Nuclear Engineering and Technology 53 (2021) 1483–1490

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Influence and analysis of a commercial ZigBee module induced by gamma rays

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ARTICLE INFO

Article history:
Received 9 September 2020
Received in revised form
17 November 2020
Accepted 18 November 2020
Available online 24 November 2020

Keywords:
Wireless communication
ZigBee
Mesh network
NPP
DBA
TID effect
Radiation hardened device
Irradiation test
PER
Decommissioning

ABSTRACT

Many studies are undertaken into nuclear power plants (NPPs) in preparation for accidents exceeding design standards. In this paper, we analyze the applicability of various wireless communication technologies as accident countermeasures in different NPP environments. In particular, a commercial wireless communication module (WCM) is investigated by measuring leakage current and packet error rate (PER), which vary depending on the intensity of incident radiation on the module, by testing at a Co-60 gamma-ray irradiation facility. The experimental results show that the WCMs continued to operate after total doses of 940 and 1097 Gy, with PERs of 3.6% and 0.8%, when exposed to irradiation dose rates of 185 and 486 Gy/h, respectively. In short, the lower irradiation dose rate decreased the performance of WCMs more than the higher dose rate. In experiments comparing the two communication protocols of request/response and one-way, the WCMs survived up to 997 and 1177 Gy, with PERs of 2% and 0%, respectively. Since the request/response protocol uses both the transmitter and the receiver, while the one-way protocol uses only the transmitter, then the electronic system on the side of the receiver is more vulnerable to radiation effects. From our experiments, the tested module is expected to be used for design-based accidents (DBAs) of "Category A" type, and has confirmed the possibility of using wireless communication systems in NPPs.

1. Introduction

The safety and reliability of nuclear power plants (NPPs) are of particular concern, especially following the critical accident at the Fukushima Daiichi Nuclear Power Plant in Japan in March 2011. For safety, modern NPPs have been constructed using wired communication systems, based on the requirements of design-based accident (DBA) planning [1–5]. However, the thousands of cables in such systems do not provide adequate protection from natural disasters such as earthquakes, floods, and fires [6]. These cables also need to be maintained with respect to more general issues such as high temperatures and aging. Moreover, in the case of an accident, a wired system could be disconnected, resulting in a safety failure due to a loss of function or an instrumentation malfunction. For the most part, however, wireless communication systems are now well developed and used across many industries. Furthermore, wireless technologies have been considered for use in NPPs for maintaining, repairing, and monitoring measurement systems and control devices. For instance, the High Flux Isotope Reactor (HFIR) Equipment Health Monitoring System of Oak Ridge National Laboratory in the United States installed a wireless communications system to check the operational status of a cooling fan, to allow for simultaneous maintenance and repair. The system has been working properly without any power loss from errors or malfunctions for the past five years [7]. Applying a wireless communication system to an NPP, as opposed to a wired one, could be more reliable and safer in certain cases.

A number of advantages can be gained by employing wireless systems in NPPs. First, the time and monetary costs can be considerably reduced, including the cost of the thousands of cables used in a wired system. Maintenance and repair processes can also be enhanced by preparing for malfunctions and errors in advance. Second, safety and reliability can be improved by designing a secondary or backup communication system, to complement an existing wired system in cases of network interruption or instability. Last, unlike a wired system, a wireless system can be used promptly in emergency cases, such as the Fukushima accident. As

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https://doi.org/10.1016/j.net.2020.11.017

shown in Fig. 1, a wireless radiation sensor network system can be quickly built, with thousands of radiation sensors deployed throughout a target field in the form of a mesh network. This can provide critical data to help ease an emergency condition by monitoring the spread of radiation leakage.

On the other hand, a wireless communication module (WCM) could eventually be disabled by total ionizing dose (TID) effects. These can degrade the performance of transistors in the module, due to leakage currents, threshold voltage shifts, and increases in electrical noise [10–12]. A WCM can be divided into digital and radio frequency (RF) modules. The digital part, including the microprocessor and packet modem, can experience propagation delays due to TID effects [13,14]. Moreover, an RF module with a low noise amplifier (LNA) and voltage-controlled oscillators (VCOs) was shown in prior research to lessen gain and noise increases [15,16]. For this reason, comprehensive irradiation tests for integrated WCMs are required before they can be applied to NPPs.

2. Background

2.1. ZigBee

There are several wireless communication protocols such as Wi–Fi, Bluetooth, ZigBee, ultrawide band, and WiMax. The reason for its selection here is that ZigBee is an IEEE 802.15.4 standard [17], with low power consumption, low data rates, and a relatively large communication distance, as shown in Table 1.

