Energy-efficient Relay MAC with Dynamic Power Control in Wireless Body Area Networks

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Abstract

Wireless body area network (WBAN) is an emerging short-range wireless communication network with sensor nodes located on, in or around the human body for healthcare, entertainment and ubiquitous computing. In WBANs, energy is severely constrained which is the prime consideration in the medium access control (MAC) protocol design. In this paper, we propose a novel MAC protocol named Energy-efficient Relay MAC with dynamic Power Control (ERPC-MAC) to save energy consumption. Without relying on the additional devices, ERPC-MAC employs relaying nodes to provide relay service for nodes which consume energy fast. Accordingly the superframe adjustment is performed and then the network topology can be smoothly switched from single-hop to multi-hop. Moreover, for further energy saving and reliability improvement, the dynamic power control is introduced to adjust the power level whenever a node transmits its packets to the coordinator or the relaying node. To the best of the authors' knowledge, this is the first effort to integrate relay, topology adjustment and power control to improve the network performance in a WBAN. Comprehensive simulations are conducted to evaluate the performance. The results show that the ERPC-MAC is more superior to the existing standard and significantly prolongs the network lifetime.

Keyword: WBAN, MAC, relay, power control

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1. Introduction

Wireless body area network (WBAN) is a short-range wireless communication network which is human-centered with several sensor nodes located on, in or around the human body. Through these intelligent, lower-power, miniaturized sensor nodes, information such as blood pressure, Electrocardiograph (ECG) can be processed and forwarded to the coordinator for diagnosis and prescription. WBAN has the ability to provide continuous and reliable health monitoring for human body also with great freedom and comfort. It greatly alleviates the contradiction between the growth of aging population and the limited financial resources of healthcare systems. Moreover, WBAN is also widely used in entertainment, military and disabilities assistance. WBAN's convenience and wide applications draw more and more attention all over the world and bring brilliant prospects.

On one hand, as a special case of wireless sensor network (WSN), WBAN actually has some characters similar with the general sensor networks. On the other hand, WBAN is human-centered, which makes it greatly different from the general sensor networks [1-2]. For instance, WBAN heterogeneous traffic arrival rate should be emphatically considered for the protocol design. The WBAN MAC should take the diverse traffic nature of in-body and on-body nodes into account. For example, the data rate of in-body nodes varies, ranging from few kbps in pacemaker to several Mbps in capsular endoscope. How to support these heterogeneous nodes with different duty cycle and integrate their traffic in a superframe efficiently is a challenging issue in a WBAN. However, a WSN normally only considers homogenous sensors. Also, most of the traffic in WBANs is correlated [3], which is a distinct phenomenon in WBANs. In addition, leisure and entertainment applications are also supported by WBANs [4]. Moreover, movements of tens of centimeters can cause topological change in WBANs while the mobility in WSNs is considered on a scale of meters. Some major differences between WSNs and WBANs are listed in [5]. Finally, WBAN has unique wireless channel properties because of the fact that human body becomes one portion of the network. The channel pathloss and connectivity between nodes will be greatly affected by geometrical characteristic and movements of the human body. Therefore, high reliability and low emission power level are required in WBANs. Beside these requirements, the most challenging issue is the energy efficiency of the battery-powered sensors especially for the nodes which are implanted in the human body. Therefore, how to extremely prolong the network lifetime is the top concern in the medium access control (MAC) protocol design.

Most energy conserving MAC protocols have been proposed based on time division multiple access (TDMA) or contention mechanisms. In [6-10], authors proposed different protocols based on TDMA type. In [11], PNP-MAC was proposed based on TDMA for a variety of applications with the purpose of QoS guarantee. VLPM [12] was a protocol applying wakeup radio mechanism to avoid useless wake-up periods for energy saving. However, most of these protocols scarcely consider the heterogeneous traffic which will lead to the reduction of the entire network lifetime. Moreover, WBAN is used around human body and then the path loss is much higher than the free space propagation [13]. Sometimes the direct communication is impossible even increasing the transmission power when the communication parties are in non-line of sight (NLOS). For instance, when the coordinator is located on the human body, some nodes located on the head or legs cannot implement direct communication well with the coordinator. Therefore, the protocol design should consider not only the issue of the power consumption rate of different nodes but also with the reliable link established between nodes through multi-hop connection.

There are few researches on the topology adjustment in WBANs. Restricted Tree Topology (RTT) [14] was proposed with additional relaying nodes for two-hop WBANs. The triggering criterion is the number of missed acknowledgements (ACKs) or expected uplink data from the sensors that are missed by the coordinator for a predefined period. The superframe modification was based on IEEE 802.15.4. CICADA [15] was a spanning tree based protocol that aimed for high network lifetime and low delay. In [16], the authors presented two mechanisms to improve the reliability of CICADA. However, the two protocols did not consider the heterogeneous property of WBAN applications. In addition, relaying for improving the network lifetime in WBANs was presented in [17]. Nevertheless， it introduced extra device cost when these protocols employed additional nodes called relaying nodes to spread out transmission effort over the entire network.

On the other hand, as we know, dynamic power control mechanism plays a significant role in improving energy efficiency in wireless networks. It can use as little power for transmission as possible. Moreover, power control can effectively ensure the transmission quality of the link. In order to improve the network performance, i.e., prolonging the network lifetime without deteriorating the link reliability, the combination of a variety of technologies becomes necessary. Therefore, in our protocol design, we not only consider constructing an optimal network formation in which the network topology can be adaptively adjusted but also employ dynamic transmission power control for each data packet transmission for further energy saving. To the best of our knowledge, it is the first time to consider both of adaptive topology adjustment using relay and dynamic power control in MAC design for a WBAN.

Power control mechanism has the ability to save energy consumption and improve the reliability of the link. There are a few works using power control mechanism in WBANs. In [18], the power control mechanism assumed that sensor nodes in the BAN could vary its transmission power from -30dBm to 0dBm with the step index of 0.5dBm. Sensors adjusted their transmission power according to the channel predication based on the last sampled received signal strength or channel gain. Although this method reduced energy consumption, the sensors' frequent sample may offset the saved energy by the power control. A dynamic power control mechanism that performs adaptive body posture inference for optimal power assignments was proposed in [19]. The mechanism assigns the best possible power level to a link through inferring a subject's current postural position and ensures a balance between energy consumption and packet loss. Dynamic power control mechanisms for prolonging the network lifetime were also presented in [20]. In our work, we adjust the transmission power level dynamically based on the feedback information from the receiver. The adjustment procedure is different according to the offset degree of the received signal strength indicator (RSSI) value from the target RSSI threshold range.

