SN Computer Science (2024) 5:34
https://doi.org/10.1007/s42979-023-02381-0

ORIGINAL RESEARCH

Development of a Multi-hop Network Using XBee3 Micro-modules for Different Indoor Scenarios: Autonomous Parameter Setting and Signal Monitoring

Puwasit Hirunkitrangsri[1] · Yoschanin Sasiwat[1] · Apidet Booranawong[1]

Received: 19 April 2023 / Accepted: 30 September 2023

Abstract

In multi-hop wireless sensor networks (WSNs), since the coverage area is larger than the radio range of a single node, relay nodes in the network are employed to transfer the data to the destination with hop-by-hop communication. Here, autonomous and effective multi-hop communication to satisfy wireless communication reliability is significantly required. In this work, the development and the experimental evaluation of a 2.4 GHz indoor multi-hop WSN system are presented. The contributions and novelties of this work are that, first, we develop a multi-hop WSN utilizing IEEE 802.15.4 Xbee3 micro-modules, and we build the communication protocol for all wireless sensor nodes, as well as the graphical user interface (GUI) for autonomous parameter setup and signal monitoring. Second, the proposed system is tested in different indoor scenarios, including line-of-sight (LoS) communications, non-line-of-sight (NLoS), different floor communications, and spiral staircase tower scenarios. The effects of different node placement locations, communication directions, and transmission powers are also explored. Experimental results demonstrate that the proposed system can operate autonomously and efficiently in all test scenarios, where a packet delivery ratio (PDR) reaches 100% as the successful rate of packet transmission. Additionally, the end-to-end delay (ETED) from the transmitter to the receiver nodes and the received signal strength indicator (RSSI) level measured from each communication link are also reported for evaluation and analysis. Experimental results indicate our success in implementation and usability for WSN indoor deployment.

Keywords Multi-hop · WSN · 2.4 GHz · IEEE 802.15.4 · XBee3 micro

Abbreviations

WSN	Wireless sensor network
GUI	Graphical user interface
LoS	Line-of-sight
NLoS	Non-line-of-sight
PDR	Packet delivery ratio
ETED	End-to-end delay
RSSI	Received signal strength indicator
ADC	Analog-to-digital converter
EMG	Electromyography
BS	Base station
GPS	Global positioning system
EEG	Electrocardiogram
QoS	Quality of service
SD	Standard deviation
ISM	Industrial, scientific, and medical
BLE	Bluetooth low energy

Introduction

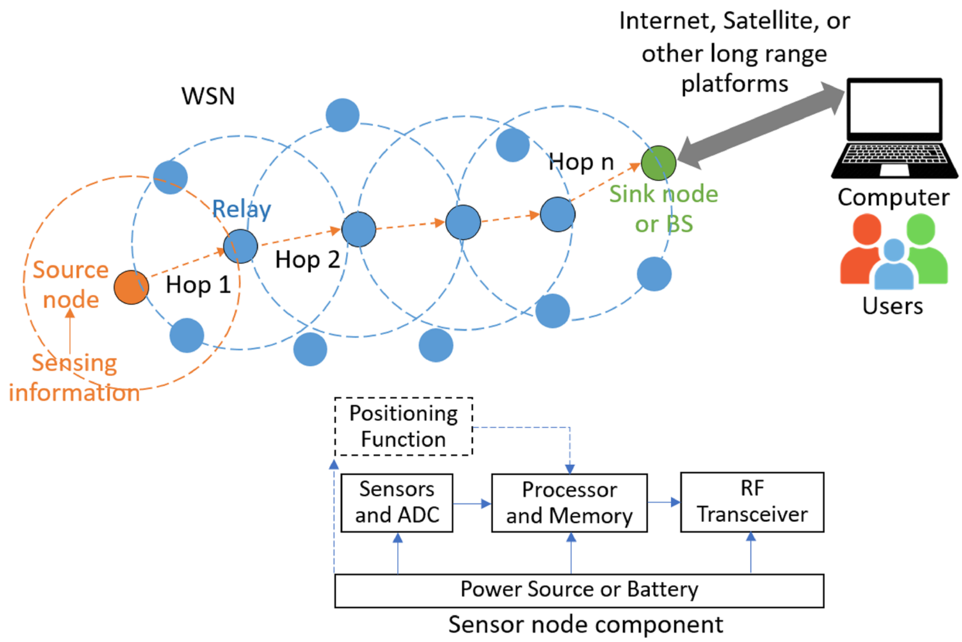
In recent years, wireless sensor networks (WSNs) have been considered one of the technological fields that are rapidly evolving [1, 2]. WSNs refer to a group of dispersed sensor nodes or motes that are interconnected by wireless communication, as shown in Fig. 1. A sensor node as an electronic device consists of a processor with a storage unit, a transceiver module, a single or multiple sensors, an analog-to-digital converter (ADC), and a limited power source (a battery). It may optionally include a positioning unit for better utilization. The sensor node, as the source node, measures and collects information from physical environments or interested sources, such as temperature, gas, vibration,

✉ Apidet Booranawong
apidet.boo@gmail.com; apidet.b@psu.ac.th

1 Department of Electrical and Biomedical Engineering, Faculty of Engineering, Prince of Songkla University, Songkhla 90110, Thailand

Published online: 27 November 2023

Fig. 1 Wireless sensor network and sensor node component



motion, image, electromyography (EMG) data, etc. It then transmits the sensory data to the base station (BS) or the sink node for monitoring and processing [3]. Since the coverage area is larger than the radio range of a single node (i.e., short-range communication), other relay or forwarder nodes in the network with forwarding functions are used to transfer the data to the destination with a hop-by-hop connection. Thus, efficient multi-hop communication that satisfies communication reliability and network lifetime is significantly required [4, 5].

Due to this characteristic of WSNs, WSNs with Internet of Things (IoT) technology [2] can be employed in various fields. Applications for WSNs from the past to present have been growing continuously, including military, health, environmental, flora and fauna [6], industrial [2], and urban applications [1]. We also summarize WSN applications from the past to present as presented in the literature, in Table 1.

To the best of our knowledge, according to the literature survey [7–17] provided in Sect. "Related Works", we summarized that several works developed multi-hop WSN for

Table 1 Wireless sensor network applications

WSN applications					
Military	Health	Environmental	Flora and fauna	Industrial	Urban
Battlefield surveillance Combat monitoring Intruder detection	Patient wearable monitoring Home assisting systems Hospital patient monitoring Wireless body area network Sport training and monitoring Medical service	Water/air/weather/gas monitoring Marine monitoring Underwater WSN Underground coal mines Underground chemical plume tracking Natural disaster management Snow monitoring Emergency alerting Seismic activity Landslide Volcanic activity Forest fire Tsunami detection	Greenhouse Crop monitoring Smart agriculture Plant disease and insect pests Livestock farming Animal monitoring and tracking	Industrial monitoring and control Industrial safety and ecological monitoring Logistics Robotics Machinery health monitoring	Smart cities Smart homes Shopping mall service Underground/ tunnel/ worker tracking Construction site Transportation systems Traffic monitoring and management Road lighting energy-saving and control Railway infrastructure monitoring Structural health monitoring Electric power /Smart grid monitoring Smart meter monitoring and control

