A Cross-Layer Media Access Control Protocol for WBANs

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Abstract: Wireless body area network (WBAN) is an emerging comprehensive technology that can deeply integrate with e-health and smart sports. As a wearable network, improving the quality of network service and user experience is crucial. Due to the miniaturized design of sensors, their available energy from batteries is limited, making the extension of their lifetime a key research challenge. Existing studies have proposed methods to improve energy efficiency, but there are still limitations in addressing dynamic adaptive aspects of differential energy distribution and channel conditions. In order to further extend the lifetime of sensor nodes and networks while ensuring quality of service, and to provide a reliable transmission mechanism for heterogeneous application data, this paper presents a cross-layer optimized MAC protocol mechanism. The protocol takes into account the transmission requirements of different types of data and redesigns the superframe. To improve the lifetime of nodes, we propose an energy-adaptive adjustment mechanism considering the channel conditions. At the same time, a cooperative transmission mechanism is proposed to further enhance network lifetime. In experiments conducted on two typical networks, compared to IEEE 802.15.6, the power adjustment scheme improves the network lifetime by 2.8 to 3.7 times, and the cooperative mechanism between nodes further increases the network lifetime by 17% to 44%. Our proposed scheme effectively extends the network lifetime while ensuring quality of service, avoiding frequent battery resets for users, and effectively improving the user experience quality.

Keywords: wireless body area network; power control; network lifetime; cooperative transmission

1. Introduction

Cardiovascular diseases (CVDs) have become the top killer, endangering human health [1], which brings a heavy burden to the healthcare systems of many countries. Sometimes, people even die without warning during sleep [2], and even young athletes experience sudden death caused by CVD. Obtaining correct diagnosis and prevention ahead of sudden cardiac arrest or death is generally preferable to in-the-field reanimation [3]. However, CVD has the characteristics of concealment, suddenness, harmfulness, and urgency, which increase the difficulty of disease prevention, diagnosis, and monitoring, posing challenges to the traditional medical system. A sustainable medical system must adhere to the simultaneous development of efficiency, quality, and safety. It is necessary to continuously research new technological methods to improve the effectiveness of medical diagnosis and treatment, improve the efficiency of medical services, and reduce resource consumption.

For sports, traditional education methods rely on the experience of teachers [4]. Sustainable sports education should introduce new technological methods to evaluate athletes' training effects based on detailed and accurate data and develop targeted strategies. At the same time, it should ensure the health of athletes during training and prevent accidents such as sudden death caused by inappropriate exercise. The sustainable development of sports science requires the establishment of scientifically standardized and digitally intelligent training and assessment methods that can iterate and evolve. In fact, with increasing...
awareness, sustainable development has become a development strategy for numerous countries in human society. Whether it is in the fields of healthcare, sports, or education, optimizing the development models through technological innovation is necessary.

Thanks to the advancement of science and technology, the integrated e-healthcare system provides an efficient way to resolve the above issues. Wireless body area network (WBAN) plays an important role in the e-healthcare system [5], as the integrated biosensors can collect and transmit vital human-centered data, such as electrocardiograms, temperature, heart rate, oxygen saturation, and posture. These data are then uploaded to the remote server to provide health assessment and exception warnings. Potential patients can be identified from a large population, diseases can be diagnosed and treated earlier, and the use of medical resources will be more precise and effective, which is of great significance for the sustainable development of the healthcare system. Meanwhile, the training of athletes will be more scientific and efficient with the help of WBANs, which is helpful for sustainable smart sports development.

A WBAN is a wireless network composed of a coordinator and a set of miniaturized sensors. There are many challenges associated with WBANs that need to be solved and optimized. Firstly, energy is precious for sensors since their battery size is limited; thus, energy efficiency should be maximized to prolong the network lifetime. Furthermore, Quality of Service (QoS) should be satisfied, and the heterogeneity of data and the dynamic network environment should be considered when designing network scheduling schemes. Moreover, wireless resources should be managed efficiently to reduce transmission collisions and idle listening. MAC protocol [6], routing protocol [7], and power adjustment scheme [8] are usually optimized to solve the above problems. Existing related work has shown effectiveness in improving network performance. However, these works typically consider power adjustment and cooperative transmission separately, and the power adjustment process of nodes usually only takes into account the impact of channel conditions. There is a lack of consideration for the differentiated performance requirements of heterogeneous data transmission and the design of data loss retransmission mechanisms. This leads to inefficient allocation of network resources, as they cannot be adjusted based on the importance of data packets, making it difficult to achieve coordinated optimization of service quality and energy efficiency.

To address the issues above, we present a power adjustment and cooperative relay-combined cross-layer MAC (PACR-MAC) protocol for WBANs. The differentiated transmission requirements of heterogeneous data are considered. It provides flexible power adjustment and data retransmission mechanisms, ensuring both improved energy efficiency and network service quality for important data transmission. Additionally, through a lightweight point-to-point cooperative transmission scheme, we determine whether low-energy nodes require assistance from other nodes and select the optimal collaborating node for relay transmission, further enhancing the network’s overall lifetime. The main contributions of this paper are summarized as follows:

1. We optimize the MAC protocol to accommodate the differentiated reliability requirements of heterogeneous data transmission. Both TDMA and CSMA mechanisms are simultaneously adopted to meet the transmission requirements of both periodic data and event-triggered data. Meanwhile, taking into account the importance of data, the protocol incorporates a mechanism for data retransmission to ensure reliable transmission of critical data.