In this paper, to prolong the network lifetime, we propose a novel MAC protocol named Energy-efficient Relay MAC with Dynamic Power Control (ERPC-MAC) based on IEEE 802.15.4 multi-hop superframe structure [21]. When a sensor node's residual energy is suffering shortage, ERPC-MAC adjusts the superframe structure to choose a proper relaying node through relay election policy for the energy shortage nodes. Once relaying nodes are selected, the network topology is switched from one-hop type to multi-hop type. In the process, whenever nodes transmit their data packets to the coordinator or its relaying node, dynamic power control algorithm is performed for choosing an optimal transmission power level to save energy and improve reliability. This proposed energy-efficient protocol can be also applied to other large scale wireless networks [22-23]. In short, the contributions of ERPC-MAC are presented below.

- Instead of the one-fold network formation which most existing research focus on, the network topology in this paper can be adjusted adaptively between the single-hop type and multi-hop type. Accordingly, the superframe structure is adaptively adjusted, which was not discussed before.
- An efficient relay election method is proposed for the coordinator to choose a proper relaying node for the relayed node, which is scarcely involved before.
- A dynamic power control algorithm is proposed for sensor nodes to choose an optimal transmission power level in ERPC-MAC. As far as we know, it is the first time to design the MAC protocol integrating both of the relay and dynamic power control.
- Performance evaluations are conducted in terms of network lifetime, average packet delay and average energy consumption per packet. Simulation results demonstrate ERPC-MAC significantly prolongs the network lifetime.

The rest of the paper is organized as follows. The next section is the overview of IEEE 802.15.4. In Section 3, we will discuss the details of the ERPC-MAC protocol. We then present the simulation results of ERPC-MAC in Section 4. The final section summarizes the conclusions that can be drawn from the work.

2. Overview of IEEE 802.15.4

IEEE 802.15.4 standard specifies physical layer (PHY) and MAC layer for low data rate short-range wireless personal area network (WPAN). The standard may operate in either of the two topologies: the star topology and the peer-to-peer topology, as illustrated in **Fig. 1** [21]. In the star network, each device directly communicates with the PAN coordinator. However, the peer-to-peer network allows a device to communicate with any other devices as long as they are in the range of one another. In either of the topologies, beacon-enabled mode and nonbeacon-enabled mode could be adopted in the network. The network is called beacon-enabled if there are beacons which are transmitted periodically by the coordinator. Otherwise, it's nonbeacon-enabled mode which can't support energy saving application.

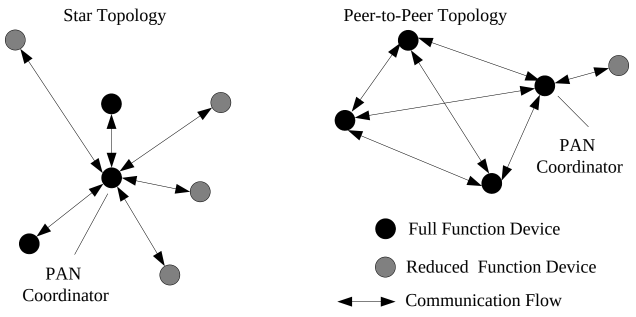

Fig. 1. Star and peer-to-peer topology examples

In the beacon-enabled mode, two kinds of superframe structure are defined. One is for one-hop star network as shown in **Fig. 2**, the other is for multi-hop network as shown in **Fig. 3**.

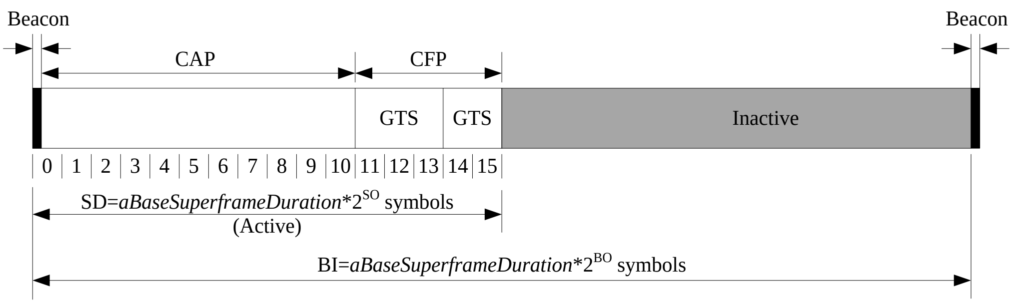

Fig. 2. An example of the superframe in one-hop star topology

For one-hop superframe structure, the time is divided into equivalent periodic interval and each of the superframes bounded by the transmission of a beacon frame consists of an active portion and an inactive portion. All the devices transmit packets in the active period and enter a sleep mode during the inactive period. The active portion is partitioned into 16 slots evenly and consists of three parts: a beacon, a contention access period (CAP) and a contention free period (CFP). In CAP, nodes employ CSMA/CA mechanism to access the channel. The CFP period is divided into guarantee time slots (GTSs) on a reservation-based approach to support time critical data application. The coordinator can allocate a maximum of seven GTSs to the devices. When a node wants to transmit data in CFP, it first sends a GTS request in the CAP using CSMA/CA, and then the coordinator will decide the GTS allocation. Nodes transmit packets in CFP without concerning of colliding with another one. The beacon interval (BI) is determined by the parameter of beacon order (BO) and the superframe duration (SD) by superframe order (SO), as shown in **Fig. 2**.

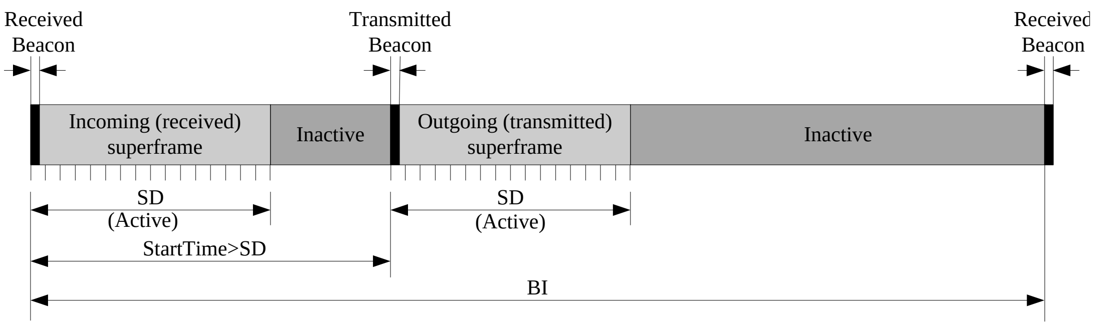

Fig. 3. An example of the superframe in multi-hop star topology

For the multi-hop superframe structure, both of the PAN coordinator and any ordinary coordinator may periodically transmit their own beacons. A coordinator that is not the PAN coordinator shall maintain the timing of both the superframes in which its coordinator transmits a beacon (the incoming superframe) and the superframes in which it transmits its own beacon (the outgoing superframe). The relationship between incoming and outgoing superframes is illustrated in **Fig. 3** [21]. Actually, the incoming and outgoing superframe structure is actually the consecutive overlaps of its parent's superframes and its own superframes. The beacon order and superframe order are equal for all superframes on a PAN and all devices interact with their parent nodes only during the active portion of the superframe.

