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A Priority-based Data Transmission for Energy Efficiency MAC Protocol with Wireless Body Area Networks

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ABSTRACT

Wireless Body Area Networks (WBANs) are a collection of vital and electrical signals measured from various body parts to help analyze therapeutic approaches for patients using wireless data transmission. The significant data has to communicate with collision avoidance to obtain high throughput. In this paper, a hybrid MAC layer communication is implemented between CSMA/CA and TDMA. CSMA/CA communication has been introduced to manage the TDMA sequence of transmissions without a central node. The experimental results in this system implement real wireless devices, TelosB, with the IEEE 802.15.4 standard. We studied the convergence speed of transmission sequence allocation, which was measured in the CSMA/CA period. When the number of nodes is small, the convergence time is slower than a large number of nodes. However, the number of nodes does not affect the number of rounds entering the transmission period. This parameter has been evaluated for the network and energy efficiency in WBANs. Packet delivery ratio, packet numbers, and energy consumption are examined for the different priority-based nodes in the TDMA period. The energy consumption can reduce to 40% for no priority when compared with high priority in the case of a priority-based node.

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1. INTRODUCTION

Wireless communication technology helps to collect information from the patient's vital signs to see how it has changed to take timely assistance to the patient. WBANs was developed to respond to medical technology applications. Currently, there is a communication design in the MAC layer that uses the advantages of each protocol to obtain a high data throughput, such as slotted ALOHA with time-division multiple access (TDMA) [1] or carrier sense multiple access with collision avoidance (CSMA/CA) with TDMA [2-4].

This research aims to develop a form of communication for distributed Wireless Body Area Networks (WBANs) with the IEEE 802.15.6 standard that defines the needs of Wireless Body Area Networks. Nevertheless, the actual experiments were performed with the IEEE 802.15.4 standard to study the effects of attaching a communication node on the body and improving communication in the MAC Layer. In this research, the efficiency of data transmission ordering was measured without any central node to manage all the devices.

This paper [3] presents a low-power wireless communication pattern from human body-tracking sensor nodes using the AD-MAD protocol as a communication manager. There are three levels where level 0 is the most important and level 2 is the lowest priority. The high-priority nodes have the least contention window (CW) bounds. In paper [4], the sensor nodes suffer a power shortage that affects the network lifetime. To address this problem, they designed a new MAC layer protocol to increase power efficiency and extend the existence of body sensor nodes (BSNs). The proposed WBAN protocol uses a hybrid model which takes advantage of both CSMA/CA and TDMA. In the design of the WBAN system, the network is star-topology to communicate with each other. For [6] offers a reliable method of communication in implantable wireless body sensor networks (IWBSNs). It is very small in size, has a long battery

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life, and has efficient data collection, processing, and wireless transmission.

The paper is organized as follows: The next section from the first section introduces related work and the proposed concept. Then, section three presents the implementation of the system. The section on results and discussion presents the experimental results, including exploration. Our conclusion sums up in the last area.

2. METHODOLOGY

2.1 Proposed System

The protocol design of the MAC layer consists of two phases: the time interval for which the transmission interval is allocated using the CSMA/CA beacon race distribute the transmission interval; and defining the priority of the sensor node. The second phase is the time interval for the node to transmit packets at its own slot time that it was initially allocated, like the TDMA protocol. After the packet has been sent, the node will go into sleep mode to maximize the energy consumption of the sensor node.

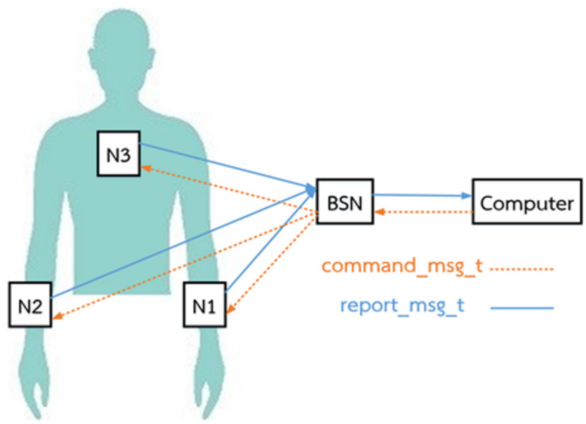


Fig.1: *Overview of the operation system.*

The overall network by the computer has initially transmitted the message, namely command_msg_t, to the base station (BSN), as demonstrated in Figure 1. Then the BSN broadcasts by sending packets to all nodes in the network (dash line). When the node obtains the received value from command_msg_t and processes it, it starts sending the data, namely report_msg_t, back to BSN (solid line). At the same time, command_msg_t is a message which informs all nodes to initiate data communication and control the parameters for transmission of the data, such as the number of packets, packet inter-arrival time, and packet size.

