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A 2.4 GHz IEEE 802.15.4 Multi-Hop Network for Mountainous Forest and Watercourse Environments: Sensor Node Deployment and Performance Evaluation

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Abstract: In this paper, we demonstrate the realistic test of a 2.4 GHz multi-hop wireless network for mountainous forest and watercourse environments. A multi-hop network using IEEE 802.15.4 XBee3 micro-modules and a communication protocol among nodes were developed. A wireless node deployment solution was introduced for practical testing. The proposed system's communication reliability was tested in two different scenarios: a mountainous forest with sloping areas and trees and a watercourse, which referred to environmental and flooding monitoring applications. Wireless network performances were evaluated through the received signal strength indicator (RSSI) level of each wireless link, a packet delivery ratio (PDR), as the successful rate of packet transmission, and the end-to-end delay (ETED) of all data packets from the transmitter to the receiver. The experimental results demonstrate the success of the multi-hop WSN deployment and communication in both scenarios, where the RSSI of each link was kept at the accepted level and the PDR achieved the highest result. Furthermore, as a real-time response, the data from the source could be sent to the sink with a small ETED.

Keywords: multi-hop; IEEE802.15.4; implementation; mountainous forest; watercourse

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1. Introduction

Wireless sensor network (WSNs) are one of the sensor and communication technologies that are rapidly expanding and gaining popularity among users and researchers. Since they are regarded as an essential basic component of the Internet of Things (IoT) [1,2], WSNs with the IoT can be used in many smart scenarios and applications.

WSNs refer to a group of sensor nodes, and they are linked by wireless connections. Generally, the sensor node is composed of four major units: the processing unit, the sensing unit, the communication unit, and the power supply unit. The sensor node, which serves as the source node, collects interesting data from the environment, such as temperature, vibration, water level, images, and so on. Such sensing data are then sent to a sink node, which is the monitoring or control center. Due to the short-range communication characteristic, the radio range of a single node cannot fully cover the test area. Therefore, multi-hop communications are then applied, where each node forwards data to the destination via other relay nodes in the network. In order to achieve successful data delivery in multi-hop networks, appropriate sensor node deployment and efficient wireless communication are required. Since the use of multi-hop WSNs is increasing significantly, they are applied for a variety of purposes, including environmental monitoring, disaster management, military operations, flora and fauna [3], transportation, healthcare, home automation, industrial applications, smart cities, protection and surveillance, object tracking, farming and agriculture, etc.

For environmental monitoring applications, many communication technologies, such as the global positioning system (GPS), 4/5G, unmanned aerial vehicles (UAVs), Lora, narrow band (NB)-IoT, and ZigBee, have been applied. Each technology has its advantages and shortcomings. For this work, ZigBee technology is used for this application. The ZigBee IEEE 802.15.4 standard was developed to satisfy the requirements for simple, low-power, and low-cost wireless communications. It operates in the 2.4 GHz ISM band, making the technology simple to use and accessible worldwide. Because the IEEE 802.15.4 protocol focuses on low-power-consumption, low-cost, and low-data-rate wireless networking, it is suited for WSNs. The involvement of low-power wireless communications is an appropriate choice in WSNs aimed at long-term monitoring.

Because this work focuses on the actual testing of a multi-hop wireless network in outdoor situations, a review of related works to this issue is discussed here. A summary is also provided in Table 1. John et al. [4] demonstrated the development of a multi-hop network for agricultural field surveillance. Twenty-four TelosB motes with CC2420 transceivers, the IEEE 802.15.4 standard, were implemented, and soil temperature, soil moisture, atmospheric temperature, and relative humidity were included. The authors evaluated RSSI levels, the number of packets sent, packet losses, battery voltage, and residual capacity. The authors found that the wireless connections in the agricultural areas were quite stable, where the system could collect sensor data while saving energy consumption.

Table 1. A comparison between related works and this work.

Works	Multi-Hop Technology	Applications	Major Study
[4]	2.4 GHz, IEEE 802.15.4	Agricultural field surveillance	• The development of a multi-hop network for agricultural field surveillance • The evaluation of RSSI levels, the number of packets sent, packet losses, battery voltage, and residual capacity
[5]	IEEE 802.11af-compliant network	Deployment of a multi-hop network in a university (University of San Carlos)	• The implementation and evaluation of a multi-hop network at the University of San Carlos • Throughput evaluation
[6]	2.4 GHz, IEEE 802.15.4	• Monitoring the health of heritage buildings • Rognosa tower in the medieval village of San Gimignano, Tuscany, Italy	The development of a real-time WSN for monitoring the health of heritage buildings
[7]	Mica2 motes with Chipcon 1000 RF modules (433 MHz frequency)	• Wildfire tracking • Pinole Point Regional Park (Contra Costa County, California, near San Francisco)	The development of a multi-hop WSN for wildfire tracking
[8]	Arduino Nano board with the 2.4 GHz nrf24L01 module	Forest fire detection	The development of a WSN system for forest fire identification
[9]	ZigBee nodes with CC2520-CC2591EM	Mar Menor lagoon monitoring	The development of a WSN system for the monitoring of Mar Menor lagoon
[10]	2.4 GHz, IEEE802.15.4	Multi-hop WSN for different environments	• The development of a multi-hop WSN for different environments • The evaluation of communication reliability in terms of the PDR

Table 1. *Cont.*

Works	Multi-Hop Technology	Applications	Major Study
[11]	2.4 GHz, IEEE 802.15.4	Multi-hop network for indoor environments	• The development of a multi-hop WSN for LoS communications, the NLoS, different floor communications, and spiral staircase tower scenarios • The evaluation of the effects of communication directions and transmission powers
[12]	UAV with IEEE 802.15.4	UAV WSNs	The evaluation of the quality of aerial links in low-power WSNs in terms of RSSI signals and the PDR
This work	2.4 GHz, IEEE 802.15.4	Multi-hop network for mountainous forest and watercourse environments	• The development of a 2.4 GHz multi-hop network for mountainous forest and watercourse environments • A wireless communication protocol and sensor node deployment solution • The evaluation of communication reliability in terms of the RSSI, PDR, and ETED

Montejo et al. [5] detailed the implementation of a multi-hop network at the University of San Carlos using an IEEE 802.11af-compliant network. The two-hop communication was tested, with the first hop being a line-of-sight (LoS) case and the second being a non-line-of-sight (NLoS) scenario. The installed network achieved a highest throughput of 4.81 Mbps for the uplink and 4.93 Mbps for the downlink using a single channel. Rain had a significant impact on the quality of service (QoS), with a 17.76% decline in throughput noted. The authors also demonstrated that the system could transmit voices and data over Skype.

A real-time WSN method for monitoring the health of heritage buildings was developed in [6]. The multi-hop network was built with humidity, temperature, masonry crack, rain gauge, and light sensors. Sensor nodes with the CC2420 RF module, the IEEE802.15.4 standard, were employed on the Rognosa tower in the medieval village of San Gimignano, Tuscany, Italy. The experimental findings showed that a battery-saving approach with a low-power mode and wake-up option could increase the network lifespan.

Doolin and Sitar [7] described wildfire tracking using a multi-hop WSN. During planned test fires, sensor nodes recorded temperature, relative humidity, and barometric pressure in a field at Pinole Point Regional Park (Contra Costa County, California, near San Francisco). TinyOS was used to set up ten sensor nodes using Mica2 motes with Chipcon 1000 RF modules (at 433 MHz) and combined with global position systems (GPSs). The authors reported that their system successfully delivered data, and they advised that the sensor nodes should be positioned 0.5 m above the top of the fuel to prevent transmission packet loss. The authors of [8] also stated that forest fires have become a significant danger around the globe, causing damage to human habitats and forest ecosystems. Particularly, a higher percentage of forest fires are from human activities. To minimize the devastation caused by forest fires, the authors suggested a system that could identify forest fires early on using a WSN. Furthermore, a machine learning algorithm was used to obtain more precise fire detection. In the study, a sensor node using an Arduino Nano board with a 2.4 GHz nrf24L01 module was used to measure the temperature, humidity, light intensity level, and CO level. Experiments in actual tropical forest locations revealed that the system was effective in alerting the authors to forest fires with a lower latency.

A WSN for the real-time surveillance of the Mar Menor lagoon was installed in [9]. Sensor nodes were strategically positioned in the ocean and recorded water factors such as temperature, pressure, salinity, suspended nutrients, current velocity, and so on. ZigBee sensing nodes were installed at a maritime buoy, where the radio module was a Texas Instruments CC2520-CC2591EM with an output power ratio of 17 dBm. A sensing node was placed 1.5 m above sea level to ensure reliable communication with another Zigbee node in the LoS. The authors concluded that their system could provide useful information to oceanographic experts, allowing them to obtain an in-depth understanding of the lagoon's hydrodynamic behavior.

Communication reliability in terms of the PDR in a 2.4 GHz IEEE 802.15.4 multi-hop WSN was assessed in [10]. Experiments using Tmote Sky sensing nodes with a basic communication protocol were conducted in various indoor situations, at the Prince of Songkla University's Faculty of Engineering. According to the results, the PDR could achieve nearly 100% for the LoS, but only 14.40% for outdoor-to-indoor environments with different floors and the NLoS scenario. The work in [11] developed a 2.4 GHz indoor multi-hop WSN system utilizing IEEE 802.15.4. This system was tested in various indoor environments, including LoS communications, a NLoS, different floor communications, and spiral staircase tower scenarios. The effects of communication directions and transmission powers were investigated.