Table 2 A comparison between this work and related works

Work	Wireless technology	Simulation/Experiment Outdoor/Indoor test	Objects and major findings
[7]	MICA2 motes 868–916 MHz	Experiment Indoor	Relay nodes could be used to extend the communication range via multi-hop relaying
[8]	IEEE 802.11b/g standard	Experiment Indoor	Mobile multi-hop wireless networks were investigated Wireless connection quality was dynamic in nature, particularly in mobile situations
[9]	XBee Series 2, XB24-ZB 2.4 GHz, IEEE 802.15.4	Experiment Indoor	Using the cyclic sleep mode, the power consumption of ZigBee devices could be lowered, extending the network's lifetime
[10]	Mica2 motes with Chipcon 1000 RF modules, 433 MHz	Experiment Outdoor	Development of the multi-hop WSN for wildfire monitoring The sensing nodes should be placed 0.5 m above the top of the fuel to prevent transmission packet loss
[11]	TelosB motes with CC2420 transceivers 2.4 GHz, IEEE 802.15.4	Experiment Outdoor	Development of the multi-hop WSN for agricultural field monitoring RSSI levels, packet losses, PDR, and the relationship between battery voltage and remaining capacity were evaluated
[12]	Sensor nodes with Chipcon CC2420 2.4 GHz, IEEE 802.15.4	Experiment Indoor	Development of the multi-hop WSN for monitoring the health of heritage buildings Low-power mode setup and wake-up techniques could help increase the network's lifespan
[13]	Zigbee modules, Ubec UZ2400 2.4 GHz, IEEE 802.15.4	Experiment Indoor	Development of the multi-hop WSN for patient monitoring Proposed transmission strategy assured the successful delivery of crucial messages
[14]	IEEE 802.11 WLANs	Experiment –	Performance evaluation of video streaming in multi-hop wireless networks Inter- and intra-flow interference had a significant influence on video quality
[15]	Zigbee node 2.4 GHz, IEEE 802.15.4	Experiment Indoor	Development of a home security system that used a jumping robot as a surveillance terminal There were no lost packets in the first three hops, but here were multiple packets lost in the fourth and sixth hops
[16]	ITRI ZBnode with Chipcon CC2420 2.4 GHz, IEEE 802.15.4	Experiment Indoor	Performance evaluation of a ZigBee wireless network The greater the number of hops, the greater the packet loss rate
[17]	Tmote sky sensor node 2.4 GHz, IEEE 802.15.4	Experiment Indoor	Development of the multi-hop WSN for indoor environments The PDR achieved over 100% in LoS settings, but dropped to 14.40% in outdoor-to-indoor contexts with NLoS
This work	XBee3 micro-modules 2.4 GHz, IEEE 802.15.4	Experiment Indoor	Development of the multi-hop WSN for different indoor scenarios The reliable wireless transmission protocol and the GUI for autonomous parameter setup and monitoring are proposed The proposed system is tested in various indoor scenarios: LoS, NLoS, different floors, and a spiral staircase tower Different node installation positions, communication directions, and transmit powers are included for study The PDR is close to 100% with a small ETED. The RSSI levels are measured and reported for evaluation

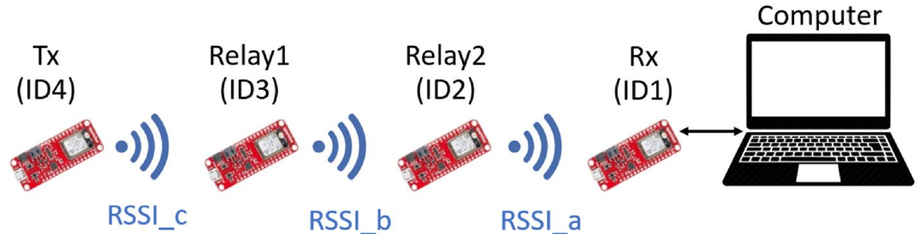
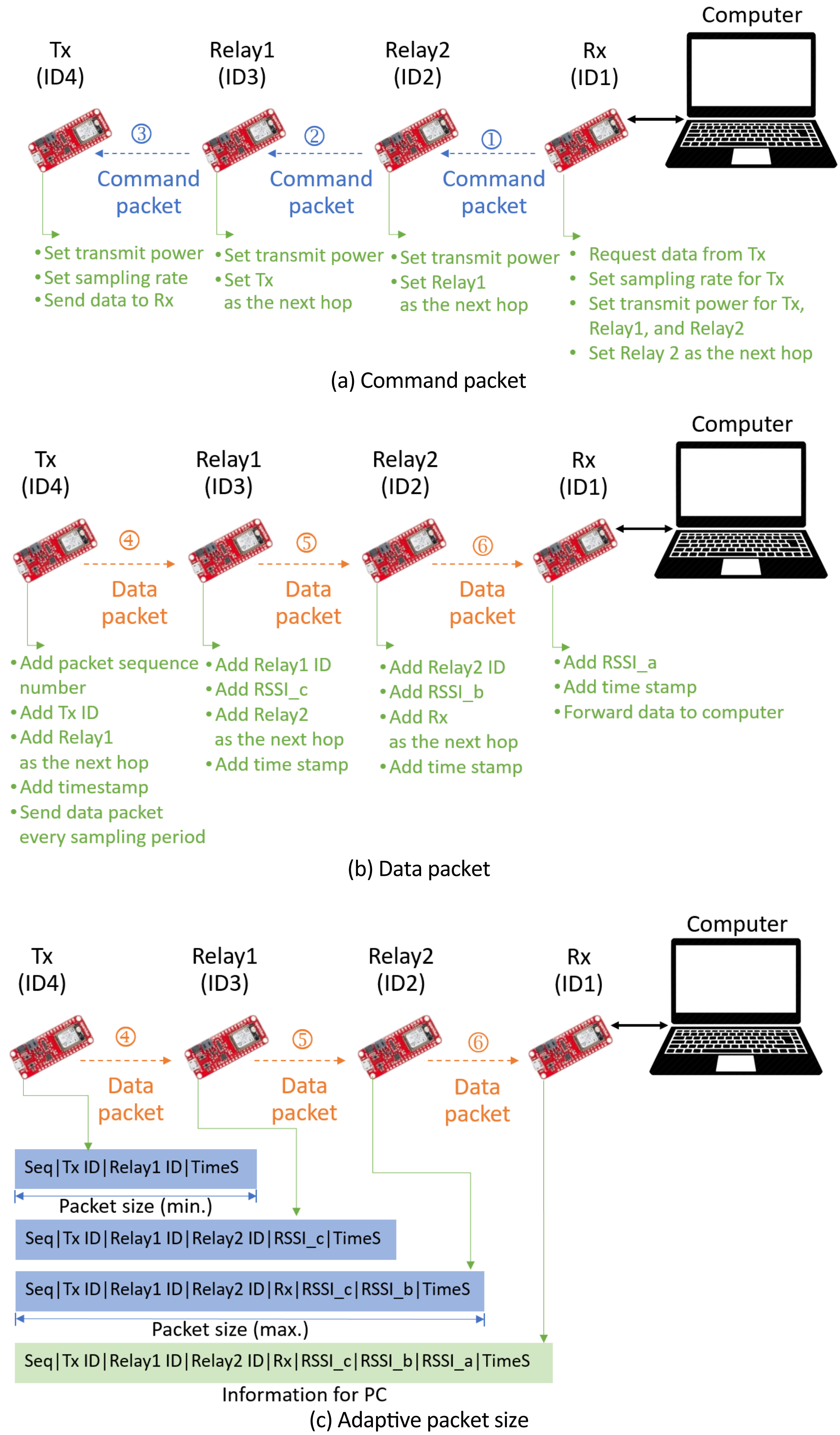


Fig. 2 A multi-hop WSN using XBee3 micro-modules

Fig. 3 The commination sequence of all nodes in the network



specific applications [10–13, 15]. Relay node deployment [7, 10], wireless link quality and radio interference [7, 8], energy consumption and network lifetime [9, 11, 12], and multi-hop transmission strategy to achieve communication reliability [13–17] are the important issues that should be taken into account in order to develop more efficient multi-hop WSNs. Additionally, performance evaluation of multi-hop WSNs includes measuring RSSI level, PDR, network throughput, packet delay, packet loss, network recovery time, battery voltage, remaining capacity, energy consumption, the network's lifespan, and node connectivity.

In this work, the development and the practical testing of a 2.4 GHz indoor multi-hop WSN system are presented. The contributions and the novelties of this work are twofold:

- First, we build the multi-hop WSN utilizing low-power IEEE 802.15.4 Xbee3 micro-modules, where we propose the reliable wireless transmission protocol as well as the GUI for autonomous parameter setup and signal monitoring.
- Second, the proposed system is tested in various indoor scenarios, such as LoS, NLoS, different floors, and a spiral staircase tower. Here, different node installation positions, communication directions, and transmit powers are also included for investigation.

Findings show that the proposed system can function independently and effectively in all test scenarios. The PDR indicating multi-hop communication reliability is close to 100% with a small ETED. The RSSI levels are also measured and reported for evaluation. The experimental findings confirm that we were successful in terms of implementation and usability for multi-hop WSN.

The structure of this paper is as follows: Related works are discussed in Sect. "Related Works", and the implemented multi-hop WSN, including hardware, specifications, wireless communication protocol, and GUI for parameter setting and monitoring, are presented in Sect. "Development of a Multi-Hop WSN Using XBee3 Micro Modules". Sect. "Experiments" describes the experimental setup, test scenarios, and performance metrics. Results and discussion are in Sect. "Experimental Results and Discussion". Finally, we conclude the paper and also list the future work in Sect. "Conclusions."