2.2 MAC Protocol

The system in this paper studies a protocol for data communication in the MAC layer. It is designed to combine CSMA/CA and TDMA to make the high network performance and energy efficient. In the first phase, it will use CSMA/CA to compete for the order in which the data is transmitted. When the sequencing is complete, it enters the TDMA phase. We use CSMA/CA communication method to allocate the time interval for sending packets to each node in the system, as well as utilize TDMA protocol to transmit packets for efficient communication and energy efficiency. When the node is not at the time of data transmission, it enters asleep mode, making it more energy-saving.

First, we have designed a CSMA/CA communication mechanism to compete for beacon transmissions to allocate a time interval within one T_{frame} to each node in the system so that they do not collide. Each node transmits and listens to the beacon from the previous and next node and adjusts its transmission interval according to the first equation [5].

$$t_{curr}^{(k+1)} = (1-\alpha)t_{curr}^{(k)} + \alpha\frac{t_{prev}^{(k)} + t_{next}^{(k)}}{2} \qquad (1)$$

Where $t_{curr}^{(k+1)}$ is the time interval for the node to send a beacon packet in the next T_{frame}. α is called alpha which is a parameter that determines how much we are based on the time interval of your own or neighbor node. $t_{curr}^{(k)}$ is the time interval for the node to send a beacon packet. $t_{prev}^{(k)}$ is the timing to receive beacon packets from the previous node. $t_{next}^{(k)}$ is the time interval to receive beacon packets from the next node.

The operation of the system presented in this paper is to design a data communication method in the MAC Protocol layer. It is designed to combine the CSMA/CA communication method and the TDMA communication method. The amount of data has been sent in each node. The node knows the sequence of slots of its own and neighboring nodes. The total number of slots is in one T_{frame}. Once the transmission sequence has been allocated after convergence time, it waits for short intervals, T_0, and then starts the TDMA period. TDMA concept has been used to send data to the base station. The first node to send the data will send an initial beacon, letting all nodes in the network know that it has started, and then send the data immediately. After finishing data

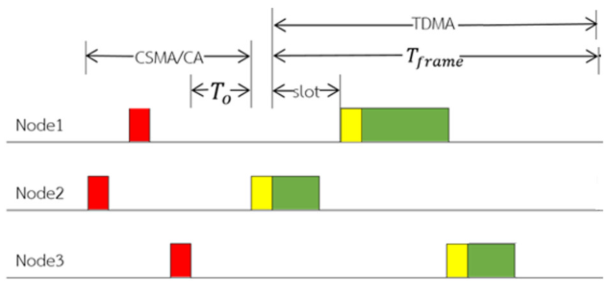


Fig.2: *Our proposed protocol for slot allocation.*

transmission, it goes into sleep mode, and wakes up again only when it reaches its sending queue in the next T_{frame}. The length of data on each node is based on the priority of the data.
In mesh communication design, each node communicates within the network to devote the transmission interval, as shown in Figure 2. Our network consists of three nodes and a base station node. Each node uses a CSMA/CA data communication mechanism to assign the location of the data for sending the packets. After transmitting the beacon signal to the base station, it uses the TDMA data communication mechanism to transmit the data to be able to prevent data collision in each node. There will be a guard time after the transmission is completed, and then it will go to sleep mode.

2.3 Energy computation

We estimate the energy consumption with a device to measure the electricity through the USB port. From the values, we can determine the current. It is divided into two ranges: the first one where the CC2420 communication chip is enabled and the range where the CC2420 radio chip is off. It is used to combine these two phases, which can calculate from this equation (2).

$$E_{total} = T_{awake}VI_{awake} + T_{sleep}VL_{sleep} \quad (2)$$

Where E_{total} is the total energy that a node uses in one T_{frame} in joules per T_{frame} $[J/T_{frame}]$

V is the voltage at which the node operates in volts [v]

T_{awake} is the length of time a node sends a packet in seconds [s]

I_{awake} is the current consumed by the node during the node transmits the packet, in amperes [A]

T_{sleep} is the time interval that the node does not send a packet, otherwise goes to sleep, in seconds [s]

I_{sleep} is the current consumed by the node during the time the node is in an idle state, in amperes [A]

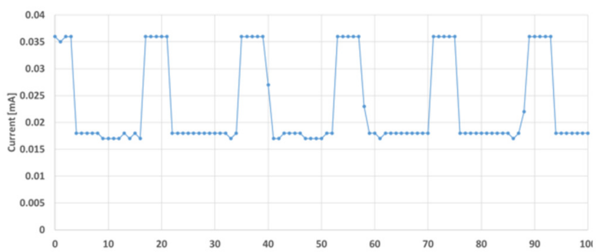


Fig.3: *The current consumed by a node.*

This study involved sending data to the base station and continuously recording the results while turning one of the CC2420 communication chips on and off in the network. Setting the opening and closing intervals as slots have been shown in Figure 3's explanation of the on-off operation. A T_{frame} lasts 10 seconds, while one slot time takes 3 seconds. We must allow three seconds for every slot because of the low sampling rate of the device. Figure 3 shows that the current curve was consistently measured. According to the testing findings, the enabled CC2420 communication chip consumes approximately 36 mA of current. The current consumption drops to 18 mA when the CC2420 communication chip is disabled. The experimental result finds that when CC2420 goes to sleep, the current consumption is cut in half.