In addition, ZigBee networks can be constructed with the following topologies:

- Star: each node communicates with other nodes through a central node. Discovery is easy to manage. However, if the primary node fails, the entire network could be unavailable.
- Tree: several nodes are connected to one node in a tree form. Network extension is easy to manage. However, if a problem occurs in an upper node, all lower nodes are affected. If network expansion increases, traffic becomes concentrated.

Table 1
Technical summary of IEEE 802.15.4

Item	Content	Remark
Data transfer rate	<250 kbps	Maximum transfer rate
Number of network nodes	<65,500	
Network configuration	star, tree, mesh	
Physical standard	IEEE 802.15.4	
Standby current	<1 uA	@power down
Modulation method	O-QPSK	@2.4 GHz
Multiple access	CSMA-CA	

- Mesh: all nodes are interconnected in a net. Even if a problem occurs in a specific node, data can be transferred through another path. However, one disadvantage is that network management, installation, and reconfiguration can be relatively more difficult.

In particular, ZigBee modules can be constructed into a mesh network specialized for redundancy. This redundancy is required in safety systems, such as those used in nuclear power plants. In this work, a radiation sensor cluster network was built using XBee S2C modules from Digi International [18]. This is expected to improve reliability and redundancy in radiating environments, which can significantly impact electronic circuits.

2.2. Nuclear power plant environment

Extreme environments, such as those found during an accident at a nuclear facility, must be considered in terms of the total cumulative exposure dose and the exposure dose rate. Components generally should be reinforced to withstand the following characteristics of an NPP accident environment [8]:

1. A cumulative dose of radiation (gamma rays) of about 200 kGy.
2. A gamma ray exposure dose rate of less than 10 kGy/h.

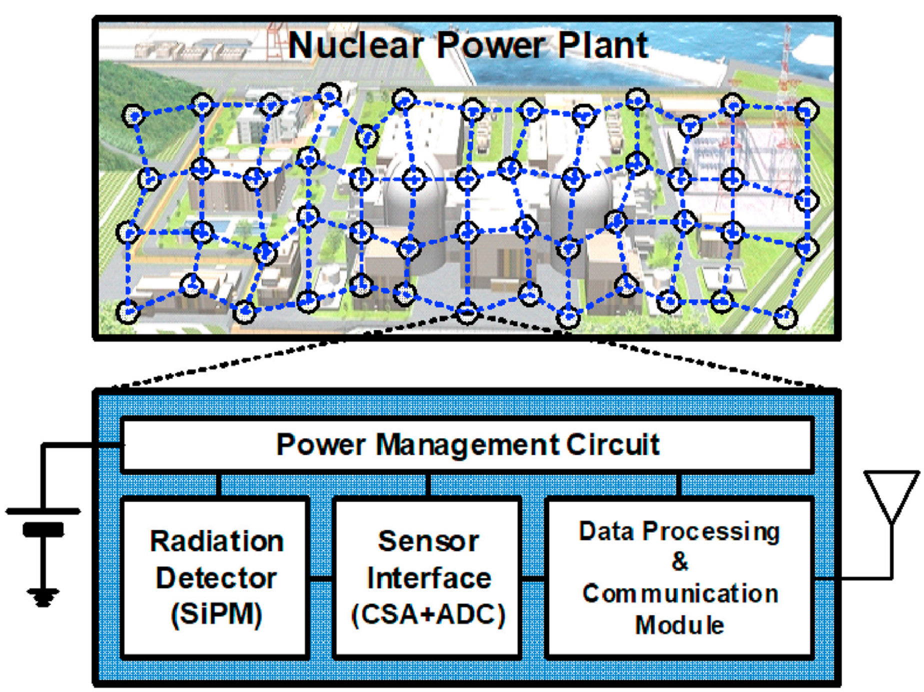

Fig. 1. Proposed wireless radiation sensor network.

These environmental conditions are specified by three categories, according to their locations at the nuclear facility. As described in Table 2, Category C is exposed to less than 4 Gy/year, Category B to 4–100 Gy/year, and Category A anything higher than that [9]. The target of the device under test (DUT) in this work is approximately 1 kGy in TID that satisfies the criteria for Category B. In addition, Category A where radiation dose may be high, can also be satisfied, depending on plant locations in some cases.

2.3. Radiation effect on wireless communication module (WCM)

Components of a WCM generally consist of a microprocessor module, a baseband packet modem, and an RF module. The microprocessor module controls the operation of a WCM by sending signals to the control registers of the baseband packet modem. These operations determine what type of communication mode and data format will be used. The packet modem stores data transmitted from the microprocessor module, and formats the data. In addition, this packet modem converts data received from the RF module and stores it in memory. The RF module transmits data from the packet modem to the outside, or receives external signals.