Related Works

A review of related works related to multi-hop WSNs is presented here. We also summarized them in Table 2. According to [7], when the range of single-hop wireless communication is limited by distance or harsh radio propagation conditions (such as in large buildings made of heavy construction or underground structures), relay nodes can be used to extend the communication range via multi-hop relaying. Thus, [7] demonstrated and tested MICA2 motes operating at 868–916 MHz using a relay deployment and link assessment method in an office building context. The authors claimed that selecting proper relay nodes could greatly increase communication performance. In [8], the experiment used the IEEE 802.11b/g standard to investigate the mobile multi-hop wireless network for a building environment. The authors found that wireless connection quality was dynamic in nature, particularly in mobile situations, and that the packet delivery ratio, which indicates communication reliability, varied from high to low levels over time. The performance of ZigBee networks in an indoor

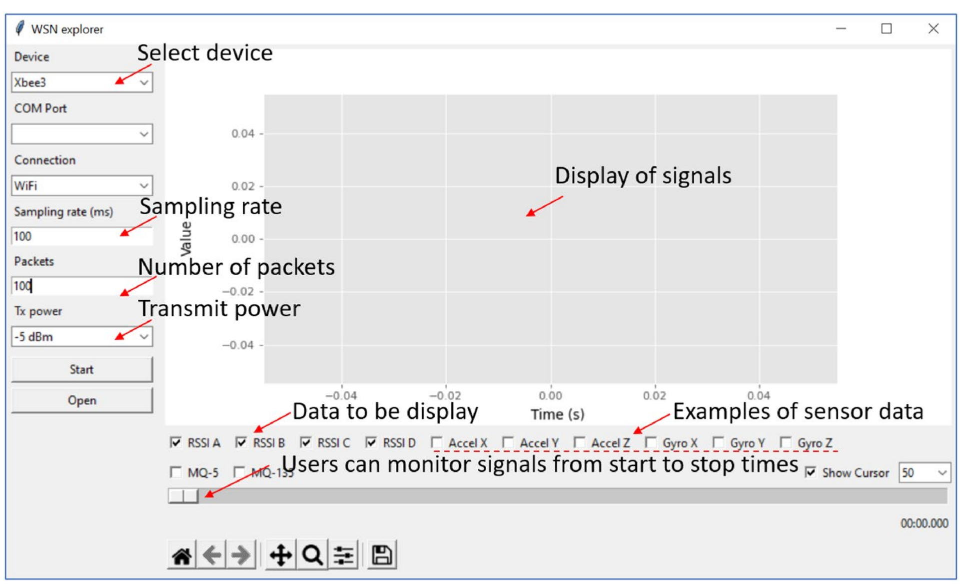
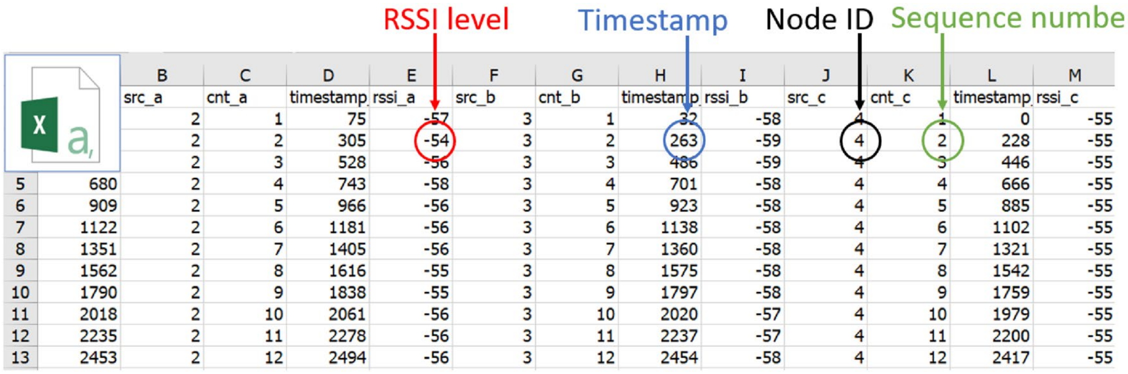


Fig. 4 GUI for parameter setting and signal monitoring



		B	C	D	E	F	G	H	I	J	K	L	M
		src_a	cnt_a	timestamp	rssi_a	src_b	cnt_b	timestamp	rssi_b	src_c	cnt_c	timestamp	rssi_c
		2	1	75	-57	3	1	32	-58	4	1	0	-55
		2	2	305	-54	3	2	263	-59	4	2	228	-55
		2	3	528	-56	3	3	486	-59	4	3	446	-55
5	680	2	4	743	-58	3	4	701	-58	4	4	666	-55
6	909	2	5	966	-56	3	5	923	-58	4	5	885	-55
7	1122	2	6	1181	-56	3	6	1138	-58	4	6	1102	-55
8	1351	2	7	1405	-56	3	7	1360	-58	4	7	1321	-55
9	1562	2	8	1616	-55	3	8	1575	-58	4	8	1542	-55
10	1790	2	9	1838	-55	3	9	1797	-58	4	9	1759	-55
11	2018	2	10	2061	-56	3	10	2020	-57	4	10	1979	-55
12	2235	2	11	2278	-56	3	11	2237	-57	4	11	2200	-55
13	2453	2	12	2494	-56	3	12	2454	-58	4	12	2417	-55

Fig. 5 Example of data collected from the multi-hop network

setting was examined in terms of the following performance measures in [9]: RSSI, network throughput, packet delay, network recovery time, and energy consumption. The studies were carried out in a 40 m indoor area utilizing XBee Series 2 modules from Digi International, model XB24-ZB. The authors suggested that using the cyclic sleep mode, the power consumption of ZigBee end devices could be efficiently lowered, extending the network's lifetime.

The authors of [10] developed a multi-hop WSN for wildfire tracking. Temperature, relative humidity, and barometric pressure were measured in the field at Pinole Point Regional Park (Contra Costa County, California, near San Francisco) during prescribed test burns. Ten sensor nodes, Mica2 motes with Chipcon 1000 RF modules (433 MHz frequency) and global positioning systems (GPS), were configured and tested using TinyOS. According to the results, all sensor data were successfully transmitted. The authors also stated that the sensing nodes should be placed 0.5 m above the top of the fuel to prevent transmission packet loss. The development of a multi-hop network for monitoring applications is presented in [11]. The WSN was built with twenty-four nodes that were placed in an agricultural area. TelosB motes equipped with IEEE 802.15.4-compliant CC2420 transceivers were employed as wireless sensor nodes, with different sensors monitoring soil moisture, soil temperature, air temperature, and relative humidity included. As part of the system performance evaluation, the authors also assessed RSSI levels, the number of packet losses, the number of packets delivered, and the relationship between battery voltage and remaining capacity. According to the testing results, wireless networks in agricultural fields were relatively robust in nature. Their technology could be utilized to collect sensor data over time while reducing energy use.

A WSN system for monitoring the health of heritage buildings in real time is presented in [12]. The multi-hop WSN was created, which included temperature sensors, humidity sensors, masonry crack sensors, rain gage sensors, and light sensors. The sensor nodes with Chipcon CC2420 (2.4 GHz, an IEEE 802.15.4 standard) were placed and tested on the Rognosa tower in the historic village of San Gimignano, Tuscany, Italy. According to the authors, from the perspective of a communication network, an adequate energy-saving policy with low-power mode setup and wake-up techniques could help increase the network's lifespan. [13] demonstrated a wireless patient monitoring system based on ZigBee. To accomplish real-time fall detection and physiologic monitoring, the authors develop a ZigBee-based prototype of a fall monitoring system comprising a tri-axial accelerometer and an electrocardiogram (ECG) sensor. When a fall event was detected, the data was delivered through multi-hop communications to the destination or the emergency center. The authors concluded that their transmission strategy assured the successful delivery of crucial messages and was quick and reliable based on their testing using seven ZigBee modules.

Performance evaluation of video streaming in multi-hop wireless networks based on IEEE 802.11 WLANs was evaluated in [14]. The authors found that the unreliability and shared media of multi-hop connections made it challenging to implement multimedia solutions. Interference from radio signals harmed video performance in this case. Inter- and intra-flow interference both had a significant influence on video quality. As a result, well-designed and deployed multi-hop wireless networks for quality of service (QoS) provisioning to support multimedia applications should be taken into account. [15] described a home security system that used a jumping robot as a surveillance terminal. The system featured the jumping robot, a gateway, and PIR sensor nodes that create a ZigBee WSN. The sensor nodes were placed above the house's doors and windows to detect intruders and send intrusion detection alerts to the robot. The robot could jump to the sensor coverage area and capture images, which it could then communicate to the gateway and the home server via multi-hop communications. The photos will be obtained by the owner of the remote residence over the Internet.