An example of the total energy consumed by the node in one T_{frame} can be calculated from the second equation, where voltage (V) equals 3 volts while time for T_{awake} equals 3 seconds and time for T_{sleep} equals 7 seconds. Whilst the current (I_{awake}) equals 0.036 A, and I_{sleep} equals 0.018 A. The total energy consumption is $E_{total} = (3)(3)(0.036) + (7)(3)(0.018) = 0.702[J/T_{frame}]$

The CC2420 communication chip is turned on and off during the node's operation. TDMA is started by the node periodically based on T_{frame}. Because nodes in WBANs at different times have varying transmission throughput requirements and the importance of each node is not equal, each increased priority has more considerable transmission privileges. The human body has measured the electrical and vital signals used in WBAN deployment. Since each data has a different preference for transmission, priorities must be differentiated.

3. IMPLEMENTATION

3.1 Experimental Setup

In the experiment, beacons are sent from the sensor node to another sensor node in the system to manage the data transmission without any collision. It applies with TelosB sensor nodes based on RF Chip Texas Instruments® CC2420 frequency band 2.4GHz $\sim$ 2.485GHz and processed MCU TI MSP430F1611 RAM 10Kb with IEEE802.15.4 standard.

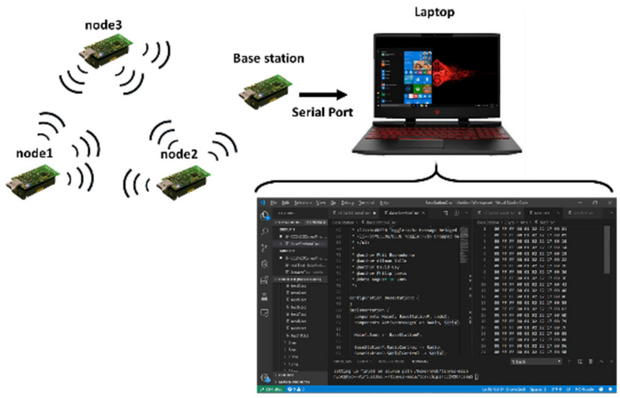


Fig.4: *The architecture of the network system.*

While the nodes send beacons, the base station receives the beacons from the nodes to store the results

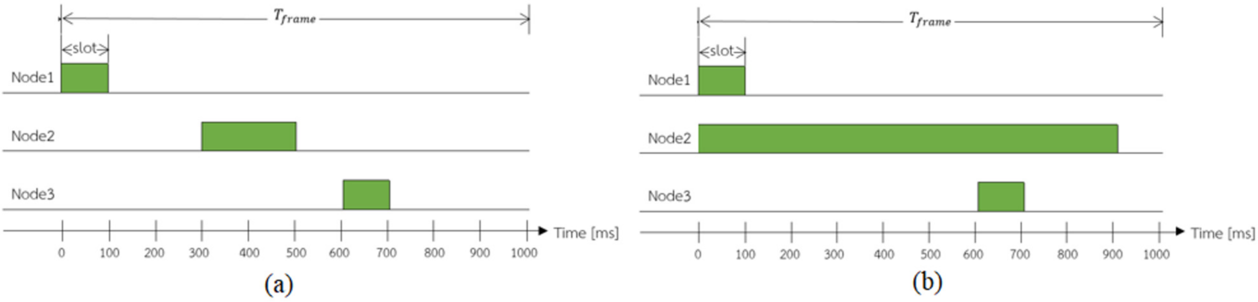


Fig.5: *The priority-based data transmission in each case (a) Low Priority and (b) High Priority.*

and collect them in the computer using TelosB as a base station connected to the computer via serial port with a baud rate of 115200 bps. As seen in Figure 4, the experiment has been set up.

3.2 Convergence Time

We study the convergence time in the CSMA-CA phase to realize how long for starting the TDMA phase and to understand the network behavior when changing the number of nodes and some parameters. In the test case I sends beacons between nodes in the network to prioritize transmission. We have selected the three alpha values between [0,1] and increased the number of nodes entering the network from 3 to 12. This can discover the effect on the number of cycles that go into convergence, as illustrated by the parameters used for the experiment in Table 1.