The operations of the microprocessor module and the packet modem are performed digitally. The RF module, on the other hand, includes analog circuits such as a power amplifier (PA), a VCO, an analog-digital converter (ADC), a digital-analog converter (DAC), and a phase-locked loop (PLL). Unlike digital circuits, analog circuits process continuous data, so radiation effects are more critical. For example, an inverter chain, which is part of the digital circuit, experiences a propagation delay of 21% due to an increased leakage current when exposed to an accumulated radiation dose of 0.4 kGy [14]. In comparison, an amplifier, which is part of an analog circuit, experiences critical effects such as signal attenuation and an increase in noise after only 1 kGy of accumulated radiation [15]. For a systems level analysis, we investigated the effect of TID on entire WCMs while varying the dose rate and operating protocol.

3. Radiation test plan

3.1. Device under test (DUT)

The test devices used in this work were XBee Zigbee Through-Hole S2C series modules, part number XB24CZ7SIT-004, from Digi International Incorporated, as described in Table 3. This module relies on an MC13193 RF chip, which provides low-power, low-cost, and robust wireless capabilities. ZigBee protocols provide mesh networking features, and support the IEEE 802.15.4 m standard for wireless communication [17]. In total, 10 end nodes were used for testing, each connected to a 3.3 V external power supply. Each experiment was conducted on six DUTs, and the reported results all came from the worst-case measurements.

Table 3
Sample ZigBee Module Specification [19].

Specifications	XB24CZ7SIT004
TRANSCEIVER CHIPSET	Silicon Labs EM357 SoC
DATA RATE	RF 250 Kbps, Serial up to 1 Mbps
INDOOR/URBAN RANGE	200 ft (60 m)
OUTDOOR/RF LINE-OF-SIGHT RANGE	4000 ft (1200 m)
FREQUENCY BAND	ISM 2.4 GHz
ADC INPUTS	(4) 10-bit ADC inputs
DIGITAL I/O	15
ANTENNA	RPSMA Connector
OPERATING TEMPERATURE	−40 °C to +85 °C
PROTOCOL	ZigBee PRO 2007
ENCRYPTION	128-bit AES
CHANNELS	16 channels
SUPPLY VOLTAGE	2.1–3.6V
TRANSMIT CURRENT	33 mA
RECEIVE CURRENT	28 mA
POWER-DOWN CURRENT	<1uA @25 °C

3.2. Test configuration

The irradiation tests were performed according to the ESCC-22900 procedure [19], as shown in Fig. 2. The wireless link distance of the WCM was set at 5 m between the ZigBee coordinator (ZC) node and the ZigBee end device (ZED) node. The ZC is connected to a PC to record data packets, and the packet error rate (PER) was calculated by measuring the number packets per second, as visualized by the flow chart in Fig. 3. Whether or not the electronic system is malfunctioning due to TID effects was determined by the current consumption, which was measured by multiplying a 10 Ω resistor on the power supply line by the voltage of 3.3 V. This is described by the circuit diagram shown in Fig. 4. For the irradiation configuration, the current consumption and PER were measured against the radiation intensity, shown in Fig. 5, and against the two protocols (*i.e.*, request/response and one-way), as shown in Fig. 6.

3.3. Irradiation test facility

As shown in Fig. 7, irradiation tests were performed at the Cobalt-60 Gamma-ray facility at the Korea Atomic Energy Research Institute (KAERI). The capacity of the source is 490 kCi. The radiation chamber is installed behind a labyrinth-shaped concrete shield in a bunker. When it is not in operation, the source is stored in a pool with treated and demineralized water. The DUT to be investigated is placed on a stainless table, and the distance from the

Table 2
Nuclear power plant categories by area described in DBA (TID = total ionizing dose) [7].

Category	Definition	Environmental requirements	
A	Any location within the containment and exceeding the environmental requirements of Category B	Exceeded Category B requirements	
B	Outside the containment and the following environmental requirements apply	Radiation (TID)	4 Gy/Years~100 Gy/Years
		Temperature (Accident)	≒ 38 °C (100 °F) ≒ 90% of maximum operating temperature
		Humidity (Accident)	≒ 80% ≒ 95% (noncondensing condition)
C	Outside the containment and the following environmental requirements apply	Radiation (TID)	≤4 Gy/Years
		Temperature (Accident)	<38 °C (100 °F)
		Humidity (Accident)	≤80% ≤95% (noncondensing condition)