2. We propose a priority-based power adjustment scheme to improve the network QoS and energy efficiency. The proposed method allows nodes to calculate the base transmission power based on the channel state and further adjust the data transmission power according to the real-time importance of the data. This provides differentiated transmission power for heterogeneous data.

3. We present a cooperative relay scheme to further prolong the network lifetime. A concise point-to-point cooperation determination mechanism is used to decide whether...
there is a need for intermediate nodes to relay data and to determine the optimal cooperative node for the task.

The remainder of this paper is organized as follows: Section 2 presents the related works. Section 3 introduces the network model. Section 4 explains the proposed work. Performance evaluations and results are discussed in Section 5. Finally, Section 6 concludes the paper.

2. Related Works

Many strategies have been proposed to prolong the network lifetime and meet the QoS requirements of nodes in a WBAN. In this section, we categorically discuss some existing works on MAC protocols, route protocols, and power adjustment schemes.

2.1. MAC Protocol

The mobile edge computing (MEC) network technology is applied in [9], and a multi-channel MAC protocol is also designed for WBAN based on the Markov decision process (MDP). Both the channel condition and the reward value are considered in the protocol. In order to improve the network throughput while reducing the overhead of the protocol, the FETRO protocol is proposed in [10]. When assigning time slots to sensors, the data rate is an important parameter considered by the coordinator, and different transmission requirements can be satisfied. The MG-HYMAC protocol [11] aims to improve the network energy efficiency and prolong the lifetime of the bio-sensors. A transmission scheduling scheme is proposed to allow bio-sensors with less critical information to upload packets following the duty cycle operation of the coordinator. The data uploading plan can be scheduled among nodes to reduce transmission collisions and prolong the network lifetime. A slot allocation mechanism based on a bargaining game theory approach is proposed in [12], which optimizes the slot allocation among competing devices in a WBAN. A slot allocation mechanism is optimized in [13], which assigns dedicated slots to high-priority data flows while optimizing a dynamic superframe structure to improve the transmission delay and network throughput performance of WBANs. Differentiated priorities can be assigned to different data types in WBANs according to a priority-based MAC protocol proposed in [14], which improves energy efficiency and reduce energy consumption. A slot allocation mechanism is optimized in [15], which assigns dedicated slots to high-priority data flows while optimizing a dynamic superframe structure to improve the transmission delay and network throughput performance of WBANs. Differentiated priorities can be assigned to different data types in WBANs according to a priority-based MAC protocol proposed in [14], which improves energy efficiency and reduce energy consumption. A Hybrid Multi-Class MAC Protocol for IoT-Enabled WBAN Systems is proposed in [16], which presents a hybrid MAC protocol that combines both TDMA and CSMA/CA schemes to improve the efficiency of data transmission in WBANs. Traffic class prioritization is considered in [17], which adopts slotted-CSMA/CA to improve the reliability and delay performance of intra-WBAN communication. AT-MAC [18] is an adaptive MAC protocol that adjusts the payload size of the MAC frame according to the wireless channel quality, which improves the performance of data transmission in WBANs.

2.2. Route Protocol

An Energy-Efficient Multihop routing protocol (ESTEEM) is proposed in [19], which aims to improve the network performance based on a multihop routing scheme. Proper relays can be selected to forward data generated by remote sensors to the coordinator. Using the least energy and choosing the shortest distance are desired when selecting the routing path in ESTEEM. A temperature-aware clustering routing method is presented in [20], which adopts a fuzzy logic scheme. Similar sensors can form a cluster to aggregate their data. The clustering method considers multiple factors such as the temperature of the cluster head, the number of similar neighbors, the number of neighbors, energy distribution, and the wireless channel state. A blockchain-based Adaptive Thermal-/Energy-Aware Routing (ATEAR) protocol for WBAN is proposed in [21], where both energy limitation and temperature value are considered when choosing the routing path for remote sensors. An Adaptive Thermal-Aware Routing algorithm for WBAN is proposed in [22] to prevent...
overheating of implanted biomedical sensor nodes. The proposed scheme can switch routing paths according to the temperature situation of nodes in the network. The AMERP routing protocol [23] is designed based on the Adaptive Moment Estimation (Adam) optimizer-trained deep learning network. The performances of both homogeneous and heterogeneous network configurations can be effectively enhanced. The proposed protocol performs well under various network environments. A two-tier cooperation-based high-reliable and lightweight forwarding (TTCF) scheme is presented in [24], which aims to improve reliability and prolong the network lifetime. Transmitted data are minimized, and relay selection is optimized to reduce energy consumption.

