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Implementation and experimental evaluation of dynamic capabilities in wireless body area networks: different setting parameters and environments

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Abstract

It is well known that a wireless body area network (WBAN) is a special proposed wireless sensor network (WSN) that can assist in monitoring physiological signals for the evaluation and planning of patient treatment. One of the most challenging issues for WBANs is communication reliability, with acceptable communication efficiency and packet loss. To obtain such network characteristics, collision-free data transmission in networks of wireless sensor nodes is an interesting research problem. In this paper, the experiments of dynamic capabilities in several WBAN scenarios are focused, where the novelty and major contribution of our tests is that the effects of packet inter-arrival times, packet sizes, and the number of nodes deployed in the network, including human movements, indoor and outdoor environments, and transmitter and receiver positions, are all taken into consideration and evaluated. This is achieved by implementing the WBAN using IEEE 802.15.4 low-power sensor nodes. Experimental results illustrate the significant factors that impact the communication reliability of WBANs as measured by the packet delivery ratio (PDR). The experimental results show that the diverse environment testbed can affect network performance for WBAN data transmission. Our findings also show that the best network reliability needs to be set at more than 15 ms in packet interval time to achieve over 90% PDR for every test scenario. More details of the experimental results related to WBAN reliability obtained from all test cases are also discussed and summarized in the paper. To the best of our knowledge, our findings can be useful for users and researchers to consider the optimal point for WBAN setting and configuration to achieve the communication reliability requirements and also to deploy and develop a more reliable WBAN system.

Keywords WBAN, IEEE 802.15.4, Communication reliability, Experiments, Indoor, Outdoor

Introduction

Wireless body area networks (WBANs) involve specific monitoring applications such as health care, rehabilitation, and sports. All sensor nodes are located around the human body with wireless communications. They all require low energy consumption for wireless devices and high performance for data transmission [1]. Data have been measured for WBANs for both electrical signals such as electromyography (EMG), electrocardiography (ECG), etc. and vital signs, for example, temperature, blood pressure, heart rate, and so on [2].

The wireless communication for WBANs generally uses the standard MAC protocol [3–5] which is the carrier sense multiple access with collision avoidance (or CSMA/CA) protocol, to access the medium for data transmission. There are some protocols, such as the T-MAC [6] and the X-MAC [7, 8] which operate the CSMA/CA for WBANs. When the system demands enhanced network efficiency for data transmission, it utilizes the time-division multiple access (or TDMA) protocol to perfectly distribute the bandwidth. The network applies only the TDMA such as the low duty-cycle TDMA (LD-TDMA) [9] and the CF-MAC [10]. However, it has also been found that there are employing both the TDMA and the CSMA/CA techniques to extend the network capability, such as the hybrid context-aware MAC protocol (CA-MAC) [11], the all dynamic MAC (AD-MAC) protocol [12], and the Hybrid MAC (HyMAC) protocol [13]. Furthermore, there are others using FDMA-based or slotted protocols to access the transmission medium, for example, the cooperative MAC [14], the HUA-MAC [15], and the ECTP-MAC [16].

The T-MAC protocol [6] is studied in simulation in OMNeT++ and actually implemented in EYES devices at 868.35 MHz with four nodes. It modifies the active time in different cycles for each node to be used flexibly. When a node wants to transmit data, a message is broadcast to every node in the network to avoid a data collision. Whereas the X-MAC [7] is operated in nine sensor nodes with the Chipcon CC2420, 2.4 GHz. It has been developed using the principles of duty-cycled WSNs. A node wakes up to examine the channel for a short time using the operation of low power listening. This makes more efficient energy consumption because of selecting the optimal sleep and listening intervals. For the AD-MAC protocol [12], a communication manager is introduced to divide the sensor node priority into three levels. Here, the highest priority is level 0 and the lowest priority is level 2, where the contention window is used as a priority divider. Note that the AD-MAC is evaluated its performance through the OMNeT++ simulator, where the performances of time delay distribution, energy consumption, and packet loss rate are taken into consideration. Additionally, in the simulation, different transmitted packet rates are assigned to each node based on the data communication demand, diversely. Finally, in the HyMAC protocol [13], the star communication topology is configured for body sensor nodes deployed in the network (i.e., nine sensor nodes), and the personal station is also assigned to enforce and gather data reported by all body sensor nodes. Note that, in [13], to support the Internet of Things (IoT) system, the body sensor nodes can automatically access and analyze data in the network. Additionally, the HyMAC is designed and tested on the NS-3.26 simulator as the simulation study. For the work in [17], ECG data, as the sensing data in wireless networks, are divided into different priorities, including low, medium, and high priorities, respectively. Here,

unnecessary data to be frequently detected, like heartbeat data, are assigned as a low frequency with the defined sampling rate and packet size.

In this work, the experimentation of WBAN communications in various scenarios is focused. The CSMA/CA is used as the standard and fundamental MAC protocol for wireless network communications. TelosB sensor nodes based on the IEEE 802.15.4 standard are applied for the real implementation [18]. The major contribution of our work is that the WBAN communication reliability in terms of the packet delivery ratio with respect to the packet inter-arrival time, the packet size, and the number of nodes in the network is studied, and such considered factors are varied dynamically. Furthermore, environmental factors, including human movement effects, indoor and outdoor environments, and transmitter and receiver positions deployed in the network, have also been considered in this evaluation. These are in line with the WBAN requirements for either patients in healthcare applications or athletes in physical fitness monitoring [19–22].

The structure of this paper is organized as follows. Materials and methods, including the proposed wireless body area network system and experiments, are provided in “Methods” section. “Results and discussion” section presents results and discussion. Finally, the paper is concluded in “Conclusions” section.

Methods

Proposed wireless body area network system

Wireless device and network architecture

WBANs support several real-time health monitoring applications. The IEEE 802.15.6 standard for WBANs aims to provide a standard for low power consumption, short range communication, and reliable wireless communication within areas of the human body. The typical data rate for the WBAN standard is in the range of 10 kbps to 10 Mbps [22, 23]. In particular, the ECG signal of WBAN applications requires a data rate of 6 kbps at a frequency of 500 Hz [23]. Whereas the real-world implementation uses the IEEE 802.15.4 standard to study the characteristics of WBANs. This standard also aims to provide low-data rate wireless personal area networks (WPANs) with low power requirements. The effective data rate for this network is in the range of 80–250 kbps. The standard has the ability to operate the CSMA/CA access modes. These techniques have been studied on the actual hardware of WSNs.

In our proposed system, data from sensor nodes are sent to a base station. Then, the base station forwards the data to the computer via a serial port for collection. Here, sensor nodes are attached to the human body, while the base station connects to the laptop via serial communication using the 115,200 bps baud rate. All of them are implemented on TelosB wireless sensor motes running the TinyOS v2.1.2 operating system [18]. The processor uses the MCU TI MSP430F1611, 10 Kb of RAM and the RF module with the CC2420 (i.e., frequency band 2.4–2.485 GHz based on the IEEE 802.15.4 standard). As shown in Fig. 1, the experiment has been conducted to study the network performance for WBAN communications from many sensor nodes. A single-hop network has been built by placing three TelosB motes around the TelosB base station. The base station broadcasts the Command message to start the node’s transmission altogether in the network only for the first time. This message has also