Table 3 Experimental information and objectives for each test scenario

Test scenarios	Objectives	Environments		Additional details
		LoS/NLoS	Floor	
#1 Figure 7(a)	To check the correction of the communication sequences among nodes (i.e., multi-hop communications in Fig. 3) and RSSI levels at each test distance	LoS	2nd floor	Tx and Rx are outside the room, on the 2nd floor Test distances at 1 m, 3 m, and 5 m
#2 Figure 7(b)	To study multi-hop LoS communications	LoS	2nd floor	Tx and Rx are outside the room, on the 2nd floor Longer distance and different node deployment compared with the case #1
#3 Figure 7(c)	To study multi-hop NLoS communications, where all nodes are on the same floor	NLoS	2nd floor	Tx is outside the room, and Rx is in the room All nodes are on the 2nd floor
#4 Figure 7(d)	To study multi-hop NLoS communications, where nodes are on the different floors	NLoS	2nd floor to 1st floor to 2nd floor	Tx is outside the room and Rx is in the room Tx, Rx, and relay 1 are on the 2nd floor, while relay 2 is on the 1st floor
#5 Figure 7(e)	To study multi-hop NLoS communications, where nodes are on the different floors	NLoS	1st floor to 2nd floor	Tx and Rx are outside the room Tx and Rx are on the opposite side compared with the cases #3 and #4 Tx and relay 1 are on the 1st floor, while relay 2 and Rx are on the 2nd floor
#6 Figure 7(f)	To study multi-hop NLoS communications in the spiral staircase tower, where different node placements and transmit powers are considered	NLoS	Multi-floors Spiral staircase tower	Tx is at the top level, and Rx is at the ground level All nodes are in the same vertical position Transmit powers from -5 to 8 dBm
#7 Figure 7(g)	To study multi-hop NLoS communications in the spiral staircase tower, where different node placements and transmit powers are considered	LoS	Multi-floors Spiral staircase tower	Tx is at the top level, and Rx is at the ground level Nodes are in the different vertical positions Transmit powers from − 5 to 8 dBm

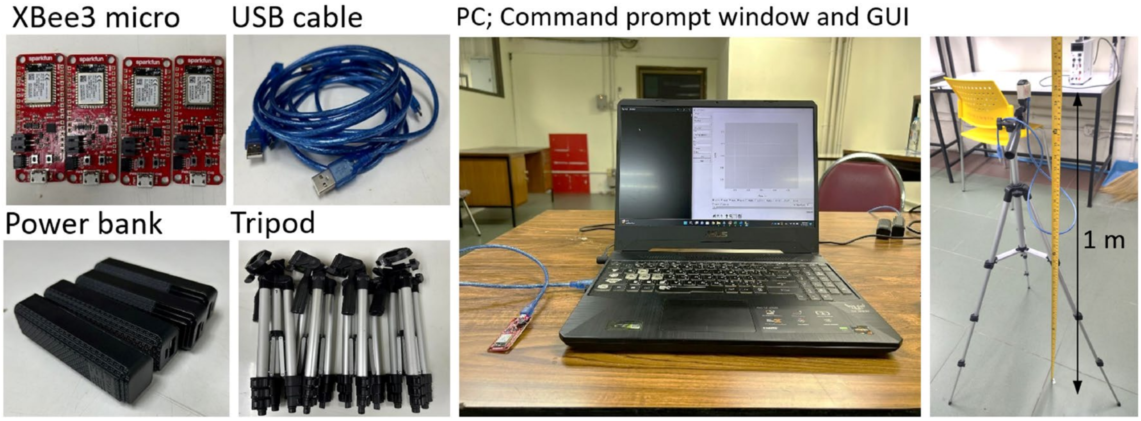


Fig. 6 List of the system's devices

The multi-hop photo transmission test revealed that the time delay of data transmission rises very little as the number of communication hops grows. There were no lost packets in the first three hops, but here were multiple packets lost in the fourth and sixth hops, with a loss rate of 40.8%.

The authors of [16] created a realistic indoor environment for evaluating the performance of a ZigBee wireless network. Several sets of practical experiments were carried out utilizing ITRI ZBnode with Chipcon CC2420, including node connectivity, packet loss rate, and transmission throughput evaluations. The results demonstrated that their built ZigBee platforms performed effectively in multi-hop transmission. The authors also determined that the greater the number of hops between the transmitter and the receiver, the greater the packet loss rate. Furthermore, by employing a more effective communication mechanism, the rate of packet loss could be reduced. Finally, [17] described the deployment of a 2.4 GHz multi-hop WSN in which multi-hop communication was suggested and communication reliability was investigated. Tmote sky sensor node experiments were carried out. The authors reported that communication reliability as assessed by the PDR achieved over 100% in LoS settings, but dropped to 14.40% in outdoor-to-indoor contexts with NLoS.

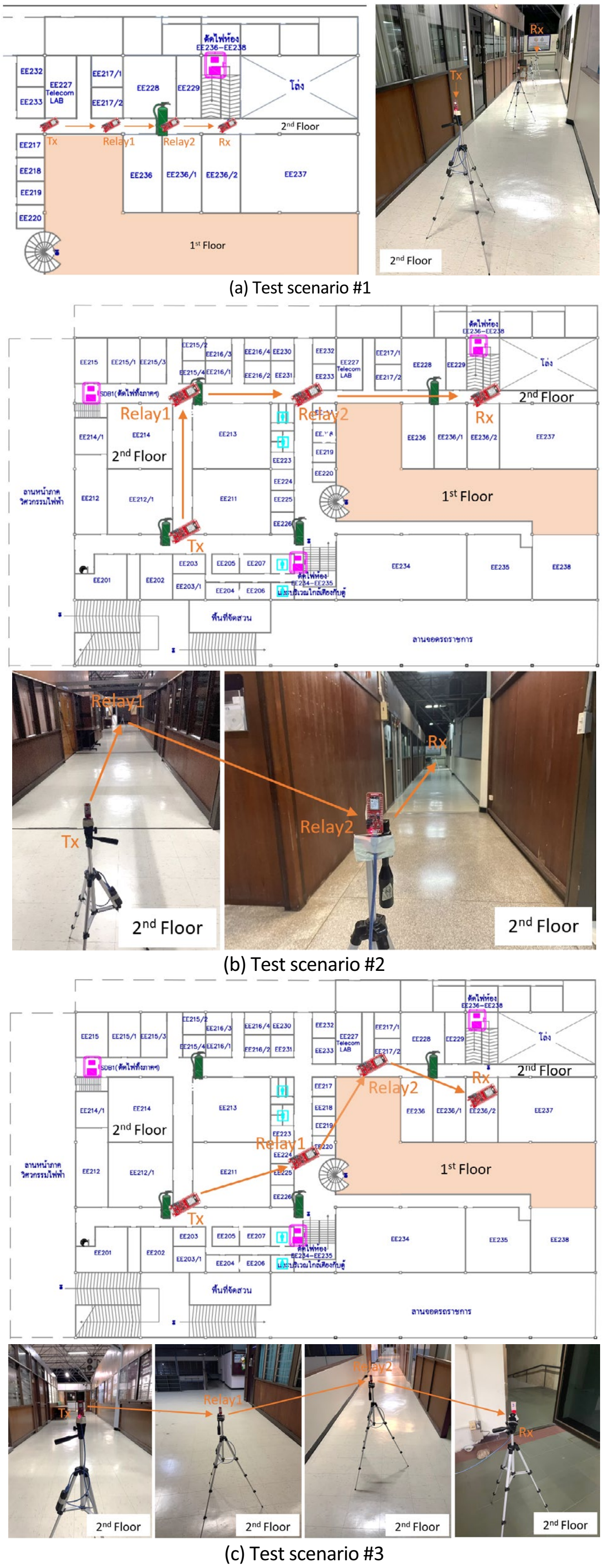
Development of a Multi-hop WSN Using XBee3 Micro-modules

Hardware and Specification

Figure 2 shows the proposed system presented in this work. Four wireless sensor nodes using XBee3 micro-modules include the transmitter node (i.e., Tx node), the relay node 1, the relay node 2, and the receiver node (i.e., Rx node) connected to the computer as the monitoring and evaluation center. The IDs of these nodes are set to ID 1 to ID 4 as shown in the figure. The Rx node will control all nodes in the network that will be described in the next section. XBee3 micro-modules with an on-board chip antenna from SparkFun Thing Plus [18] were selected. It is based on the ZigBee standard, the IEEE 802.15.4, and operates at ISM 2.4 GHz with a data rate of 250 kbps for RF communication and 1 Mbps for serial data rates. The transmit power can be set to − 5 to 8 dBm, and the supply voltage is 2.6 VDC to 3.6 VDC.

