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► **To cite this version:**

Jean-Marc Armani, Jean-Francois Gibrat, Josselin Martinez. Total ionizing dose tolerance of LoRa wireless devices. Radecs 2022 - RADiation and its Effects on Components and systems conference, University of Padova, Oct 2022, Venice, Italy. cea-03920307

HAL Id: cea-03920307

<https://cea.hal.science/cea-03920307>

Submitted on 3 Jan 2023

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Total Ionizing Dose Tolerance of LoRa Wireless Devices

J. M. Armani, J. F. Gibrat and J. Martinez

Abstract—The response of several Long-range (LoRa) wireless devices to total ionizing dose has been assessed using ^{60}Co gamma-rays. We found that the radiation tolerance of the different tested devices is comprised between 220 and 1600 Gy.

Index Terms—LoRa, Wireless Module, Sensor Network, Total Ionizing Dose.

I. INTRODUCTION

DURING the last decades, wireless technology has become essential in our daily lives and in many industrial sectors. It has profoundly changed the way of exchanging information between people or machines through the new services and possibilities it provides. The number of Internet connected devices is continuously increasing and the development of the Internet of things (IoT) even further accelerates this trend. A study predicted that the global number of connected devices is expected to reach 27 billion active terminals in 2025 [1].

The nuclear industry is currently considering the introduction of wireless technologies in the facilities for maintenance tasks or asset health monitoring. The latter is a subject that is gaining importance with the growing need to extend the operational lifespan of nuclear power plants. As a matter of fact, a better knowledge of environmental conditions existing in a containment building is indispensable to assess the health state of equipments.

In order to cover this need, EDF and CEA have developed an autonomous portable dosimeter hardened up to 3 kGy (300 krad), aimed to record temperature and total ionizing dose (TID) levels seen by electric cables installed in nuclear power plants (NPP) [2]. Now, EDF wishes to extend the possibilities of this device by adding a wireless communication capability for transmission of the measurement data to the control room. Following several on-site tests which gave good results, the Long-range (LoRa) wireless technology was chosen by EDF to equip the portable dosimeter.

In some previous works [3] [4] [5], LoRa wireless technology has been implemented for transmitting data generated by radiation monitors inside NPP or particle accelerators. The monitoring systems were designed either for the radiation protection of people or the supervision of commercial off-the-shelf (COTS) equipments. In those studies the radiation robustness of the material was not evaluated.

Actually, few papers have studied the effects of TID on LoRa wireless modules. In [6], the authors present a study of the radiation effects on different wireless modules using various protocols including ZigBee and LoRa. They found that all the tested modules failed between 0.16 and 1.1 kGy (16 and 110 krad), while LoRa module withstood 0.4 kGy (40 krad) before failure. The limited data available on irradiated LoRa devices highlights the relevance of testing new parts.

In this study, we have irradiated several COTS LoRa wireless modules and materials from different manufacturers for evaluating their TID robustness. The goal was to find radiation tolerant parts which could be compatible with the operation of the current portable dosimeter.

II. TESTED DEVICES

A. The LoRa standard

LoRa is a radio frequency (RF) modulation technology designed for low-power, wide area networks (LPWAN) [7]. It targets mainly ultra-low power devices that transmit over long distances small amounts of data, such as wireless sensor networks (WSN) or the Internet of things. LoRa refers to the technology that controls the lowest levels of the stack, i.e. the modulation and physical layer. It uses chirp spread spectrum (CSS) modulation to transmit each bit of a message as a series of chirps, which are single tones with frequency linearly increasing or decreasing. LoRa provides far longer range than WiFi or Bluetooth and shows great transmission performances indoors.

Long range wide area network (LoRaWAN) is an upper layer protocol built on top of LoRa that defines the network's communication and architecture for securely connecting devices. The LoRaWAN network architecture is a star-of-stars topology, similar to a local area network. The end-nodes connect to their gateway (base station), which has an Internet protocol (IP) address for accessing the Internet. All LoRaWAN networks use specific unlicensed frequencies that vary by country.

B. Selection of wireless components

In order to simplify the test procedure and avoid designing dedicated RF boards, we decided to use the demo kits that are available from some manufacturers of LoRa RF chips. We defined several criteria for the selection of the LoRa components: different manufacturers, compatibility with European frequency band (868 MHz), demo kit rapidly obtainable from different vendors. We retained finally for the test the SX1261 and SX1276 from Semtech, along with the RN2483 from

Manuscript received April 8, 2022.

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Microchip. The main characteristics of these components [8] [9] [10] are given in Table I.

