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Experimental Characterization of Dosimeter Based on a Wireless Sensor Network for A Radiation Protection Program

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***Abstract*— In this paper, we show our instrumental design and experimental results on the use of personal dosimeters for determining the radiation dose received by a radiation worker in real-time. We used the wireless sensor networks (WSN) technology to monitor five personal dosimeters. This instrument includes cost-effective sensors, developed as an alternative efficient method for a radiation protection program. A coordinator node, along with a graphic user interface (GUI) was developed for this purpose. The main component of a sensor node consists of commercial radiation made from photodiode type *X*-100 7, an *Arduino* microcontroller as a microprocessor, and a low power consumption *Xbee* module for wireless communication. Testing has been carried out to see the characteristics of the wireless sensor in an open space and a laboratory building. Based on the analysis of packet error rate (PER) values, the communication between the sensor node and coordinator node can be run properly in open space at a maximum distance of 140 m, whereas in the laboratory building at about 45 m due to the blockage by some concrete walls. The radiation count received by the sensor must be at least 30 seconds, and the counting is stable up to 400 seconds. By determining the radiation dose received in real-time, radiation workers may receive an early notification related to the dose received in their working environment with a better log documentation system.**

***Keywords*— Dosimeter; radiation protection; real-time measurement; wireless sensor network; gamma radiation.**

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I. Introduction

The negative effect of ionizing radiation, or simply in this paper, is referred to as radiation that may affect the skin and may trigger cancer [1], damaged cells, and genetic effects [2]–[4]. Therefore, a radiation protection program should be provided for radiation workers [5]. Due to the complexity of the human body, radiation effects and the negative impacts on the human body become serious concerns[6]. In addition, the human body and many organs that mainly consist of water are very sensitive to radiation [7]. When radiation impinges the human body, there are two possibilities, either it interacts with the body, or it just passes by. Once interaction occurs, the radiation may be able to ionize or excite the atoms in organs. Organic molecules may absorb the radiation energy in important cells, such as DNA. Meanwhile, any interactions between the radiation and water molecules in cells may affect a chemical change or harmful biological effects [8], [9].

To prevent and reduce the negative impacts of radiation when using radiation technology, a limitation on radiation dose received by the radiation worker should be stipulated. The Basic Safety Standard (BSS) IAEA defines dose limit as a dose value that is effective or equivalent for all human beings and value that in any practical activity is controlled and not allowed to exceed the standard [10]. Therefore, work exposure for each worker should be controlled and limited by the mean of effective dose, e.g., at 20 mSv per year for five consecutive years and the equivalent dose for hands, feet, and skin at 500 mSv for one year [11], [12].

However, human senses unable to detect radiation directly, while radiation causes negative effects. Therefore, a dosimeter is required to identify locations of the radiation source or the contaminated area by nuclear radiation. A radiation dosimeter system is a device for measuring and evaluating the amount of exposure, absorbed dose, or equivalent dose-related to ionizing radiation either directly or indirectly [13].

There are passive and active dosimeters are available in practical use. The popular one is the passive radiation dosimeters based on the luminescent material detector, i.e., TLD (Thermo Luminescent Dosimeter) [14]. TLD is small in size, cheap, and available in various forms. However, it needs a TLD reader to read the radiation dose stored in TLD. This makes a TLD unable to be used for instant radiation measurement. Instead, it is applied for cumulative monitoring of radiation exposure in the short term (≥ one day) and long term (1-3 months) durations. Under certain circumstances, the amount of radiation dose received by radiation workers in a nuclear installation must be identified in real-time. Both evaluation and documentation of the radiation dose, as well as an immediate response to radiation accident or excessive radiation dose, should be manageable. Regarding these issues, we attempt to design a customized wireless sensor network (WSN) based system for monitoring personal radiation dose [15].

The WSN technology is important for large-scale, complex arrangement and real-time measurement [16]. The WSN has been widely applied to many purposes in the military, medical, environment, safety, and security systems [17], [18]. In nuclear technology applications, the WSN has supported a quick recovering process. The WSN supports active personal dosimeters and real-time dosimeters to reduce radiation workers' radiation [19]–[23].

In this paper, we design and test multiple radiation dosimeter systems that are connected based on WSN. Its design is relatively low cost and low power consumption by utilizing Xbee radio modules. The tests are conducted to examine the WSN performance in terms of package error when used outdoors and in a radiation environment. The basic overall performance tests, such as the detection range and the Poisson sensitivity, are also carried out.

II. Materials and Methods

This section explains the materials used, i.e., a sensor node, coordinator, software, and methods to test the system. A research flowchart containing several stages is indicated in Fig.1.