2.3. Power Adjustment Scheme

In order to improve the network throughput, a proper AP selection scheme is proposed in [25], considering the condition of the wireless channel. Meanwhile, transmission power is adjusted according to the wireless channel condition in the uplink and downlink to save energy. A Transmission Power Control (TPC) scheme is proposed in [26] to improve the network performances during on-body communications. The proposed solution combined the neural network and the fuzzy inference system to model the wireless channel, which considered different body postures. A power adjustment scheme is used when designing the ERPC-MAC protocol in [27]. Without relying on additional devices, ERPC-MAC employs relaying nodes to provide relay service for nodes that consume energy fast. To further reduce the energy consumption ratios of sensors in WBANs, a power adjustment scheme is proposed in [28], which considers an adaptive transmission power correction scheme in a one-hop star network. Because human motion is one of the dominant factors that affect the channel characteristics in WBAN, a motion classification scheme is proposed in [29], the power control scheme considers both the body motion and the temporal to enable efficient communication among nodes.

Table 1 presents a summary of the related works. In related works, it is common to design power adjustment and relay cooperation separately. The power adjustment process often overlooks the quality of service requirements for heterogeneous data, and there is a lack of specific designs for the retransmission of heterogeneous data in case of data loss. The existing approaches also lack an integrated design that combines power adjustment, data loss retransmission, and cooperative transmission mechanisms when transmitting heterogeneous data. This makes it difficult to achieve synergistic optimization of network QoS and energy efficiency.

Our work comprehensively considers the optimization design of the MAC protocol, cooperative relay, and power control scheme. The power control scheme aims to prolong the lifetime of sensors, the cooperative relay aims to further prolong the lifetime of the network, and the MAC protocol is responsible for enabling efficient cooperation among sensors and improving the QoS of the network.
Table 1. Characteristics of the related works.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Authors</th>
<th>Contributions</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A  B  C  D  E</td>
</tr>
<tr>
<td>[9]</td>
<td>This study applied an MEC-based network architecture and an MDP-based MAC protocol was proposed. The energy utility model and optimization problem were solved using a learning algorithm.</td>
<td>N  Y  N  N  N</td>
<td></td>
</tr>
<tr>
<td>[10]</td>
<td>Channel structure and MAC frame format are redesigned. The sensor node data rate requirements are considered while assigning the scheduled access slot duration.</td>
<td>Y  N  N  N  N</td>
<td></td>
</tr>
<tr>
<td>[11]</td>
<td>Both the CSMA/CA and the TDMA schemes are adopted in the superframe, and a transmission scheduling technique is combined to prolong the network lifetime.</td>
<td>Y  Y  N  Y  N</td>
<td></td>
</tr>
<tr>
<td>[12]</td>
<td>Optimal allocation of data transmission slots among heterogeneous sensors is solved using a game-theoretic approach.</td>
<td>Y  Y  N  N  N</td>
<td></td>
</tr>
<tr>
<td>[13]</td>
<td>To allocate dedicated slots for each sensor device, a prioritized dedicated slot allocation mechanism using the criteria importance is proposed.</td>
<td>Y  Y  N  N  N</td>
<td></td>
</tr>
<tr>
<td>[14]</td>
<td>In this scheme, nodes with higher priority are arranged to data frames in the time slots with better channel conditions.</td>
<td>Y  Y  Y  N  N</td>
<td></td>
</tr>
<tr>
<td>[15]</td>
<td>A modified superframe structure is proposed, in which separate access phases are introduced for the emergency event and regular event.</td>
<td>Y  Y  N  N  N</td>
<td></td>
</tr>
<tr>
<td>[16]</td>
<td>This study proposes a hybrid MAC protocol that can efficiently and effectively optimize the communication channel access of a WBAN multi-class system.</td>
<td>Y  Y  N  N  N</td>
<td></td>
</tr>
<tr>
<td>[17]</td>
<td>The main advantage of the scheme is to provide prioritized channel access to heterogeneous-natured BMSNs of different traffic classes with better network performances.</td>
<td>N  Y  N  N  N</td>
<td></td>
</tr>
<tr>
<td>[18]</td>
<td>AT-MAC prioritizes sensor nodes based on the seriousness of the health parameters that are being measured by the respective sensor nodes.</td>
<td>N  Y  N  N  N</td>
<td></td>
</tr>
<tr>
<td>[19]</td>
<td>A relay selection scheme is proposed considering both the energy state and the relative distance. A hidden Markov chain model is developed to improve the performance.</td>
<td>N  N  Y  N  Y</td>
<td></td>
</tr>
<tr>
<td>[20]</td>
<td>A clustering-based routing protocol is proposed; both energy state and channel state are considered when selecting relays.</td>
<td>N  N  Y  N  Y</td>
<td></td>
</tr>
<tr>
<td>[21]</td>
<td>The proposed scheme considers the energy state and node temperature factors when choosing relays. A blockchain-based scheme is also proposed to improve network security.</td>
<td>N  N  N  N  Y</td>
<td></td>
</tr>
<tr>
<td>[22]</td>
<td>A Multi-Ring-based routing scheme is proposed to choose the proper route according to the network state. Avoiding the temperature rise of implanted sensors is the main goal.</td>
<td>N  N  N  N  Y</td>
<td></td>
</tr>
<tr>
<td>[23]</td>
<td>The proposed scheme estimates the mobility of the nodes and selects the proper relays according to the network topology.</td>
<td>N  N  N  N  Y</td>
<td></td>
</tr>
<tr>
<td>[24]</td>
<td>This paper considers multiple attribute factors to evaluate the social relations among nodes and further provides a data-forwarding mechanism to improve the network performances.</td>
<td>N  N  N  N  Y</td>
<td></td>
</tr>
<tr>
<td>[25]</td>
<td>Multiple APs are deployed in the network and an optimized AP selection scheme is proposed. Meanwhile, a max–min power control scheme is proposed to improve network performances.</td>
<td>N  N  Y  Y  Y</td>
<td></td>
</tr>
<tr>
<td>[26]</td>
<td>This paper provides a power control and packet scheduler combined scheme to reduce energy consumption and packet loss.</td>
<td>N  N  N  Y  N</td>
<td></td>
</tr>
<tr>
<td>[27]</td>
<td>Power control is adopted according to the wireless channel state and a forward scheme is further used to improve the lifetime of lower power nodes.</td>
<td>Y  N  Y  Y  Y</td>
<td></td>
</tr>
<tr>
<td>[28]</td>
<td>This paper considers the transmission power adjustment scheme in a ZigBee star network model to reduce energy consumption.</td>
<td>N  N  Y  Y  N</td>
<td></td>
</tr>
<tr>
<td>[29]</td>
<td>Human motion classification is considered and nodes adjust transmission power according to the channel state correlated with the motion type.</td>
<td>N  N  Y  Y  N</td>
<td></td>
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</tbody>
</table>