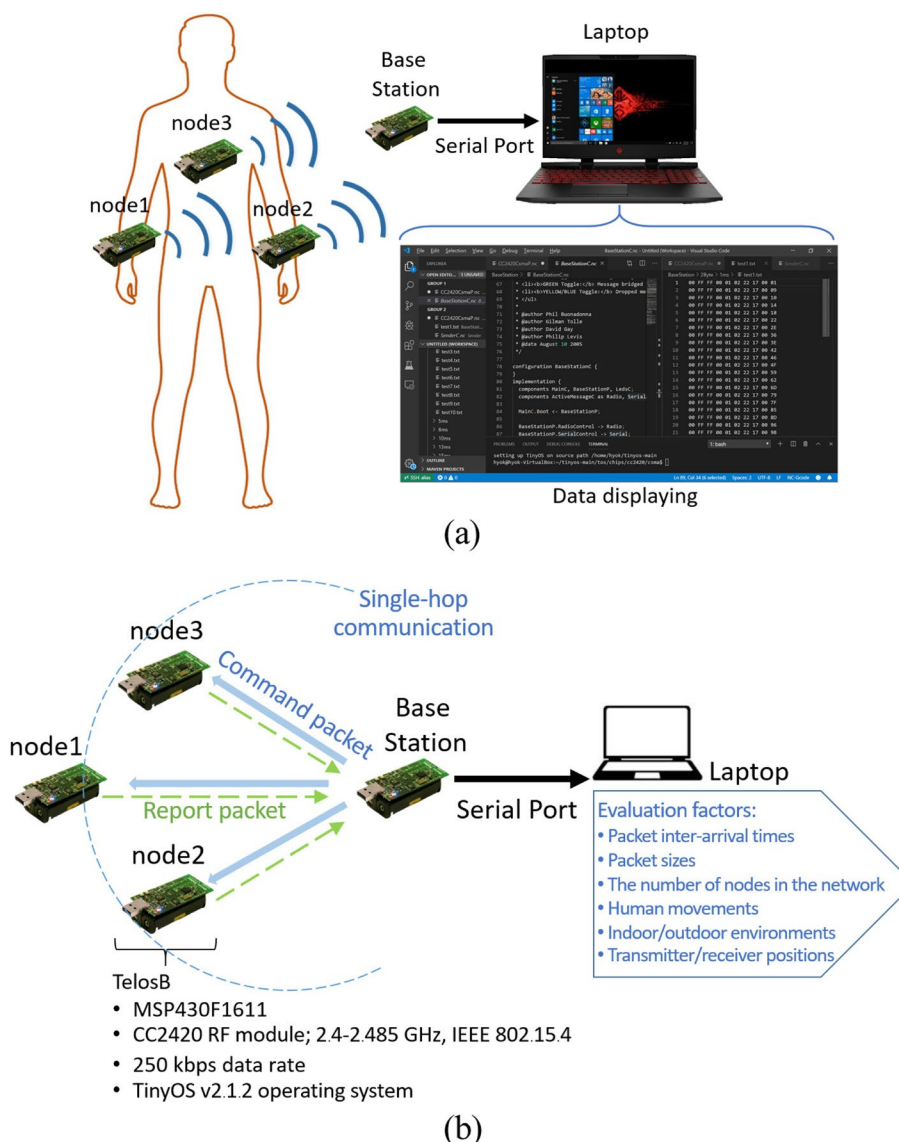


Fig. 1 WBAN architecture

been used for setting up an important parameter. As the base station receives the data message once the experiment starts. The transmission power has been set at the maximum level of 0 dB to ensure every packet is able to be received by the base station. Whereas the received sensitivity of the TelosB mote is approximately $\pm 0.01\%$.

As mentioned above, in this work, TelosB motes were used in the implemented WBAN, where the RF module with the CC2420 from Texas Instruments was employed. The CC2420 was designed for low-cost, low-power wireless applications. It required low current consumption in each communication mode. Note that in WBAN applications, the sensor node is attached to the human body to monitor physiological signals. Thus, energy saving to prolong network lifetime is required.

Compared with other RF transceivers, the CC2420 requires low current consumption; 17.4 mA for the Tx mode (at 0 dBm) and 18.8 mA for the Rx mode. It requires only 8.5

mA for the TX mode at -25 dBm, and 0.426 mA in the idle mode. For this reason, many existing works also used the CC2420 to develop WBAN systems. Another reason is that in the TelosB node, the CSMA/CA protocol to access the medium for data transmission has been available for study, modification, and development.

Packet structure and communication sequence

In this paper, packet structure has been designed into two types of packets which are called `command_msg_t` and `report_msg_t`. The radio message used TinyOS's standard, 9-byte data for the command packet and 8-byte data for the data packet as demonstrated in Fig. 2. The first packet is a message that is sent from the base station to all sensor nodes in the network to initiate and control the data transmission. The parameters in the packet for sending consist of Nodestart, Numberpacket, Interarrivaltime, and Payloadsize for 1, 4, 2, and 2 bytes, respectively. These parameters are the data payload for the command packet, as seen in Fig. 2a. Whereas the second packet is the message which is sent from the node to the base station and then forwarded to the computer via serial port. This message consists of 4 bytes of payload1 and 4 bytes of payload2 for the data packet, as illustrated in Fig. 2b.

The node operation when the CC2420 communication chip is enabled in all test cases is shown in Fig. 3. It is started by the command message to enable the CC2420 Chipcon and the node waits for the signal from the base station. Then the node takes the variable values (Interarrivaltime and Payloadsize) that are sent from `command_msg_t` to store in variables which are created by the node. After the nodes receive the command packet, they setup the system based on the obtained variables and begin to transmit the data simultaneously. When the node starts to add data, the data packet, which consists of a counter in payload1, is collected for every cycle from packet transmission and also a timestamp from the local time in a payload2 variable. Whenever the channel is available, the node will generate a `report_msg_t` with the created values for payload1 and payload2 and then send it to the base station for evaluation and analysis of network performance.

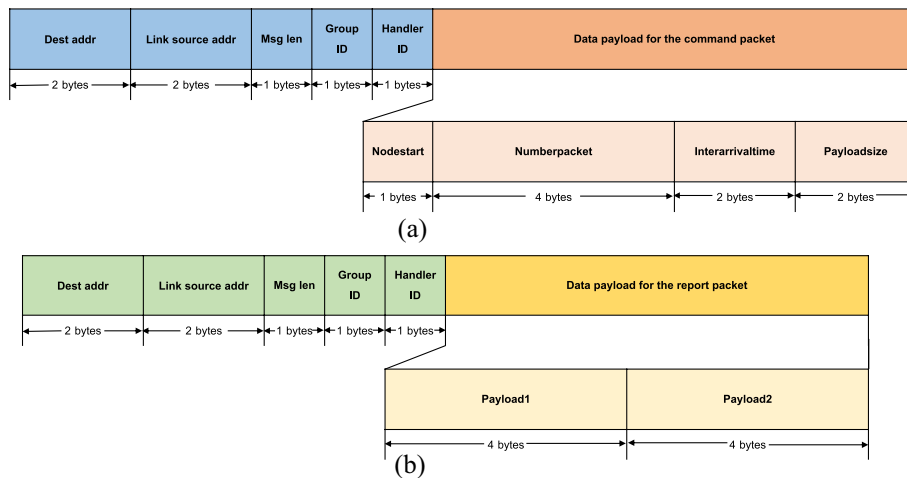


Fig. 2 The packet format for the proposed system

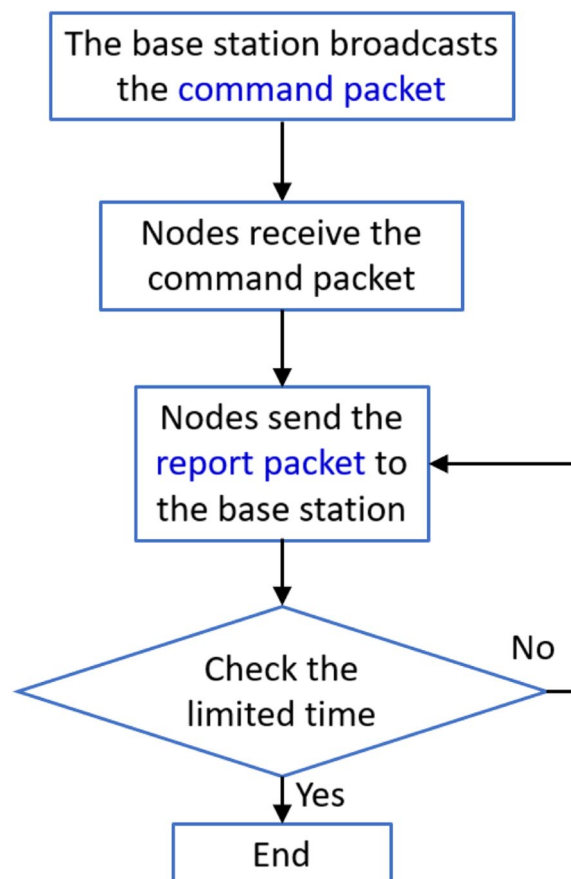


Fig. 3 Flowchart of WBAN communications

In the system, the transmission efficiency has been studied when the network changes the communication parameters. The important parameters include the packet size, the packet inter-arrival time, and the number of nodes in a system. This experiment also tests the communication performance when changing test environments, such as all the systems being placed indoors and outdoors, the base station's position inside or outside of the room to study the wireless communication when patients move in an area of a hospital.

Experiments

To evaluate the proposed WBAN system in terms of dynamic capabilities, a set of experiments with several WBAN scenarios is performed. The effects of packet inter-arrival times, packet sizes, the number of nodes, human movements, indoor and outdoor environments, and transmitter and receiver positions are considered. Details of all test cases, parameter setups, and performance metrics are described below.