3. ERPC-MAC

In this section, we will present the details of ERPC-MAC protocol. The protocol employs both relaying node to prolong the network time and dynamic transmission power control mechanism for further energy saving. First, we will give a detailed introduction of the dynamic transmission power control algorithm in ERPC-MAC, and then we turn to discuss how to adjust the network topology adaptively.

3.1 Dynamic Power Control Algorithm in ERPC-MAC

In WBANs, sensor nodes usually use a fixed transmission power to interact with the coordinator. This method may work worse due to the fast change of wireless link quality in WBANs. When the link quality is poor, low transmission level results in unreliability; whereas the link quality is good, high transmission level will waste energy. Therefore, considering the reliability and the scarce energy in WBANs, it is a good way to adjust the transmission power adaptively based on the feedback information from the receiver.

In this paper, we design a dynamic transmission power control algorithm based on the feedback information – RSSI from the receiver. When the current RSSI value isn’t in the target RSSI threshold range, the coordinator or the relaying node will reply an ACK frame which contains the piggybacked information of adjustment strategy. As the result of the power adjustment, it may be increased, decreased or remained without any change, which can be indicated by two bits in the ACK frame. Based on the received ACK frame, the transmitter adjusts its next transmission power accordingly. Before the power control algorithm is stated in detail, two assumptions are made as follows.

- PHY layer can support the frame transmission with a specified power;
- PHY layer can notify MAC layer of the RSSI of the frame which is received;

3.1.1 Preliminary Knowledge

When nodes interact with each other, the transmitter should know what the least power level is to guarantee the data received correctly by the receiver. There is a computational formula of the minimum transmission power for the receiver to receive a packet correctly from the sender in [24], which was also called as Friis formula:

$$P_r = P_t \left(\frac{\lambda}{4\pi d} \right)^n G_t G_r \qquad (1)$$

where P_r represents the power value that the receiving node receives the sending node’s data frames, P_t denotes the power value that the sending node transmits its data frames, λ is the carrier wavelength, d represents the distance between the sending node and the receiving node, n is the channel fading coefficient and G_t, G_r is the gain of the emitting antenna and receiving antenna, respectively.

Furthermore, in Friis formula let R_t denotes the energy threshold that the receiver can detect and decode a signal correctly, then the minimum transmission power P_m to guarantee the correct packet receiving and signal decoding can be obtained by

$$P_m = \frac{R_t}{G_t G_r} \left(\frac{4\pi d}{\lambda} \right)^n \qquad (2)$$

From the two formulas, we can obtain that

$$P_m = \frac{P_t R_t}{P_r} \tag{3}$$

Let formula (3) multiplied by an adjustment coefficient c which can be determined by experiments, and then we have

$$P_m = \frac{P_t R_t}{P_r} c \tag{4}$$

Using formula (4), when P_t, R_t and P_r are given, the receiver can calculate the minimum power which is expected by the sending node, P_m, under which the frames transmitted by the sender can be successfully received by the receiving node.

3.1.2 Details of the Power Control Algorithm

The main idea of power control mechanism is to increase or decrease the transmission power based on the link quality. And the link quality can be characterized by observing the RSSI at the receiver sensor node. Hence, we choose a target RSSI threshold range as the adjustment criterion of the power control. When the RSSI value of a packet which the coordinator or the relaying node received isn't in the target RSSI threshold range, we carry out power control mechanism on the nodes to adjust their power level for the next packet transmission.

A. Trigger Mechanism of the Power Control Algorithm

The trigger mechanism of the power control algorithm is that the RSSI of the packet is out of the target RSSI threshold range [R_L, R_H]. Once the RSSI value isn't within [R_L, R_H], the coordinator or the relaying node should perform the power control to adjust the power level. The reason for choosing a target RSSI threshold range instead of a single target RSSI value is to minimize the frequency of corrective control actions and its associated energy and capacity overhead. The choice of [R_L, R_H] should guarantee a high packet delivery ratio. In [19], [R_L, R_H] was determined by conducting an experiment. The authors used [-88, -82] (dBm) as the target RSSI threshold range, guaranteeing perfect delivery performance and balancing the frequency of corrective control actions and energy performance. In [20], [R_L, R_H] was set to [-85, -80] (dBm) through the experiments to achieve the desired trade-off between energy saving and reliability.

B. Parameters Setting

We assume that the coordinator or the relaying node receives a packet with the RSSI denoted by R, and the link quality is regarded as good if $R > R_H$. Let $\alpha = \frac{R - R_H}{R_H - R_L}$, the parameter α denotes the offset degree of the received R which is greater than R_H from the [R_L, R_H]. Similarly, the link quality is regarded as bad if $R < R_L$. Let $\beta = \frac{R_L - R}{R_H - R_L}$, the parameter β denotes the offset degree of the received R which is less than R_L from the [R_L, R_H]. Based on parameters α and β, we use a fixed step or variable step to adjust the transmission power level, which will be presented in the next subsection.

C. Adjustment Strategy of the Transmission Power Level

The transmission power level of the sensor's next packet is determined by the offset degree of the received *R* from the range of [R_L, R_H]. If the coordinator or the relaying node receives *R* which is greater than R_H, the adjustment strategy is stated as follows.

i) When $0 < \alpha = \dfrac{R - R_H}{R_H - R_L} \le \alpha_t$ (a parameter can be set), it means that the offset degree is small. In this case, the node decreases its transmission power level by a fixed step length l_c. The procedure of the adjustment is that: the coordinator or the relaying nodes calculate the parameter α and obtain that the parameter is less than α_t, then the coordinator or the relaying nodes notify the sensor node by feedback mechanism to decrease the transmission power level gradually with a fixed step l_c until *R* satisfies the inequality $R_L < R < R_H$. It's worth noting that for a certain node l_c is fixed, but different nodes may use different l_c which can be determined by the coordinator or the relaying nodes.

ii) When $\alpha = \dfrac{R - R_H}{R_H - R_L} > \alpha_t$, it means that the offset degree is greater. In this case, the node decreases its transmission power level by a variable step length. The procedure is that: the coordinator or the relaying node obtains the parameter α is greater than α_t by calculating α, and then it informs the node by feedback mechanism to decrease the next transmission power level first by $l_1 = [\alpha](R_H - R_L)$, subsequently the node decreases its transmission power level at a time by $l_2 = l_3 = \ldots\ldots = l_c$. This procedure comes to an end until *R* satisfies the inequality $R_L < R < R_H$. Therefore, under this situation we adjust the transmission power level first with a big step length and then with a small fixed step length. Similarly, step length l_c for a certain node is fixed, but different nodes may use different l_c which can be determined by the coordinator or the relaying nodes.