Features: A: redesign the superframe, B: considering data priority, C: considering channel state, D: power control, E: cooperative relay.

3. System Model

3.1. Network Model

We consider a typical WBAN system as consisting of a single coordinator and several sensors, as shown in Figure 1. All nodes are single-antenna devices that operate in a half-duplex scheme. Sensors are deployed in different positions on the body and have limited energy. Sensors package their remaining energy values in the header of the periodically uploaded packets, enabling the coordinator to understand the energy distribution status in the network and formulate targeted cooperative transmission schemes. Let $T_i$ denote the lifetime of sensor node $i$; the lifetime of the network $T^*$ is defined as:
Maximized $T^*$ is desired on the basis of ensuring the QoS of the network. To prolong the lifetime, each sensor adjusts transmission power adaptively. As shown in Figure 1, because node $n_1$ is located closer to the coordinator compared with $n_2$, sensor $n_1$ can choose a smaller transmission power on the premise of ensuring network performance. Except for power control, a point-to-point relay transmission scheme is adopted. When the energy of sensor $n_i$ is relatively low and potential relay nodes exist, the coordinator will assign a proper cooperator to $n_i$ to relay packets generated by $n_i$. Then, $n_i$ can transmit its data to the relay instead of the coordinator, using a smaller transmission power. As illustrated in Figure 1, nodes $n_3$ and $n_4$ form a point-to-point collaborative group, $n_3$ can transmit data to $n_4$ using a small transmission power to further prolong its lifetime, and $n_4$ needs to consume more energy to relay packets generated by $n_3$. In this paper, the path loss model $PL(d)$ with distance dependency can be described by Equation [30]

$$PL(d) = PL(d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right),$$

(2)

where $d_0$ denotes the reference distance, $PL(d_0)$ denotes the path loss at the reference distance $d_0$, $n$ represents the path-loss exponent, and $d$ is the distance between the sender and the receiver.

Figure 1. Network model.

### 3.2. Superframe Structure

The time is divided into periodic superframes, beginning with the beacon frame. As shown in Figure 2, the superframe consists of the Beacon Period (BP), Contention-Free Period (CFP), Ack Period (AP), and Contention-Based Period (CBP). During each BP, the coordinator broadcasts a beacon packet containing control information. The CFP is further divided into multiple time slots and sensors upload their data during assigned time slots. At the end of the CFP, the coordinator broadcasts a combined Ack packet to inform all sensors about the successful reception of their uploaded packets. If a packet uploaded by sensor $n_i$ is lost during the CFP, $n_i$ decides whether to retransmit the packet during the CBP based on its priority. The CBP is primarily used for sensors to upload event-triggered and emergency information. If these packets are generated during the CBP, sensors access the channel immediately using a CSMA/CA scheme.
4. The Proposed Cross-Layer MAC Protocol

The PACR-MAC protocol is designed to prolong the network lifetime while maintaining the QoS of the network. In this section, we provide a detailed explanation of the operational processes, which include base transmission power determination, priority-based transmission power adjustment, and point-to-point cooperative relay.

4.1. Base Transmission Power Determination

Two efforts are made to enhance the packet reception ratio, mitigate packet collisions, and ensure sufficient signal strength. As the majority of packets transmitted are periodic health information, the TDMA scheme is employed during the CFP, allowing sensors to upload packets without collisions. During the CBP, only a smaller number of packets are transmitted, further reducing the chances of collisions. In the absence of collisions, the packet reception ratio depends on the signal-to-noise ratio. Taking non-coherent FSK as an illustration [31], the packet reception ratio can be mathematically expressed as follows:

\[
\Theta(\gamma) = (1 - f(\gamma))^L = (1 - \frac{1}{2} \exp^{-\frac{\gamma B^2 R L}{2}})^L, \tag{3}
\]

where \( f(\gamma) \) denotes the bit error rate, \( \gamma, R, L, \) and \( B \) represent the signal-to-noise ratio (SNR) at the coordinator, the transmission rate, the packet length in bits, and the noise bandwidth, respectively. By improving its transmission power, a sensor can achieve a higher \( \gamma \), thereby increasing the probability of successful packet reception. However, higher transmission power leads to faster energy consumption and shorter network lifetime. Hence, there exists a trade-off between the packet reception ratio and network lifetime. To address this trade-off, a dynamic determination scheme is required to adjust the transmission power based on the data type. For instance, in the case of event-triggered emergency data, the loss of such data may result in serious consequences. Therefore, higher transmission power is desired to ensure the reliability of the data. Conversely, for periodic health monitoring, a longer network lifetime is preferred. As long as the user’s state is healthy, the loss of a frame in the continuously detected periodic data would not have a significant impact. Thus, a relatively lower transmission power is acceptable to ensure that more packets can be uploaded within the sensor’s life cycle.