Table 1: *Parameters used for the experiments.*

Setting Parameters	Value (Test case I)	Value (Test case II)
Number of nodes	3, 6, 9, 12	3, 6, 9, 12
Alpha	0.25, 0.55, 0.85	0.85
T_{frame} (seconds)	1	1, 2, and dynamic

While test case II sends beacons between nodes in the network with the fixed alpha at 0.85 and then scaled the T_{frame} for 1, 2 seconds, and the dynamic T_{frame} calculated from the equation (3), where the number of nodes in the network affects the T_{frame} size.

$$T_{frame} = N_{nodes} \times T_{send} \quad (3)$$

From this equation, N_{nodes} is the number of nodes in the network, and T_{send} is the time for sending data or packet inter-arrival time in seconds.

3.3 Energy Consumption

We investigate how much energy WBANs using CC2420 chip receivers use to transmit data in the TDMA phase. The transmission and reception of data are crucial aspects of energy efficiency. We divide the radio control scenario into three categories, for example, no priority, low priority, and high priority. We aim to calculate energy consumption in each priority-based data transmission using equation (2).

3.3.1 On/Off Radio Control with No Priority

In this study, we have divided slots in each node to send packets to the base station asynchronously. The splitting of packets is equal for each node. Each slot is 100 milliseconds (ms), and one T_{frame} is one second. Node1 sends packets from time 0-100 ms. Node2 sends packets from time 300-400 ms, and Node3 sends packets from time 600-700 ms. All nodes have the same data transmission interval. For this case, it demonstrates in a normal situation for transmitting the packet.

3.3.2 On/Off Radio Control with Low Priority

In this scenario, we tried to have different priorities for each node. The more important node obtains the authority to transmit packets rather than the less critical node. Each slot in Figure 5(a) has a node's packet distribution assigned to it. The time scale is 100 ms, while T_{frame} has a time scale of 1000 ms. From time 0 to 100 ms, Node1 transmits packets. Node2 and Node 3 send packets between 300 and 500 ms as well as 600 and 700 ms, respectively. Node2 is more importance than the normal level.

No priority or normal mode is the general stage to send the data in your own periods for this system. As a result, the second node's significance has increased from sending during one timeslot to two timeslots. The statistics of the vital signs, including body temperature, pulse rate, respiration rate, and blood pressure, are supported by this case. They may require data with a longer duration in emergency cases.

3.3.3 On/Off Radio Control with High Priority

Given that each slot lasts 100 ms and that one T_{frame} contains 1000 ms. Figure 5(b) depicts the packet fragmentation of each node. Node1 delivers packets between the intervals of 0 and 100 ms. While Node3 also sends packets for 100 ms from 600–700 ms. The second node needed to send more packets; thus, it expanded from the initial one to nine timeslots, sending packets from time 0-900 ms.

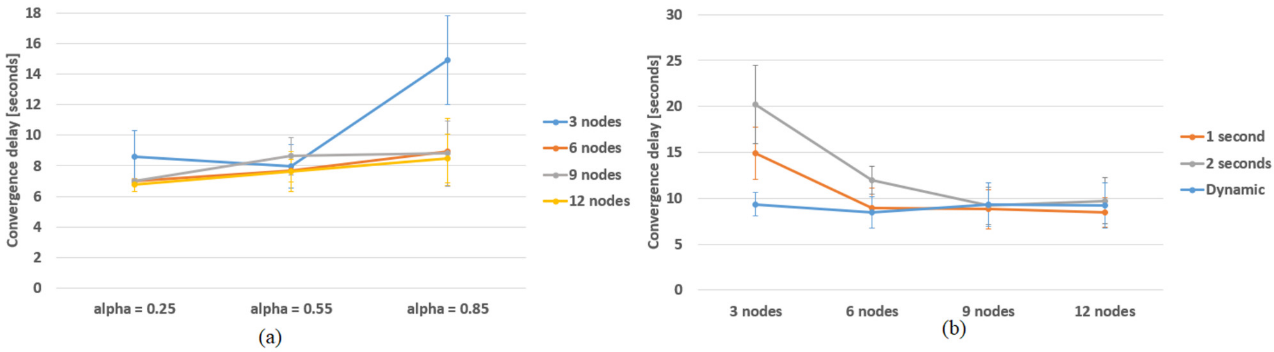


Fig. 6: *The number of cycles until the steady state in each test (a) case I and (b) case II.*

One slot is left empty to distinguish between each T_{frame}. This boosts the second node's importance by sending packets throughout the T_{frame}. In WBANs, electrical signals that require constant data transmission all the time, such as EMG, EEG, and ECG, are carried by this case.

4. RESULTS AND DISCUSSION

In this section, we study two parameters which are convergence time to go to TDMA data transmission and also throughput when sending data with prioritizing method in terms of packet delivery ratio and packet loss.