Table I
SELECTED LoRa CHIPS

Manufac.	Chip	Freq.	TX pow.	Sens.
Semtech	SX1261	150-960 MHz	14 dBm	-148 dBm
Semtech	SX1276	137-1020 MHz	14 dBm	-148 dBm
Microchip	RN2483	433, 868 MHz	14 dBm	-146 dBm

Each Semtech demo kit is built around two boards: one for the RF shield and another for the STM32L073 microcontroller that runs the LoRa stack. The RF board is mounted atop the microcontroller board via Arduino compatible connectors. On the other hand, the kit from Microchip is composed of only one board containing the RF module and the debug hardware.

C. ARCYS LoRa Endpoint

The company ARCYS has developed a range of wireless sensors based on LoRa technology. To supplement this study, ARCYS has provided a complete data acquisition system based on a LoRa wireless sensor node. The sensor used for the test is the “ANA” endpoint from ARCYS. It has two 0 – 10V voltage inputs for connecting external analog sensors. The “ANA” endpoint architecture is given in Figure 1. It is built around a STM32L0xx microcontroller and a SX1276 chip.

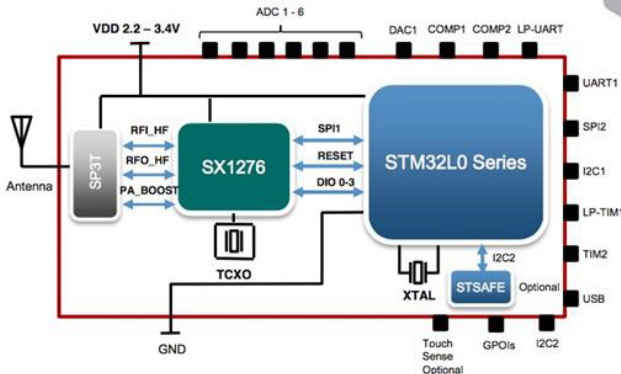


Figure 1. “ANA” sensor architecture (ARCYS).

The LoRa endpoint is configured to transmit every 30 seconds on the 866.1 MHz frequency with a spreading factor SF12. It transmits its battery voltage as well as the internal temperature of the microcontroller.

D. Devices Under Test

For each part in Table I, we used a pair of wireless nodes configured as Transmitter and Receiver to establish a direct communication link. Only one sample of each wireless couple has been tested in order to keep the test bench architecture simple. Similarly, only one sample of the ARCYS “ANA” endpoint was available for the experiments.

Table II gives the list of the LoRa wireless devices that have been irradiated during the different experiments. The microcontroller boards of the Semtech kits are not part of the material to be tested and thus are not included in this table.

Table II
IRRADIATED DEVICES

Manufac.	Type	Ref.	Chip	Sampl.
Semtech	Demo kit	SX1261DVK1BAS	SX1261	1 pair
Semtech	Demo kit	SX1276MB1MAS	SX1276	1 pair
Microchip	Demo kit	DV164140-1	RN2483	1 pair
ARCYS	Endpoint	“ANA” sensor	SX1276	1

III. EXPERIMENTAL PROTOCOL

A. Test procedure

1) *LoRa modules*: In the portable dosimeter, the major part of electronic circuits is switched-off almost all the time to save battery power. A low-power hardware time base wakes the embedded microcontroller at regular time intervals to perform measurement of the TID and temperature sensors. To take into account this operating mode, the two Semtech demo boards were powered-up periodically by the test bench during the experiment (the boards were off most of the time, and every 15 minutes, a power cycling was applied to test them). On the other hand, the configuration possibilities of the Microchip demo board were limited and so we had to test it continuously powered.

As the Microchip board includes other components than the RF circuit, we have protected it partially with a lead wall for preventing any unwanted failure of these components. Similarly, the STM32L073 microcontroller boards of the Semtech kits are deported using long wires and placed behind a comparable lead wall. The lead walls were sized to attenuate the gamma rays by a factor of 60. Therefore, the protected components should not be exposed to a dose greater than 50 Gy (5 krad).

As mentioned before, a pair of wireless nodes is used for each LoRa part to test the wireless communication. The two RF modules with their antenna are placed close to each other on a single test board. Hence, three test boards were put together in the irradiator. On each test board, one node is configured as Master and the other as Slave. The test involves a “ping-pong” dialog between the two nodes: the Master sends a “ping” frame to the Slave which acknowledges with a “pong” frame.

The main objective of this experiment was to evaluate the radiation tolerance of LoRa components. As the presence of a protocol stack is not determinant for the irradiation response of the electronic modules and for the sake of simplicity, we decided to test the wireless modules without implementing a full LoRaWAN stack, i.e. at the physical layer level only.

During the experiment, a dedicated bench records the report data sent by the Master node of each test board. Additionally, the power consumption is also measured and recorded for the Semtech test boards. The report data is a frame that contains, among different informations, the signal to noise ratio (SNR) values measured by the Master and Slave nodes, and also for the Semtech kits, the received signal strength indicator (RSSI) values of both nodes.