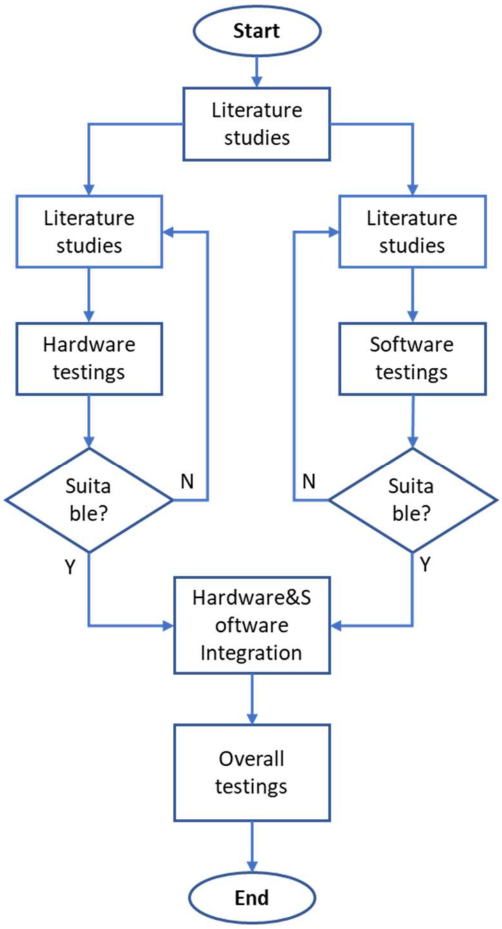

Fig. 1 Research flowchart

A. The Wide Sensor Network System

The WSN architecture of a personal real-time dosimeter system is designed using high sensitivity photodiode radiation sensors type of X100-7 [24], [25]. The general circuit diagram for a commercial radiation sensor can be found at the radiation-watch.org used for gamma radiation detection.

The radiation sensor used is a type 5 radiation sensor issued by radiation-watch.org. This type 5 sensor may be designed for remote sensing using embedded microcontrollers, such as Arduino®, AVR®, or PIC®. It is also suitably combined with the X100-7 sensor to serve as a gamma radiation monitor. We used Arduino with an AT-Mega microcontroller as a processing unit. It receives input from the radiation sensor. For data transmission, we used efficient power consumption of Xbee module communication devices. This module is referred to as a sensor node.

The WSN system was built by utilizing the Xbee-PRO S2C Zigbee radio module from DIGI International. It is referred to as a coordinator node since it can communicate with multiple sensors. The schematic configuration of the WSN system that connects several sensor nodes follows a star topology network where every sensor node can communicate independently to the coordinator node, but it cannot communicate between sensor nodes. A PC with GUI-based software controls the coordinator node.

Each sensor node comprises a radiation sensor, an Arduino microcontroller, an Xbee shield, an Xbee pro S2, a wired PCB, and a power supply. A wired PCB is specifically designed to minimize terminals and cables connection. The radiation dose data received by the sensor node is sent sequentially to the coordinator node, and it is saved as a text file.

The coordinator node comprises an Arduino microcontroller, an Xbee module, an Xbee shield, an Xbee Pro S2C 63mW Wire Antenna Wireless Module, and a USB power supply connection. The Xbee Pro S2C 63mW acts as a wireless data communication coordinator following the IEEE 802.15.4 standard modules. The Xbee module connects to the computer through the Arduino microcontroller.

The coordinator node that is mainly supported by an Arduino microcontroller can communicate serially with the computer. We designed custom software for this research using Arduino IDE, X-Configuration, Test Utility (X-CTU), and Visual Studio. The Arduino IDE is an open-access software that helped us develop the Arduino microcontroller application, from writing the source program, compiling, uploading the compilation results, and testing it. The X-CTU is an approved software developed by DIGI for the Xbee module configuration, either setting the function or updating the firmware. The Visual Studio is a development software tool to develop the radiation dose data acquisition program.

B. Research Method

The tests were conducted in the Department of Physics, Universitas Gadjah Mada Yogyakarta Indonesia. The tests cover (1) characterization of wireless device communication in open space, (2) characterization of wireless device communication in a laboratory building, (3) sensor node test: sensor performance characteristic, detector response at each sensor node for delivery time variation (dose data storage capability), and detector response to gamma radiation intensity by varying the detector distance to a radiation source, Cs-137.