Test cases and parameter setups

There are five different test cases to be evaluated. These cases are able to present all possible WBAN communications in a place. All related parameters set for the experiments are also illustrated in Table 1.

Table 1 Parameters set for each test case

Test cases	Number of transmitter nodes	Packet sizes	Packet inter-arrival times	Test fields	Human movements	Tx-Rx position	Objectives
#1	1	10 bytes, 16 bytes, 24 bytes, and 36 bytes	5 ms, 8 ms, 10 ms, 13 ms, 15 ms, 18 ms, and 20 ms	Indoor	No	1-m height from the ground	To study the effects of PZ and PIAT
#2	1, 2, and 3	16 bytes	5 ms, 8 ms, 10 ms, 13 ms, 15 ms, 18 ms, and 20 ms	Indoor	No	1-m height from the ground	To study the effects of PIAT and NN
#3	3	16 bytes	5 ms, 10 ms, 18 ms	Indoor Outdoor	No	1-m height from the ground	To study the effects of PIAT, NN, and indoor/outdoor environments
#4	3	16 bytes	5 ms, 10 ms, 18 ms	Indoor outdoor	Yes The man walks in a straight line (5 m).	1-m height from the ground	To study the effects of PIAT, NN, indoor/outdoor environments, and human movements
#5	3	16 bytes	10 ms	Indoor	Yes The man walks in the building.	1-m and 2.5-m height from the ground	To study the effects of NN, building environments, human movements, and transmitter and receiver positions

PZ packet sizes, PIAT packet inter-arrival times, NN number of nodes

Test case #1: one transmitter node and one receiver node (i.e., the base station) are attached to the human body; a man with a body width of 26 cm, a shoulder size of 52 cm, a height of 169 cm, and a weight of 110 kg. During the test, the man stands in the room (i.e., the indoor environment), as demonstrated in Fig. 4. The transmitter node (i.e., node 1) continuously sends data to the receiver node, where the packet sizes are varied from 10 to 36 bytes, and the packet inter-arrival times are varied from 5 to 20 ms. Note that each test is repeated 10 times for data collection and performance evaluation. For this test case, the effects of the packet sizes and the packet inter-arrival times on the WBAN communication reliability will be investigated.

Test case #2: more sensor nodes are added to the network; one to three nodes for data transmission, as shown in Fig. 5. This scenario refers to the case where more sensor nodes are applied in the WBAN to collect and report different sensory data to the base station, like ECG, EMG, heart rate, blood pressure, etc. During the test, the man stands in the room, and all transmitters send 1000 packets as the data to the base station at the same time, with the packet size of 16 bytes (i.e., the middle value of the test case #1).



Fig. 4 Test case #1

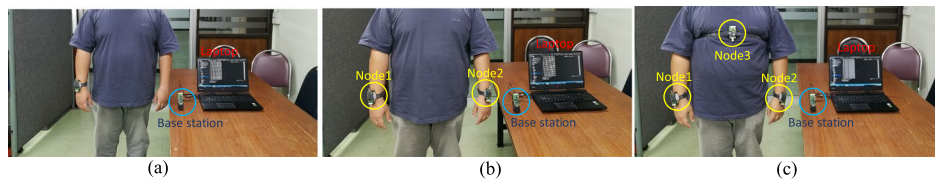


Fig. 5 Test case #2, changing the number of nodes from 1 to 3; **a** one transmitter node, **b** two transmitter nodes, and **c** three transmitter nodes

However, like in the test case #1, the packet inter-arrival times are also varied from 5 to 20 ms to study the effects of the packet inter-arrival times and the number of nodes on the WBAN communication reliability.

Test case #3: three transmitter nodes are used for data transmission, and all transmitters send their data to the base station at the same time, with a 16 bytes packet size and the packet inter-arrival times of 5 ms, 10 ms, and 18 ms (the middle values of the test case #2), respectively. Note that the base station is placed on the table. In this case, there are two subcases depend on the surrounding environment: (a) the man stands in the room, and (b) the man stands on the ground (i.e., the outdoor environment), as demonstrated in Fig. 6. For this purpose, the effects of the packet inter-arrival times, the number of nodes, and indoor and outdoor environments on the WBAN communication reliability will be investigated.

Test case #4: three transmitter nodes are used for data transmission, and all transmitters send their data to the base station at the same time, with a 16 bytes packet size and packet inter-arrival times of 5 ms, 10 ms, and 18 ms, respectively. In this case, there are two subcases: a) the man walks in a straight line in the room with a walking distance of 5 m, and (b) the man walks in a straight line in the outdoor environment with the same walking distance, as shown in Fig. 7. For this purpose, the effects of the packet inter-arrival times, the number of nodes, indoor and outdoor environments, and human movements on the WBAN communication reliability will be investigated.

Test case #5: three transmitter nodes are used for data transmission, and all transmitters send their data to the base station at the same time, with a 16 bytes packet size and packet inter-arrival times of 10 ms (i.e., the middle value of test cases #3 and #4). In this case, there are three subcases, as shown in Fig. 8. The man walks in the building (i.e.,

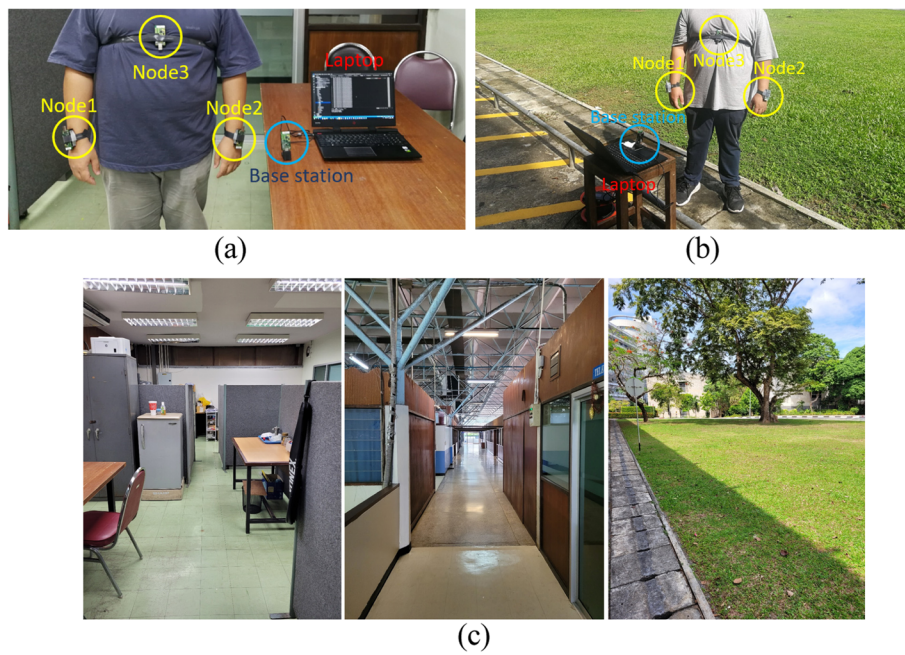


Fig. 6 Test case #3, changing the environments; **a** the man stands in the room, **b** the man stands on the ground outside the building, and **c** room, building, and outdoor environments

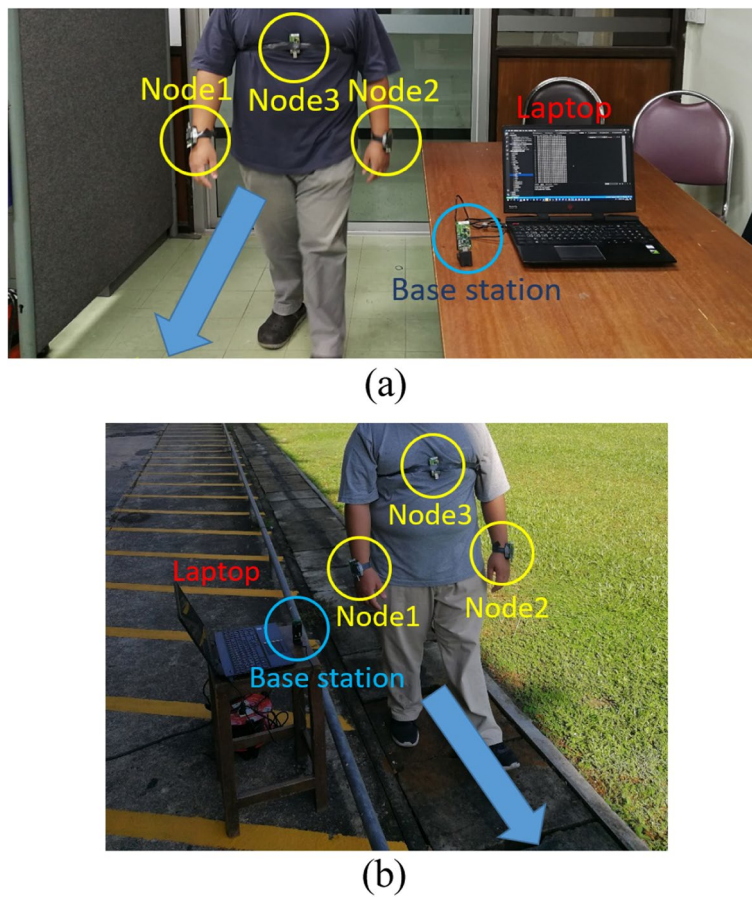


Fig. 7 Test case #4, a moving person; **a** the man walks in a straight line in the room, and **b** the man walks in a straight line in the outdoor environment