Finally, in [12], the evaluation of the quality of aerial links in low-power WSNs was presented. The experiments consisted of eleven IEEE 802.15.4-compliant transceivers. Nine of these were deployed on the ground in a grid topology, while two were attached to a UAV. RSSI signals and the PDR were evaluated. The experimental results indicated that radio signal interference was the most significant factor affecting the quality of aerial links, where the radio technology used by the UAV significantly impacted the link quality of the IEEE 802.15.4.

According to the literature review discussed above, existing works have tried to implement multi-hop WSNs for their specific applications and focused on different points to fulfill their system efficiency. In this work, a 2.4 GHz multi-hop wireless network is developed and evaluated. The major contributions of this work are that the system was developed and tested in real-world scenarios, including mountainous forest and watercourse environments. We introduced the multi-hop network using IEEE 802.15.4 XBee3 micro-modules with an autonomous communication protocol. Additionally, the wireless node deployment solution being able to maintain reliable communications for practical testing was presented. The system's performances were evaluated through the RSSI level, PDR, and ETED, and the experimental results showed the success of the multi-hop WSN deployment and real-time communications.

The structure of this paper is as follows: Section 2 describes the multi-hop WSN, including the wireless network and sensor node deployment solution. The experiments are explained in Section 3, while the performance metrics are in Section 4. Section 5 provides the results and a discussion. Finally, we conclude the paper in Section 6.

2. Materials and Methods

2.1. Proposed Wireless Network

Figure 1 depicts the multi-hop network described in this work. There are four sensor nodes: a transmitter, relay 1, relay 2, and a receiver, where the receiver is linked to the computer as the monitoring center [11]. The wireless sensor node is a SparkFun Thing Plus XBee3 micro-module with an on-board chip antenna [13]. It is built on the IEEE 802.15.4 2.4 GHz ZigBee standard, with a data rate of 250 kbps for radio transmission and 1 Mbps for serial data transfer. The RF transmit power is set to +8 dBm, or 6.3 mW, which is the maximum power for this task, and the supply voltage ranges from 2.6 VDC to 3.6 VDC. More specification details are also provided in Table 2.

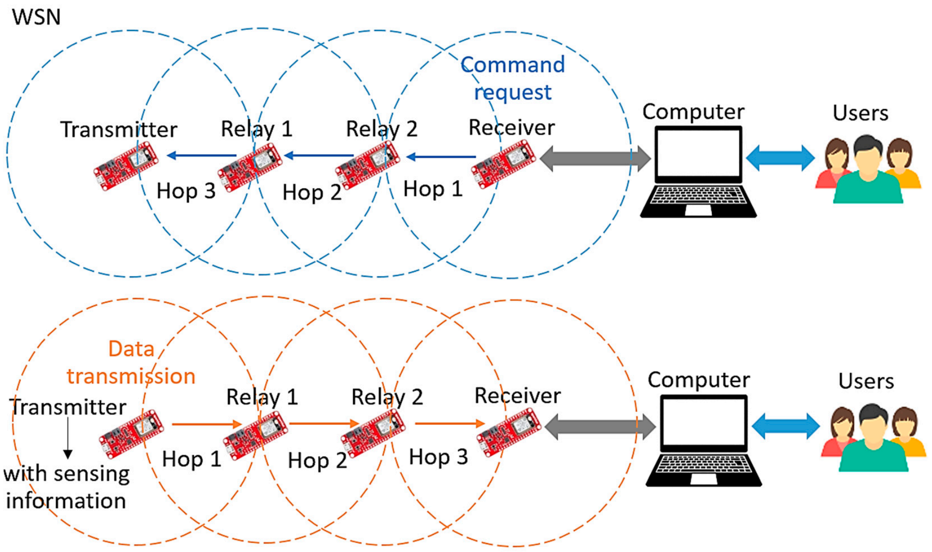


Figure 1. A multi-hop WSN with the communication protocol among the nodes.

Table 2. XBee3 micro-module specifications [13].

Specifications	
Operating frequency band	ISM 2.4–2.4835 GHz
RF and serial data rates	250 Kbps RF, 1 Mbps
Indoor/urban range	Up to 200 ft (60 m)
Outdoor/RF line-of-sight range	Up to 4000 ft (1200 m)
Transmission power	+8 dBm (maximum power) or 6.3 mW
Receiver sensitivity	−103 dBm
Serial communications	UART, I^2C
Supply voltage	2.6 VDC–3.6 VDC
Antenna	On-board chip antenna
Operating temperature	−40 to 85 °C (industrial)
Operating current (transmit, typical)	40 mA, @ +3.3 V, +8 dBm
Operating current (receive, typical)	17 mA
Power-down current, typical	2 µA @ 25 °C
Number of channels	16 direct sequence channels Channels 11 to 26

The protocol for communication between the nodes [11] is explained here, as shown in Algorithm 1. When the computer, acting as the monitoring center, wishes to gather sensing data from the source node (in this case, the transmitter), the receiver first transmits a command message to the source node via relays 2 and 1, respectively. This command packet also includes the desired transmit power (i.e., 8 dBm) and sampling rate (i.e., 200 ms) for the sensing data transfer. As a result, we can adjust the transmission power and sampling rate to meet the needs of the network. Following the receipt of the command packet, the transmitter sends a data packet containing sensing data to the receiver via relays 1 and 2, respectively. Using our solution, the packet sequence number of the sensing data, node IDs, time stamps at each node, and RSSI information from each hop are then sent to the computer via a serial interface for tracking. During data transmission, an acknowledgment message among the hops is also used to confirm the successful data transmission. For example, when relay 1 receives data from the transmitter, it will send back the acknowledgment message to the transmitter, and it then forwards the data to the next hop. Further details can be found in [11].

Algorithm 1: The communication procedure

Transmitter

```
IF Receive any packet from Relay 2 and Receiver THEN
    Discard such a packet
END IF
IF Receive the data packet from Relay 1 THEN
    Discard such a packet
END IF
IF Receive the command packet from Relay 1 THEN
    Transmit power setting
    Sampling rate setting
    Packet number configuration
    Send all data packets to Relay 1 by unicasting
    Stop to send the packet
    Resetting transmit power and sampling rate
    to the defaults
END IF
IF Receive the acknowledgement packet from Relay 1 THEN
    Accept the acknowledgement packet and
    send the data packet
END IF
```

Relay 1

```
IF Receive the data packet from Relay 2
    or the command packet from Receiver
    or the acknowledgement packet from Receiver
THEN
    Discard such a packet
END IF
IF Receive the command packet from Relay 2 THEN
    Forward the packet to Transmitter by unicasting
END IF
IF Receive the data packet from Transmitter THEN
    Forward the packet to Relay 2 by unicasting
END IF
IF Receive the acknowledgement packet from Relay 2 THEN
    Accept the acknowledgement packet and
        forward the data packet
END IF
```

Relay 2

```
IF Receive the data packet from Transmitter
    or the command packet form Relay 1
    or the acknowledgement packet from Relay1 THEN
    Discard such a packet
END IF
IF Receive the command packet from Receiver THEN
    Forward the packet to Relay 1 by unicasting
END IF
IF Receive the data packet from Relay 1 THEN
    Forward the packet to Receiver by unicasting
END IF
IF Receive the acknowledgement packet from Receiver THEN
    Accept the acknowledgement packet and
        forward the data packet
END IF
```

Receiver

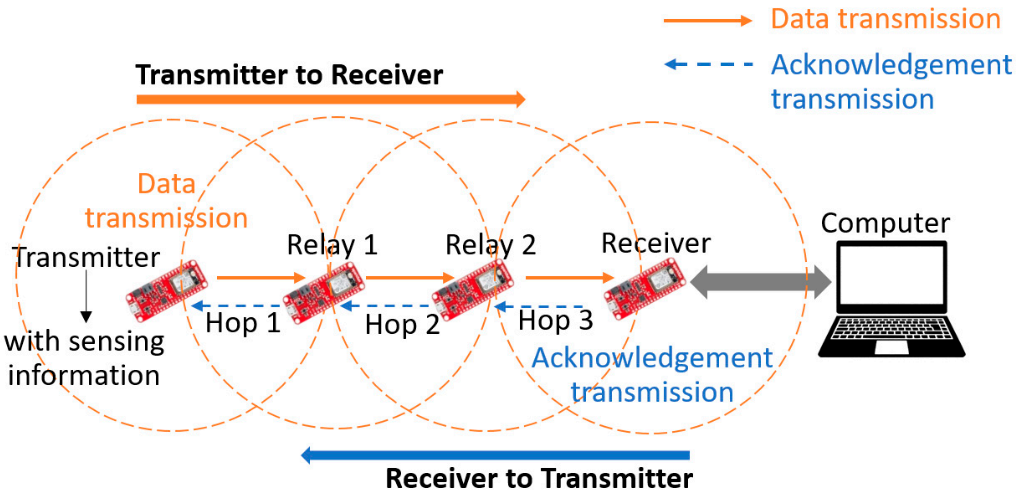
```
IF Receive the data packet from Transmitter or Relay 1
    or the acknowledgement packet from Relay1 or Relay2 THEN
    Discard such a packet
//Note: to check multi-hop operations in this work, receiver can receive transmitter's data only from Relay 2
END IF
IF Receive the command packet from any nodes THEN
    Discard such a packet
END IF
IF Receive the data packet from Relay 2 THEN
    Extract the any information form the packet
    Forward all information to Computer via the serial port
END IF
IF Receive the request from Computer THEN
    Set required transmit power
    Set required sampling rate
    Send the command packet packets to Relay 2 by unicasting
END IF
```

2.2. Sensor Node Deployment Solution

According to the specifications for Xbee3 micro-modules, the transmission range for LoS outdoor situations can be up to 400 feet. (1200 m). This range depends on free-air terrain with few interference sources. The actual range varies depending on the transmitting power, orientation of the transmitter and receiver, height of the transmitting antenna, height of the receiving antenna, weather conditions, interference sources in the area, and terrain between the receiver and transmitter, including walls, trees, buildings, hills, and mountains. To obtain a strong communication signal and data transfer success rate for a practical multi-hop network deployment, we propose the following solution for deploying each sensor node in the test field.