Proposed Wireless Communication Protocol

Figure 3 illustrates the communication sequence of all nodes in the proposed multi-hop network. When the computer as the control center wants to collect the sensor data from the Tx node as the source node, the RX node first sends a command packet to the Tx node via the relay node 2 and the relay node1, respective. In this command packet, the requested transmit power (i.e., − 5 to 8 dBm) and sampling rate information are included for the node's configuration. We note that to build a multi-hop connection in the command packet transmission phase, the Rx node ID1 is only connected to the relay node ID2, while the relay node ID2 is connected to the relay node ID3, and the relay node ID3 is connected to the Tx node ID4. When each node receives the command packet, it sets the transmit power to be used. Finally, upon receiving the command packet, the Tx node transfers all data packets with the requested sampling rate to the Rx node via the relay node 1 and the relay node 2, respectively. In this phase, the relay node 1 will read the RSSI information received from the Tx node (i.e., RSSI_c in Fig. 2), while the relay node 2 and the Rx node also do the same (i.e., reading RSSI_b and RSSI_a). These RSSI levels



(a) Test scenario #1

(b) Test scenario #2

(c) Test scenario #3

Fig. 7 Seven test scenarios

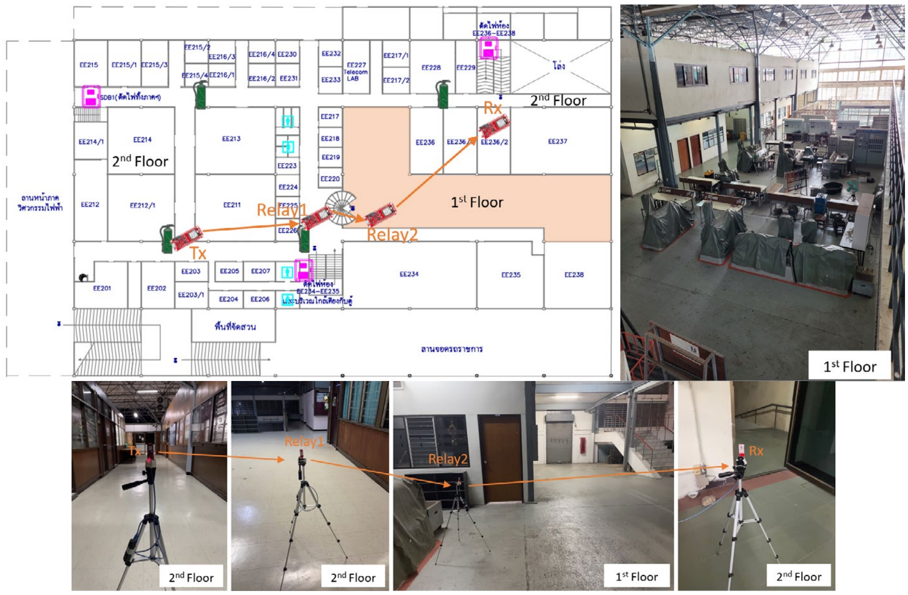
are also encapsulated in the data packet and forwarded to the computer. With this solution, at the Rx node, the data, including packet sequence number, node ID, time stamp at each node, and RSSI information from each link, are then forwarded to the computer via a serial port for collection, processing, and evaluation.

Both in the command packet and data packet transmissions of each link, the acknowledge message is used. When nodes receive the command packet or the data packet, they will send an acknowledgment message to the sender to confirm the successful delivery. If the sensor nodes cannot connect together, the retransmission will be tried within the default network timeout. Additionally, as seen in Fig. 3(c), for the data packet transmission, the packet size of the data packet can be adaptive to achieve actual usability and energy consumption. The data packet sent from the Tx (ID4) to relay 1 (ID3) has the smallest packet size, while the data packet sent from the relay 2 (ID2) to the Rx (ID1) has the highest packet size since it contains all the information of all nodes in the communication path. We note that our solution can work adaptively. For example, if the relay node 2 acts as the source node, only the sequence number, its ID, destination ID, timestamp, and data are stored in the packet. Therefore, the packet size can be automatically reduced.

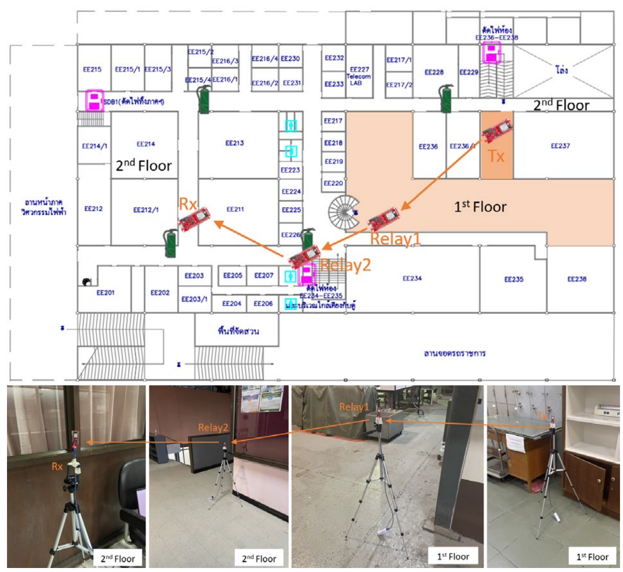
GUI for Parameter Setting and Monitoring

On the computer, a GUI for parameter setting and monitoring has been implemented. The developed GUI is demonstrated in Fig. 4. As seen in the figure, the device to be used can be selected. We note that ESP32 Wi-Fi, Bluetooth, and LoRa can also be selected for testing. However, for this work, XBee3 is focused. The communication port, sampling rate (ms), number of packets to be sent, and transmit power can also be assigned. Additionally, users can also select specific signals and sensor data to be displayed on the graph. As seen in the example, the RSSI_a to RSSI_c, 3-axis accelerometer signals, and gyroscope signals can be selected. Users can monitor selected signals from the start time to the stop time using this GUI window. Finally, when the last data packet from the Tx node is successfully sent to the Rx node, all output information will be saved in the Excel file as shown in Fig. 5, where packet sequence number, node ID, time stamp at each node, and RSSI information from each link are collected and can be used for performance calculation and evaluation.

We note that in this work, to satisfy the practical use, we send real data packets in every sampling period (sampling can be adjusted as in Fig. 4) from the Tx to the destination but have not yet included the sensor information. The sampling periods to be set also impact energy consumption and the network lifetime of the multi-hop network.



(d) Test scenario #4



(e) Test scenario #5

Fig. 7 (continued)

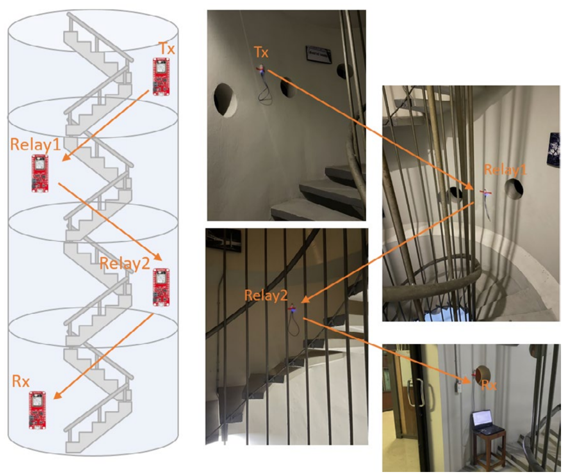
Experiments

Experimental Setup and Test Scenarios

To verify and evaluate the proposed multi-hop wireless network, experiments with various test scenarios were carried out in the Department of Electrical Engineering at Prince of Songkla University, Thailand. In the test field, there are many rooms and corridors on the second floor, including lecture rooms, staff rooms, electronic rooms, storerooms, bathrooms, graduate student rooms, etc. On the first floor, there is the electrical engineering laboratory, which includes electric machines, tables, cabinets, etc. A spiral staircase tower with multiple floors is also located in this test field.

Seven test scenarios, including LoS with different node placements, NLoS with the same floor and different floors, and spiral staircase scenarios with different node placements and transmit power settings, are all taken into consideration. For all test scenarios, the sampling rate is set to 200 ms. Each experiment is repeated five times, and the average results with standard deviation (SD) are reported. The experimental information and objectives for each test scenario are presented in Table 3. Figure 6 shows the list of

(f) Test scenario #6



(g) Test scenario #7

Fig. 7 (continued)

the system's devices, and Fig. 7(a–g) also illustrate the test scenarios.