1) Characterization of wireless device communication in open space: This test was intended to determine the maximum range and the value of the packet error rate (PER) for the WSN system that has been developed. The test was carried out by varying the distance between the coordinator node and the sensor node from 10 m to 200 m with a variation of 10 m. This test was carried out using X-CTU software, especially in the form of Application Programming Interface (API) mode. For each distance, the measurement was repeated three times. We identified our data as the local $RSSI_{dBm}$ values, remote $RSSI_{dBm}$ values, packets sent, packets received, Tx errors, and lost packets. The PER value, as formulated by Eq. 1, was calculated. This PER value also identifies the signal strength.

$$PER(\%) = (\frac{ps-pr}{ps})x100\% \quad (1)$$

where *Ps* is packets sent, *Pr* is packets received, and *PER* is packet error rate (%).

2) Characterization of wireless device communication in the laboratory building: The characterization testing on device communication was conducted in the laboratory at the Physics Department building of Universitas Gadjah Mada using a gamma radiation source of Cs-137. Its activity at the time of testing was (72483.97 ± 3%) Bq, and its peak emission energy was 661 keV [26]. It emitted beta particles and gamma radiation. The building was constructed on three floors. This building comprised several rooms separated by brick and concrete walls. The wireless data communication tests were conducted in three stages. At 1^{st}-stage, the sensor node was put on the 2^{nd}-floor, whereas the coordinator node was put on the 1^{st}-floor, at about 10 m below. At 2^{nd}-stage, the sensor node was put on the 2^{nd}-floor, whereas the coordinator node was put on the 3^{rd}-floor, at about 10 m above. At 3^{rd}-stage, the sensor node was put on the 2^{nd}-floor, whereas the coordinator node was anywhere within 5 meters on the 2^{nd}-floor. This stage was also extended for a distance from 15 m to 90 m, with a variation of 15 m. The maximum distance setup was followed by the datasheet specification of Xbee-Pro S2C Zigbee. In this stage, some walls and bricks were considered a natural obstacle for a wireless communication system. The measurement was conducted for 5200 secs, and the measurement was grouped every 100 secs. Like the previous test, several data sets are collected, namely local $RSSI_{dBm}$ and remote $RSSI_{dBm}$ values, packets sent, packets received, Tx errors, and lost packets. The PER value is calculated, whereas the signal strength and the farthest distance are identified.

3) Sensor node test: The system was designed to collect radiation doses from a large number of radiation workers. So it needs several sensor nodes. We developed five sensor nodes. Each node used the same Type 5 Pocket Geiger Radiation Sensor. The sensor was made of photodiode semiconductor material with an active area of 100 mm^2. The test on the sensor nodes to the radiation source of Cs-137 was undertaken in a box covered perfectly by a concrete wall (Pb) as a radiation shield. This ensured the working environment was safe from any undesired radiation exposure. The radiation source was put into a box and let its radiation emitted from a hole of 3 mm in diameter. During the test on detector response to the radiation, the detector was put at a distance x of 5 mm from the box of the isotope Cs-137. The coordinator node collected a set of 100 radiation data from all five sensor nodes. The next test was testing detector response to data storage time variation, following the Poisson Statistics. The time variations were 5 secs to 40 secs with a variation of 5 secs. The distance between radiation and detector was kept at 5 mm, and 100 radiation data were collected. We tested the detector for the Poisson statistic distribution conformity, as depicted in Eq.2.

$$P(n) = \frac{e^{-N}N^m}{m!} \quad (2)$$

where *N* was the average count rate (cpm), *m* was the count rate, and the standard deviation $\sigma=\sqrt{N}$ for the Poisson distribution.

The next test was testing the detector response to detector position variation. The test was conducted by varying the distances between the detector and the source from 5 mm to 50 mm, with a variation of 5 mm. The measurement was repeated 100 times to collect the mean data measurement and its standard deviation.

III. RESULT AND DISCUSSION

A. Characterization of Wireless Device Communication in Open Space

The performance of data transmission from the sensor node to the coordinator has been evaluated in an open space by placing the receiver (coordinator) in a fixed position with the sensor node placed at various distances between 10 m to 200 m. The packet error rate (PER) was determined. The signal strength at the sensor nodes and coordinators was measured in dBm units. The signal was considered lost if the coordinator and sensor node exit -110 dBm. It was indicating no communication between the devices.

The performance of data transmission from the sensor node to the coordinator is presented in Fig. 2. The graph shows the detection ranges determined up to 140 m with a PER value of 0%. The PER for 150 m and 160 m is 3% and 4%, respectively. The 140 m distance is recommended as the maximum distance when the device is used in an open space when using the Xbee S2C Pro radio module type.