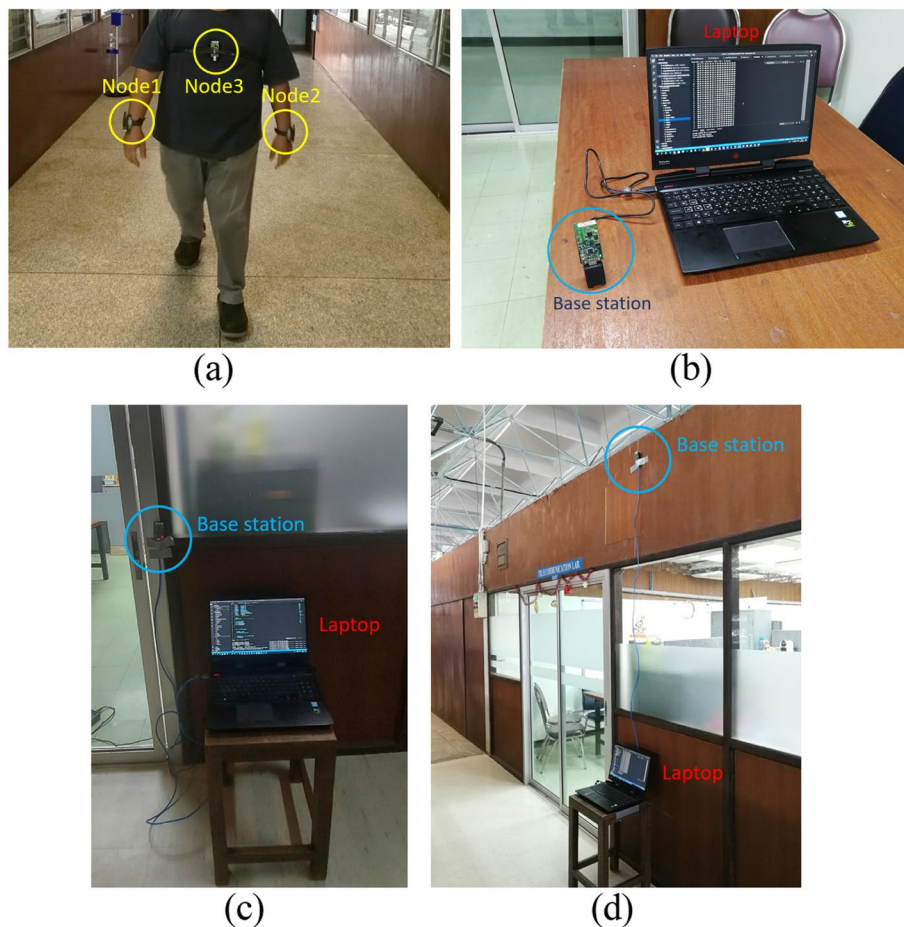


Fig. 8 Test case #5, changing the receiver's positions; **a** the man walks in the building, **b** the base station is at the altitude of 1-m height from the ground, **c** the base station is at the altitude of 1-m height from the ground outside the room, and **d** the base station is at the altitude of 2.5-m height from the ground outside the room

at the Department of Electrical Engineering, Faculty of Engineering, Prince of Songkla University, Thailand), where the transmitters and the base station (placed in the room) in the first subcase are at the same level from the ground (i.e., 1-m height), while in the second and the third subcases, the base station is at the altitudes of 1-m high and 2.5-m height from the ground outside the room, respectively. Note that the walking pattern of the man is also shown in Fig. 9. Thus, for this purpose, the effects of the number of nodes, building environments, human movements, and transmitter and receiver positions on the WBAN communication reliability are taken into consideration.

Performance metrics

The packet delivery ratio (PDR) is selected and used as the performance metric for the evaluation of WBAN communication reliability. The PDR is the ratio of the number of received packets at the base station to the number of transmitted packets from the transmitter, as shown in Eq. (1). This metric is chosen because it can indicate the success rate of data transmission performed by all network nodes. This is in line with WBAN

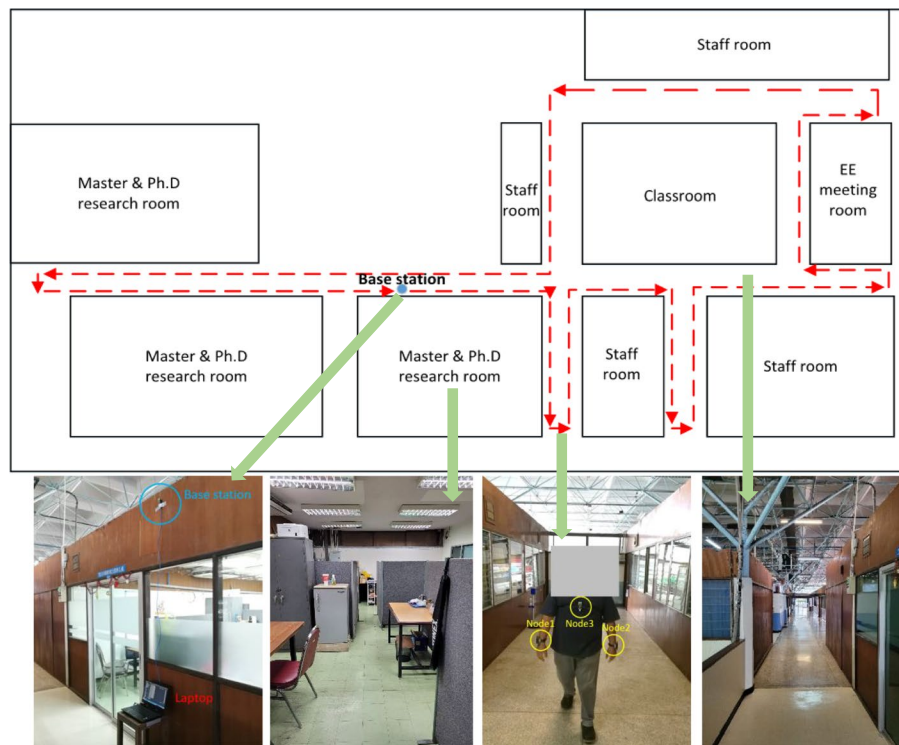


Fig. 9 The walking direction for the test case #5

requirements, since the sensor nodes for measuring human physiological signals have several data transmission needs. In this work, the 95% confidence interval (i.e., 95% CI) is also given for the average result.

$$\text{Packet Delivery Ratio (PDR)} = \frac{\text{Number of received packets}}{\text{Number of transmitted packets}} \times 100\% \quad (1)$$

Results and discussion

The experimental results and discussion are presented in this section. For the test case #1, as shown in Fig. 10, the results indicated by the PDR show that changing packet sizes and packet inter-arrival times significantly affects the WBAN communication reliability. It can be observed that, as packet sizes increase, the PDR then decreases. Whereas, increasing of packet inter-arrival times, the PDR increases. At 10 bytes of the packet size and 5 ms of the packet inter-arrival time, the PDR is 50.31%. When the packet size is configured to 36 bytes, the PDR decreases by almost 10% (i.e., 41.08%). Thus, increasing the packet sizes causes the PDR decrease. At the same point, compared with the cases of 10 bytes of the packet size and 13 ms of the packet inter-arrival time, the PDR result increases to 99.03%. Consequently, increasing the packet inter-arrival times to 15, 18, and 20 ms, the PDRs are then 100%, 99.84%, and 99.99%, respectively. The results in this case can be explained that, in communications with larger packet sizes and shorter packet inter-arrival times (i.e., a high flow rate), both the transmitter and receiver have