Performance Metrics

To evaluate multi-hop WSN performances in the seven test scenarios above, the RSSI signal level, the PDR, and the ETED in (1) to (3) are employed as the performance metrics. The RSSI is a measurement of the power present in a received radio signal. The strong RSSI level represents good signal quality, where the packet can be correctly received. This RSSI level depends on the distance between the transmitter and the receiver, hardware types, time and period of measurement, interference from nearby devices, human presence and movement, and environment factors (i.e., building types, materials, obstacles, etc.) [19, 20]. For the PDR, it is the ratio of the total number of packets successfully received at the Rx node to the total number of packets sent by the Tx [17]. The PDR represents the level of the delivery data to the RX and can directly indicate the communication reliability [21, 22]. Finally, the ETED is the difference between the receiving time of the last packet (i.e., the last sequence number) and the receiving time of the first packet at the Rx node. Thus, the ETED represents how long the network takes to process all data transmissions. We note that since the calculation is performed only at the Rx node, a time synchronization problem among nodes can be avoided.

$$\begin{aligned}&\left[RSSI_{relay1,i}, RSSI_{relay2,i}, RSSI_{receiver,i}\right]\\&=\left[\frac{1}{N}\sum_{i=1}^{N}RSSI_{Txtorelay1,i}, \frac{1}{N}\sum_{i=1}^{N}RSSI_{relay1torelay2,i},\right.\\&\left.\quad\frac{1}{N}\sum_{i=1}^{N}RSSI_{relay2toreceiver,i}\right]\end{aligned} \tag{1}$$

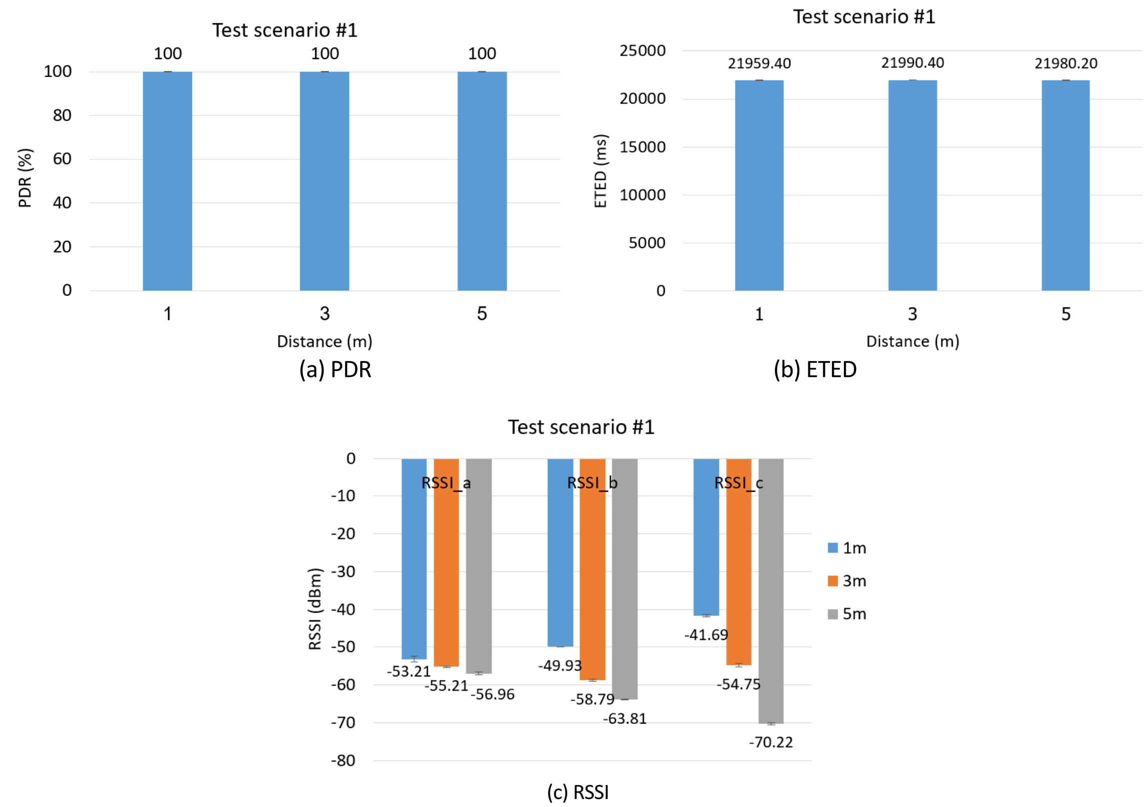


Fig. 8 PDR, ETED, and RSSI results of the test scenario #1

Table 4 PDR and ETED results for the test scenario #2

Test scenario #2			
PDR (%)	SD	ETED (ms)	SD
100	0	22,528.80	108.84

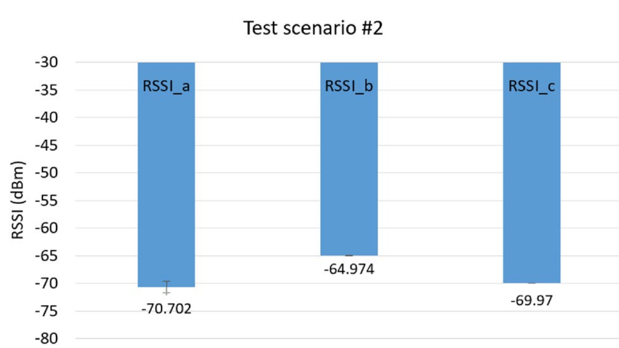


Fig. 9 RSSI result of the test scenario #2

$$\mathrm{PDR} = \frac{\text{Num. packets received}}{\text{Num. packets sent}} \times 100 \quad (2)$$

$$\begin{aligned}\mathrm{ETED} = {} & \text{Receving time of the last packet} \\ & - \textit{Receving} \text{ time of the first packet}\end{aligned} \quad (3)$$

Experimental Results and Discussion

The PDR, ETED, and RSSI results of test scenario #1 are demonstrated in Fig. 8. As we stated in Table 3, for this test scenario, we want to check the correction of the proposed communication sequences among nodes (i.e., implemented multi-hop WSN) and RSSI levels at each test distance (i.e., 1 m, 3 m, and 5 m), where all nodes are outside the room, on the 2nd floor, with a LoS connection. Experimental results show that we have achieved our objective since the average PDRs are 100% for all test distances, and the average ETEDs are similar and very close. Furthermore, based on the RSSI levels, they are in the correct trend. The RSSI is high at small distances, like 1 m (i.e., − 53.21 dBm for RSSI_a, − 49.93 dBm for RSSI_b, and − 41.69 dBm for RSSI_c), while it is lower at higher distances, like 5 m (i.e., − 56.96 dBm for RSSI_a, − 63.81 dBm for RSSI_b, and − 70.22 dBm for RSSI_c). However, the RSSI level strongly depends on test locations and environmental factors. Each communication link in our test case is at a different location, so it has a different radio propagation effect.