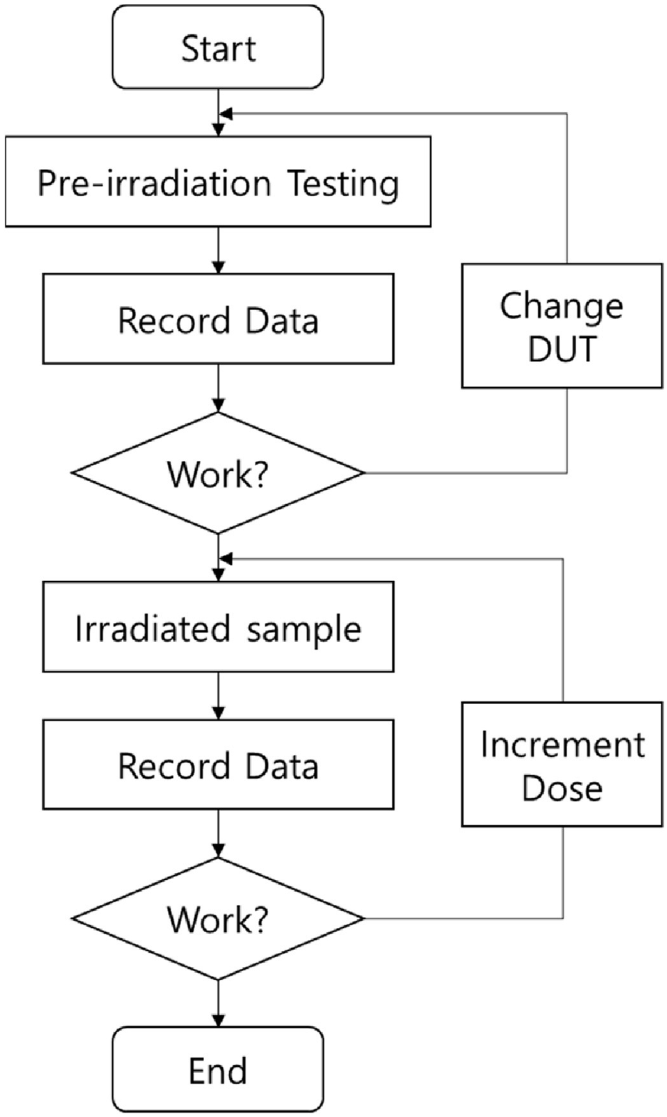

Fig. 2. Flow charts for irradiation tests based on the standard of ESCC-22900.