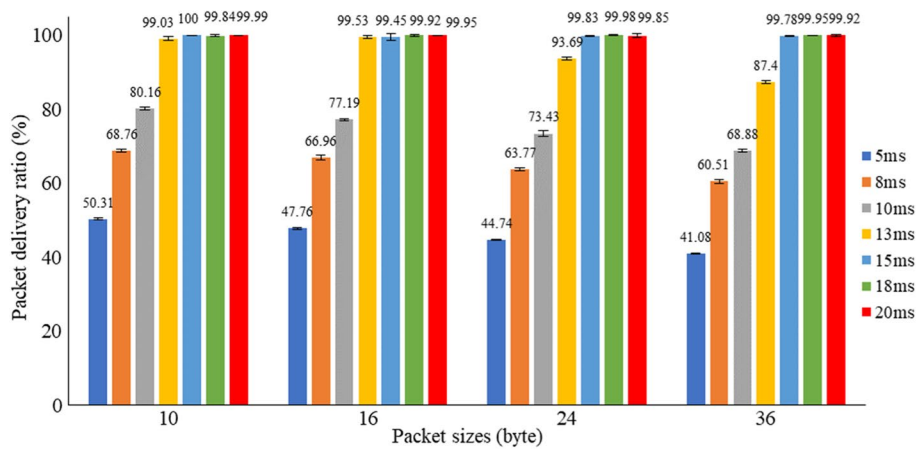


Fig. 10 The PDR for the test case #1; varying the packet size and the packet inter-arrival time

to process a large amount of data in a short period of time. Since the receiver cannot appropriately process and handle such a congested situation, it results in failure of transmission and packet loss.

By these experimental results, it has been shown that, for one transmitter and one receiver communication, the packet inter-arrival time bigger than 13 ms will not influence the PDR results, where the communication reliability can achieve 100%, approximately.

The PDR results for the test case #2 are provided in Fig. 11. The results indicate that increasing the number of nodes and the packet inter-arrival time can significantly affect the PDR. Here, increasing of the number of nodes, the PDR then decreases, while increasing of packet inter-arrival times, the PDR increases. At 5 ms of the packet inter-arrival time and 16 bytes of the packet size, the PDRs are 47.76%, 43.41%, and 38.69% for one, two, and three transmitter nodes, respectively. The results here illustrated that, in communications with more transmitter nodes and small packet inter-arrival times or a high flow rate, one receiver cannot process data, resulting in collisions of data transmission and packet loss.

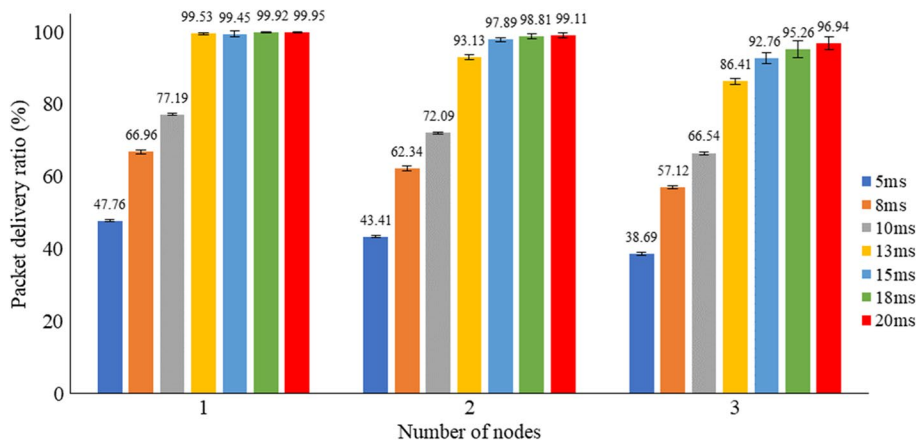


Fig. 11 The PDR for the test case #2; varying number of nodes and the packet inter-arrival time

The experimental results in Fig. 11 also demonstrate that the PDR of more than 80% corresponds to 13 ms of the packet inter-arrival time or higher. As seen in the graph, at 13 ms of the packet inter-arrival time, the PDR results for one transmitter to three transmitter nodes are 99.53%, 93.13%, and 86.41%, respectively. At 15 ms of the packet inter-arrival time, the PDRs then equal to 99.45%, 97.89%, and 92.76%, respectively. At 18 ms of the packet inter-arrival time, the PDRs are 99.92%, 98.81%, and 95.26%, respectively. Finally, at 20 ms of the packet inter-arrival time, the PDRs reach 99.95%, 99.11%, and 96.94%, respectively.

The PDR results for the test case #3 (i.e., the man stands in the room and on the ground outside the building) and the test case # 4 (i.e., the man walks in a straight line in the room and outside the building, with a walking distance of 5 m), when three transmitter nodes are used and the packet-inter-arrival time is varied, are illustrated in Figs. 12 and 13, respectively. The experimental results here indicate that the PDR results are not different for the cases of the man standing and walking in the indoor and outdoor environments with a short walking distance (5 m). For example, at 10 ms of the packet inter-arrival time, the PDRs are 64.45% (standing in the indoor), 64.57% (walking in the indoor), 64.30% (standing in the outdoor), and 63.64% (walking in the outdoor), respectively. Note that only the packet inter-arrival time factor significantly influences the PDR results, as demonstrated by the previous results of the test cases #1 and #2.

The PDR results for each transmitter node when varying the packet inter-arrival times for the test cases #3 and #4 are also illustrated in Fig. 13a–c. These results represent the PDR variation, and the results indicate that the PDRs of all nodes are not much different. For example, at 10 ms of the packet inter-arrival time as in Fig. 13b, the PDRs of the node 1 are 62.51% (standing in the indoor), 65.48% (walking in the indoor), 65.63% (standing in the outdoor), and 64.78% (walking in the outdoor), respectively. Compared with the cases of node 2 and node 3, they are (63.30%, 64.11%, 63.48%, and 64.03%) and (67.32%, 64.10%, 63.72%, and 62.03%), respectively. Since all nodes in this work use the CSMA/CA protocol as the standard MAC protocol for channel access, all nodes then have the same priority for data transmission and PDR balance.

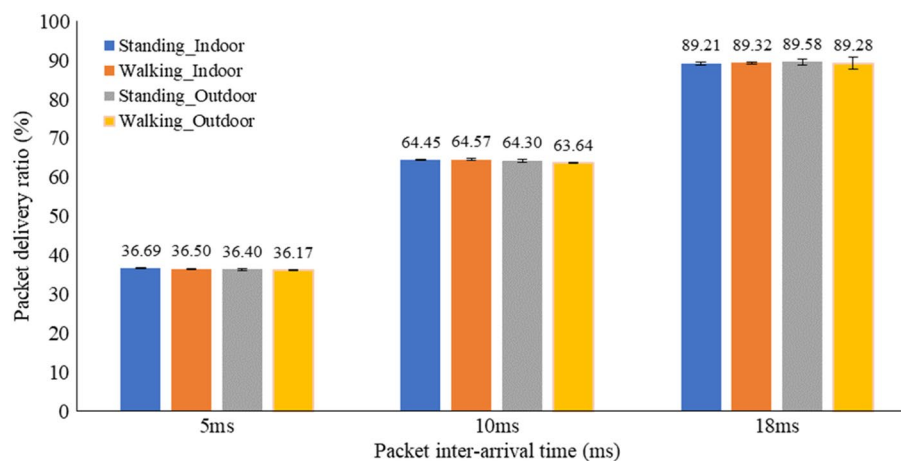
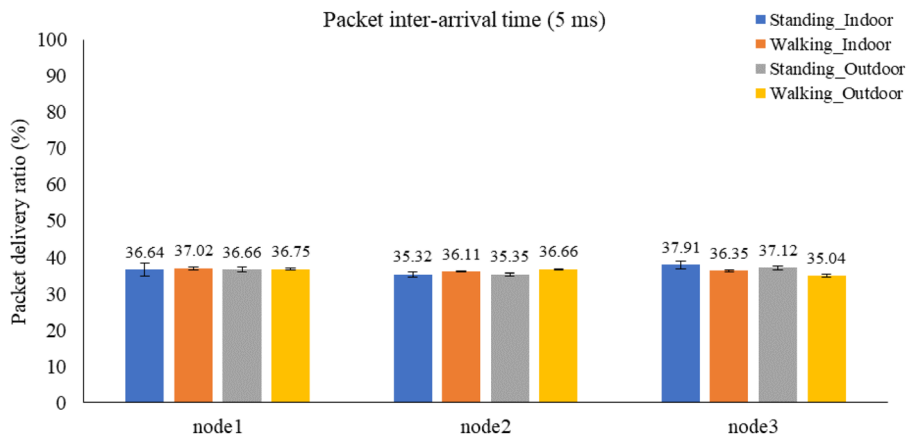
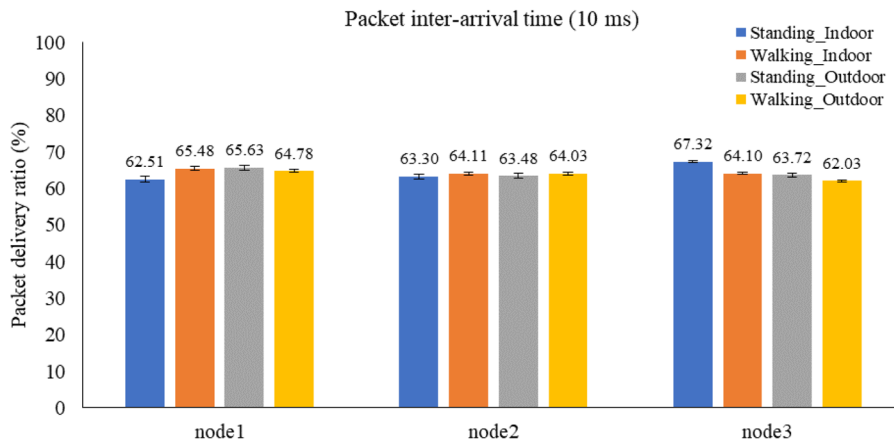