We need to determine a base transmission power to meet the requirements of low-priority data, and a transmission power adjustment scheme is also needed, which can choose the proper power for data with different priorities. The base transmission power is calculated according to the wireless channel state. When sensor \( n_i \) transmits data using power \( P_i \), the received SNR at the coordinator is

\[
\gamma_{ic} = \frac{p_i |g_{ic}|^2}{\sigma^2}, \tag{4}
\]

where \( \sigma \) and \( g_{ic} \) denote the power of the noise signal and the channel gain. Correspondingly, when the coordinator broadcast beacons using power \( P_c \), the received SNR at sensor \( n_i \) is

\[
\gamma_{ci} = \frac{p_c |g_{ci}|^2}{\sigma^2}, \tag{5}
\]

According to the wireless channel reciprocity, the receiver and the transmitter of one wireless link observe the same channel simultaneously [32], and the channel gains are equal as \( g_{ic} = g_{ci} \). Then, the base transmission power \( P_i^* \) can be calculated according to
where $\Phi$ denotes the threshold value of the packet reception ratio.

Instead of using a fixed transmission power $P_{\text{max}}$, the lifetime of a sensor can be effectively improved by using the base transmission power $P_{i}^{*}$. Then, sensors can upload low-priority data using $P_{i}^{*}$ to prolong the lifetime and further improve the reliability of high-priority data through priority-based transmission power adjustment.

### 4.2. Priority-Based Transmission Power Adjustment

To handle heterogeneous data generated by different sensors, we divide these data into three types: period data, event-triggered data, and emergency data. As shown in Table 2, different priority levels are assigned to these data, corresponding to differentiated initial transmission power. Emergency data have the highest priority and sensors use the maximum power to upload these data to guarantee transmission reliability. Once a packet uploaded by sensor $n_{i}$ is lost, $n_{i}$ will determine whether the packet should be re-transmitted.

For periodic data transmitted in the CFP, a packet will not be re-transmitted during the CBP if the value of the health parameter is within the reasonable range. Other kinds of data will be re-transmitted once occurring a loss.

Table 2. Data priority of heterogeneous data.

<table>
<thead>
<tr>
<th>Priority</th>
<th>Data Category</th>
<th>Initial Transmission Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>level 3</td>
<td>emergency data</td>
<td>$P_{\text{max}}$</td>
</tr>
<tr>
<td>level 2</td>
<td>event-triggered data</td>
<td>$P_{i}^{*}$</td>
</tr>
<tr>
<td>level 1</td>
<td>period data</td>
<td>$P_{i}^{*}$</td>
</tr>
</tbody>
</table>

Figure 3 is an illustration of the data uploading process. Sensors $n_{1}$, $n_{2}$, and $n_{3}$ upload packets during slots assigned to them in the CFP, and a packet containing all the Acks for the received packets is broadcast by the coordinator in the AP. Packets uploaded by $n_{1}$ and $n_{3}$ are received successfully by the coordinator, but the packet uploaded by $n_{2}$ is lost due to a transmission failure. Thus, the packet broadcast by the coordinator during the AP contains the Acks for $n_{1}$ and $n_{3}$, and no Ack for $n_{2}$ is packed since the packet sent by $n_{2}$ is lost. Then, $n_{2}$ knows about the transmission failure after receiving the packet as no Ack for itself can be found. No re-transmission is needed if the value of the lost data is within a healthy range. Otherwise, $n_{2}$ will re-transmit the packet during the CBP. As shown in Figure 3, $n_{2}$ uploads the packet again during the CBP. Because the coordinator sends an Ack immediately after receiving a packet during the CBP, $n_{2}$ knows the re-transmitted packet has been uploaded successfully. For event-triggered data and emergency data uploaded during the CBP, sensors always re-transmit the data once a transmission failure occurs. As shown in Figure 3, sensor $n_{3}$ uploads one packet during the CBP but does not receive the ACK sent by the coordinator. Then, $n_{3}$ re-transmits the packet again.