In the same way, when *R* received by the coordinator or the relaying node is lower than R_L, the parameter $\beta = \dfrac{R_L - R}{R_H - R_L}$ denotes the offset degree of the received *R* from [R_L, R_H]. The adjustment strategy of the transmission power control is the same with the above method.

In conclusion, the dynamic power control algorithm adjusts the transmission power level with a fixed or variable step length based on the value of offset degree. In this method, the sensor node can obtain an optimal transmission power level in fewer steps, and at the same time, energy consumption is reduced, combined with the link quality improvement.

3.2 Relay Procedure in ERPC-MAC

In the previous subsection, we give a detailed discussion of power control algorithm in ERPC-MAC for energy saving. Provided that there is data transaction between nodes, dynamic power control algorithm is performed. Although the above power control algorithm can efficiently save energy, the phenomenon of link breaking still occurs and power control becomes weak. Therefore, to maximize the network lifetime as long as possible, adjusting the network topology adaptively is desired. In this subsection, we will present the details of adaptive topology adjustment for energy saving.

In ERPC-MAC, a mechanism for the coordinator to choose a relaying node for the energy shortage node (becoming a relayed node) is provided. After the relaying node is determined, the relayed node transmits its subsequent packets to the relaying node. Through this energy balance strategy among nodes, the energy shortage node's lifetime is prolonged, and the network lifetime is extended correspondingly.

Initially, we assume that all the sensor nodes working on different power levels communicate with the coordinator node through IEEE 802.15.4 star-type network. For the time being, the superframe is the same with the example depicted in **Fig. 2**. Sensor nodes have the ability of calculating their residual battery power. We set P_i to be the ratio of the residual battery power to the initial battery power for node i. When P_i drops below a predefined threshold P_{thr}, node i begins to ask relaying nodes for help and decreases its transmission power for energy saving. Then the relaying node provides relay service for node i. Therefore, the network topology is changed from one-hop to multi-hop, and correspondingly the adjustment of the superframe is needed to support this change. In ERPC-MAC, the main operations consist of relay request, relay response and superframe adjustment.

3.2.1 Relay Request

When a node denoted by node i detects its current P_i below P_{thr}, it initiates the relay request operation to inform the coordinator of its energy shortage (ES). Through piggyback information or an exclusive frame named ES frame, the coordinator realizes the energy shortage of the node. Then an ACK frame is sent by the coordinator for the successful acquisition of the status of the ES node.

3.2.2 Relay Response

After successful reception of the ES notification from node i, the coordinator performs relay response to select a proper relaying node for the ES node in the next superframe which has been modified as shown in **Fig. 4**. The modified superframe consists of five parts: beacon, neighbor discovery period (NDP), relay decision period (RDP), CAP and CFP. NDP and RDP are based on TDMA to guarantee the relay success. The other parts of the modified superframe are worked as the IEEE 802.15.4 superframe. The characteristics of the newly added parts in the modified superframe are discussed as below.

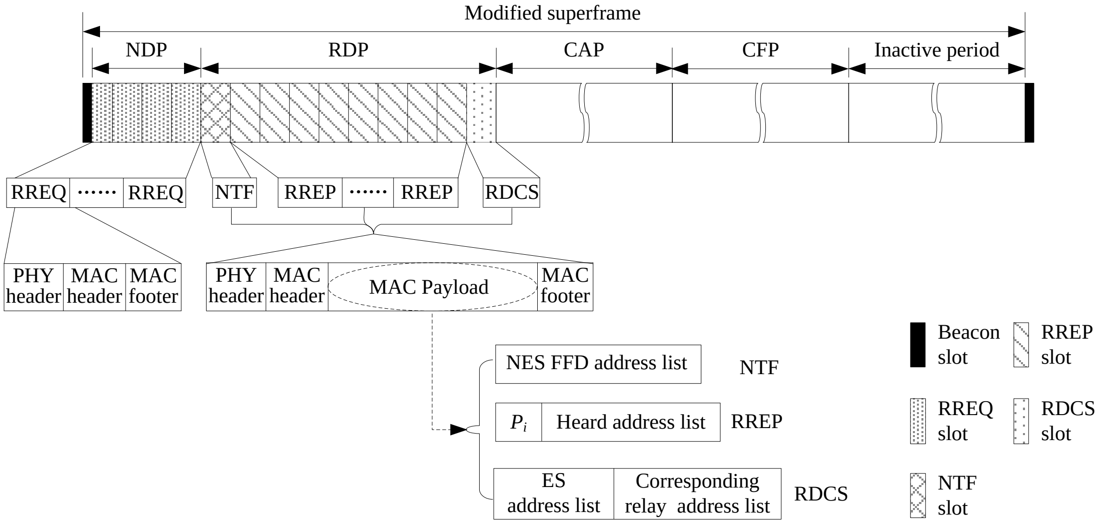

Fig. 4. Superframe structure in relay response

A. Beacon

The beacon frame is transmitted by the coordinator in the first time slot to notify the start of relaying response. Unlike the beacon frame format in IEEE 802.15.4, the frame format of the beacon frame here is modified as illustrated in **Fig. 5**. We add relay pending address fields in its MAC payload to notify what ES nodes are in the network. The relay pending address fields contain the list of addresses of the devices that currently already notified their ES status to the WBAN coordinator successfully and the position in the relay pending address fields indicates the order to broadcast a relay request (RREQ) frame. Through the beacon frame listening, the ES node knows at which time slot it can broadcast its RREQ frame in NDP.