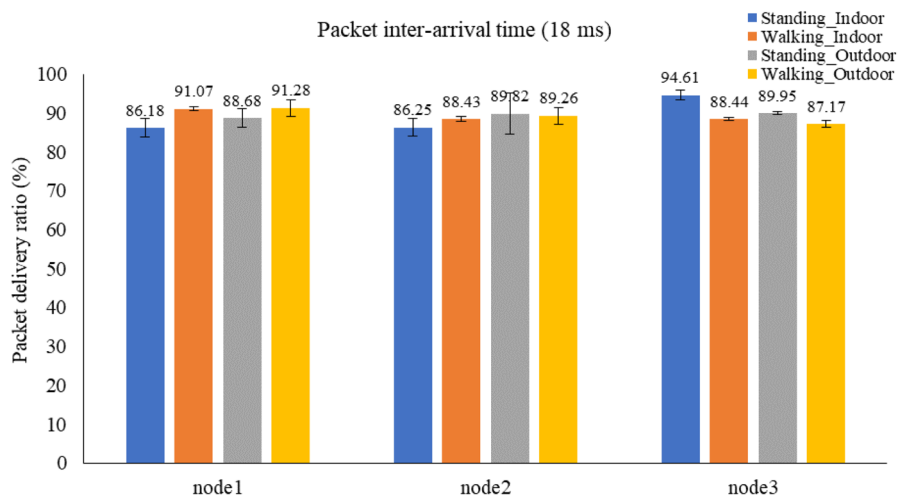
Fig. 12 The PDR for the test cases #3 and #4 for three transmitter nodes; varying the packet inter-arrival times



(a) The packet inter-arrival time of 5 ms



(b) The packet inter-arrival time of 10 ms



(c) The packet inter-arrival time of 18 ms

Fig. 13 The PDR for each transmitter node for the test cases #3 and #4. **a** The packet inter-arrival time of 5 ms. **b** The packet inter-arrival time of 10 ms. **c** The packet inter-arrival time of 18 ms

Note that based on the results in Fig. 13c, the results indicate that when three transmitter nodes with a 16 byte packet size are used for the case of the man who stands and walks a short distance in the room and outside the building, using the packet inter-arrival time of 18 ms can help to achieve the PDR of more than 85%.

In the test case #5, the PDR results (averaged from three nodes) when the base station is at an altitude of 1-m height from the ground in the room, at the altitude of 1-m height from the ground outside the room, and at the altitude of 2.5-m height from the ground outside the room are compared and illustrated in Fig. 14. Here, the average PDRs are 30.12%, 39.62%, and 37.14%, respectively. The results here suggest that, to appropriately apply the WBAN for the case of the man walking in the big building as shown in Figs. 8 and 9, the base station node should be placed outside the room, since higher PDR results can be obtained. However, in our test scenario, the PDRs from the cases of the base station placed outside the room is at an altitude of 1-m height and 2.5-m above ground level are not much different.

The PDR results versus time index (by plotting every 1000 ms) are also provided in Fig. 15. These results demonstrate that the PDRs can vary from 0 to 80%, approximately. Here, the PDR decreases drastically when the man walks through the corner or there is no line of sight (LoS) communications between the transmitter nodes and the receiver node, as indicated by the walking direction in Fig. 9.

By our experimental results obtained from the test cases #1 to #5, how packet inter-arrival times, packet sizes, the number of nodes, human movements, indoor and outdoor environments, and transmitter and receiver positions affect the WBAN communication reliability can be evaluated. Our findings are summarized here.

- In the test case #1: increasing the packet sizes, the PDR then decreases, while increasing the packet inter-arrival times, the PDR increases. For one transmitter and one receiver communication, when the packet size is 10 bytes (i.e., the minimum packet size to be tested) and the packet inter-arrival time is greater than 13 ms, the PDR reaches 100%, approximately.

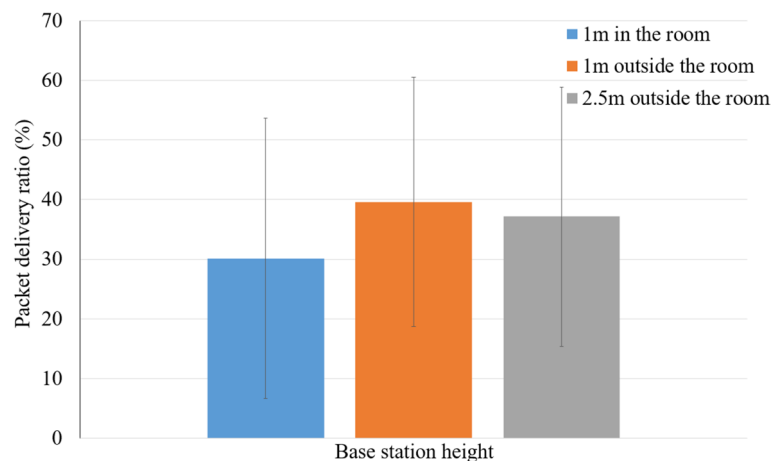
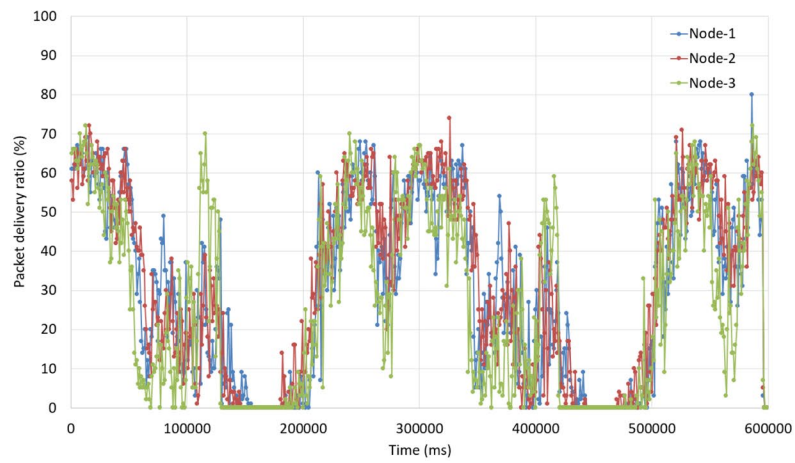
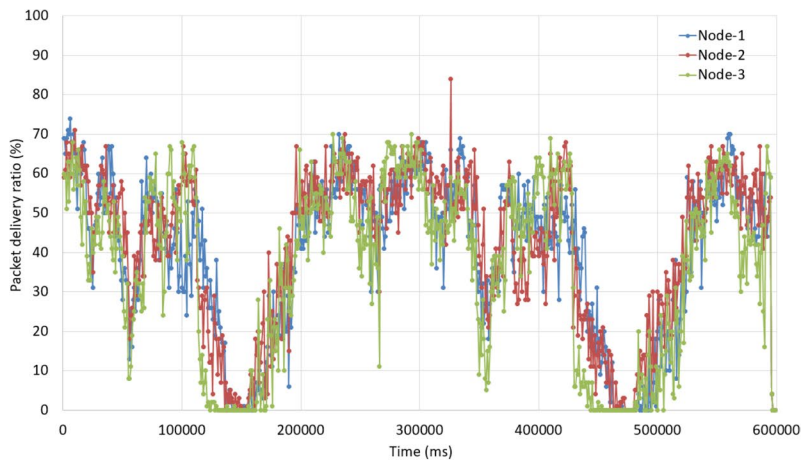