4.1 Network Setting

According to test case I, the experiment adjusts alpha at 0.25, 0.55, and 0.85, respectively. It can be seen that the alpha value is 0.25 and 0.55 for the different number of nodes; they obtain the same number of cycles for convergence time to go to a steady state. Whereas the alpha value is 0.85, the number of rounds entering the constant state is more than twice for three nodes in the system when compared to the other number of nodes, as seen in Figure 6(a). Because it depends on the time of neighbor nodes, it will make more unstable to enter convergence.

From the dynamic T_{frame} scaling experiments according to test case II, it can be seen that at one second and two seconds for T_{frame} as well as three nodes take quite a long time for the number of cycles for convergence time when comparing the other parameter settings, as demonstrated in Figure 6(b). We discover that convergence time when fewer nodes takes longer than with many nodes.

From the experimental results, it can be seen that when the value of alpha increases, the intervals of neighboring nodes are used to affect the next beacons sent with regard to increase the number of cycles to enter the convergence. Moreover, when the length of the T_{frame} is resized to match the number of nodes in the network for dynamic case, keeping the number of cycles to reach until steady state constantly for the different number of nodes.

In the following work, after we select the suitable parameters from these two experiments, we then study the prioritized network communication for measuring the throughput and energy efficiency to present the distributed hybrid MAC protocol for WBAN application in terms of network capability.

4.2 Network Performance

The following experimental results are when sending data from three nodes in case of high priority with a T_{frame} of one second. The nodes go to a steady state for sending data to BSN with a checking threshold of 15 ms. We study the network performance when data transmission is in priority mode. The packet delivery ratio (PDR) and packet loss in percentage are interesting characteristics. PDR is the proportion of source packets transmitted to the total packets received by the destination node. The packet loss is the proportion in contrast to PDR. The other nodes send data when the priority-based node is transmitting the data as well. Another test is without sending data from the other nodes, while the priority-based node is sending data. A priority-based node would not be the same node in each T_{frame} to be fair for experimental results.

Whether other nodes would transmit data or not, it is not affected by the priority-based node at all. This is related to CSMA/CA mechanism for collision avoidance in WSNs. Regarding the packet delivery ratio, we discovered that the packet loss is vice versa. Additionally, to surround all potential data in the WBANs area, the energy consumption has been estimated for all scenarios. In this section, no priority, low priority, and high priority have all been investigated with the exact size of the T_{frame} and the different lengths of data transmission. In the following experimental results in other priority-based nodes, we also study the parameter, packet inter-arrival time with 10 and 15 ms, which affects the number of packets. Based on the experimental packet inter-arrival time from 15 ms onwards, the increase in packet sizes did not affect the PDR value significantly.

4.2.1 CC2420 Transceiver with No Priority

We have divided the slots in each node as a result of this experiment so that packets can be sent to the base station asynchronously. The number of packets of the base station received from each node in the range is shown in Figure 9(a) by the base station. The average number of packets that can be sent in a T_{frame} using a packet inter-arrival time of 10 milliseconds is 7.64. With this number, we can get the average from the experimental results.

We have also tested with another packet inter-arrival time to study the varied data transmission durations. Figure 9(a) uses a packet inter-arrival time of 15 milliseconds with an average of 5.93 packets per T_{frame}. Our findings are that the higher the packet inter-arrival time, the smaller number of packets in a limited time.

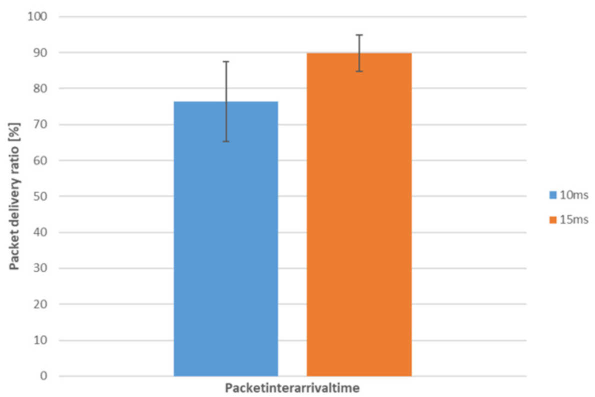


Fig.7: *The PDR value of both the packet inter-arrival times is 10 and 15 ms in the case of no priority.*

The following experimental results have been studied about the packet delivery ratio for this case. Because we know exactly the number of packets has been transmitted from all nodes, that is why we can find the ratio of the total number of packets received by the destination node to the number of source packets sent. Each node in each experiment delivered a packet to the base station for five minutes to gather data which was then averaged. Figure 7 shows a PDR comparison between packet inter-arrival times 10 and 15 milliseconds with an average PDR of 76.45% and 89.84%, respectively. An increase in packet inter-arrival time results in higher PDR values. A smaller packet inter-arrival time also makes high variances.