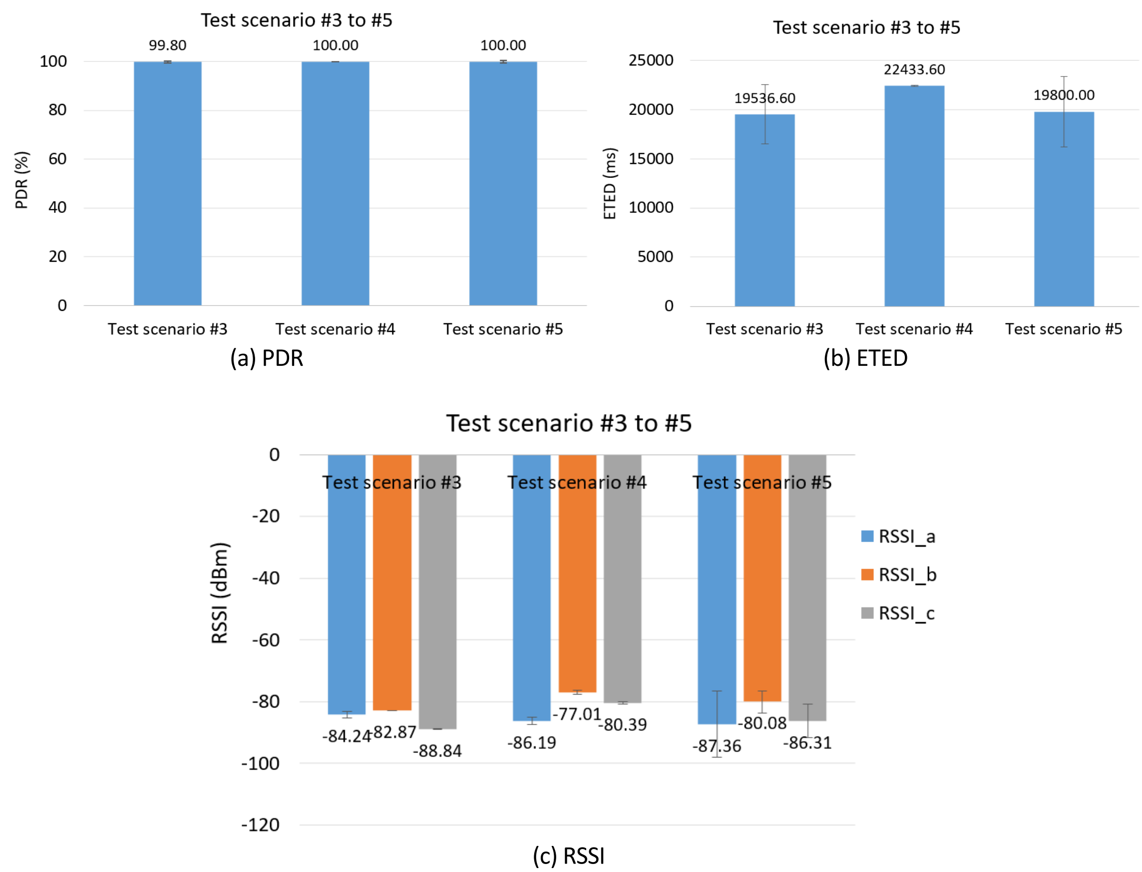
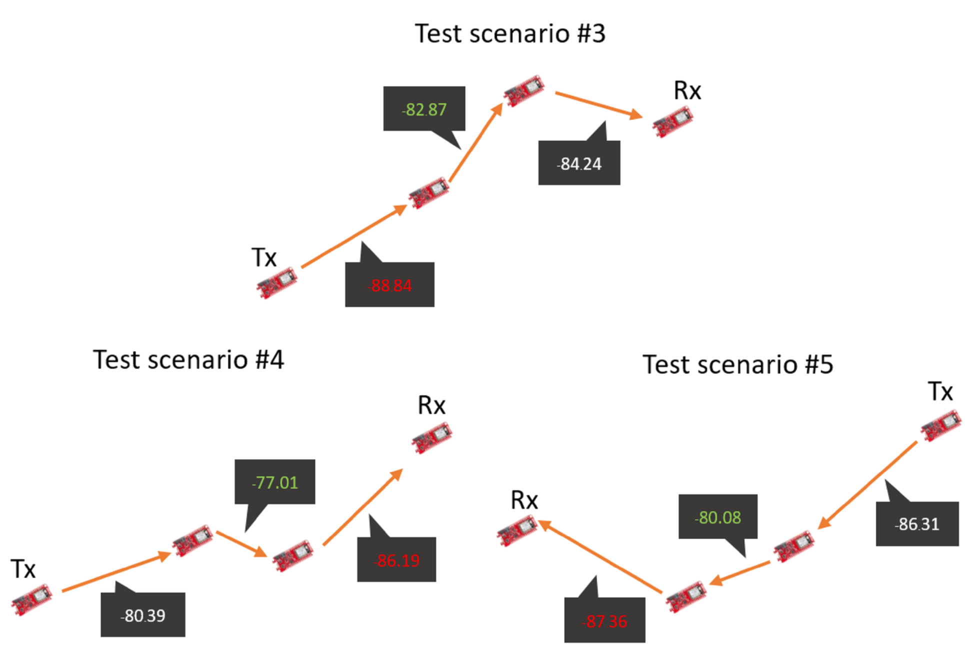


Fig. 10 PDR, ETED, and RSSI results of the test scenario #3 to #5

Fig. 11 RSSI results of the test scenario #3 to #5; strongest and lowest RSSI levels



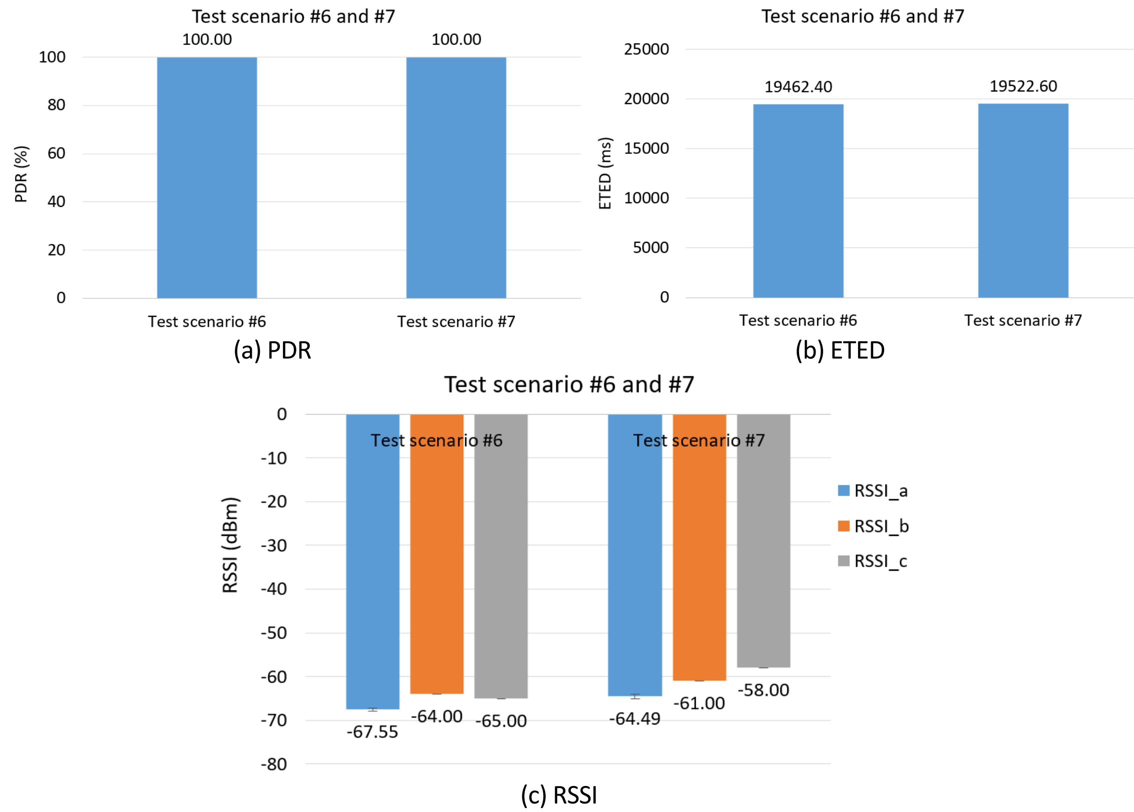


Fig. 12 PDR, ETED, and RSSI results of the test scenarios #6 and #7 at 8 dBm transmit power

Table 5 PDR, ETED, and RSSI results vs. transmit powers of the test scenario #6 and #7

Cases	Transmit power (dBm)	Average RSSI			Average ETED (ms)	Average PDR (%)
		RSSI_1	RSSI_2	RSSI_3		
Test scenario #6	8	– 67.55	– 64.00	– 65.00	19,462.40	100.00
	2	– 73.06	– 69.00	– 69.98	19,471.80	100.00
	– 5	– 80.01	– 76.00	– 76.90	19,433.20	99.80
Test scenario #7	8	– 64.49	– 61.00	– 58.00	19,522.60	100.00
	2	– 70.38	– 66.00	– 63.95	19,305.60	99.80
	– 5	– 77.07	– 72.98	– 69.88	19,468.60	100.00

Table 4 and Fig. 9 report the PDR, ETED, and RSSI results of test scenario #2, where multi-hop LoS communications have been tested and longer distances and different node deployments compared with case #1 are considered. The results show that the average PDR is still 100% (100% for five testes), while the average ETED is not different from case #1. The RSSI results also make sense since they are – 70.70 dBm for RSSI_a, – 64.97 dBm for RSSI_b, and – 69.97 dBm for RSSI_c which correspond to relay 2 to Rx distance, relay 1 to relay 2 distance, and Tx to relay 1 distance, respectively, as seen by the distances in Fig. 7(b).

The results for the test scenarios #3 to #5, as the multi-hop NLoS communication cases, are demonstrated in Fig. 10. The results also reveal that the implemented system is also appropriately used for various NLoS scenarios since high PDRs can be obtained (99.80%, 100%, and 100%, respectively), while the ETEDs are not different when compared with the LoS scenarios. We note that the SD of ETED is higher in comparison to test scenarios #1 and #2, indicating that the results of the five tests vary.

Figures 10 (c) and 11 also show the RSSI results. For the test scenario #3 (all nodes are on the 2nd floor), the strongest RSSI level (– 82.87 dBm) is at the link (relay 1 to relay 2), which is the shortest distance link compared with others, while the lowest RSSI level (– 88.84 dBm) is at the link (Tx to relay 1), which is at a longer distance with walls blocking radio signals. We note that for the link (relay 2 to Rx), although the distance is not large, the RX is in the room. In the test scenario #4, the strongest RSSI (– 77.01 dBm) is at the link (relay 1 to relay 2), where relay 1 is on the 2nd floor and relay 2 is on the 1st floor. Since the distance of this link is quite short and there is no obstacle between two floors, the RSSI is quite strong. In this case, the lowest RSSI level (– 86.19 dBm) is at the link (relay 2 to Rx), which is at a longer distance, and the RX is in the room on the 2nd floor. Finally, in test scenario #5, Tx (outside the room) and relay 1 are placed on the 1st floor, and relay 2 and Rx (outside the room) are on the 2nd floor. The RSSI results from both links are not much different. Results from this part indicate that the proposed system can efficiently work in scenarios of NLOS with different floor communications, node placements, and communication directions.

