41.954567, no. 5, pp. 1025–1033, 2001.
- [5] A. Willig, "Polling-based MAC protocols for Improving Real-time Performance in a Wireless PROFIBUS," *IEEE Transactions on Industrial Electronics*, vol. 50, DOI 10.1109/TIE.2003.814992, no. 4, pp. 806–817, 2003.
- [6] J. Haehnicke and L. Rauchhaupt, "Radio Communication in Automation Systems: the R-fieldbus Approach," in *2000 IEEE International Workshop on Factory Communication Systems. Proceedings (Cat. No. 00TH8531)*, DOI 10.1109/WFCS.2000.882564, pp. 319–326, 2000.
- [7] M. Alves, E. Tovar, F. Vasques, G. Hammer, and K. Rother, "Real-time communications over hybrid wired/wireless profibus-based networks," in *Proceedings 14th Euromicro Conference on Real-Time Systems. Euromicro RTS 2002*, DOI 10.1109/EMRTS.2002.1019194, pp. 142–151, 2002.
- [8] A. Kutlu, H. Ekiz, and E. Powner, "Performance analysis of mac protocols for wireless control area network," in *Proceedings Second International Symposium on Parallel Architectures, Algorithms, and Networks (I-SPAN'96)*, DOI 10.1109/ISPAN.1996.509031, pp. 494–499, 1996.
- [9] P. Morel, A. Croisier, and J.-D. Decotignie, "Requirements for Wireless Extensions of a FIP Fieldbus," in *Proceedings 1996 IEEE Conference on Emerging Technologies and Factory Automation. ETFA '96*, vol. 1, DOI 10.1109/ETFA.1996.573264, pp. 116–122 vol.1, 1996.
- [10] P. Morel and A. Croisier, "A Wireless Gateway for Fieldbus," in *Proceedings of 6th International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 1, DOI 10.1109/PIMRC.1995.476413, pp. 105–109 vol.1, 1995.
- [11] A. Willig, K. Matheus, and A. Wolisz, "Wireless technology in industrial networks," *Proc. IEEE*, vol. 93, DOI 10.1109/JPROC.2005.849717, no. 6, pp. 1130–1151, 2005.
- [12] J. Song, S. Han, A. Mok, D. Chen, M. Lucas, M. Nixon, and W. Pratt, "Wirelessart: Applying wireless technology in real-time industrial process control," in *2008 IEEE Real-Time and Embedded Technology and Applications Symposium*, DOI 10.1109/RTAS.2008.15, pp. 377–386, 2008.
- [13] "Wireless Systems for Industrial Automation: Process Control and Related Applications," ISA, Standard, May. 2009.
- [14] S. Deghaye and E. Fortescue-Beck, "Introduction to the BE-CO Control System," 2020. [Online]. Available: <https://cds.cern.ch/record/2748122>
- [15] G. Penacoba, P. Alvarez, E. Gousiou, J. Palluel, J. Serrano, and E. V. der Bij, "Design of an fpga-based radiation tolerant agent for worldfip fieldbus," *Journal of Instrumentation*, vol. 7, DOI 10.1088/1748-0221/7/03/C03027, no. 03, p. C03027, Mar. 2012. [Online]. Available: <https://dx.doi.org/10.1088/1748-0221/7/03/C03027>

- [16] Q. Huang, J. Jiang, and Y. Deng, "Comparative evaluation of six wireless sensor devices in a high ionizing radiation environment," *IET Wireless Sensor Systems*, vol. 10, DOI <https://doi.org/10.1049/iet-wss.2020.0035>, no. 6, pp. 276–282, 2020. [Online]. Available: <https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/iet-wss.2020.0035>
- [17] J.-M. Armani, J.-F. Gibrat, and J. Martinez, "Total ionizing dose tolerance of LoRa wireless devices," in *Radecs 2022 - RADIation and its Effects on Components and systems conference*. Venice, Italy: University of Padova, Oct. 2022. [Online]. Available: <https://cea.hal.science/cea-03920307>
- [18] A. Zimmaro, R. Ferraro, J. Boch, F. Saigné, R. G. Alía, A. Masi, and S. Danzeca, "Radiation test flux selection methodology to optimize see observability on systems with different operating modes," in *2022 22nd European Conference on Radiation and Its Effects on Components and Systems (RADECS)*, DOI 10.1109/RADECS55911.2022.10412576, pp. 1–8, 2022.
- [19] A. Scialdone, R. Ferraro, L. Dilillo, F. Saigne, J. Boch, A. Masi, and S. Danzeca, "Exploring Radiation-Induced Vulnerabilities in RFICs Through Traditional RF Metrics," *IEEE Transactions on Nuclear Science*, vol. 70, DOI 10.1109/TNS.2023.3270206, no. 8, pp. 2068–2075, 2023.
- [20] A. Scialdone, R. Ferraro, R. G. Alía, L. Sterpone, S. Danzeca, and A. Masi, "FPGA Qualification and Failure Rate Estimation Methodology for LHC Environments Using Benchmarks Test Circuits," *IEEE Transactions on Nuclear Science*, vol. 69, DOI 10.1109/TNS.2022.3162037, no. 7, pp. 1633–1641, 2022.
- [21] G. Spiezia, P. Peronnard, A. Masi, M. Brugger, M. Brucoli, S. Danzeca, R. G. Alia, R. Losito, J. Mekki, P. Oser, R. Gaillard, and L. Dusseau, "A new radmon version for the lhc and its injection lines," *IEEE Transactions on Nuclear Science*, vol. 61, DOI 10.1109/TNS.2014.2365046, no. 6, pp. 3424–3431, 2014.
- [22] A. Scialdone, P. Gkountoumis, R. Ferraro, M. B. Marin, L. Dilillo, F. Saigne, J. Boch, S. Danzeca, and A. Masi, "Cratebo: a high-speed, radiation-tolerant and versatile testing platform for fpga radiation qualification for high-energy particle accelerator applications," *Journal of Instrumentation*, vol. 19, no. 01, p. P01012, Jan. 2024.
- [23] Q. King *et al.*, "Advanced uses of the worldfip fieldbus for diverse communications applications within the lhc power converter control system," *ICALEPCS, Geneva, October, 2005*.
- [24] R. García Alía, M. Brugger, F. Cerutti, S. Danzeca, A. Ferrari, S. Gilardoni, Y. Kadi, M. Kastriotou, A. Lechner, C. Martinella, O. Stein, Y. Thurel, A. Tsinganis, and S. Uznanski, "Lhc and hl-lhc: Present and future radiation environment in the high-luminosity collision points and rha implications," *IEEE Transactions on Nuclear Science*, vol. 65, DOI 10.1109/TNS.2017.2776107, no. 1, pp. 448–456, 2018.