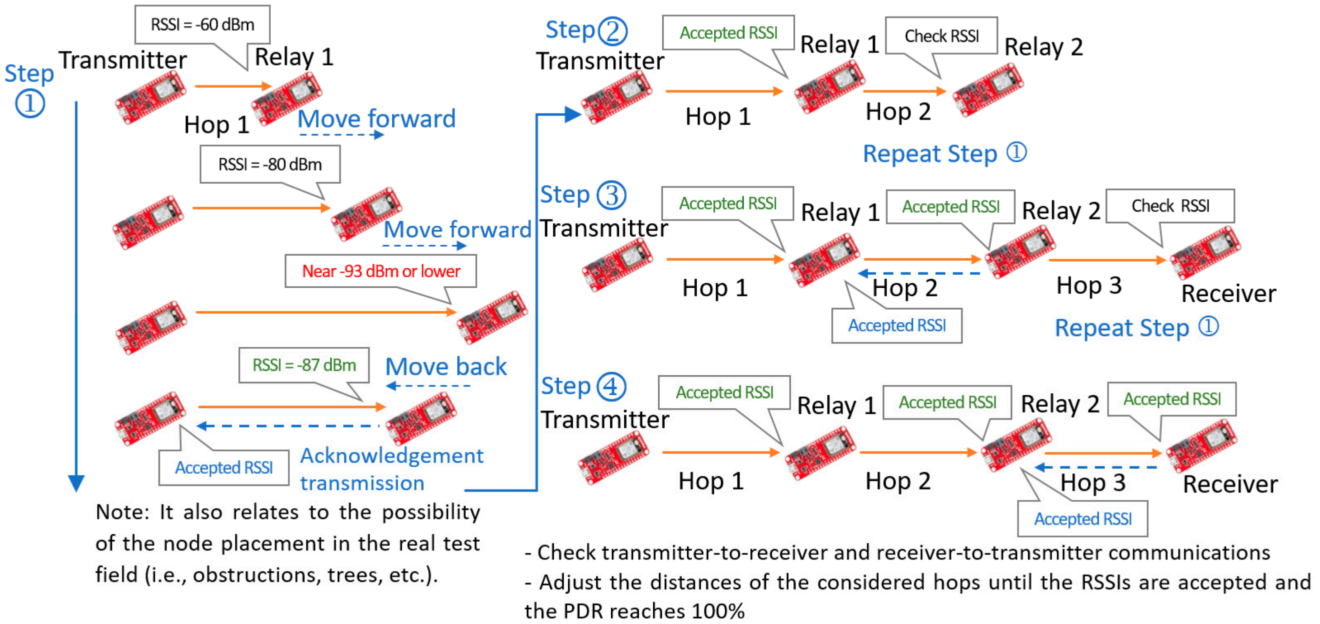
Since the receiver sensitivity of the Xbee3 micro-module is −103 dBm with an acceptable packet error rate, the RSSI signal level at each hop will be monitored first. In this work, the RSSI of each link is kept higher than −93 dBm (−10 dBm from the receiver sensitivity) by adjusting and controlling the distance between two nodes that satisfy the RSSI level. Additionally, when all links are deployed, the RSSI levels of all links and the success rate of the data transmission from the transmitter to the receiver are again checked. We stop the process if the success rate reaches 100%. If not, the link with a lower RSSI level or high possibility of a weak signal will be rechecked and adjusted. This deployment process is also demonstrated in Figure 2, where two-way communications (i.e., transmitter-to-receiver (for data packet transmission) and receiver-to-transmitter (for command and acknowledgement packet transmission)) are considered, as in Figure 2a, and the deployment processes are illustrated in Figure 2b. The final deployment result is shown in Figure 2c, where all hop distances have been adjusted according to the environment of the test field, threshold requirements, and PDR achievement. We note that −93 dBm is the illustrated threshold. It can differ depending on the test fields or applications, environmental/weather conditions, user needs, and the particular goal of each task. Finally, Figure 2d summarizes the flowchart for the node deployment process.

We should keep a strong RSSI level since, at the border of the communication range, the RSSI can fluctuate and the packet can be lost [14,15]; so, to guarantee reliable communications, this issue should be taken into consideration. Additionally, in this work, we also considered the placement of the transmitter, the relays, and the receiver, since the transmitter and the relays can be sensing sources, which should be at the optimal sensing positions, and the receiver should be placed at the optimal monitoring position to upload data to the cloud or be connected to the internet and IoT.



(**a**) Two-way communications: receiver-to-transmitter and transmitter-to-receiver.

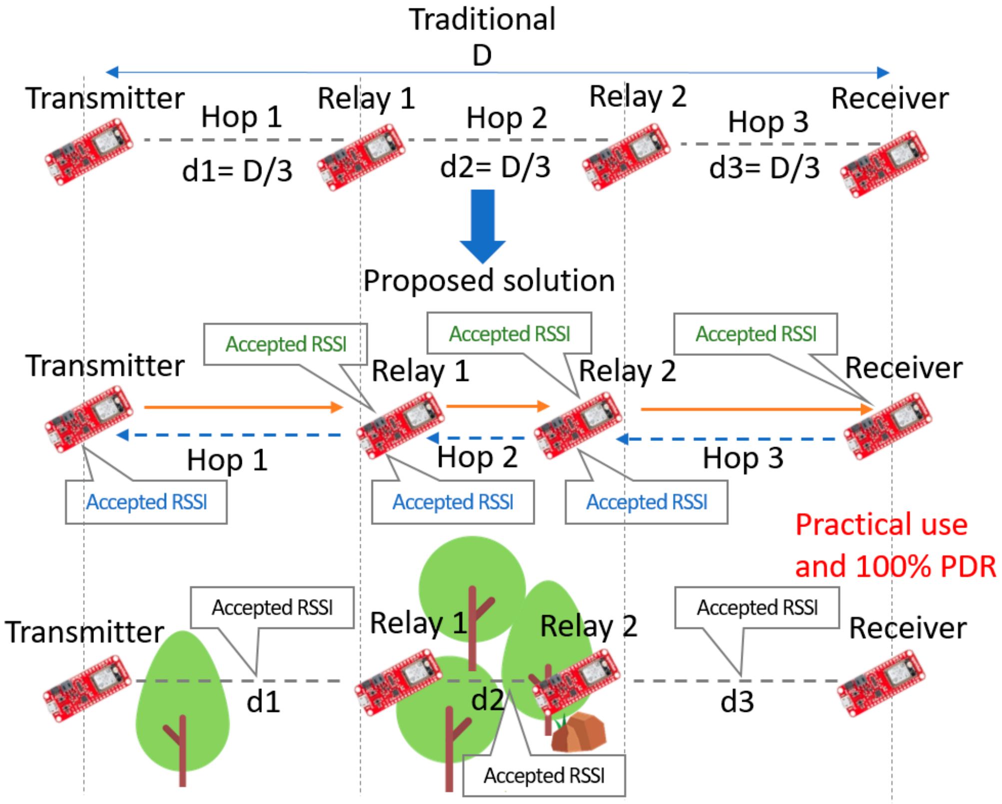
Figure 2. *Cont.*



Note: It also relates to the possibility of the node placement in the real test field (i.e., obstructions, trees, etc.).

- Check transmitter-to-receiver and receiver-to-transmitter communications
- Adjust the distances of the considered hops until the RSSIs are accepted and the PDR reaches 100%

(**b**) Proposed sensor node deployment solution.