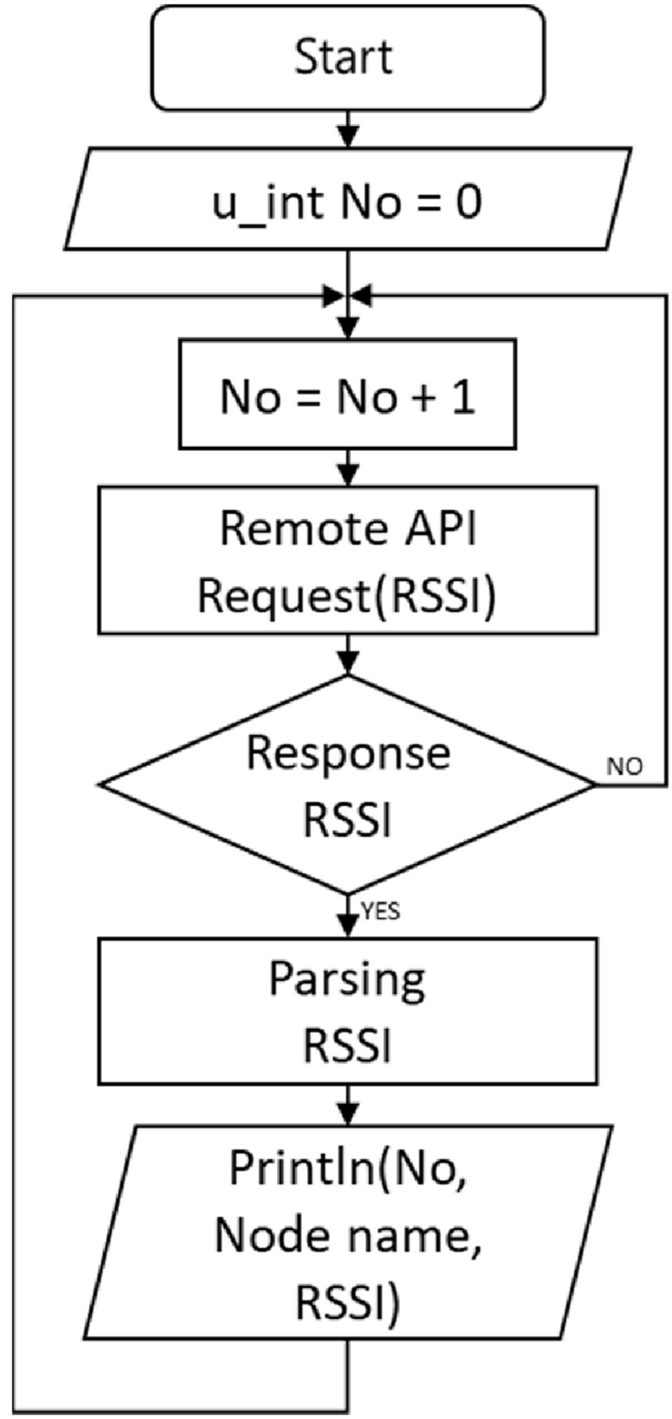

Fig. 3. Flow charts for irradiation tests based on operation of the ZC.

source can be adjusted in order to achieve the required dose rates.

4. Results and discussions

4.1. Results of different radiation dose rates

As shown in Figs. 8 and 9, the ZigBee modules were irradiated with two different dose rates: 185 and 486 Gy/h. Whether or not the test module was malfunctioning due to TID effects was verified by monitoring two indicators: current consumption and PER. Complete system faults occurred after a total cumulative exposure dose of 940 Gy in the case of the 185 Gy/h dose rate, and 1079 Gy for the 486 Gy/h rate. Fig. 8 shows the current consumption for the two dose rate experiments, with normal operating values of 30 mA. When the system faults occurred, current consumption was measured at 33 mA for the 185 Gy/h dose rate, and at 37 mA for the 486 Gy/h dose rate. In Fig. 9, PER is shown for the same set of tests, and this is a representation of the fraction of error packets caused by TID effects when the system fault occurs. At the point when the complete system faults occurred, PER was measured at 3.6% for the 185 Gy/h dose rate, and at 0.8% for the 486 Gy/h dose rate.

According to previous studies, lower dose rates actually affect electronics more severely than higher dose rates [20,21]. Holes generated by radiation impact events in semiconductors are trapped in devices for a relatively longer time at lower dose rates, when controlling for the total amount of radiation absorbed. This supports the results we see from our own dose rate experiments. Note that these modules will also experience enhanced low dose sensitivity (ELDRS) effects, similar to those found in bipolar circuits. This is because CMOS transistors also contain active bipolar elements, as all bulk CMOS processes produce such parasitic bipolar

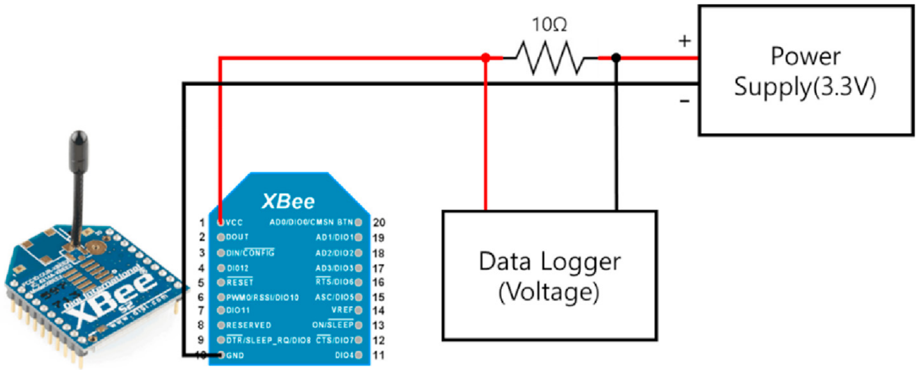

Fig. 4. Configuration for measuring current consumption.