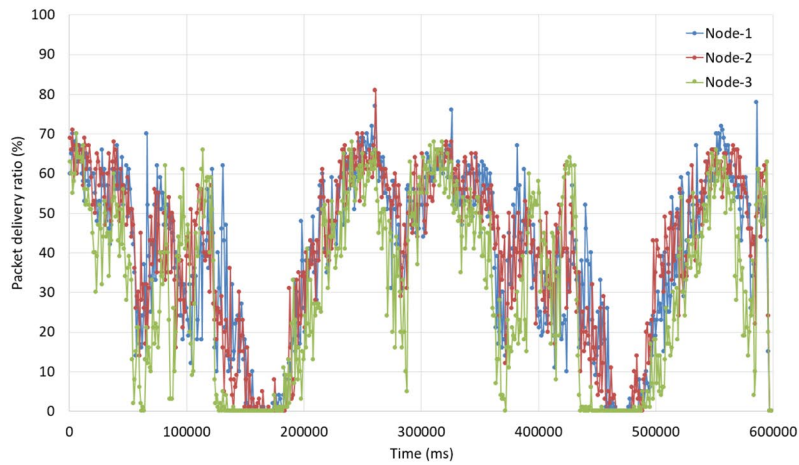
Fig. 14 The PDR for the test case #5



(a) The base station is at an altitude of 1 m above the ground in the room



(b) The base station is at an altitude of 1 m above the ground outside the room



(c) The base station is at an altitude of 2.5 m above the ground outside the room

Fig. 15 The PDR versus time index for the test case #5. **a** The base station is at an altitude of 1 m above the ground in the room. **b** The base station is at an altitude of 1 m above the ground outside the room. **c** The base station is at an altitude of 2.5 m above the ground outside the room

- In the test case #2: increasing the number of nodes (one to three transmitter nodes), the PDR then decreases. However, at three transmitter nodes (i.e., maximum number of transmitters), increasing the packet inter-arrival times from 13 to 20 ms, the PDR results are greater than 86%, approximately (i.e., 86.41 to 96.94%).
- In the test cases #3 and #4: the PDR results are not different for the cases of the man standing and walking in the indoor and outdoor environments with a short walking distance (5 m). Also, since all nodes in this work use the CSMA/CA protocol for medium access, all nodes then have the same priority for data transmission and PDR balance. Additionally, the results indicate that when three transmitter nodes with a 16-byte packet size are used for the cases of the man standing and walking a short distance in the room and outside the building, using 18 ms of the packet inter-arrival time or the sampling rate of approximately 55 samples/second can help to achieve the PDR higher than 86%, approximately.
- Finally, in the test case #5, to appropriately apply the WBAN for the case of the man walking in the big building, the base station should be placed outside the room, since higher PDR results can be achieved. The PDR more decreases when the man walks through the corner or there is no LoS communication. Also, the PDR results from the cases of the base station is at the altitudes of 1-m height and 2.5-m height from the ground level and placed outside the room are not much different.

Comparisons of experimental settings and results between this work and WBAN systems from the literature are also summarized in Table 2. By our research methodology and experiments, researchers and users can consider the optimal point for WBAN setting and configuration to achieve the communication reliability requirement.

In future work, an appropriate WBAN communication protocol in the MAC layer will be designed and developed to achieve network efficiency from both a simulation and an experimentation point of view, where the effects of the packet inter-arrival times, the packet sizes, and the number of nodes will be taken into consideration. More performance metrics related to WBAN communication reliability will be employed for evaluation. Additionally, a proposed solution that focuses on network performance as well as energy efficiency will be implemented. Finally, radio propagation models with path loss coefficients measured in WBAN environments will be considered.

Conclusions

This paper studied the standard multiple access mode and validated it experimentally based on TinyOS TelosB wireless nodes. This scheme has been implemented on real hardware with respect to WBAN characteristics. The experimental results demonstrate the effects of the packet inter-arrival times, the packet sizes, the number of nodes in the network, human movements, indoor and outdoor environments, and transmitter and receiver positions on the WBAN communication reliability in terms of the packet delivery ratio. The success rate obtains over 90% when setting up the appropriate limiting factors for data transmission. Our approach can help to setup the fundamental parameters in the CSMA/CA for WBANs applications without requiring a new developed protocol and enhance higher throughput for data communication by avoiding retransmission and data collisions in the network.

Table 2 Comparisons of experimental settings and results between this work and WBAN systems from the literature

Works	Objectives	Wireless technology	<ul style="list-style-type: none"> • Type of study • Test cases/scenarios 	Results and major findings
[24]	A WBAN system with motion sensors for physical rehabilitation was presented.	ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Experiment • Sensor data including motion sensor, ECG, oxygen saturation, temperature, and humidity were gathered. They were sent to the medical servers. 	<ul style="list-style-type: none"> - Sensor data from the WBAN as the real-time data were measured and collected. - The system provided guidance and feedback to the user, and could generate warnings based on the user's state, level of activity, and environmental conditions. - All recorded information could be transferred to medical servers via the Internet.
[25]	Performance evaluation of a WBAN for remote patient monitoring was presented.	ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Simulation • The performance of a remote patient monitoring system was analyzed, where patient data recorded in the hospital database were transmitted through the WBAN. 	<ul style="list-style-type: none"> - It was possible to monitor patients from remote locations using the WBAN over the Internet without reasonable delay. - The transmission control protocol (TCP) used in a fixed network did not work very well in wireless networks. Thus, it would be sensible to use a multi-hop network to optimize the transmission time.
[26]	A wearable IEEE 802.15.4-based body sensor network for blood pressure monitoring was presented.	ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Experiment • Arterial blood pressure estimated based on the pulse arrival time, which was measured using a single lead ECG patch on the chest and a photoplethysmogram (PPG) sensor on the finger was collected in the WBAN. 	<ul style="list-style-type: none"> - Arterial blood pressure data could be measured and collected. The acquired data were stored and displayed on a personal digital assistant (PDA) or a wristwatch. - The system could operate for up to 8 h.
[27]	Performance evaluation of the IEEE 802.15.4 for WBANs was presented.	IEEE 802.15.4	<ul style="list-style-type: none"> • Simulation • Three different access schemes in the IEEE 802.15.4 MAC, including unslotted CSMA-CA, slotted CSMA-CA, and contention free period (CFP), were evaluated. 	<ul style="list-style-type: none"> - The unslotted mode had better performance than the slotted one in terms of throughput and latency but with the cost of much power consumption. - The guaranteed time slot (GTS) in CFP could not guarantee the successful transmission of the CFP frames without sufficient GTS allocation.

Table 2 (continued)

Works	Objectives	Wireless technology	• Type of study • Test cases/scenarios	Results and major findings
[28]	Design and implementation of a WBAN-based real-time Electroencephalogram (EEG) monitoring system was presented.	ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Experiment • EEG signals were sent from sensor nodes and collected at the gateway, where a Zigbee/Internet Gateway (ZIGW) had been developed. 	<ul style="list-style-type: none"> - EEG signals could be measured and collected, where the received signal strength indicator (RSSI) value at each different communication distance and the packet reception ratio under different RSSI levels were reported. - The worst case delay was observed as 20 s when the distance between the active subject and the gateway was 15 m. - Medical data could be monitored less than 300 ms when the active subject was within a distance of 1m and facing the gateway.
[29]	Implementation of WBANs for healthcare systems was presented.	ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Experiment • Patient data including ECG, EEG, temperature, and pulse rate were measured in the WBAN. • WBAN performance in terms of the end-to-end delay were measured and evaluated in the case of the patient walking in different distances from the gateway. 	<ul style="list-style-type: none"> - Wearable sensor data collected from the human body were sent to a coordinator using the IEEE 802.15.6 standard. - The IEEE 802.15.4 performed better than IEEE802.15.6 in terms of the packet loss rate (PLR), while for longer payloads, the IEEE 802.15.6 achieved lower PLRs. - The delay obtained from the IEEE 802.15.4 was lower than the case of the IEEE 802.15.6. Thus, depending on the application requirements, the IEEE 802.15.4 could be more suitable in some cases than the 802.15.6.
[30]	Performance evaluation of the IEEE 802.15.6 WBAN was introduced.	IEEE 802.15.6	<ul style="list-style-type: none"> • Simulation • The IEEE 802.15.6 network performance in terms of packet loss rate, delay, and throughput was evaluated. • A comparison with a WBAN based on the IEEE 802.15.4 standard was also carried out. 	<ul style="list-style-type: none"> - WBAN packet error rate, packet loss, packet generation rate, and delay profile when varying payload sizes and the number of patients were measured and reported. - The payload size could influence the performance of the WBAN.
[31]	Performance evaluation of WBANs for medical applications was presented. The design of MAC protocols and power consumption profiles of WBANs were emphasized.	IEEE 802.15.6	<ul style="list-style-type: none"> • Simulation • Blood pressure, respiratory rate, body temperature gathered from the human body were sent to a central coordinator unit, where communication performances were measured. 	<ul style="list-style-type: none"> - WBAN packet error rate, packet loss, packet generation rate, and delay profile when varying payload sizes and the number of patients were measured and reported. - The payload size could influence the performance of the WBAN.