Note:

d1 → Transmitter-to-Relay 1 or Relay 1-to-Transmitter distance

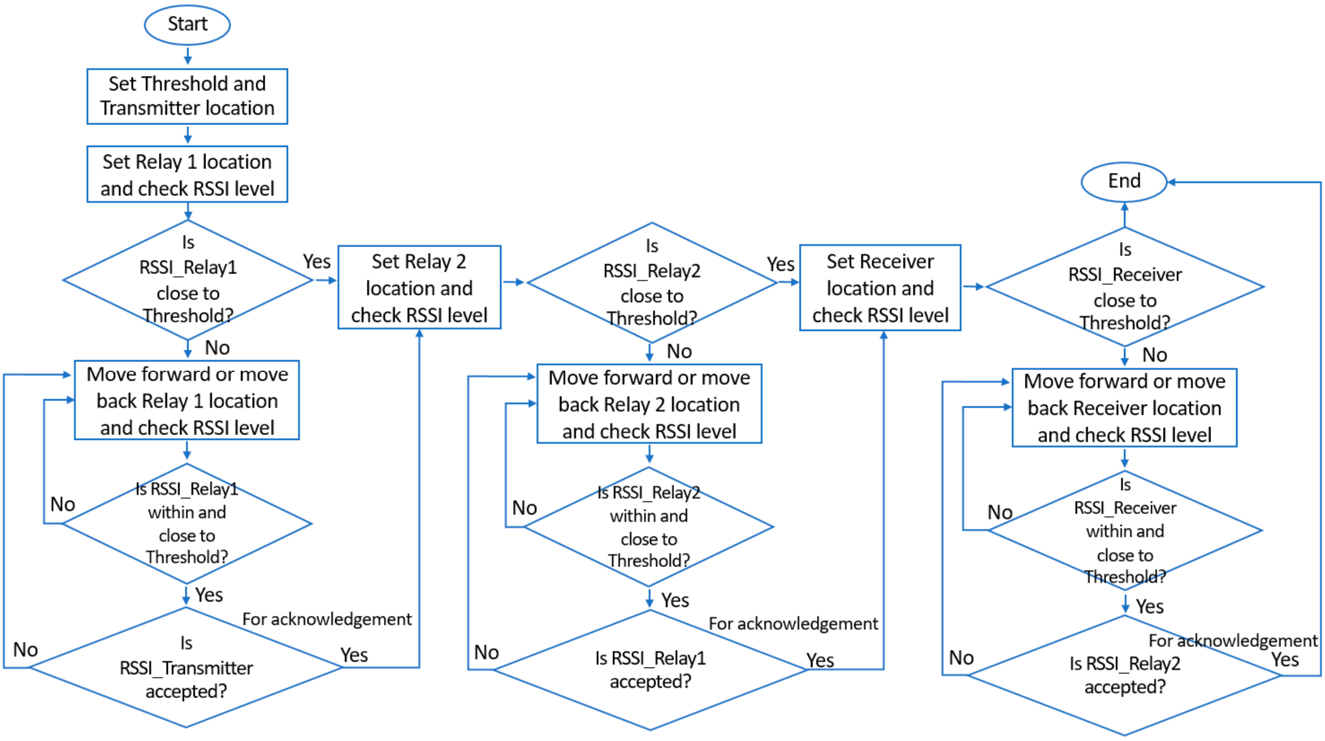
d2 → Relay 1-to-Relay 2 or Relay 2-to-Relay 1 distance

d3 → Relay 2-to-Receiver or Receiver-to-Relay 2 distance

Set d1, d2, and d3, where the RSSIs for both directions are within the Threshold and PDR → 100%

(**c**) Final deployment result.

Figure 2. *Cont.*



(**d**) Flowchart for sensor node deployment process.

Figure 2. Example of the proposed sensor node deployment process (before the data collection phase.

3. Experiments

As we mentioned before, our multi-hop WSN system was tested in two environments: mountainous forests and watercourses. The test environments were in a part of the Kho Hong Mountain in Hat-Yai City, Thailand. Test scenarios #1 and #2 are shown in Figures 3–5.

In test scenario #1, we placed all nodes in the mountainous forest environment, where the transmitter was located at the top level of the mountain (above the sea level of 75 m) and the receiver was at the lower level (above the sea level of 5 m). In this test field, the location of the sensor nodes was on sloping terrain, and there were many small and big trees, which could affect the radio signal propagation. In test scenario #2, all nodes were placed at the watercourse. The transmitter node was located at the top, near the mountain, while the relay nodes were along the watercourse and the receiver was near the reservoir.

Test scenario #1 can be referred to as the environmental monitoring application since, in such a test area, forest fire protection, landslide monitoring, and plant and animal reservations are the city's requirements. Test scenario #2 can be referred to as the flooding monitoring application since, during the rainy season, the huge amount of water from the mountain floods to the lower area, which has an effect on the city's population. Flooding in this case is also demonstrated in Figure 6. For both scenarios, each experiment was repeated twenty times, and the average results are reported.

We note that, in these experiments, we sent real data packets in every sampling period from the transmitter to the receiver, and we included the sensor information. As illustrated in Section 5.2, in the ongoing work of our research group, a three-axis accelerometer and Gyro sensors using the GY-521 module for monitoring applications have been included in the XBee3.

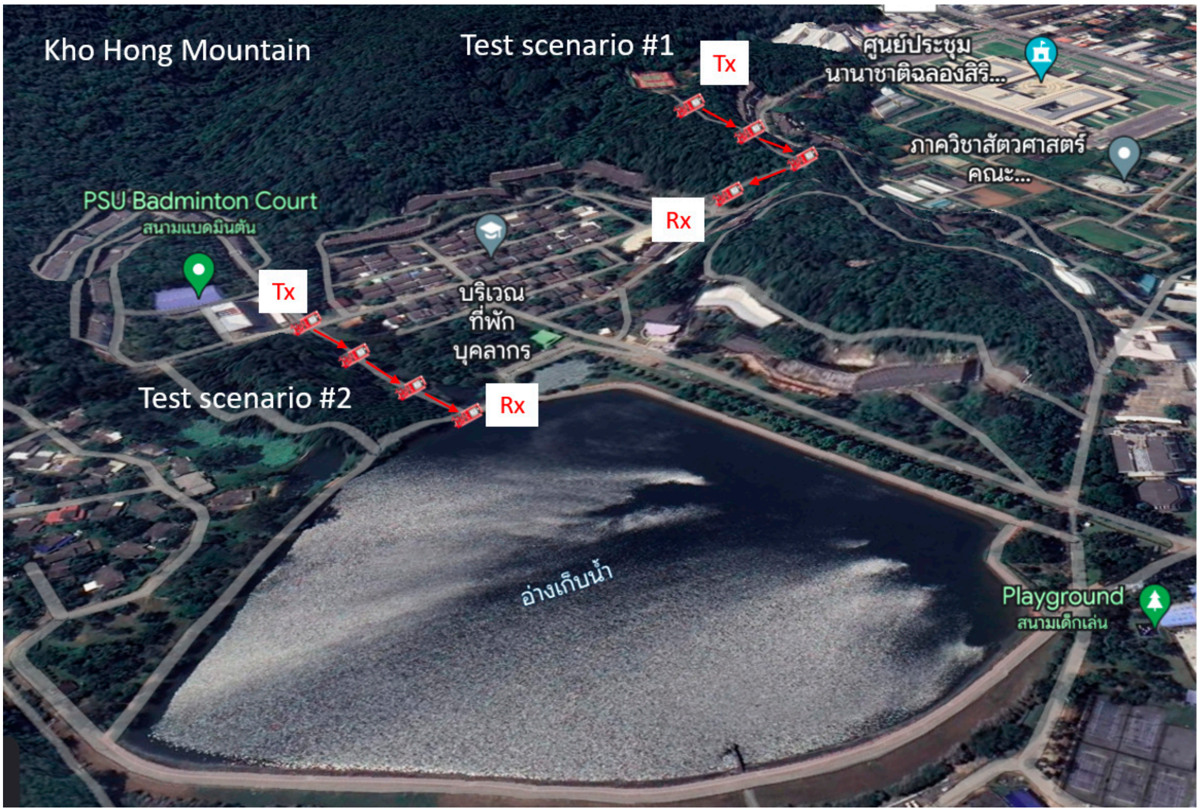
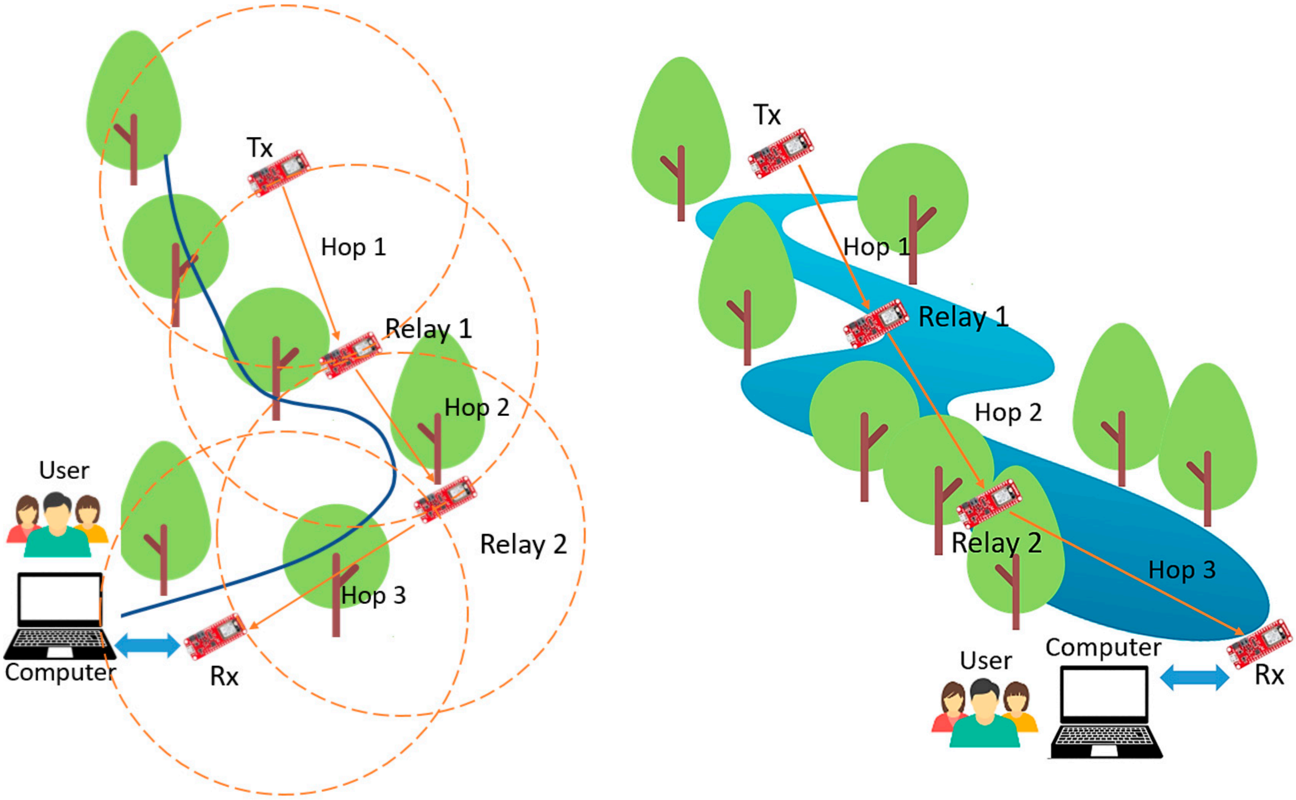
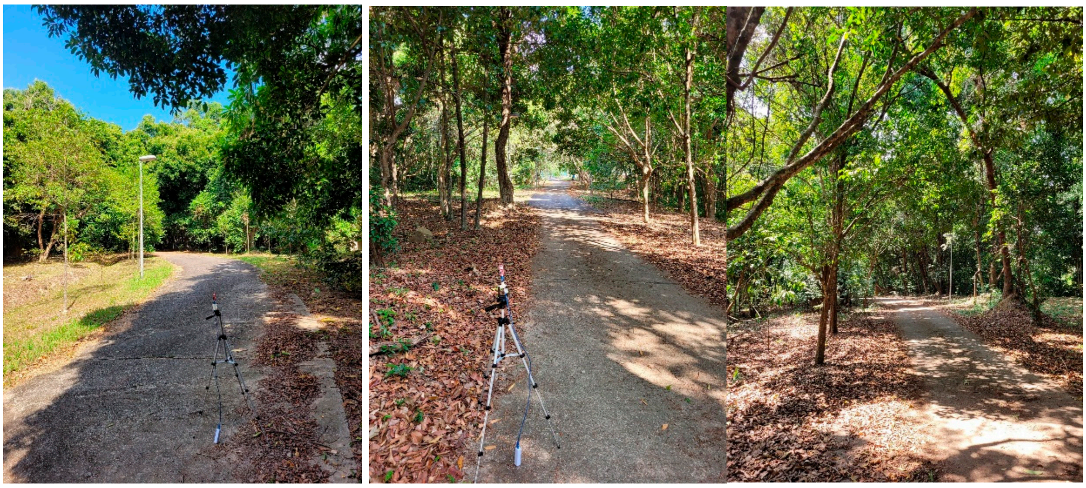