4.2.2 CC2420 Transceiver with Low Priority

With all nodes in the network, the priority of each node in this experiment is unequal, with the more significant node having more authority to deliver more packets than the less important node. Figure 9(b) specifies a packet inter-arrival time of 10 and 15 ms, respectively, to trial with Node2 as an intermediate priority. Considering the regular transmission interval for the packet inter-arrival time of 10 milliseconds, the number of packets at the base station received from each node over a period with averaged packets 7.51 per T_{frame}, and the interval when setting Node2 priority to mid-level with an average of 10.33 packets per T_{frame}. During packet inter-arrival time of 15 ms regarding normal transmission range, the number of packets at the base station receives from each node throughout time-averaged 5.89 packets per T_{frame}. When the midrange of Node2 was increased, the average number was 8.48 packets per T_{frame}. In each experiment, each node sent a packet taking five minutes to transmit the packets.

4.2.3 CC2420 Transceiver with High Priority

In order to test using Node2 as the highest priority, Figures 9(c) indicate a packet inter-arrival time of 10 and 15 ms, respectively. The base station received an average of 7.66 packets per T_{frame} from each node during the typical transmission interval of 10 milliseconds for the packet inter-arrival time. An average of 27.09 packets per T_{frame} during the interval when Node2's priority was set to a high level. While the standard transmission range requires a packet inter-arrival time of 15 ms, the base station received an average of 5.93 packets per T_{frame} for each node throughout a period. The average number of packets per T_{frame} was 23.59 when Node2's priority was increased. Each node in the experiment sent a packet in five minutes.

The following experimental results have been studied about the packet delivery ratio and packet loss for data transmission. This case shows that priority-based data transmission, especially in the case of high priority, affects to the success rate for sending data or not. At 5 ms of the packet inter-arrival time and 16 bytes of the packet size and other nodes with sending data simultaneously, the PDRs are 71.83%, 70.86%, and 62.88% for Priority_Node-2, Other_Node-1, and Other_Node-3, respectively. However, in case other nodes have not transmitted any data at the same time, the PDR is 73.06% for Priority_Node-2 only. As seen in Figure 8(a), this shows that the result has not been significantly different. By the way, the packet loss, as illustrated in Figure 8(b), is 38.16% and 36.48% for other nodes with and without sending data, respectively.

4.3 Energy Efficiency

The total energy consumed by the node when no priority in one T_{frame} can be calculated from equation (2), where V is 3 volts, T_{awake} is 100 ms, T_{sleep} is 900 ms, I_{awake} is 0.036 A, and I_{sleep} is 0.018 A. The energy consumption is as follows E_{total} $= (100 \times 10^{-3})(3)(0.036) + (90010^{-3})(3)(0.018) =$ 0.0594 $[J/T_{frame}]$. Whereas we determine the whole energy consumption in the system can be triple valued at 0.1782 $[J/T_{frame}]$.

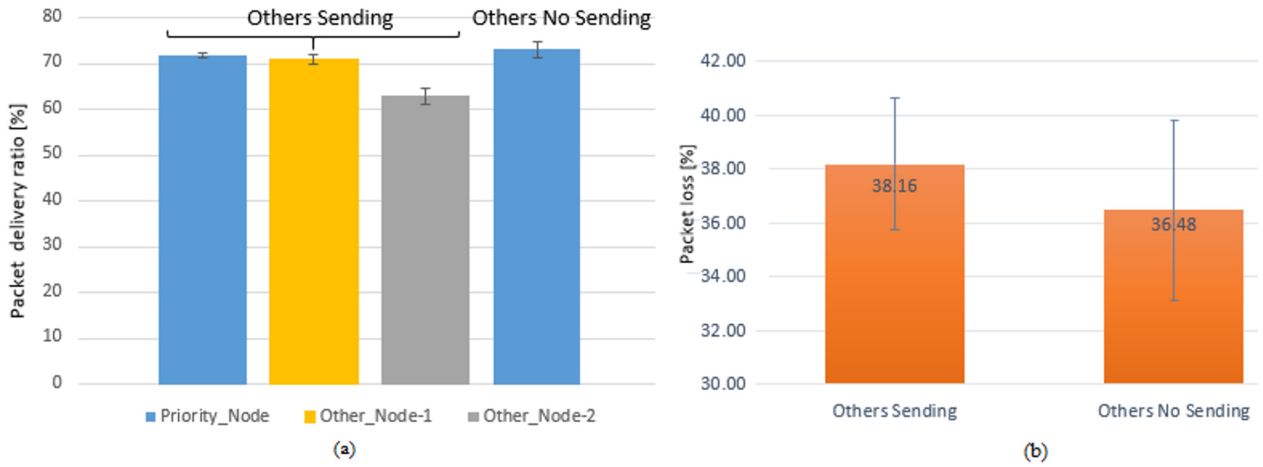


Fig.8: *When on/off radio control with the case of high priority, a study in (a) Packet delivery ratio and (b) Packet loss.*