2) *ARCYS sensor*: The LoRa sensor has been tested using a standard LoRaWAN network architecture. To check the correct operation of the sensor, ARCYS has provided its miniature mobile appliance solution (Xenon) integrated in a case. This

case integrates the following items: a LoRa Ethernet gateway, a network server, an application server, a structured query language (SQL) database, and a human machine interface (HMI). The LoRa sensor is registered in this network server, so that all received frames are decoded and the data (battery voltage and microcontroller temperature) are timestamped and stored in the local database. The data recorded in the database can be examined with the Web HMI.

B. Irradiation

In July 2021, the LoRa wireless modules were irradiated in the IRMA facility at the CEA-Saclay (France) with energetic gamma rays emitted by ^{60}Co sources. For this first experiment, the dose rate was set at 20 Gy/h (2 krad/h) in order to obtain a cumulated dose of 3.3 kGy (330 krad) after a week of irradiation. One can see in Figure 2 the test boards of the SX1261 and SX1276 modules during their installation in the irradiation chamber.

In October 2021, the ARCYS “ANA” sensor was irradiated with a nominal dose rate of 20 Gy/h (2 krad/h) in the same facility. This second irradiation started at around 3:00 p.m. on October 18 and lasted about 168 hours. At the end of the irradiation, the cumulated dose was therefore approximately 3.36 kGy (336 krad).

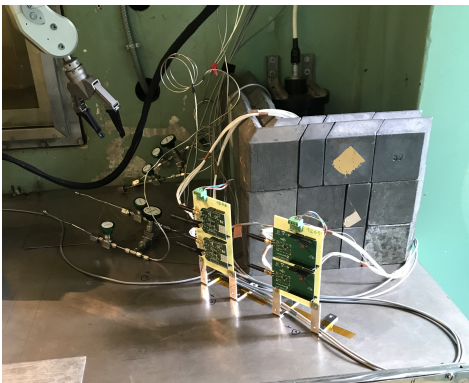


Figure 2. SX1261 and SX1276 test boards in the irradiator. The lead wall in the background protects the microcontroller boards.

IV. RESULTS

A. LoRa modules

Figure 3 shows the plot of the SNR and RSSI parameters as functions of the cumulated ionizing dose for the Master node of the SX1261, SX1276 and RN2483 test boards.

We do not observe any evident degradation of the Semtech SX12xx devices on this graph. The SNR and RSSI values of both devices remain essentially constant. However, we can see with the missing points that the dialog between the bench and the SX1261 board failed many times during the experiment. The same thing appeared, but to a lesser extent, with the SX1276 board. Nevertheless, the two SX12xx boards were still functional at the end of the irradiation after a cumulated dose of 3.3 kGy (330 krad). This suggests that the communication losses could be related to a synchronisation problem between

the bench and the test boards, which seems particularly critical with the SX1261 board.

On the other hand, the RN2483 devices failed early, between 230 and 290 Gy (23 and 29 krad). The wireless modules stopped emitting frames starting from this point. As these modules were permanently powered during the test, this result is not surprising. This biasing mode corresponds actually to the worst case for CMOS technologies. The radiation tolerance of the RN2483 devices would be much better with a switched power supply like the Semtech modules.

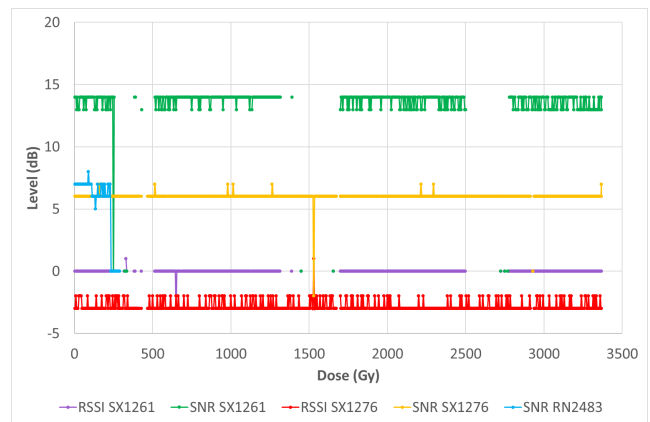


Figure 3. SNR and RSSI values measured during irradiation by the Master node on SX1261, SX1276 and RN2483 test boards.

The power supply currents of the SX12xx test boards were recorded during the test. When CMOS devices are irradiated, it is common to observe an increase in their power consumption once they are severely degraded. However, it is not the case with the SX12xx modules that we have tested. Their power supply current remains unchanged throughout the irradiation. This could mean that the maximum radiation dose of these components was not reached at 3.3 kGy (330 krad).