Figure 3. Test scenarios #1 and #2.



(**a**) Test scenario #1. (**b**) Test scenario #2.

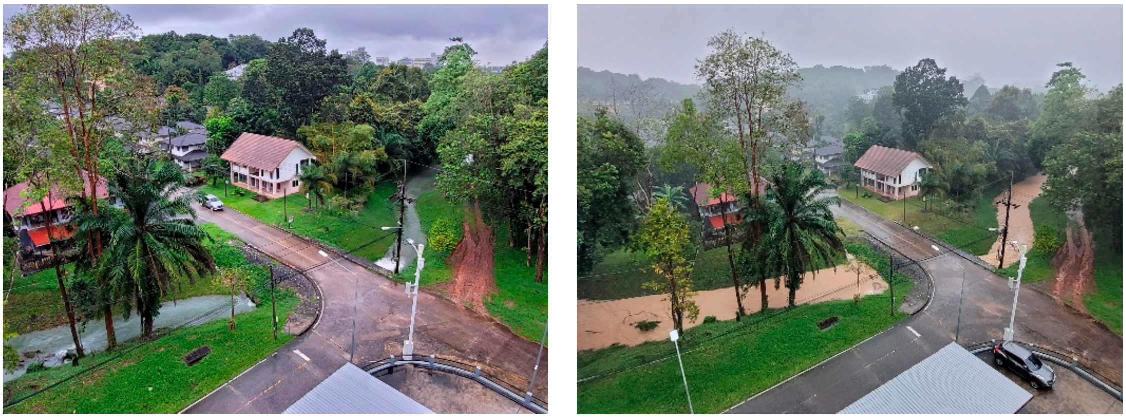
Figure 4. The test field layouts.



(**a**) Test scenario #1.

(**b**) Test scenario #2.

Figure 5. Illustration of sensor node deployment and environments.



(**a**) Before. (**b**) After.

Figure 6. An example of water flooding during the rainy season for field #2.

4. Evaluation Metrics

To study the performances of the proposed multi-hop network introduced above, three performance metrics were measured and evaluated, including the RSSI level of the three hops, the PDR, and the ETED, as shown in Equations (1)–(3).

$$\left[RSSI_{relay1,i}, RSSI_{relay2,i}\ , RSSI_{receiver,i}\right] = \begin{cases} Avg.\ from\ all\ RSSI\ samples; for\ tranmitter\ to\ relay1 \\ Avg.\ from\ all\ RSSI\ samples;\ for\ relay1\ to\ relay2 \\ Avg.\ from\ all\ RSSI\ samples; for\ relay2\ to\ receiver \end{cases}$$

$$\left[Avg.RSSI_{relay1,i}, Avg.RSSI_{relay2,i}, Avg.RSSI_{receiver,i}\right] = \begin{cases} \frac{1}{N}\sum_{i=1}^{N} RSSI_{relay1,i} \\ \frac{1}{N}\sum_{i=1}^{N} RSSI_{relay2,i} \\ \frac{1}{N}\sum_{i=1}^{N} RSSI_{receiver,i} \end{cases} \tag{1}$$

$$PDR = \frac{Num.received\ packets\ at\ receiver}{Num.\ sent\ packets\ by\ transmitter} \times 100 \tag{2}$$

$$ETED(at\ receiver) = Finish\ time\ to\ receive\ the\ last\ packet - Staring\ time\ to\ receive\ the\ first\ packet \tag{3}$$

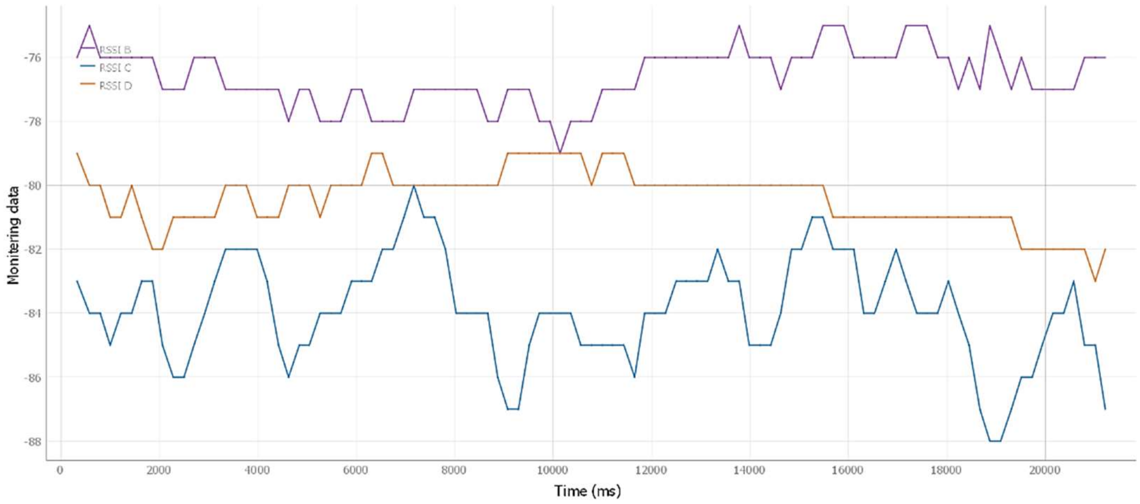
The RSSI indicates the signal power at the receiver side. In this work, both the raw RSSIs and average RSSIs of all wireless links, including transmitter-to-relay 1, relay 1-to-relay 2, and relay 2-to-receiver, were collected. A weak RSSI level can represent poor signal quality when the RSSI is significantly influenced by environmental factors [11,16,17]. The PDR represents the success level of the delivery of data from the transmitter to the receiver [18], while the ETED measures how long the network processes data transmissions. To cope with the time synchronization problem of all nodes in the network, the ETED is calculated at the receiver's side with its clock. It is the difference between the finish time of the receipt of the last data packet and the starting time of the receipt of the first data packet. As mentioned before, each experiment (test scenarios #1 and #2) was repeated twenty times, and the average RSSI, PDR, and ETED were measured and reported.