As demonstrated with the CC2420 transceiver of low priority in Figure 5(a), we can compute the total critical node energy consumed in one T_{frame} from equation (2), where V is 3 v, T_{awake} is 200 ms, T_{sleep} is 800 ms, I_{awake} is 0.036 A, and I_{sleep} is 0.018 A. The energy usage is $E_{total} = (200 \times 10^{-3})(3)(0.036) + (800 \times 10^{-3})(3)(0.018) = 0.0648$ $[J/T_{frame}]$. We also can calculate the total energy consumed on the critical node with high priority as illustrated in Figure 5(b) in one T_{frame} from equation (2), where V is 3 v, T_{awake} is 900 ms, T_{sleep} is 100 ms, I_{awake} is 0.036 A, and I_{sleep} is 0.018 A. The following is how much energy is used $E_{total} = (900 \times 10^{-3})(3)(0.036) + (100 \times 10^{-3})(3)(0.018) = 0.1026$ $[J/T_{frame}]$. While the total energy consumption in the system can be 0.1872 $[J/T_{frame}]$ and 0.2214 $[J/T_{frame}]$ for low and high-priority-based cases, respectively.

In all these calculations, we assumed that Node2 when sending packets for some time is the priority-based node with increasing its importance to the middle level, as shown in Figures 9(b), and to the highest level, as seen in Figures 9(c). The higher the priority node is, the more packets can be sent at the cost of the node requiring more energy. It can be seen that the data with a packet inter-arrival time of 10 ms is a larger variance than the data with a packet inter-arrival time of 15 ms for all priority cases.

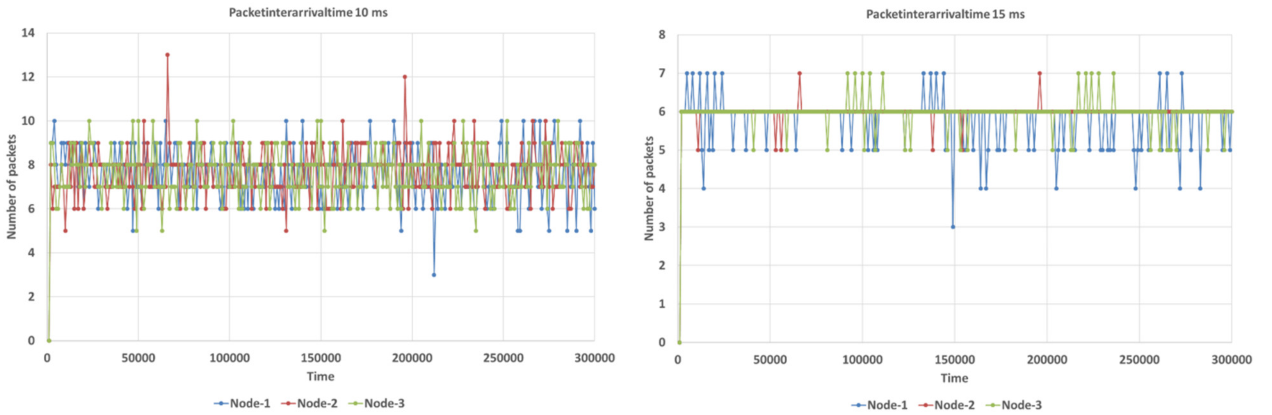
Table II shows the energy consumption in each priority level for both the priority-based node and the whole network. We explore the energy for the priority node based on the normal level or no priority. This case consumes 45% less energy in a T_{frame} than when enabling the communication chip. Normal priority utilizes less than 40% when compared with the energy per one T_{frame} in the critical node phase, which is very important. The high priority case consumes 5% less energy than the case that enables the CC2420 radio chip. However, priority cases consume less energy than the node energy while the communication chip is turned on.

Our experiment about energy and priority is divided into two sub-experiments. The first study is about the CC2420 communication chip on-off experiment. We discovered that when the CC2420 communication chip is in disabled mode compared with the activated manner, the energy can be reduced by 50%. The next is about adjusting the data transmission. When we enhance the node's priority to the middle level, the packet transmission interval from one slot adds to two slots, resulting in an average of 2.24 times more packets being transmitted, increasing the energy from originally 9.09% compared to the normal level. Then the priority of the node was upgraded to the highest level, increasing the packet transmission interval from one slot to nine slots, resulting in an average of 9.27 times more packets, increasing the energy consumption by 72.73% compared to the no priority.