Octets:2	**1**	**4/10**	**0/5/6/10/14**	**2**	**Variable**	**Variable**	**Variable**	**Variable**	**2**
Frame Control	Sequence Number	Addressing fields	Auxiliary Security Header	Superframe Specification	GTS Fields	Pending address fields	**relay pending address fields**	Beacon Payload	FCS
MAC header				MAC Payload					MAC footer

Fig. 5. Beacon frame format in relay response

B. Neighbor Discovery Period (NDP)

The NDP starts immediately following the beacon. The ES node broadcasts RREQ frame with the maximum power level $l_{\max}$ supported by its transceiver in its corresponding time slot to find energy-sufficient neighbors. For FFD (Full Function Device) nodes with sufficient energy (hereinafter NES FFD for short), they keep awake in NDP to respond the RREQ frames of the ES nodes.

C. Relay Decision Period (RDP)

The function of the RDP is to select a proper relaying node for the ES node. It consists of three parts: notification frame (NTF), relay reply (RREP) and relay decision (RDCS). The NTF is broadcasted by the coordinator to notify a list of addresses of the FFDs in the network, which is the order to transmit its individual RREP frame in the next RREP part. Then, each NES FFD nodes replies a RREP frame which contains its current ratio denoted by P_i and a list of addresses of the devices that it has just heard during the NDP to the coordinator. At the end of the RDP, the WBAN coordinator broadcasts the relay decision (RDCS) frame to tell the ES nodes the corresponding addresses of their relaying nodes. Subsequently, the ES node which becomes a relayed node will communicate with its relaying node using a proper power level through the dynamic power control algorithm in Section 3.1.

In a word, the beacon not only contributes to the synchronization between the WBAN coordinator and the surrounding nodes but also defines the structure of the superframe. Moreover the beacon is also used to notify what ES nodes are in the network. Then all the potential relaying neighbors of each ES node can be notified in NDP. Finally the WBAN coordinator collects all the energy-sufficient neighbors' information of each ES node and selects a proper relaying node for it in RDP. The detailed process of searching a relaying node for the ES node in relay response is illustrated in **Fig. 6**.

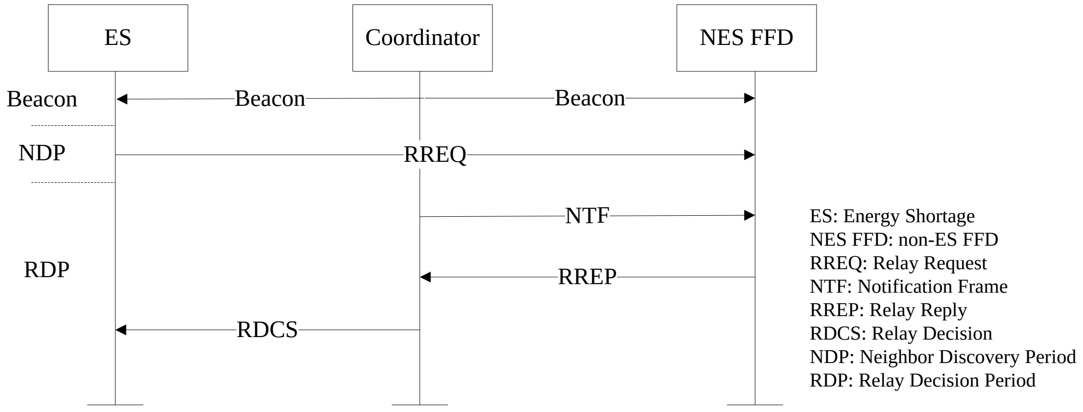

Fig. 6. Progress of searching a relaying node for the ES node in relay response

3.2.3 Superframe Adjustment

When the relaying nodes have been determined for the ES nodes, the network is ready to operate in the multi-hop topology. At this moment, there are two types of coordinators: the WBAN coordinator and the ordinary coordinator which is selected as a relaying node. Accordingly, the superframe is switched to adapt to the topology transformation as illustrated in **Fig. 3**. During the incoming superframe which is supported by the WBAN coordinator, the child node communicates with the WBAN coordinator in the active period of the WBAN superframe. However, the ES nodes which have requested relay successfully may enter a sleep mode during this time. During the inactive portion, the WBAN coordinator enters a sleep mode. At this moment, the relaying nodes begin to act as the ordinary coordinator to interact with the ES nodes (the relayed nodes) using the outgoing superframes. Therefore, the multi-hop superframe structure is formed by the continuous overlap between the WBAN superframe and the outgoing superframes from the relaying nodes. From the WBAN coordinator's viewpoint, a complete multi-hop superframe consists of the active portion of the WBAN superframe, the active portion of each outgoing superframe arranged one by one and the remaining inactive part of the WBAN superframe, as illustrated in **Fig. 7**.

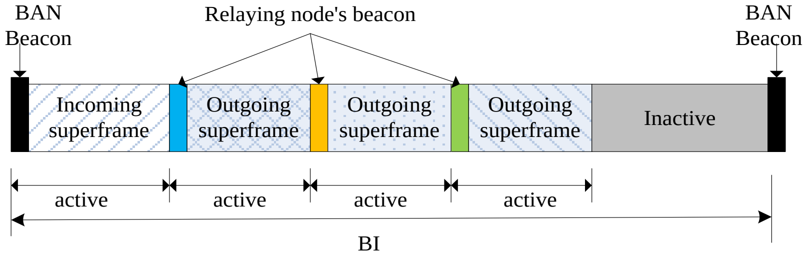

Fig. 7. An example of the multi-hop superframe structure

Moreover, the relay mechanism can provide performance enhancement in case of channel quality deterioration caused by body posture which will waste a large amount of energy. In this case, the relay request operation can be performed even its residual energy may be sufficient. In other words, the relay procedure in ERPC-MAC mainly provides an adaptive network switching framework; while how to fully use it depends on the specific communication situation of WBANs. The trigger condition may be the energy shortage or the link quality deterioration as well.

In short, the energy consumption is saved from two aspects in ERPC-MAC, i.e., dynamic power control mechanism and adaptive topology adjustment, respectively. Through the power control mechanism, the optimal transmission power level is chosen to transmit packets for energy saving and reliability guarantee. The mechanism is performed throughout the whole communication process. Furthermore, to maximize the network lifetime as long as possible, adaptive topology adjustment is also proposed.

4. Performance Evaluation

In this section, we will present the numerical results of the performance evaluation. We have implemented IEEE 802.15.4 MAC, ERPC-MAC and ERPC-MAC without power control algorithm (hereinafter ERPC-MAC without PC for short) on the platform of MIRAI-SF [25], and simulated the respective performance of different protocols in the same network scenario. All components in MIRAI-SF are provided as plug-in agents. Since the plug-in agents are easily implemented and rearranged, users can perform flexible simulations.