5. Experimental Results and Discussion

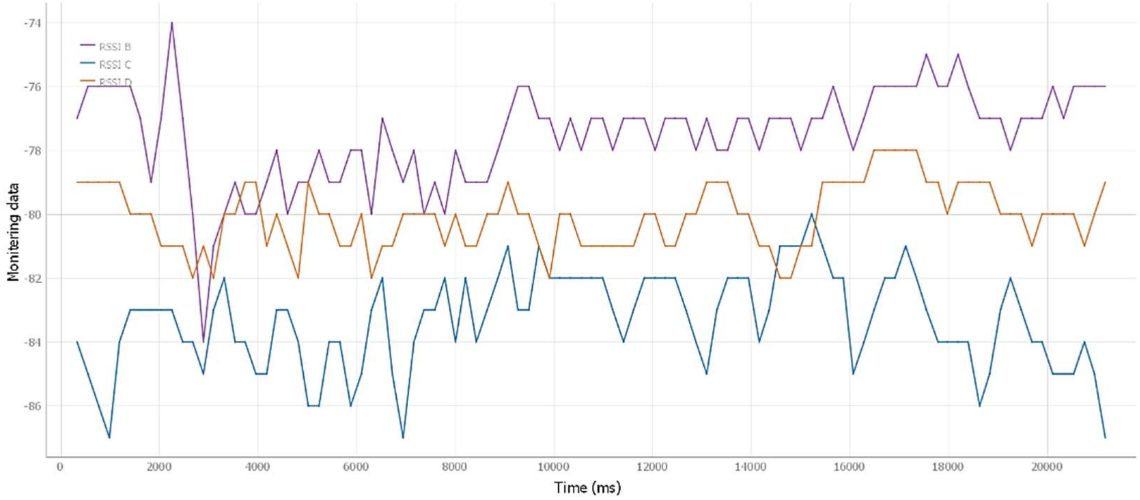
5.1. Communication Performances

The raw RSSI signals, the average RSSIs of all wireless links, the average PDR, and the average ETEDs for test scenarios #1 and #2 are demonstrated in Figures 7–10, respectively. We note that the results in Figure 7 are examples of raw RSSI signals measured and collected from test scenario # 1 (test times 5 and 15). Such signals could be displayed in real time during the test using the graphical user interface (GUI) window implemented on the computer. The average RSSI results are shown in Figure 8.

The experimental results show that during the test we could monitor the RSSI levels of all wireless links (i.e., hops 1–3) and their variations in real time. The average results from many tests in Figure 8 also show the more accurate results of the RSSI to be used for evaluation. The results here illustrate that the average RSSIs of hops 1–3 were (−80.44 dBm, −80.38 dBm, and −81.83 dBm) for test scenario #1 and (−79.78 dBm, −84.14 dBm, and −75.84 dBm) for test scenario #2. When considering the real test field, these results are correlated. Here, in test scenario #1, in the mountainous forest environment with sloping areas from high to low levels, there are many trees distributed along the road, where all sensor nodes were placed. Thus, the RSSIs of hops 1 through to 3 are not much different. For test scenario #2, at the watercourse, the transmitter node was placed at the top and near the road, and relay 1 was located at the lower level of the watercourse. Relay 2 was quite far from relay 1, and it was placed near a group of big trees, while the receiver was at the reservoir and could communicate with relay 2 via LoS communications. As a result, the RSSI level of hop 2 (−84 dBm) was the lowest in this case, while the RSSI level of hop 3 was the strongest due to the shortest distance and LoS communications. From the experiment, since each communication link in the test field was at a different location and had a different environment surrounding it, each link had a different radio propagation effect and RSSI result.



(**a**) Test scenario #1, for test time 5.



(**b**) Test scenario #1, for test time 15.

Figure 7. Examples of raw RSSI signals collected from test scenario #1 (test times 5 and 15). The signals could be displayed in real time during the test in the GUI window. Note that the y-axis is the RSSI level in dBm, and RSSI B, C, and D refer to hops 3, 2, and 1.

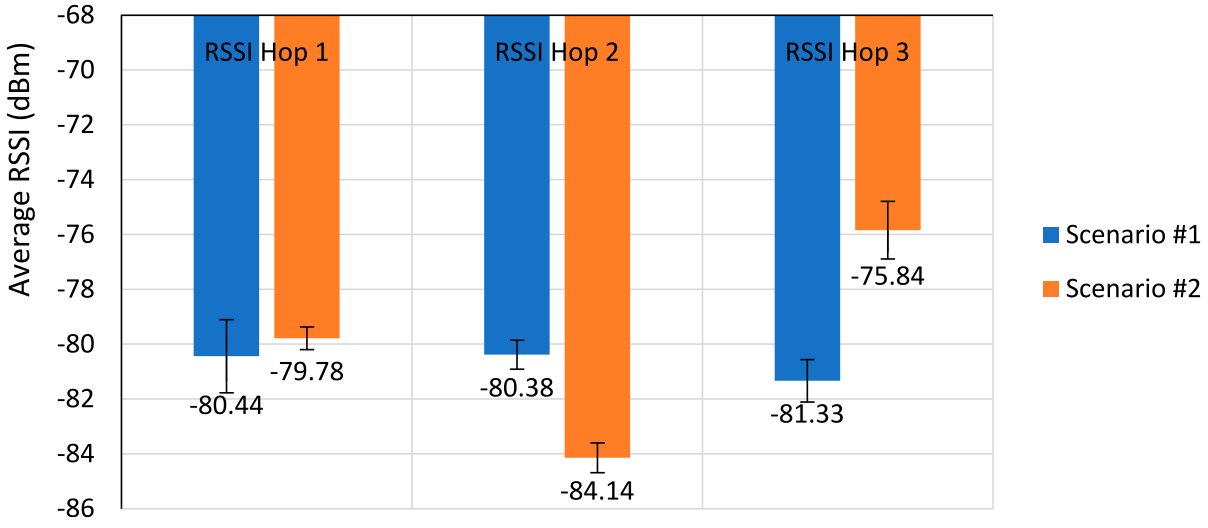


Figure 8. Average RSSIs of hops 1 to 3 for test scenarios #1 and #2.

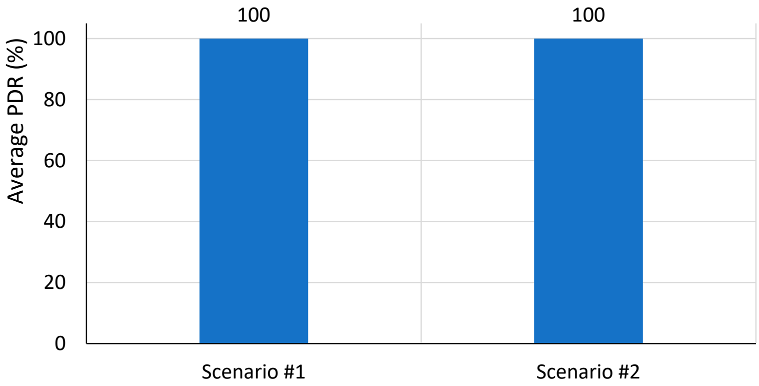
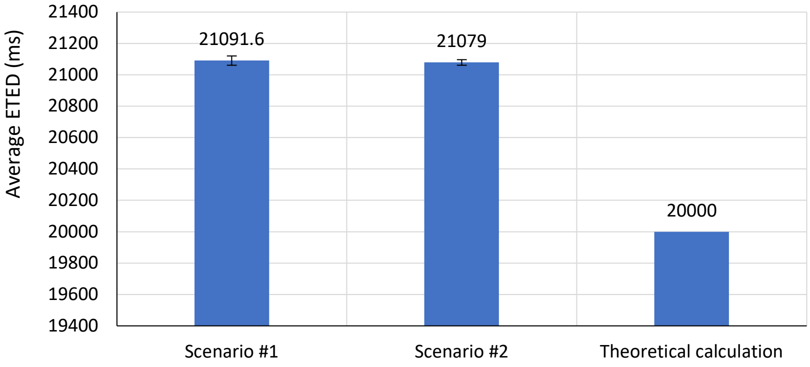
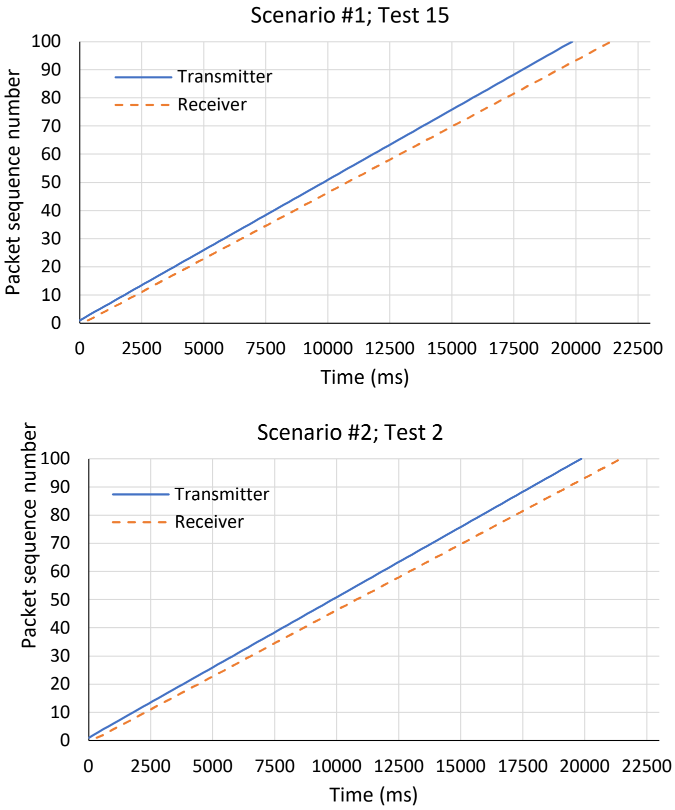


Figure 9. PDR results.