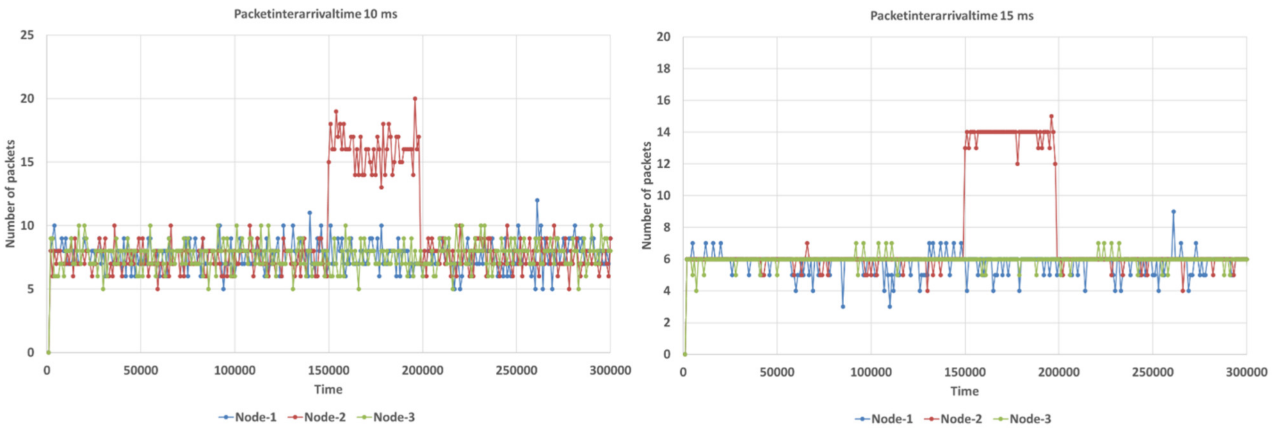
We study the experiment of energy consumption and precedence because there are a variety of sensor nodes that are both onboard and implanted in WBANs. With the need for data transmission in various sizes and types, it is necessary to develop the capability to adjust the priority-based node for the WBAN application in terms of energy efficiency.

Table 2: *Energy consumption at each priority level.*

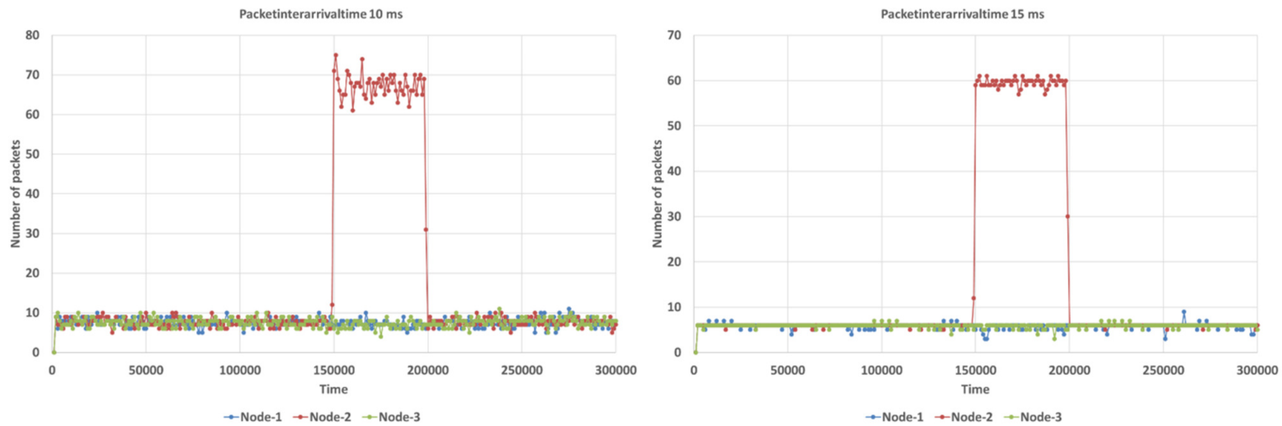
Energy in the range	**Energy consumption priority node [Joules/T_{frame}]**	**Energy consumption in all systems [Joules/T_{frame}]**
Enabling the communication chip	0.1080	0.3240
No priority	0.0594	0.1782
Low priority	0.0648	0.1872
High priority	0.1026	0.2214



(a)



(b)



(c)

Fig.9: *The number of packets at a base station has received in packet inter-arrival time 10 and 15 milliseconds for each level (a) No priority, (b) Low priority, and (c) High priority.*

5. CONCLUSIONS

The MAC protocol, both CSMA/CA and TDMA, has been studied in real implementation for the distributed wireless network. The experimental result in CSMA/CA phase shows that the alpha parameter and the number of nodes in the system have not affected much the convergence delay to go to the steady state for entering the data transmission period. When considering the priority-based node with a high priority case during the data transmission period in the TDMA phase, it can use energy consumption like enabling the transceiver all the time. While it can decrease to 30% when considering the whole system.

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