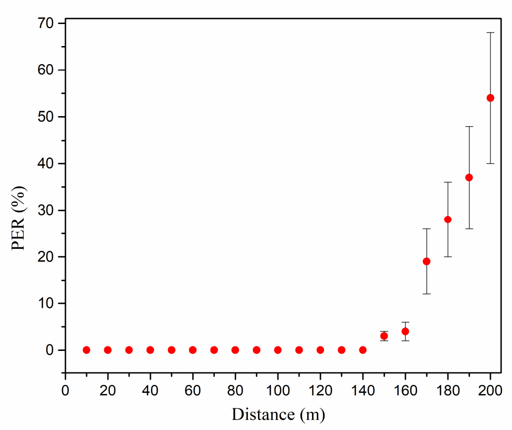

Fig. 2 A graph of packet error rate (PER) data sent versus distance between sensor nodes to the coordinator in open space up to 200 m.

B. Characterization of Wireless Device Communication in the Laboratory Building

The devices were designed and used by radiation workers in the same building. Every radiation worker may work in different rooms, but they were close to each other. The performance of the WSN system in terms of PER value between the sensor node to the coordinator node was measured. The testing results are presented in Fig. 3.

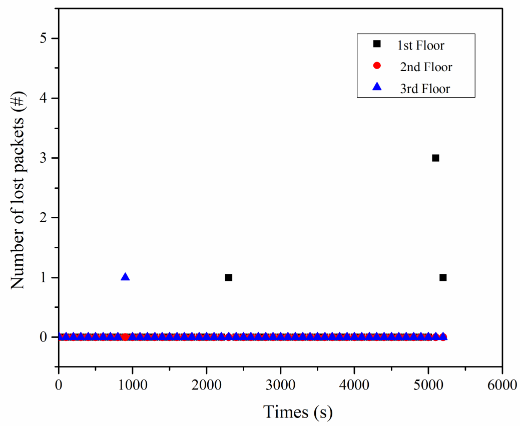

Fig. 3 Number of data packets lost when the sensor node is exposed to Cs-137 gamma radiation and where the coordinator is placed on the first, second, and third floor for 5200 seconds.

We monitored lost packages every 100 seconds on each floor, separated by a concrete floor on the 3rd-floor (blue triangle), at 2nd-floor (black round), and the 1st-floor (red square). The results show that the highest lost package was on the 1st floor, about the PER value of 0.002%. There was no data packet lost found at around 5 m in the 2nd-floor. The PER values as distance varied from 5 m to 90 m on 2nd-floor are presented in Fig. 4. The graph shows that the maximum distance between the sensor node to the coordinator node when walls present is 45 m. This result is much better than the previous study of a maximum of 11 m.

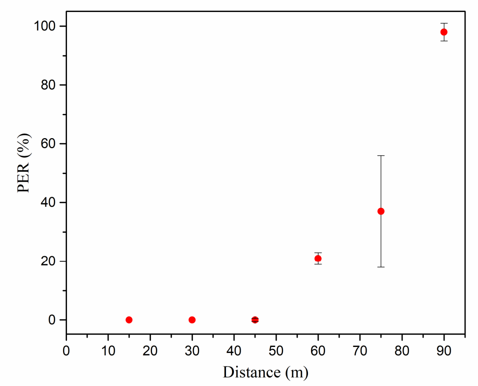

Fig. 4 A graph of packet error rate (PER) data sent versus distance between sensor nodes to the coordinator in open space up to 90 m on the 2nd- floor.

C. The hardware Implementation and Sensor Characteristic

The five sensor nodes were controlled by a coordinator node using GUI-based software on the computer. Those sensor nodes formed a star topology type of the WSN system relative to the coordinator node. The software interface could remark all sensor nodes as A, B, C, D, and E symbols. Once a radiation dose measurement was completed, the data was stored in TXT format. The real test of the WSN system was for capturing gamma radiation from Cs-137. The sensor node that was both the Xbee module and the radiation sensor required a DC power source. After the radiation sensor captured radiation data, the data were delivered by the Xbee module from the sensor node to the coordinator node. Since the coordinator node was connected to a PC with the software installed, the measurement result may be displayed in real-time counting or the real-time chart. Thus, in reality, every radiation worker could be continuously or regularly monitored.

We expect every sensor node has the same performance. The test results are shown in Fig. 5. The sensor used was sensitive to gamma radiation. However, detector E gave a jumping response after 200 seconds. The other four detectors were stable in 400 s, although detector C was a bit late to respond to the radiation counting. Such slightly different responses on the detector might be due to the different positions of the detectors.