4.1 Simulation Model

We consider a single WBAN consists of one coordinator and several sensors as illustrated in **Fig. 8**. For IEEE 802.15.4, the network topology is always one-hop star type, while for ERPC-MAC the topology may be adjusted to be multi-hop. In addition, considering the conventional application scenario of a WBAN such as a data collection system where all the data transmissions are initiated by the sensor nodes, the downlink traffic from the WBAN coordinator is not considered in this paper.

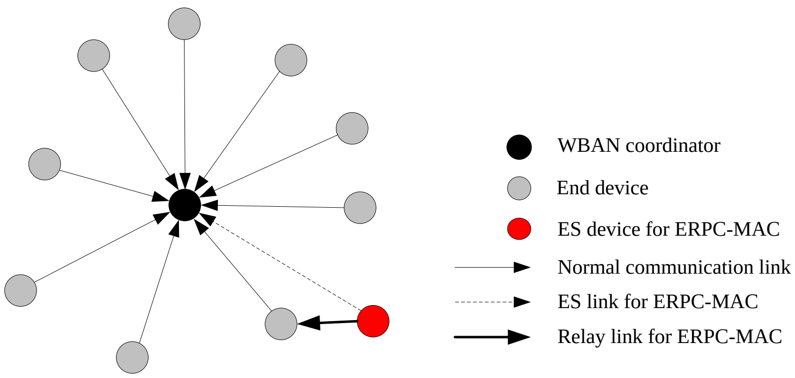

Fig. 8. Simulation topology

The relevant network parameters used in the simulation are tabulated in **Table 1**. The MACNTFFrameSize and MACRREPFrameSize are not listed in the table because of their variable MAC payload. Besides, some assumptions are made for the simulation as follows.

- Propagation delay is not considered due to the short range communications.

- The effect of bit errors in the channel has been neglected. In other words, a packet is dropped only due to packet collision or device buffer overflow.
- Acknowledgment frame is mandatory for a successful data transmission.
- Constant bit rate (CBR) traffic is chosen as the traffic model.

In addition, regarding the power level that involved in the dynamic power control algorithm, the data from CC1000 chip [26] is adopted to offer different power levels for sensor nodes.

Table 1. Simulation parameters

Parameter	Default Value
Channel rate	250 kbps
Beacon order	6
Superframe order	5
Slot duration	1920 symbols
Symbol time	16 µs
PHY symbol per octet	2
MAC MAX Frame retries	3
dataMACPayloadSize	38 bytes
MACACKSize	5 bytes
MACESFrameSize	9 bytes
MACRREQSize	5 bytes
MACHeaderSize	7 bytes
MACFooterSize	2 bytes
PHYHeaderSize	6 bytes
macResponseWaitTime	32 symbols
BufferSize for WBAN coordinator	2000 kbytes
BufferSize for end device	20 kbytes

4.2 Simulation Results

In this section, we will simulate the performance of our protocol in two major simulation scenarios, combining with IEEE 802.15.4 MAC and ERPC-MAC without PC for performance comparison. We first employ the Scenario 1 as illustrated in **Fig. 9**. In Scenario 1, there are three sensor nodes: WBAN coordinator, a relaying node (sensor B) and a relayed node (sensor A). We assume that the location of sensor A is (80, 0), and the distance between sensor A and sensor B is denoted by parameter *m*.

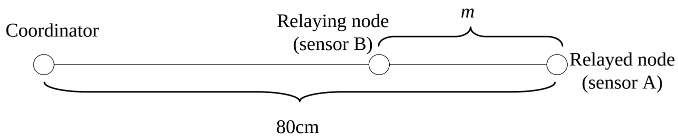

Fig. 9. Simulation Scenario 1

Furthermore, considering the heterogeneous medical applications, we also demonstrate the performance of our protocol using Scenario 2 on human body as shown in **Fig. 10**. In this scenario, 6 medical sensors are distributed on the human body according their functions. The results of the performance metrics will be given later in Section 4.2.2.

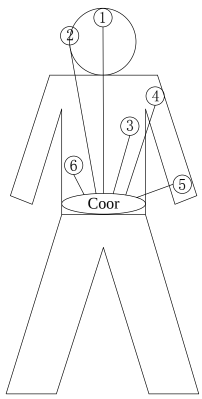

Fig. 10. Simulation Scenario 2 on a human body

4.2.1 Performance in Scenario 1

A. Simulation with distance between the relayed node and the relaying node

As ERPC-MAC has the ability of reducing energy consumption of ES nodes so as to prolong the total network lifetime by choosing relaying nodes, we first evaluate the performance of ERPC-MAC in relay mode. Node B enters relay mode since the beginning of the simulation. The relayed node's data rate is 2kbps accessing the channel in a CAP and the relaying node has sufficient energy without data to transmit. Through varying the distance between the relayed node and the relaying node, we observed the performance in terms of the relayed node's energy consumption and the whole network's energy consumption in relay mode. The whole simulation lasts for 200 seconds.

Fig. 11 depicts the relayed node's energy consumption as a function of the distance between sensor A and sensor B. It can be observed that ERPC-MAC is effective in reducing the energy consumption of the relayed node. When the distance is 10cm, the energy consumption decreases by 59% compared with IEEE 802.15.4. The relayed node's energy consumption increases as the distance increases. When the distance increases to 70cm, the reduction of the relayed node's energy consumption can still reach to 27% compared with it in IEEE 802.15.4. Without power control, ERPC-MAC consumes a little bit more energy because power control mechanism can reduce energy waste further.

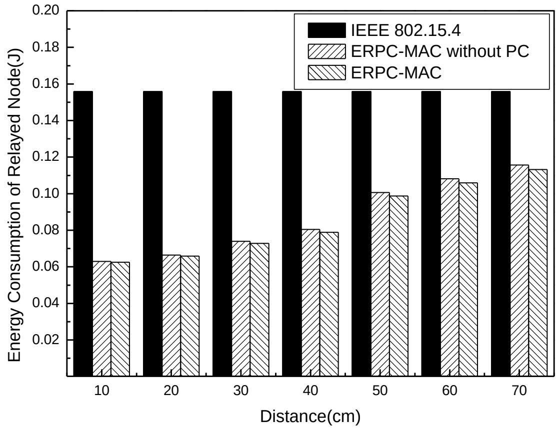

Fig. 11. Relayed node's energy consumption versus distance

The total energy consumption versus the distance is shown in **Fig. 12**. The total energy consumption here excludes the energy consumption of the coordinator. Relative to IEEE 802.15.4, it is shown that ERPC-MAC increases the total energy consumption due to the fact that the relay process leads to more energy consumption for the relaying node. If the relaying node is introduced from an additional device, usually it is energy-sufficient or can be charged easily. Most importantly, in ERPC-MAC the relay can reduce ES nodes' energy consumption and prolong the network lifetime. From **Fig. 12**, for ERPC-MAC without PC, it can be seen that the greater the distance is, the more energy the network consumes. When the distance is 70cm, the total energy consumption increases by 116% compared with IEEE 802.15.4. Whereas, for ERPC-MAC, the total energy consumption increases by 50%~72% compared with IEEE 802.15.4, which is far less than ERPC-MAC without PC. The result demonstrates the superiority of the power control scheme.