(**a**) Average ETED.



(**b**) Examples of times to process the data packets for scenario # 1 (test 15) and 2 (test 1) for the transmitter vs. the receiver. Note that, as we mentioned, each node has its own clock without network time synchronization.

Figure 10. ETED results.

The experimental results also indicate that the multi-hop network with the communication protocol and the sensor node deployment solution presented in this work could provide an average PDR of 100% for both test scenarios. This means that the transmitter could successfully send all data packets to the receiver via hop-by-hop, while the receiver could also completely receive all data streams. We note that we performed the experiments over three days in March 2023, which corresponds to the summer season in Thailand. The weather each day was quite stable. Therefore, we could obtain excellent PDRs. However, for long-term testing, the PDR may be varied due to environmental factors, so this issue should be considered for future study. Not only the PDR but also the average ETEDs obtained good results: 21,091.6 ms and 21,079 ms, for test scenarios 1 and 2, respectively. For the results here, at each test, 100 packets could be sent hop-by-hop for every sampling time (i.e., 200 ms) with a real-time response. We note that, for theoretical calculation, the ETE delay should be 20,000 ms (100 packets * 200 ms) for each test. The average ETEDs for both cases are small and very close. However, as mentioned above, long-term test should explore this point.

The experimental results in this section indicate the achievement of our objective since the implemented multi-hop network with the sensor node deployment solution obtained accepted RSSI levels, a 100% PDR, and a small ETED for the mountainous forest environment with sloping areas and the watercourse environment. We believe that our methodology and results can help users and researchers carefully consider and deploy 2.4 GHz IEEE 802.15.4 multi-hop WSNs in their work.

5.2. Sensing Results

Since, in this work, we developed the multi-hop network, the design and implementation of its wireless networks, an autonomous protocol, node deployment, and test cases related to communication evaluation were focused. For the results, as in Section 5.1, to satisfy practical use, we sent real data packets in every sampling period from the transmitter to the receiver and included the sensor information. In the ongoing work of our research group, a three-axis accelerometer and gyro sensors using the GY-521 module for monitoring applications have been included in the XBee3. It can be used to support both test scenarios #1 and #2, with scenarios such as landslide and huge water flooding monitoring [19–22].

To show the potential of our system, the proposed device and the real-time three-axis acceleration and gyro signals (i.e., acceleration: Ax, Ay, and Az; and angular velocity: Gx, Gy, and Gz) [23,24] with three different vibration behaviors collected from the multi-hop network are illustrated as examples in Figures 11 and 12, respectively. However, long-term use and performance evaluation in various scenarios should be further explored. Also, the integration of other related sensors (i.e., those recording temperature, moisture, position, etc.) and the implementation of data packet formats to achieve wireless communication capacity and satisfy applications should be further studied.

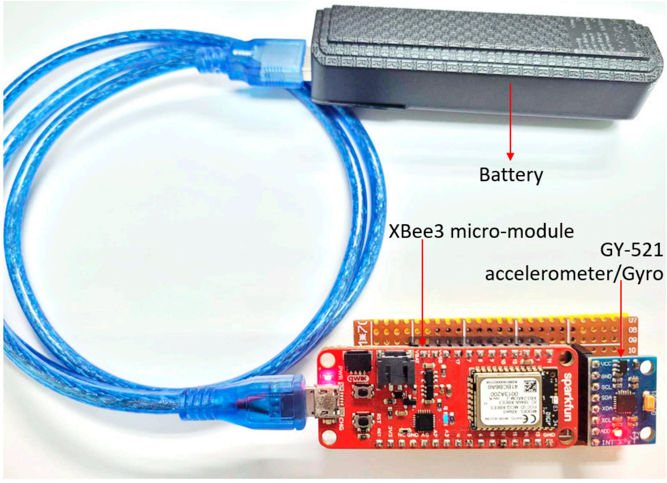


Figure 11. The XBee3 micro-module with the GY-521 accelerometer/gyro sensor and 5 V battery.

WSN explorer

Device: Xbee3
COM Port: COM7 - Silicon Labs CI
Connection: WiFi
Sampling rate (ms): 100
Packets: 300
Tx power: 8 dBm

☐ RSSI A ☐ RSSI B ☐ RSSI C ☐ RSSI D ☑ Accel X ☑ Accel Y ☑ Accel Z ☐ Gyro X ☐ Gyro Y ☐ Gyro Z
☐ MQ-5 ☐ MQ-135 ☑ Show Cursor 50
00:00.001

WSN explorer

Device: Xbee3
COM Port: COM7 - Silicon Labs CI
Connection: WiFi
Sampling rate (ms): 100
Packets: 300
Tx power: 8 dBm

☐ RSSI A ☐ RSSI B ☐ RSSI C ☐ RSSI D ☑ Accel X ☑ Accel Y ☑ Accel Z ☐ Gyro X ☐ Gyro Y ☐ Gyro Z
☐ MQ-5 ☐ MQ-135 ☑ Show Cursor 50
00:18.383

WSN explorer

Device: Xbee3
COM Port: COM7 - Silicon Labs CI
Connection: WiFi
Sampling rate (ms): 100
Packets: 300
Tx power: 8 dBm

☐ RSSI A ☐ RSSI B ☐ RSSI C ☐ RSSI D ☐ Accel X ☐ Accel Y ☐ Accel Z ☑ Gyro X ☑ Gyro Y ☑ Gyro Z
☐ MQ-5 ☐ MQ-135 ☑ Show Cursor 50
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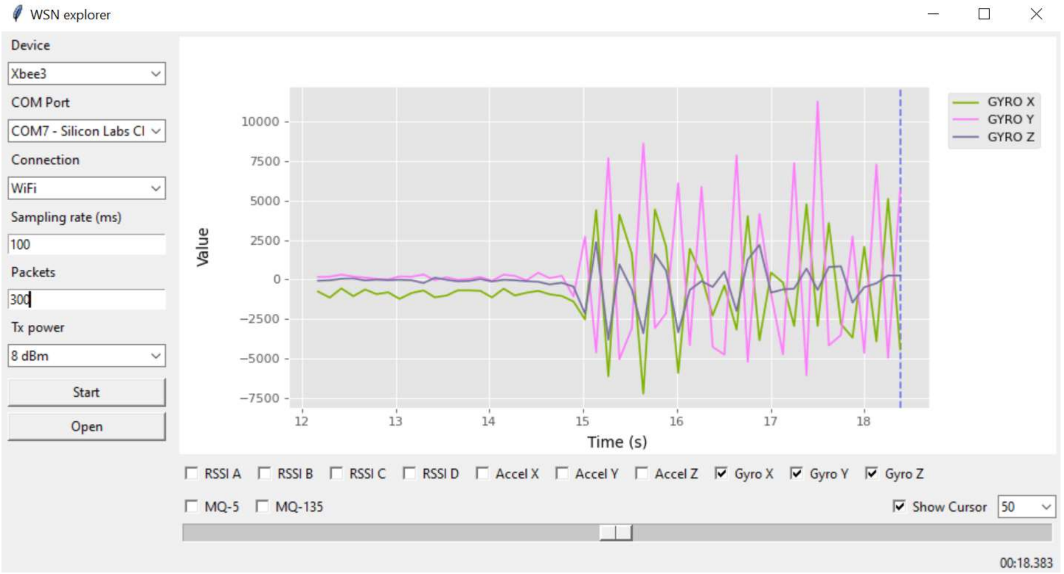
Figure 12. *Cont.*