![Figure 3. Illustration of data uploading.](image-url)
When a packet is lost and the sender decides to re-transmit the packet, the transmission power will be adjusted during the re-transmission to improve the successful arrival rate of this packet. As shown in Table 2, once sensor \( n_i \) generates a packet, an initial transmission power \( P_b \) can be gained according to the data type. For emergency data, \( n_i \) will upload the generated packet using the maximized transmission power (i.e., \( P_b = P_{\text{max}} \)) without power adjustment when a data transfer failure occurs. For periodic data, the assumed value of the detected health parameter is \( v \), and the maximum and minimum values of the corresponding health range are \( v_{\text{max}} \) and \( v_{\text{min}} \). A deviation degree \( \psi \) can be calculated as

\[
\psi = \begin{cases} 
\frac{v - v_{\text{max}}}{v_{\delta}}, & v > v_{\text{max}} \\
\frac{v_{\text{min}} - v}{v_{\delta}}, & v_{\text{min}} > v \\
0, & \text{otherwise}
\end{cases}
\]  

where \( v_{\delta} \) is a pre-set threshold value for the corresponding health parameter. A comprehensive weight considering data continuity and importance is defined as

\[
W = \lambda_1 \psi + \lambda_2 (1 - R),
\]

where \( \lambda_1 \) and \( \lambda_2 \) denote the weight values, and \( \lambda_1 + \lambda_2 = 1 \). \( R \) denotes the received ratio of the corresponding data during the last \( M \) superframes. Then, we can see that \( W \) equals zero when the lost data are within the health range and all the periodic data have been received successfully during the last \( M \) superframes.

When the value of \( W \) is bigger than a threshold value \( W_{\delta} \), the generated data need to be re-transmitted during the CBP if a transmission failure occurs. The adjusted transmission power when re-transmitting period data is

\[
P^f_t = \min\{P^*_{\text{t}} + 2^t W P^f, P_{\text{max}}\},
\]

where \( P^f \) denotes a step value for power adjustment and \( t \) is the number of transmission failures for this same data. For event-triggered data, transmission power adjustment scheme is described as

\[
P^f_t = \min\{P^*_{\text{t}} + 2^t \theta P^f, P_{\text{max}}\},
\]

where \( \theta \) is a fixed-weight value corresponding to the data type.

Through power adjustment, we hope to balance the trade-off between the network lifetime and the transmission reliability. Since heterogeneous data have different QoS requirements, an adaptive transmission power adjustment scheme is a good partner to work together with the MAC protocol to improve network performance.

4.3. Point-to-Point Cooperative Relay

Through transmission power adjustment, sensors can select appropriate powers to upload packets instead of using a fixed maximum power, thereby effectively prolonging their lifetime. However, it can be observed that different sensors choose different transmission powers based on their requirements, resulting in varying rates of energy consumption. Over time, this leads to an uneven distribution of energy in the network, with nodes that have high energy consumption rates dying first, which severely impacts network functionality. Meanwhile, nodes with low energy consumption may still have sufficient energy reserves. Therefore, a potential solution is to utilize sensors with sufficient energy as relays for other nodes, reducing the energy consumption rates of nodes with low battery levels and further extending the overall network lifetime.

Taking Figure 4 as an example, let us consider three deployed sensors responsible for collecting health data. Initially, all sensors are fully charged, as shown in Figure 4a. However, due to its relatively farther distance from the coordinator compared to \( n_2 \) and \( n_3 \), sensor \( n_1 \) requires a higher base transmission power \( P^t_1 \) to ensure energy efficiency and data reliability, resulting in a higher energy consumption rate. Consequently, the residual energy of \( n_1 \) will decrease faster over time compared to the other sensors. To prolong the lifetime
of \( n_1 \), the coordinator continuously evaluates the network and assigns a point-to-point relay to assist \( n_1 \)'s transmissions. In Figure 4b, \( n_2 \) is designated as the partner relay for \( n_1 \). This enables \( n_1 \) to transmit its data to \( n_2 \) using a lower transmission power. The updated base transmission power for \( n_1 \) is calculated similarly as described in Section 4.1. The coordinator adjusts the slot assignment strategy to ensure that \( n_1 \) uploads its packet before \( n_2 \) during the CFP. Consequently, during the assigned time slot, \( n_2 \) transitions to a listening state to receive the data sent by \( n_1 \). However, as \( n_2 \) also acts as a relay for \( n_1 \) in addition to uploading its own data, it consumes more energy. If there are additional potential relay nodes available, the coordinator can dynamically adjust the cooperation strategy based on the network conditions. As depicted in Figure 4c, sensor \( n_3 \) is assigned as a new relay for \( n_1 \), effectively utilizing the residual energy of \( n_3 \) to further prolong the lifetime of \( n_1 \). This cooperative relay approach contributes to an extended network lifetime overall.

![Figure 4](image)

**Figure 4.** Illustration of relay selection. (a) Initial state; (b) Relay node allocation; (c) Relay collaboration adjustment; (d) Network lifetime ended.

To evaluate the network condition, the coordinator needs to monitor the lifetimes of all the sensors. Since the amount of periodic data is much greater than that of other data categories, the lifetime is primarily calculated based on the energy consumed by sending periodic data. The lifetime of a remote sensor \( n_i \) without relay assistance can be calculated as follows:

\[
T_i = \frac{E_i R}{P_i^* L_i},
\]

where \( E_i \) denotes the residual energy of sensor \( n_i \), \( L_i \) means the length of packets uploaded by \( n_i \), and \( R \) is the transmission rate.