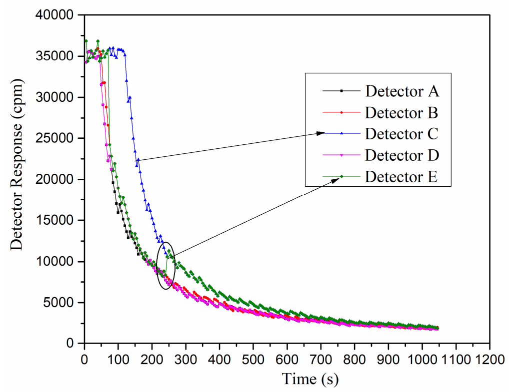

Fig. 5 Graphic characteristics of five detectors (A, B, C, D, and E) of gamma radiation sources (Cs-137) for 1050 seconds.

D. *Result of The Characterization of Detector Response to Storage Time Variation*

The detector was then tested for counting time variation of 5 sec to 40 sec. We collected 100 data for each time variation. Then, we grouped the counting frequency into 20 intervals. The results are shown in Fig. 6. Following the Poisson distribution as depicted in Eq. (2), the graphs justified the detector characterization responses. We found that the best counting time was at 30 seconds (marked as a blue graph). We confirmed that all detectors could detect gamma radiation counts following Poisson statistics in which the gamma radiation count was about (1600±40) cpm. Since the average value of the counting and its standard deviation were almost the same, the data storage time (counting time) could be set more than 30 seconds following the observer's needs.

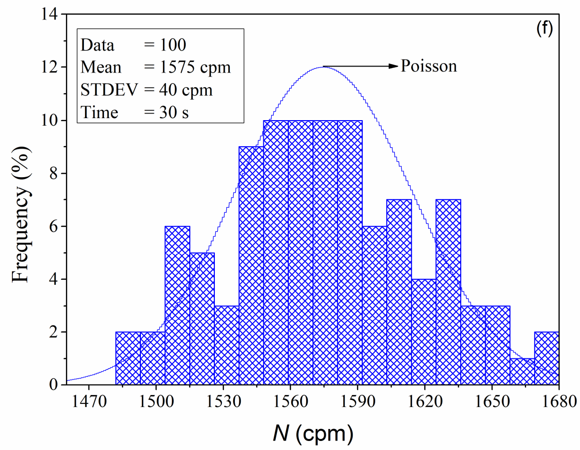

Fig. 6 Poisson distribution graph of detector characterization responses (*N*) for variations in storage time in which the best distribution found at 30 secs

E. *Detector Response to Distance Variation*

The next test result was the detector response to distance variation, as it showed in Fig. 7. The results show the mean of detector responses from 100 observation data for distance 5 mm to 50 mm, with a variation of 5 mm.

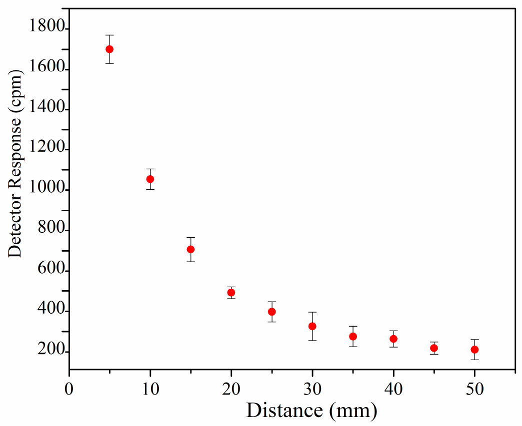

Fig. 7 Graph of detector response to changes in the distance of gamma radiation sources (Cs-137).

From the graph, we found the equation of $y = 13817x^{-1.212}$ with $R^2 = 0.984$. The significant correlation value was quite impressive at the 98% confidence level. However, we expect power -2.0 for x instead of -1.212, following the inverse square law. Such deviation may be due to the radiation was far from a pencil beam.

IV. Conclusions

The dosimeter sets developed based on the WSN system have been successfully tested. The dosimeter was reasonable since it uses commercial parts such as a photodiode type of X-100 7, Arduino microcontroller as a microprocessor, and Xbee S2C radio mode that complies with the IEEE 802.15.4 protocol. Our system reached the farthest distance of 140 m when it uses in an open space at an accepted level of PER value of 0.002%. When uses in a building, our system can accommodate radiation monitoring at floors above and below the floor where there is the radiation source. While walls and bricks separate the test on this device on the same floor, the recommended maximum distance is 45 m with the accepted PER value of 0.01%. We also concluded that the sensor node could do radiation monitoring following the Poisson statistics effectively for 30 seconds and stable up to 400 seconds. Our system is promising to improve radiation protection programs for radiation workers in a better log documentation system.

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