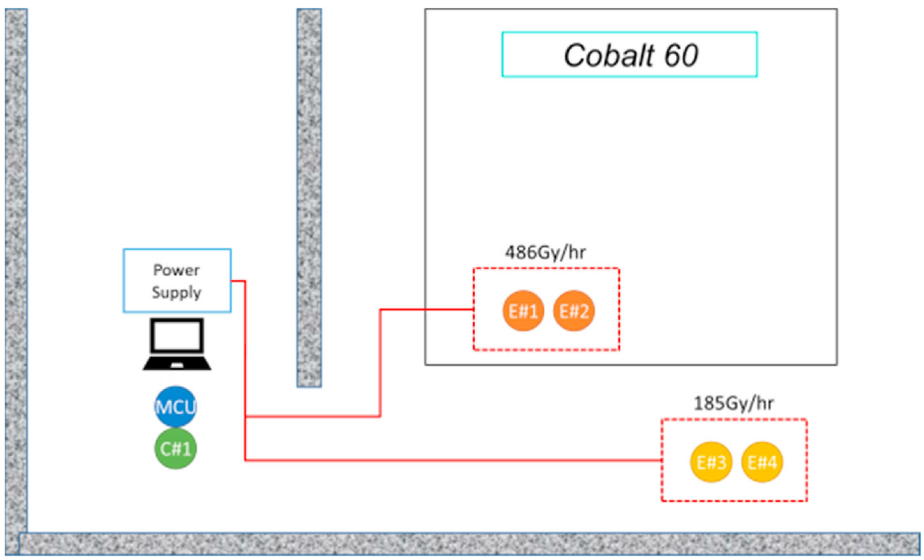

Fig. 5. Irradiation test plan for different dose rates.

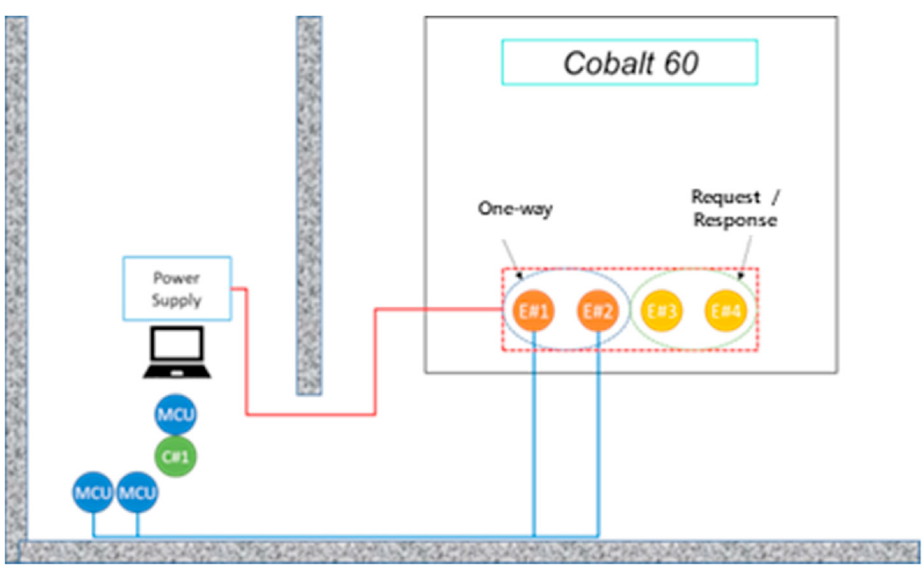

Fig. 6. Irradiation test plan for different protocols.

structures.

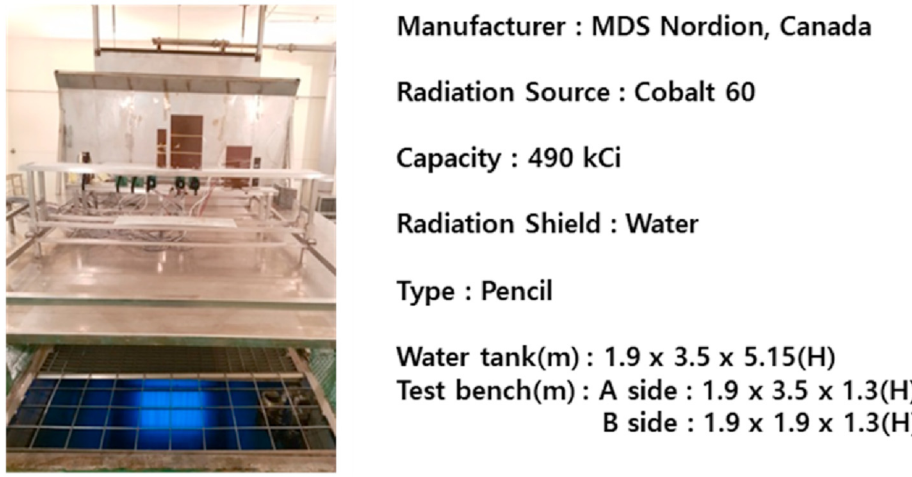

Fig. 7. Specifications of the high-level gamma irradiation facility at KAERI.