Considering the situation when a relay \( n_j \) is assigned to assist \( n_i \), lifetime of \( n_j \) will be

\[
T_j = \frac{E_j R}{P_j^* (L_i + L_j + \sum_{k\in H} L_k) + P_r (L_i + \sum_{k\in H} L_k)},
\]

where \( P_r \) means the receiving power and \( H \) is the set of sensors already assigned to \( n_j \) as the relay node. The updated lifetime of \( n_i \) when sending data to \( n_j \) using power \( P_{ij} \) is

\[
T_{ij} = \frac{E_i R}{P_{ij}^* L_i}
\]

If both \( T_{ij} \) and \( T_j \) are bigger than \( T_i \), sensor \( n_j \) will be a potential relay for \( n_i \). Assume that the set of potential relays of \( n_i \) is \( G_i \), and the number of these potential relays is \( u_i \).
Then, the coordinator will not assign a relay for \( n_i \) if \( u_i = 0 \). Otherwise, sensor \( n_r \) will be the selected relay if
\[
\min\{T_{ir}, T_r\} \geq \forall n_k \in G, k \neq j \min\{T_{ik}, T_k\}. \tag{14}
\]

The coordinator has the responsibility to dynamically adjust the point-to-point cooperation schemes based on the energy distribution in the network. Once a relay \( n_j \) is assigned to assist sensor \( n_i \), the energy consumption rate of \( n_j \) will increase. Therefore, the coordinator continuously evaluates whether \( n_j \) is the optimal relay for \( n_i \) during each superframe. If it is determined that there is a more suitable relay available, a new point-to-point relay will be assigned to \( n_i \) instead of \( n_j \). Through the cooperative efforts of nodes, sensors located at greater distances from the coordinator can operate for a longer period of time, effectively prolonging the network lifetime.

5. Simulation Results

To evaluate the proposed protocol, we conducted simulations using MATLAB in two classical WBAN scenarios, as depicted in Figure 5. The network consists of seven sensors and one coordinator. The sensors can select a transmission power ranging from \(-45\) dBm to \(-10\) dBm, whereas the receiver power is fixed at \(-30\) dBm. The values of \( P_0^i \) and \( \vartheta \) are set to 0.1 times \( P_0^* \). The values of \( \lambda_1 \) and \( \lambda_2 \) are set to 0.8 and 0.2, respectively. We compared our protocol with IEEE 802.15.6 [33] in terms of total throughput, network lifetime, and packet reception ratio. We considered two variants of our protocol: one with only power adjustment (PACR-PA) and another that incorporates both power adjustment and cooperative transmission (PACR-CP). The length of the superframe is set to 1 s, and each sensor generates an event-triggered packet or emergency data on average every ten minutes. The lengths of the generated packets range from 20 bytes to 100 bytes, with a step value of 20 bytes.

![Figure 5. Illustration of the simulation scenarios. (a) Network topology in the first scenario; (b) Network topology in the second scenario.](image_url)

Firstly, we evaluated the impact of our cross-layer protocol on network lifetime by using the adaptive power adjustment mechanism. Secondly, we assessed the additional improvement in network lifetime achieved by employing cooperative transmission. Figure 6 demonstrates the lifetimes of the two considered WBANs. When larger packets are generated, sensors need to exhaust more energy to upload data per superframe, resulting in a decrease in the network lifetime with increasing packet size. It is obvious that our proposed protocol outperforms the typical IEEE 802.15.6 since sensors can choose smaller transmission power based on the wireless channel conditions. If no power adjustment
scheme is adopted, all the sensors must choose a high transmission power to ensure that the sensor located far from the coordinator can upload packets to the coordinator successfully. Consequently, a sensor located near the coordinator would unnecessarily consume high energy, as its packets could be received by the coordinator using a relatively lower transmission power. Therefore, it is necessary for sensors in resource-constrained WBANs to adaptively adjust the transmission power to conserve energy. As shown in Figure 6, the network lifetime of the PACR-PA scheme is 3.5 to 2.9 times and 3.7 to 3.1 times that of the IEEE 802.15.6 protocol under different packet sizes in the two considered networks. Therefore, our proposed protocol can effectively improve network lifetime through adaptive adjustment of node power.

![Figure 6. Lifetimes of networks in simulated scenarios. (a) Lifetime of the first network; (b) Lifetime of the second network.](image-url)

After adopting the transmission power adjustment scheme, sensors experience different energy consumption rates, leading to an imbalance in the energy distribution within the network over time. Therefore, enabling cooperation among the sensors is necessary to further prolong the network lifetime. As depicted in Figure 5, for the first network, sensors $n_1$ and $n_7$, located relatively far from the coordinator, can potentially benefit from relays such as nodes $n_2$, $n_3$, $n_5$, and $n_6$. The network lifetime can be improved by 17% to 20% for the PACR-CP scheme compared to the PACR-PA scheme. In the second network, only $n_7$ is located relatively far from the coordinator, and four potential relays can cooperate with $n_7$. The network lifetime is improved by 38% to 44% for the PACR-CP scheme compared to the PACR-PA scheme. The simulation results indicate that our cross-layer protocol can further improve network lifetime through the provided mechanism of collaborative transmission among nodes.