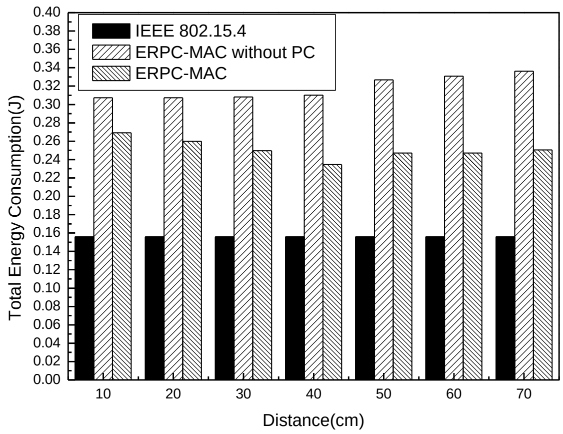

Fig. 12. Total energy consumption versus the distance

B. Simulation with the energy threshold

We perform simulations with varying energy threshold in Scenario 1. Sensor B with sufficient energy and without traffic is located on the middle position between the coordinator and sensor A.

The initial energy of Sensor A is set to 0.5J and its data rate is 2kbps. Performance metrics evaluated in this part include the lifetime of the relayed node and its average packet delay.

As depicted in **Fig. 13**, the lifetime of relayed node increases with the energy threshold. When the energy threshold reaches to 0.9, the lifetime can be extended by 95% over IEEE 802.15.4. Moreover, the lifetime of relayed node in ERPC-MAC is longer than it in ERPC-MAC without PC. The reason is that with dynamic power control, nodes transmit packets with an optimal power level instead of the maximum one to avoid energy wastage.

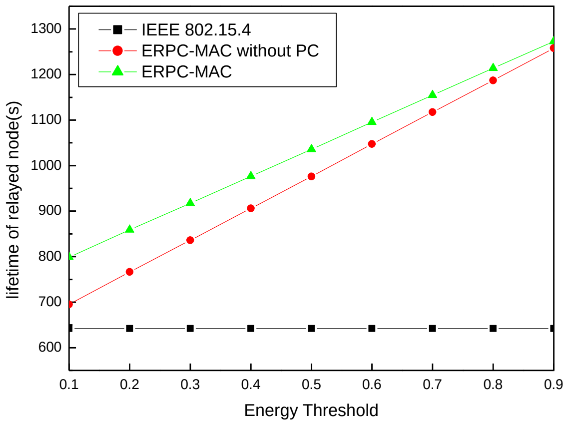

Fig. 13. Relayed node's lifetime versus energy threshold

Moreover, the average packet delay of the relayed node as a function of energy threshold is plotted in **Fig. 14**. It can be observed that both of the ERPC-MAC and ERPC-MAC without PC will increase the average packet delay compared with IEEE 802.15.4 and the larger the energy threshold is, the greater the average packet delay will be. The reason behind of this can be explained from two aspects. On one hand, a packet transmitted from the relayed node to the coordinator will be first transmitted to relaying node in the outgoing superframe, and then be forwarded to coordinator by relaying node in the incoming superframe. On the other hand, the ratio of the relay service duration time to the sensor's lifecycle will increase due to the increase of the energy threshold. Both of them result in the increase of the average packet delay. We can also see that the average packet delay of ERPC-MAC is less than ERPC-MAC without PC. This is due to that power control can save energy consumption to some extent and with the same energy threshold, ERPC-MAC without PC requests relay earlier which will result in higher delay.

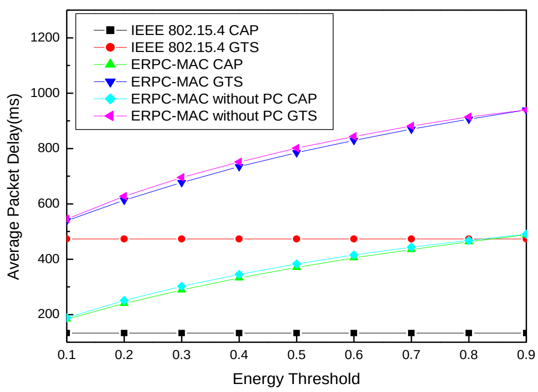

Fig. 14. Average packet delay versus energy threshold

C. Simulation with the the target RSSI threshold range $[R_L, R_H]$

To simulate the relationship between the energy consumption of the relayed node and the target RSSI threshold range [R_L, R_H], we change Scenario 1 slightly. We assume that sensor A is 40cm away from the coordinator. The data rate of sensor A is 2kbps and it accesses the channel in CAP. The simulation lasts for 100 seconds.

As is depicted in **Fig. 15**, the energy consumption of the relayed node increases with the R_H . This is due to the fact that the transmission power level of the relayed node will be set to a higher value when a greater value R_H is chosen, which will lead to unnecessary energy waste.

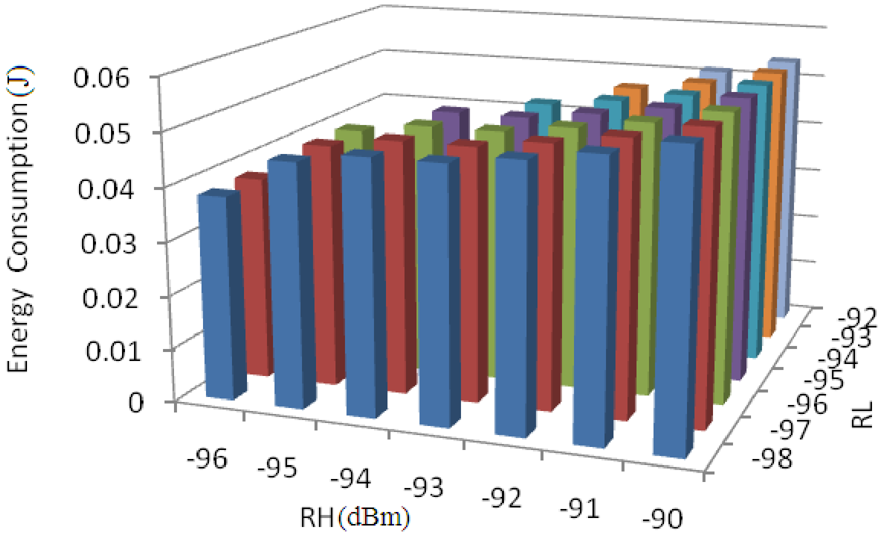

Fig. 15. Relayed node's energy consumption versus target RSSI threshold range

4.2.2 Performance in Human Body Scenario (Scenario 2)

Table 2. Detailed value of the sensor nodes on human body

Node ID	Medical Application	Data rate (bps)	Position (cm)
Coor	BAN Coordiantor		(0,0)
1	EEG	4200	(0,80)
2	Heart rate	600	(-7,70)
3	ECG	15000	(10,40)
4	Body temperature	8	(15,50)
5	Pulse oximeter	32	(20,0)
6	Respiratory rate	800	(-6,20)