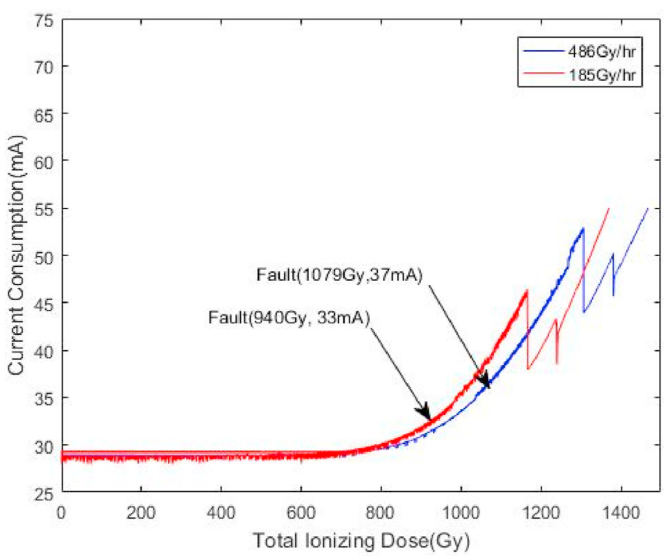

Fig. 8. Experimental results of radiation dose rates for current consumption.

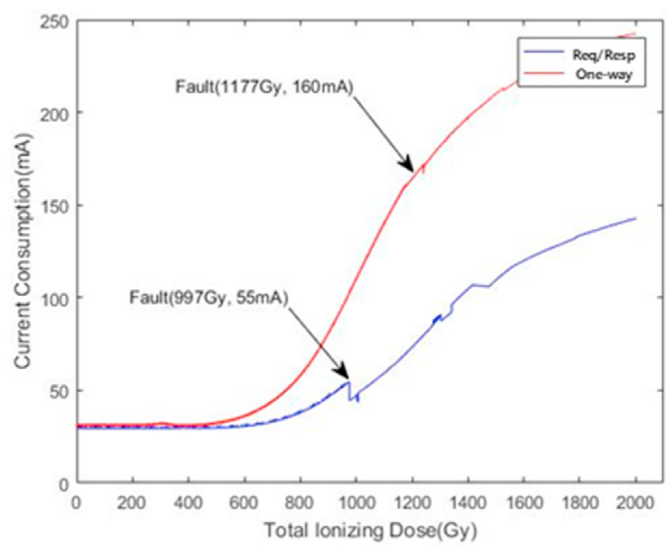

Fig. 10. Experimental results of protocols for current consumption.

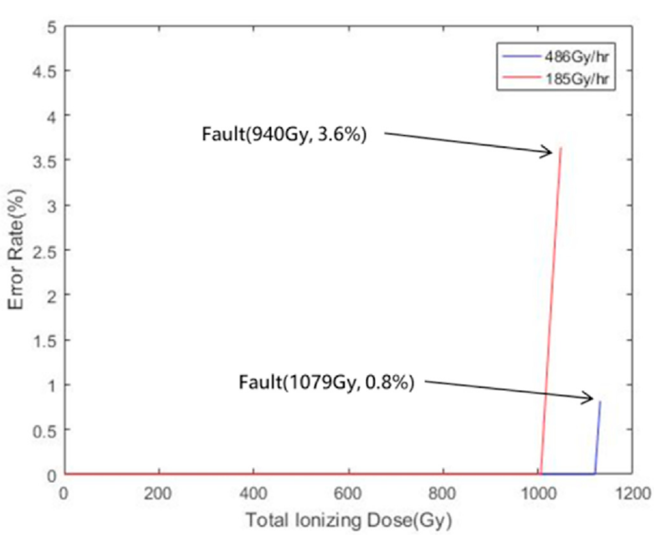

Fig. 9. Experimental results of radiation dose rates for PER versus increase of irradiating dose.

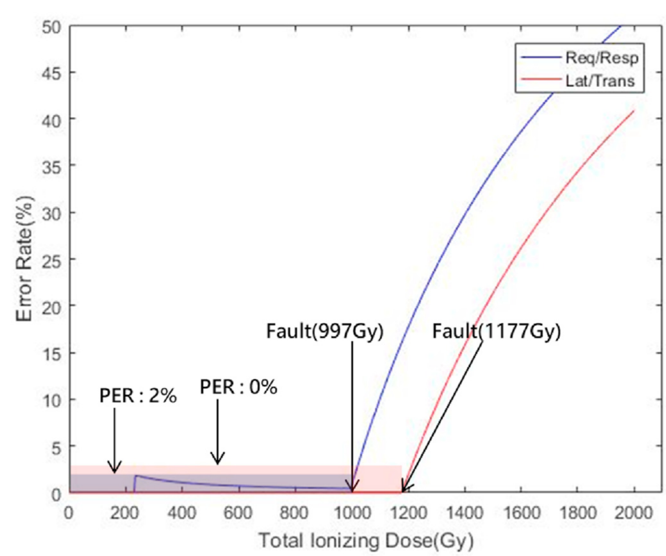

Fig. 11. Experimental results of protocols for PER versus increase of irradiating dose.