Although our proposed protocol can improve network lifetime through power adjustment, reducing the power can affect packet reception rates. Therefore, it is necessary to evaluate the packet reception rate of the network. Figure 7 illustrates the packet reception ratios of the simulated networks under different packet sizes. Since sensors always use the maximum transmission power to upload packets in the IEEE 802.15.6 scheme, a higher packet reception ratio can be achieved. When PACR-PA or PACR-CP is deployed, a base transmission power is used when uploading periodic data, and the packet reception ratio is lower compared with the IEEE 802.15.6 protocol. However, for event-triggered data, emergency data, and periodic data beyond the normal range of health, the packet reception ratio can be guaranteed since the priority-based transmission adjustment scheme is used. Data can be re-transmitted during the CAP. Adaptive adjustment of appropriate transmission power can ensure acceptable packet arrival rates while effectively extending network lifetime. Because heterogeneous data have varying priorities, it is important to guarantee the reliability of high-priority data. Our proposed scheme can effectively prolong the network lifetime and ensure the reliability of high-priority data, whereas a desired
packet reception ratio can also be achieved for periodic data. However, for applications where the importance of data cannot be determined, it can be challenging to evaluate the impact of periodic data loss.

Finally, we evaluated the overall throughput of the network to provide a better comparison of the performance improvement achieved by our proposed protocol. Figure 8 shows the total throughput of different schemes under the two considered networks. When a smaller transmission power is used to upload data, more packets can be sent by a sensor. However, sending more packets does not necessarily mean that more packets can be received by the coordinator. To achieve higher throughput, a proper packet reception ratio should also be guaranteed. In our proposed protocol, a suitable transmission power can be chosen based on the channel status, which is neither too high nor too low. This allows more packets to be sent while maintaining the desired packet reception ratio. Therefore, the total throughput is higher for our protocol compared to the IEEE 802.15.6 protocol. As shown in Figure 8, the total throughput of the PACR-PA scheme is 3.4 to 2.8 times that of the IEEE 802.15.6 protocol under different packet sizes in the first scenario. Furthermore, the total throughput is improved by 17% to 20% for the PACR-CP scheme compared to the PACR-PA scheme. In the second network, the total throughput of the PACR-PA scheme is 3.6 to 3.0 times that of the IEEE 802.15.6 protocol under different packet sizes. Moreover, the total throughput is improved by 38% to 44% for the PACR-CP scheme compared to the PACR-PA scheme. The simulation results demonstrate that with the use of our proposed cross-layer protocol, the network is able to transmit more packets and achieve higher energy efficiency, even with the initial energy distribution being the same across the network.
The simulation results above demonstrate that our proposed cross-layer protocol can effectively improve the overall performance of the network. Regarding the limitations of the protocol, firstly, the protocol mainly considers the data transmission requirements of common applications, such as periodic data and sporadic event-triggered data. However, for nodes that do not have a clear pattern in data generation timing, further research is needed on how to adaptively improve their data transmission efficiency and reliability. Additionally, for applications where the importance of data cannot be determined, it may be challenging to assess the impact of periodic data loss, which requires further optimization.

6. Conclusions

As an emerging network capable of collecting human-centered information, WBAN technology plays an important role in the deep integration of computer technology with fields such as healthcare, sports, and education. In this paper, we propose a cross-layer base MAC protocol for WBANs. The protocol considers the reliability requirements for heterogeneous data transmission and makes targeted adjustments to the superframe structure and data retransmission mechanism. Additionally, a power adjustment mechanism is proposed, taking into account the channel conditions and the reliability requirements of data transmission, effectively improving the network lifetime. Furthermore, a concise node cooperative transmission mechanism is proposed to further enhance the network lifetime. The protocol mechanism can effectively guarantee the quality of service for differentiated data and improve network lifetime and energy efficiency. It helps improve the user experience quality when using WBAN for health monitoring services, avoiding frequent battery resets of nodes in the network and making it easier for users to accept WBAN health monitoring services.

Compared to existing protocols, our proposed protocol considers the reliability requirements of data transmission when performing power adjustment. Based on the adaptability to channel conditions, nodes adjust the transmission power according to the real-time data type and importance, effectively improving the network lifetime while ensuring network service quality. Additionally, the cooperative transmission mechanism between nodes further improves network lifetime by addressing the issue of uneven energy distribution caused by differential transmission power.

The protocol design considers the common data transmission requirements of e-health applications. For nodes that generate data without clear periodicity and where the importance of data cannot be clearly measured, it is challenging to efficiently adjust the data transmission power of nodes. Additionally, when transmitting data at lower power levels, the inability to assess data importance may affect the accuracy and reliability of e-health applications if the data are not retransmitted. In future work, we will further optimize the protocol mechanism and study mechanisms that can simultaneously improve data transmission efficiency and extend the lifetime of such nodes. Based on this, we will investigate methods for cooperative transmission among nodes in multiple WBAN coexistence scenarios, exploring the efficiency and feasibility of multi-network cooperation.

Author Contributions: Conceptualization, L.Z. and Y.J.; methodology, Y.J.; software, J.H. and Y.J.; validation, J.H. and L.Z.; formal analysis, Y.J.; investigation, J.H. and L.Z.; data curation, L.Z.; writing—original draft preparation, Y.J. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the National Natural Science Foundation of China under Grants No. 61701190, Jilin Provincial Social Science Foundation under Grants No. 2022C108 and Project of Jilin Province Development and Reform Commission Grant No. 2019FGWTZC001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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