Table 2 (continued)

Works	Objectives	Wireless technology	• Type of study • Test cases/scenarios	Results and major findings
[32]	Performance analysis of a WBAN monitoring system for professional cycling was presented.	IEEE 802.15.4	<ul style="list-style-type: none"> • Experiment • The knee and ankle angles, which influence the performance as well as the risk of overuse injuries during cycling, were measured using WBANs. 	<ul style="list-style-type: none"> - The WBAN could be used for real-time monitoring of lower limb kinematics during cycling. - The wireless communication was robust enough to handle sudden drops in the RSSI values, and the energy consumption gave the sensor network a life-span of a couple of days.
[33]	Implementation of WBANs for IoT healthcare applications was presented.	BLE module with CC2541 chip (2.4 GHz)	<ul style="list-style-type: none"> • Experiment • Multiple sensor nodes were deployed on different positions of the body to measure the subject's body temperature distribution, heartbeat, and detect falls. Note that accelerometers, temperature sensors, and pulse sensors were applied. 	<ul style="list-style-type: none"> - The proposed system with solar energy harvesting demonstrated that long term continuous medical monitoring based on WBAN was possible provided that the subject stayed outside for a short period of time during the day. - Performance of the solar energy harvester with a maximum power point tracking (MPPT) circuit and current consumption of the sensor node was also evaluated.
[34]	Delay analysis of emergency vital data packets in WBANs was presented.	ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Simulation • The transmission delay of the standard ZigBee MAC, the modified MAC, and the priority-based MAC were evaluated when varying the number of ZigBee nodes and back-off periods. 	<ul style="list-style-type: none"> - For a single ZigBee node, all MAC protocols provided the same results with a minor difference in delay. - The modified MAC worked better than other methods when increasing the number of nodes.
[35]	Performance evaluation of the IEEE 802.15.4 in WBANs focusing on the broadcasting problem was studied.	IEEE 802.15.4	<ul style="list-style-type: none"> • Simulation • Nine broadcasting algorithms in IEEE 802.15.4 WBANs were tested. • Simulations were realized over a seven-node mobile network that included a dense area, as well as distant nodes in seven types of movements. 	<ul style="list-style-type: none"> - Network performances of nine broadcasting algorithms in terms of network coverage, latency, traffic load, and energy consumption were reported.
[36]	Performance analyses of the IEEE 802.15.6 WBAN with heterogeneous traffic were presented.	IEEE 802.15.6	<ul style="list-style-type: none"> • Simulation • The analytical analysis of the IEEE 802.15.6 standard with heterogeneous traffic in terms of priority was presented. 	<ul style="list-style-type: none"> - The effects of arrival rates and number of nodes on the PDR, the latency, and the queuing traffic load were reported.

Table 2 (continued)

Works	Objectives	Wireless technology	• Type of study • Test cases/scenarios	Results and major findings
[37]	A real-time wearable sport health monitoring system based on body sensor networks was developed.	nRF905 wireless transceiver, 433/868/915MHz	<ul style="list-style-type: none"> • Experiment • The wearable sport health monitoring system, including three-axis acceleration, three-axis magnetometer, three-axis gyroscope, nRF905 wireless transceiver, and MSP430F2418 microcontroller, was implemented and tested. 	The human body motion monitoring system enabled real-time monitoring of sports health.
[38]	Computational efficient wearable sensor networks have been proposed in health monitoring systems for sports athletic using IoT.	–	<ul style="list-style-type: none"> • Experiment • The wearable device for the continuous real-time monitoring of heart rate, respiratory frequency, and movement cadence during physical activity has been analyzed. 	<ul style="list-style-type: none"> - The sensor data could be uploaded to the IoT-connection system Ethernet module, and an authorized individual could access the data via the Internet to track the athletic health. - The system was user-friendly, reliable, and economical to use.
[39]	An energy efficient architecture for IoT-enabled body area networks was presented.	Wi-Fi, IEEE 802.11 ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Experiment • The system architecture had been tested with the different transceivers, including Wi-Fi and ZigBee, and with the different versions of embedded architecture. 	<ul style="list-style-type: none"> - With the developed architecture, the energy consumption of the network was reduced by 40%.
[40]	Performance evaluation of the MAC layer protocol over WBANs was introduced.	ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Simulation • ZigBee wireless networks with star, tree, and mesh topologies were evaluated under different scenarios. 	<ul style="list-style-type: none"> - ZigBee wireless networks using the mesh topology provided the highest overall performance regardless of the number of nodes.
[41]	Improving network efficiency in WBANs using forwarder selection techniques was presented.	Wi-Fi, IEEE 802.11 Bluetooth ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Simulation • The solution for grouping sensor nodes and selecting forwarder nodes was evaluated in terms of energy consumption. 	<ul style="list-style-type: none"> - Sensor node energy consumption was reduced.
[42]	WBAN monitoring with ZigBee, 5G, and 5G with MIMO for outdoor environments was presented.	ZigBee, IEEE 802.15.4 5G MIMO	<ul style="list-style-type: none"> • Simulation • ZigBee, 5G, and 5G with MIMO devices were tested in outdoor WBANs to evaluate energy consumption and transmission speed. 	<ul style="list-style-type: none"> - The Zigbee devices could minimize the energy consumption and extend the nodes' life cycles. - The 5G device increased transmission speed to achieve fast delivery of data. - MIMO added more stability to the consumption of received signal power.

Table 2 (continued)

Works	Objectives	Wireless technology	<ul style="list-style-type: none"> • Type of study • Test cases/scenarios 	Results and major findings
Proposed work	Implementation and experimental evaluation of dynamic capabilities in WBANs were presented.	ZigBee, IEEE 802.15.4	<ul style="list-style-type: none"> • Experiment • The effects of packet inter-arrival times, packet sizes, and the number of nodes deployed in the WBAN, including human movements, indoor and outdoor environments, and transmitter and receiver positions are taken into consideration and evaluation. 	<ul style="list-style-type: none"> - Experimental results illustrated the significant factors which affected the WBAN reliability as measured by the PDR. - The diverse environment testbed could affect WBAN's performance for data transmission. - The best network reliability needed to setup more than 15 ms in packet interval time to gain over 90% of PDR for every test scenario. - Experimental results related to WBAN reliability obtained from various test cases were reported and summarized.

Abbreviations

WBAN	Wireless body area network
WSN	Wireless sensor network
PDR	Packet delivery ratio
EMG	Electromyography
ECG	Electrocardiogram
MAC	Media access control
CSMA/CA	Carrier sense multiple access with collision avoidance
TDMA	Time-division multiple access
IoT	Internet of Things
WPAN	Wireless personal area network
PZ	Packet size
PIAT	Packet inter-arrival time
NN	Number of nodes
CI	Confidence interval
LoS	Line of sight
TCP	Transmission control protocol
RSSI	Received signal strength indicator

Acknowledgements

This work was supported by the Faculty of Engineering, Prince of Songkla University, Thailand, and the University of Aizu, Japan.

Authors' contributions

Conceptualization, P.T., D.B., and A.B.; methodology, P.T., Y.S., D.B., and A.B.; investigation, P.T., Y.S., D.B., and A.B.; writing—original draft preparation, P.T., D.B., and A.B.; writing—review and editing, P.T., D.B., A.B., N.J. and H.S.; supervision, N.J. and H.S. All authors have read and agreed to the published version of the manuscript.

Funding

No funding has to be declared for this work.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

All authors have agreed to submit the paper for publication. Additionally, Mr. Pitchakron Thippun, who is the first author of this paper and also performed the experiments, provided informed consent for the publication of his images in Figs. 4, 5, 6, 7, 8, and 9.

Competing interests

The authors declare that they have no competing interests.

Received: 19 September 2022 Accepted: 20 December 2022

Published online: 05 January 2023

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