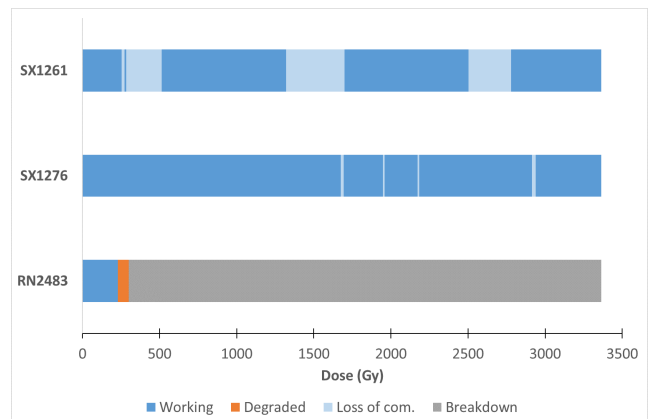


Figure 4. Summary of the response of LoRa modules to a cumulated dose of gamma rays.

The irradiation response of the tested LoRa wireless modules is summarized in Figure 4. The horizontal bars shows the health state of each pair of modules as function of the absorbed dose level. The dark blue regions correspond to a

working state, the light blue ones to a loss of communication, the orange one to a detected degradation and the grey one to a breakdown of the modules. This graph clearly confirms that the SX1276 board suffered far less communication problems than the SX1261 board.

B. ARCYS Lora Endpoint

The data recorded during the irradiation test were analysed afterward. On the network server side, we notice good frame receptions from Monday 18/10 at 10:30 a.m. until Tuesday 19/10 at 8:16 a.m. Over this period of operation, no degradation of the RF circuits occurred, the RSSI and SNR reception levels in the gateway remained stable. On the 19/10 at around 6:04, corresponding to a dose level of 301 Gy (30.1 krad), we observe a reset of the frame counter that reflects a degradation of the microcontroller's electrically erasable programmable read-only memory (EEPROM). On the 19/10 at 6:33, at a dose level of 311 Gy (31.1 krad), the message integrity code (MIC) of the sent frames becomes uncorrect. Then, at 8:16 on the 19/10, after a cumulated dose of 345 Gy (34.5 krad), the sensor no longer transmits frames.

After irradiation, the sensor was returned to ARCYS for expertise. It was found that, when the sensor is powered up, there is an abnormal power consumption and the software does not start. Thus, ARCYS decided to change the embedded microcontroller. After replacing it, the software was running again but the radio transmission was unsuccessful. The serial peripheral interface (SPI) communication between the STM32 microcontroller and the SX1276 chip was working, but the radio part was still not functional. After that observation, ARCYS decided to replace the 32 MHz temperature compensated crystal oscillator (TCXO). Then the endpoint was 100% operational again.

V. CONCLUSION

The objective of this study was to find LoRa modules suited for a portable dosimeter which was designed to be operated in a NPP containment building. Two LoRa wireless modules from Semtech and one from Microchip, as well as a LoRaWAN sensor from ARCYS, have been irradiated up to 3.3 kGy (330 krad) with gamma-rays to evaluate their TID tolerance.

We noticed that the Semtech SX1261 and SX1276 wireless modules do not exhibit any degradation of their characteristics when they are irradiated with their power supply switched-off. Both modules were still functional at the end of the test. Although several losses of communication with the bench have been noticed, we think that these LoRa modules should be able to tolerate even higher levels of ionizing radiation with this power-supply configuration. However, we will retain as a precaution that the dose tolerance of the wireless modules corresponds to the appearance of the first error, i.e. 254 Gy (25.4 krad) for the SX1261 and 1.67 kGy (167 krad) for the SX1276.

In contrast, the RN2483 module, which has been irradiated permanently powered, broke down at 290 Gy (29 krad). This

wireless module would undoubtedly tolerate a higher level of ionizing dose if it had been irradiated in off-state.

The irradiation of the "ANA" LoRaWAN endpoint provided by ARCYS confirmed these findings. This sensor node, which embeds a SX1276 circuit, is most of the time in deep sleep mode and the battery voltage is applied continuously to its internal circuits. This configuration is close to that of the RN2483 test, and thus the observed total dose tolerance is similar, around 300 Gy (30 krad).

This work was an preliminary study aimed at identifying a candidate LoRa chip for the portable dosimeter. Further studies will be performed on the selected chip. In particular, post-irradiation annealing and part-to-part variability characterization will be taken into account on the chip robustness evaluation.

Based on these results, we finally consider the SX1276 wireless module from Semtech as a good candidate to equip the portable dosimeter. A new extension board has already been designed and will be further tested as soon as possible.

ACKNOWLEDGMENT

This study has been conducted in the framework of the Institut Tripartite (I3P), a collaboration that involves EDF, CEA and Framatome.

The authors would like to gratefully thank the staff of the IRMA facility, H. Desjonquères and S. Poirier, for the support they provided during the irradiation test.

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