The PDR, ETED, and RSSI results of test scenarios #6 and #7 at 8 dBm of transmit power are provided in Fig. 12. The results of varying the transmit powers are also illustrated in Table 5. Experimental results reveal that the proposed system can work well in the spiral staircase tower. PDRs achieve 100% with ETEDs of 1946.2 ms and 1952.2 ms in both cases where the nodes are in the same vertical position and diagonal direction. This result indicates that the proposed system has high reliability in both directions. By considering the RSSI results, they indicate that placing the wireless nodes as in scenario #7 can obtain better RSSI levels than in scenario 6 (– 64.49 dBm, – 61.00 dBm, and – 58.00 dBm) and (– 67.55 dBm, – 64.00 dBm, and – 65.00 dBm). The results in Table 5 also confirm this discussion, where test scenario #7 obtains stronger RSSI levels for all tested transmit powers. The results here also indicate that although a lower transmit power is used, like -5 dBm, and the RSSI result is lower than in the case of using higher transmit powers, the system also achieves high PDRs and low ETEDs. Therefore, to approximately use this wireless multi-hop system with regard to energy consumption and network lifetime, low transmit power should be applied.

We note that the experimental results indicate that the RSSIs are ranking from – 77.01 dBm to – 88.84 dBm for test scenarios #3 to #5, while they are between – 58.00 dBm and – 67.55 dBm for test scenarios #6 and #7. Here, the test scenarios #3 to #5 obtain lower RSSI levels than cases #6 and #7. Since in the cases of scenarios #3 to #5, a longer distance between hop and Tx and Rx, walls blocking radio signals, many obstacles, the Rx located inside the room, and two-floor communication have been taken into consideration for testing, we have then obtained lower RSSI levels. In test scenarios #6 and #7, although the experiments have been performed in the spiral staircase tower, due to the short distance and smaller obstacles in the environments, the measured RSSIs are quite strong.

We believe that our methodology and findings can help users and researchers carefully consider and deploy 2.4 GHz IEEE 802.15.4 multi-hop WSNs in their work, because different WSN applications necessitate different levels of communication reliability, end-to-end delays, and energy consumption.

Conclusions

This paper describes the development and the testing of a 2.4 GHz indoor multi-hop system using IEEE 802.15.4 Xbee3 micro-modules. We propose the communication protocol for all wireless nodes communicating in the multi-hop network, as well as the GUI for autonomous parameter configuration and signal monitoring. The system is tested in several indoor situations, including LoS communications, NLoS, different floors, and a spiral staircase tower. The impacts of node installation sites, communication directions, and transmit powers are also investigated. The experimental findings show that the proposed system can function effectively in all test scenarios with a close to 100% PDR and a small ETED. RSSI levels measured from all communication connections are also analyzed. Thus, we concluded that we were successful in terms of implementation and usability for WSN indoor deployment.

In future work, a more efficient 2.4 GHz multi-hop WSN with Internet of Things (IoT) technology will be developed for practical use. Integrated sensors with multi-hop WSNs are also considered for healthcare and medical applications. Finally, the communication performance will vary with other communication protocols, like Bluetooth Low Energy (BLE) technology. Therefore, this important issue should be considered when designing and using a 2.4 GHz multi-hop wireless network.

Acknowledgements This work was supported by the Faculty of Engineering, Prince of Songkla University, Thailand.

Author Contributions Conceptualization, PH, AB; methodology, PH, and AB; investigation, PH, YS and AB; writing—original draft preparation, PH, and AB; writing—review and editing, PH, and AB; supervision, AB; All authors have read and agreed to the published version of the manuscript.

Funding Faculty of Engineering, Prince of Songkla University, Apidet Booranawong.

Availability of Data and Materials All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare that they have no competing interests.

Ethical Approval and Consent to Participate Not applicable.

Consent for Publication All authors have agreed to submit the paper for publication.

References

1. Kandris D, Nakas C, Vomvas D, Koulouras G. Applications of wireless sensor networks: an up-to-date survey. Appl Syst Innov. 2020;3(1):14.
2. Majid M, Habib S, Javed AR, Rizwan M, Srivastava G, Gadekallu TR, Lin JCW. Applications of wireless sensor networks and internet of things frameworks in the industry revolution 4.0: a systematic literature review. Sensors. 2022;22(6):2087.
3. Pang A, Chao F, Zhou H, Zhang J. The method of data collection based on multiple mobile nodes for wireless sensor network. IEEE Access. 2020;8:14704–13.
4. Ekici E, Gu Y, Bozdag D. Mobility-based communication in wireless sensor networks. IEEE Commun Mag. 2006;44(7):56–62.
5. Felemban E, Lee CG, Ekici E. MMSPEED multipath Multi-SPEED protocol for QoS guarantee of reliability and timeliness in wireless sensor networks. IEEE Trans Mobile Comput. 2006;5(6):738–54.
6. Hamami L, Nassereddine B. Application of wireless sensor networks in the field of irrigation: a review. Comput Electron Agric. 2020;179: 105782.
7. Souryal MR, Geissbuehler J, Miller LE, Moayeri N (2007) Real-time deployment of multihop relays for range extension. In Proceedings of the 5th international conference on Mobile systems, applications and services, pp. 85–98
8. Zhou J, Jacobsson M, Onur E, Niemegeers I. An investigation of link quality assessment for mobile multi-hop and multi-rate wireless networks. Wireless Pers Commun. 2012;65:405–23.
9. Piyare R, Lee SR. Performance analysis of XBee ZB module based wireless sensor networks. Int J Sci Eng Res. 2013;4(4):1615–21.
10. Doolin DM, Sitar N. Wireless sensors for wildfire monitoring. Smart Struct Mater Sens Smart Struct Technol Civ Mech Aerosp Syst. 2005;5765:477–84.
11. John J, Kasbekar GS, Sharma DK, Ramulu V, Baghini MS (2019). Design and Implementation of a Wireless Sensor Network for Agricultural Applications. arXiv preprint arXiv:1910.09818
12. Mecocci A, Abrardo A. Monitoring architectural heritage by wireless sensors networks: San Gimignano—a case study. Sensors. 2014;14(1):770–8.
13. Chen SK, Kao T, Chan CT, Huang CN, Chiang CY, Lai CY, Wang PC. A reliable transmission protocol for zigbee-based wireless patient monitoring. IEEE Trans Inform Technol Biomed. 2011;16(1):6–16.
14. Cheng X, Mohapatra P, Lee SJ, Banerjee S (2008) Performance evaluation of video streaming in multihop wireless mesh networks. In Proceedings of the 18th International Workshop on Network and Operating Systems Support for Digital Audio and Video pp. 57–62
15. Zhang J, Song G, Qiao G, Meng T, Sun H. An indoor security system with a jumping robot as the surveillance terminal. IEEE Trans Consum Electron. 2011;57(4):1774–81.
16. Lee JS, Wang YM. Experimental evaluation of ZigBee-based wireless networks in indoor environments. J Eng. 2013;2013:1–9.
17. Chaoboworn V, Sasiwat Y, Buranapanichkit D, Saito H, Booranawong A. Implementation and evaluation of a 2 4 GHz multi-hop WSN: LoS, NLoS, different floors, and outdoor-to-indoor communications. Int J Electr Comput Eng. 2021;11(6):5170.
18. SparkFun Thing Plus, XBee3 Micro (Chip Antenna). https://www.sparkfun.com/products/15454 (Accessed on 02/02/2023).
19. Chapre Y, Mohapatra P, Jha S, Seneviratne A (2013). Received signal strength indicator and its analysis in a typical WLAN system. In Proceedings of the 38th IEEE conference on local computer networks pp. 304–307
20. Booranawong A, Jindapetch N, Saito H. A system for detection and tracking of human movements using RSSI signals. IEEE Sens J. 2018;18(6):2531–44.
21. Godoi FN, Denardin GW, Barriquello CH. Reliability enhancement of packet delivery in multi-hop wireless sensor network. Comput Netw. 2019;153:86–91.
22. Wang J, Liu Y, Jiao Y. Building a trusted route in a mobile ad hoc network considering communication reliability and path length. J Netw Comput Appl. 2011;34(4):1138–49.