WSN explorer

Device: Xbee3

COM Port: COM7 - Silicon Labs CI

Connection: WiFi

Sampling rate (ms): 100

Packets: 300

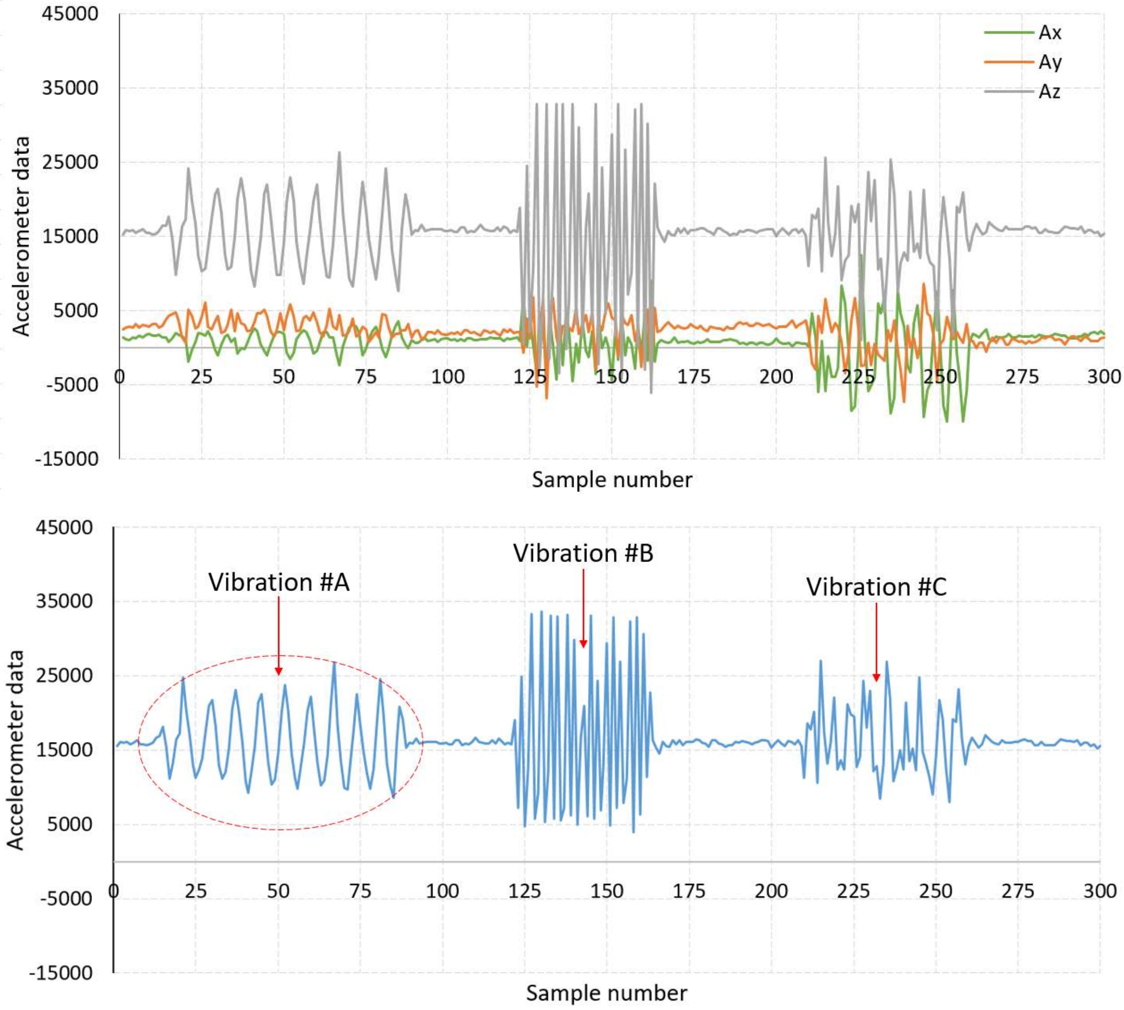
Tx power: 8 dBm

☐ RSSI A ☐ RSSI B ☐ RSSI C ☐ RSSI D ☐ Accel X ☐ Accel Y ☐ Accel Z ☑ Gyro X ☑ Gyro Y ☑ Gyro Z

☐ MQ-5 ☐ MQ-135 ☑ Show Cursor 50

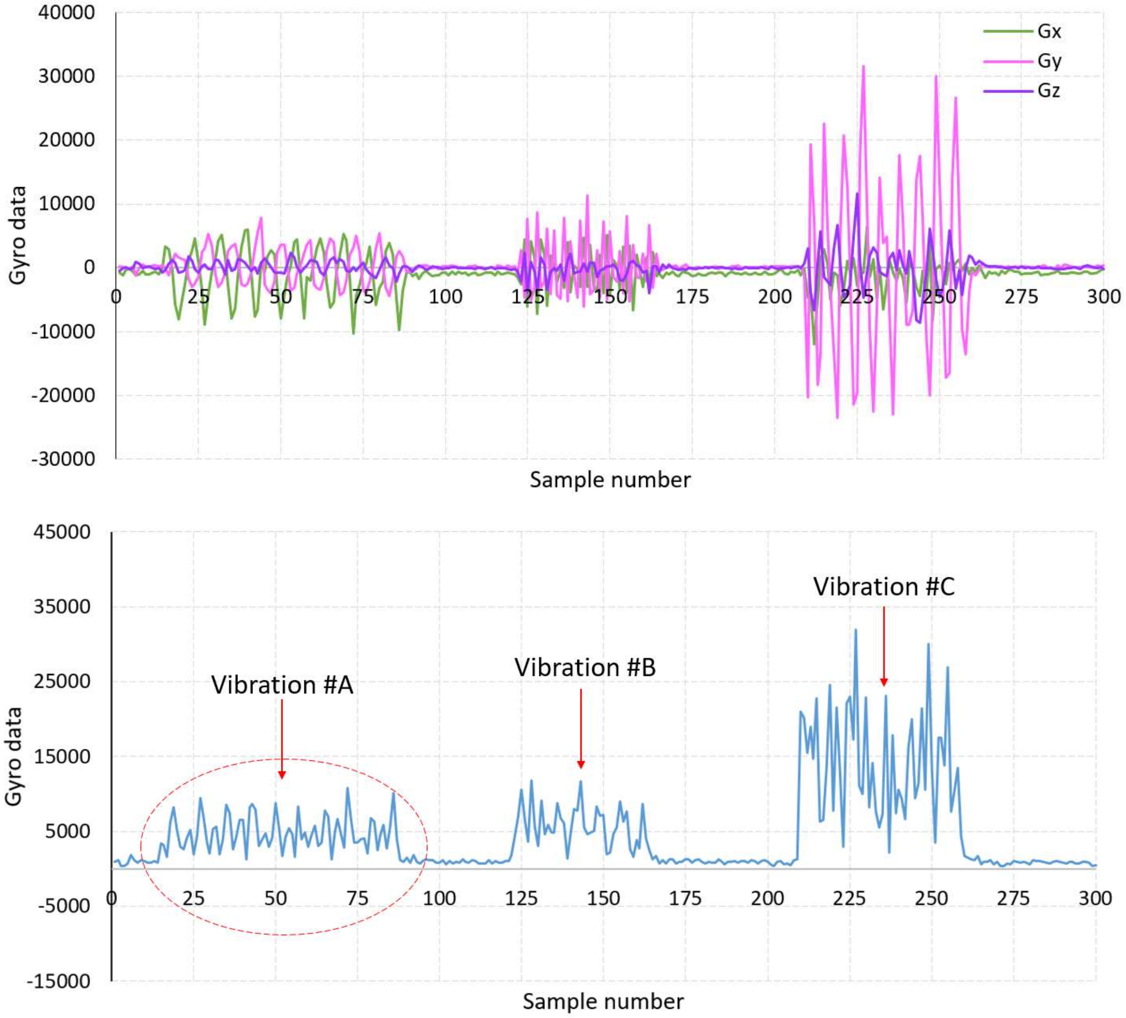
00:18.383

(**a**) Real-time three-axis acceleration and gyro signals displayed on a graphical user interface.



(**b**) Three-axis acceleration signals with three different vibration behaviors and signal vector magnitudes (SVMs) calculated from $SVM = \sqrt{(Ax^2 + Ay^2 + Az^2)}$.

Figure 12. *Cont.*



(**c**) Gyro signals with three different vibration behaviors and $SVM = \sqrt{(Gx^2 + Gy^2 + Gz^2)}$.

Figure 12. Examples of three-axis acceleration and gyro signals.

6. Conclusions

In this paper, we demonstrated the realistic test of a 2.4 GHz multi-hop wireless network for mountainous forest and watercourse environments. A multi-hop network using IEEE 802.15.4 XBee3 micro-modules and a communication protocol among nodes were developed. The wireless node deployment solution being able to maintain reliable communications for practical testing was also presented. The system was tested in two different scenarios: a mountainous forest and watercourse, which refer to environmental and flooding monitoring applications. Wireless network performances were evaluated through the RSSI level of each hop, the PDR, as the successful rate of packet transmission, and the ETED from the transmitter to the receiver. The experimental results confirm the success of the multi-hop WSN deployment and communication.

In future work, we will include more nodes in multi-hop networks where line and mesh topologies will be taken into account. Relay nodes will be integrated with sensors, and multi-source transmission in a multi-hop network will be tested. In addition, different physical protocols, node deployment densities, other frequency bands, and propagation distances in NLoS scenarios should also be considered for these applications. Finally, long-term tests should be investigated.

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Conflicts of Interest: The authors declare no conflicts of interest.

List of Abbreviations

RSSI	Received signal strength indicator
PDR	Packet delivery ratio
ETED	End-to-end delay
WSN	Wireless sensor network
IoT	Internet of Things
GUI	Graphical user interface
UAV	Unmanned aerial vehicle
NB	Narrow band
LoS	Line-of-sight
NLoS	Non-line-of-sight
GPS	Global position system
QoS	Quality of service

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