As illustrated in **Fig. 10**, we conduct another simulation based on human body environment. In the simulation, totally six sensor nodes are used to monitor EEG, heart rate, ECG, body temperature, pulse oximeter and respiratory rate respectively. The detailed values of different traffic are listed in **Table 2**. All the sensors access the channel in CAP period, and the initial energy is set to 0.5J. Performance metrics evaluated in this part include network lifetime, average packet delay and average energy consumption per packet.

Fig. 16 depicts the network lifetime as a function of energy threshold. The network lifetime here is defined as the time duration from the simulation beginning to the moment when the first sensor node runs out of its energy. It can be seen that the network lifetime of ERPC-MAC is higher than other two protocols obviously. ERPC-MAC and ERPC-MAC without PC share the same trend that the network lifetime increases first and then decreases later as the energy threshold increases. The peak performance is achieved when the energy threshold equals to 0.6 with 106% and 56.7% of performance gain in network lifetime respectively. This is because ES nodes will start to request relay too late if the energy threshold is set too low which will lead to a short relay service. Whereas, if the energy threshold is set too high, ES nodes will start to request relay too early, which has definitely benefit for ES nodes, however, for the energy sufficient node, a higher energy threshold means a trend of earlier termination of relay service, i.e., a short relay service for the relayed node. Therefore the peak performance will be achieved at a proper energy threshold. Also, it can be seen that the network lifetime of ERPC-MAC is higher than ERPC-MAC without PC because of the impact of power control.

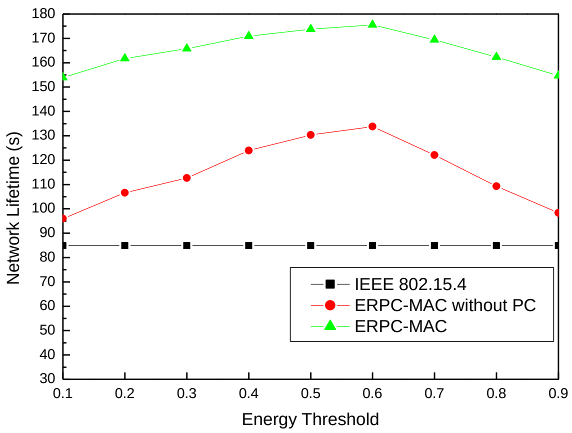

Fig. 16. Network lifetime versus energy threshold

It's worth mentioning that although the energy consumption of relaying nodes is increased due to the relay process, the whole network performance actually becomes better. Especially in a WBAN, different sensors perform different roles. For example, energy of sensors implanted into a body is much more valuable than the energy of sensors wore on the surface of a body. Therefore the manner of sensors outside the body offering relay service for the implanted sensors is acceptable and can be an efficient way to save energy consumption.

The performance of average end-to-end packet delay is plotted in **Fig. 17**. It is shown that the average packet delay increases with energy threshold and decreases later, and the peak value is achieved at the same energy threshold 0.6. In subsection 4.2.1, we have explained the reason that relay will lead to the increase of the average packet delay. Moreover, the relay service time reaches the maximum value when the energy threshold equals to 0.6. Hence, the average packet delay increases and then decreases with the peak value at 0.6. Also, it can be seen that ERPC-MAC and ERPC-MAC without PC have almost the same performance on average packet delay.

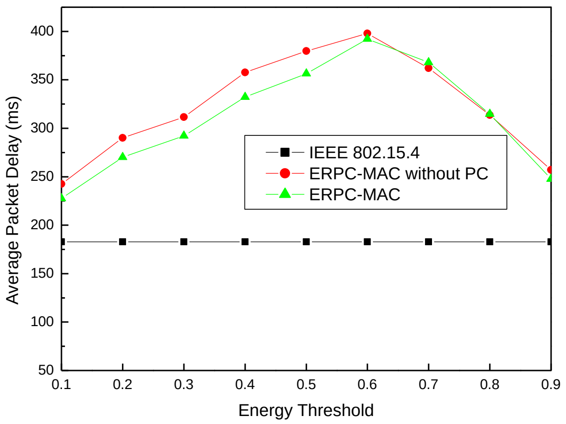

Fig. 17. Average packet delay versus energy threshold

5. Conclusions

To prolong the network lifetime, an Energy-efficient Relay MAC Protocol with Dynamic Power Control (ERPC-MAC) was proposed in the paper. On one hand, ERPC-MAC selects proper relaying nodes based on the status of nodes' energy consumption to prolong the whole network lifetime. The network topology is adaptively adjusted instead of the one-fold network formation (single-hop type or multi-hop type), correspondingly the structure of the superframe is switched from the single-hop-based superframe to the incoming and outgoing superframe. On the other hand, dynamic power control algorithm was introduced in ERPC-MAC to choose an optimal transmission power level to prolong the network lifetime further. We compared the performance of ERPC-MAC with that of IEEE 802.15.4 MAC and ERPC-MAC without power control from the perspective of network lifetime, average packet delay and so on in different scenarios. Simulation results demonstrated that ERPC-MAC significantly prolongs the network lifetime. Compared with IEEE 802.15.4 MAC and the relay scheme without power control, the network lifetime of ERPC-MAC can be extended by 106% and 49.3% at most respectively.

For the future work, it will be focused on optimizing the protocol parameters, such as P_{thr} and the target threshold range. Furthermore, we will explore the link indication factor other than RSSI to perform power control effectively through PHY-MAC cross-layer design to improve the efficiency of the protocol in the reality scenarios.

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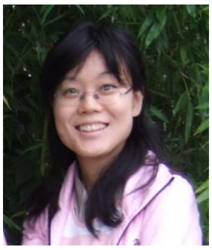

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