Table 4
Irradiation test results of different communication module.

	WiFi RF module [21]	CC2530 [22]	XBee S2C [22]	This work (XBee S2C)
Test Facility	ITN-CO60	NCRRT	NCRRT	KAERI ARTI
TID	500 Gy (200 Gy/h)	800 Gy (200 Gy/h)	500 Gy (200 Gy/h)	1097 Gy (486 Gy/h) 1177 Gy (one-way)
Note	RF module only: 3 kGy	TI RF tool	Digi X-CTU tool	Dose rate & protocol

Table 5
Summary of irradiation test results.

Variable	Test scenario	TID	PER	Current consumption
Dose-rate (request/response)	Low-rate	940 Gy (185 Gy/h)	3.6%	Up to 33 mA
	High-rate	1097 Gy (486 Gy/h)	0.8%	Up to 37 mA
Protocol	Request/Response	997 (230 Gy/h)	2%	Up to 55 mA
	One-way	1177 (108 Gy/h)	0%	Up to 160 mA

4.2. Results of different protocols

As shown in Figs. 10 and 11, the ZigBee modules were also tested for malfunctions caused by TID effects while using two different communication protocols: request/response, which involves both transmission and reception, and one-way transmission. Again, current consumption and PER were monitored. Fig. 10 shows the current consumption for the two protocols, with 30 mA being the normal operating value. In the request/response experiment, complete system faults occurred after a total exposure of 997 Gy, and current consumption at this point was measured as 55 mA. In the one-way experiment, faults occur after a total of 1177 Gy, with a current consumption of 160 mA. In Fig. 11, the PER results from the same set of tests this time represent the fraction of error packets generated by TID effects before the complete system fault appears. With the request/response protocol, PER peaked at 2% before the system fault occurred at 997 Gy, while the one-way protocol experiment recorded a PER of 0% before the system fault occurred at 1177 Gy. These two experiments verify that the receiver part of the WCM is more prone to TID effects than the transmitter part.

4.3. Comparison with other test results

Previous works testing WCMs in irradiated environments using Cobalt 60 radiation sources are listed in Table 4. From the results of a Wi–Fi communication module test, the microprocessor embedded in a communication module appears to be the most sensitive element for 500 Gy. When the RF module alone is tested, it was shown to be resistant up to about 3 kGy [22]. Other tests of ZigBee communication modules show radiation tolerances of 800 Gy for the CC2530, and 500 Gy for the XBee S2C [23].

Compared to the work that used the same Digi XBee S2C module as this research, our results here show an improvement when it comes to TID effects because of the different irradiation dose rates used. When tested at a dose rate higher than that used in the Latter E test standard of the ESCC-22900 [19], which is the standard protocol for communication modules, this better TID tolerance could be confirmed. In addition, the one-way protocol shows better tolerance than the request/response protocol. This shows that, even when using the same WCM model, performance will differ according to the test environment, including such parameters as the dose rate and the communication protocol.

5. Conclusions

In this paper, we investigated a suitable WCM for NPP applications by comparing and analyzing various wireless communication technologies. We also reviewed the applicability of the wireless communication system for use under “Category A″ radiation conditions.

As summarized in Table 5, when the irradiation dose was increased from 185 to 486 Gy/h, the TID tolerance became stronger (from 940 Gy to 1097 Gy), and the PER became lower (from 3.6% to 0.8%). Regardless of the irradiation dose, current consumption is distributed unevenly in the range of 33–37 mA. In short, the lower dose rate has a more severe impact on electronics, as discussed in previous work [20,21]. For the two communication protocols (request/response and one-way), the TID tolerance during one-way operation was stronger (997 Gy vs 1177 Gy), the PER was lower (2% vs 0%), and the current consumption was higher at the point of failure (55 mA vs 160 mA). In short, the receiver part of the WCM is more susceptible to negative TID effects than the transmitter part.

In conclusion, wireless communication systems employed in NPPs are simpler to maintain than conventional wired systems during normal operation, thus reducing costs and allowing for predictable replacement processes, based on experimental lifetime data. Even in an accident situation, a wireless communication system that can withstand DBA “Category A″ conditions can assist in accident mitigation by, for example, monitoring radiation leakage from around the facility. Moreover, irradiation test data is useful for when wireless technologies are employed as part of decommissioning processes.

For use near a nuclear reactor, additional comprehensive research is needed to look into shielding effects, indoor attenuation, cyber security, as well as more radiation-hardened designs. Eventually, wireless communication systems will become a core technology for increasing the safety and reliability of NPPs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (2017M2A8A4056388 and 2017M2A8A4017933).

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