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Research Article

An Adaptive MAC Protocol Based on IEEE802.15.6 for Wireless Body Area Networks

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The application carrier of wireless body area network (WBAN) is human; due to changes in people's sports status or physical health and other reasons, the business traffic fluctuates greatly, which requires the network to have good adaptability. In addition, the energy consumption problem is also a key factor restricting the applications of the WBAN. At present, the proposed MAC protocol is not highly adaptive and has low energy efficiency. To solve this problem, this paper proposes an adaptive MAC protocol based on IEEE802.15.6 for WBAN (A-MAC). The protocol sets the data to three priorities according to the type of service; the superframe structure of IEEE802.15.6 is improved and reorganized into four phases: the beacon phase, the contention access phase, the noncontention access phase, and the inactive phase. The length of the contention access phase and the noncontention access phase is adjusted according to the proportion of nodes that generate each priority data. The contention access phase is further divided into three subphases, and the length of the subphase is dynamically adjusted according to the data priority. In the contention access phase, all nodes compete for access channel according to the channel access policy. The random data that competes successfully transmits data directly, and the periodic data that competes successfully transmits data in the allocated time slots of the noncontention access phase. Finally through the simulation of the proposed A-MAC protocol and IEEE 802.15.6 MAC protocol and CA-MAC protocol in network performance which were compared, the results show that in terms of throughput, power consumption, and the network time delay, the network performance using A-mac protocol is better than the network performance using IEEE802.15.6 MAC and CA-MAC protocols.

1. Introduction

The wireless body area network (WBAN) [1] is a communication network centring on the human body, which is formed by connecting special sensors attached to the surface of the human body or implanted inside the human body and devices around the human body (such as mobile phones, PDA, etc.) to each other. The network is able to monitor various physiological parameters continuously of the human body (such as heart rate, body temperature, blood pressure, electroencephalogram (EEG), and electrocardiogram (ECG)) as well as body motion state and surrounding environment information [2], which can be collected by personal electronic devices or mobile phones and forwarded to remote monitoring centres. It is widely used in telemedicine, recreational activities, emergency treatment, sports training, and health care services [3, 4].

In WBAN, medium access control (MAC) protocol determines the usage of wireless channel and is responsible for the conflict detection and processing of nodes, priority control, time slot allocation, and the transmission order of nodes. Therefore, the design of MAC protocol plays a major role in the reliability and energy efficiency of WBAN. The performance of WBAN, such as network throughput, transmission delay, reliability, and network energy consumption, is closely related to the adopted MAC protocol [5].

Compared with the traditional wireless sensor networks, the WBAN has many unique characteristics; the traditional MAC protocol of wireless sensor network cannot be directly applied to the WBAN. It is necessary to design a new MAC

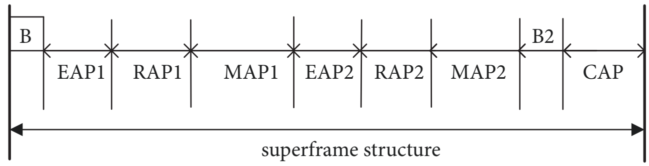

Figure 1: IEEE802.15.6 superframe structure.

protocol to meet the characteristics and requirements of WBAN. An adaptive MAC protocol based on IEEE802.15.6 for WBAN is studied in this paper. The protocol will improve the performance of the WBAN in terms of throughput, energy consumption, and latency.

The rest of this paper is organized as follows: Section 2 discusses the current work on the MAC protocol for WBAN; Section 3 details the working process of the proposed MAC protocol, while the performance of the proposed MAC is evaluated by computer simulation and compared with IEEE 802.15.6 MAC protocol and CA-MAC protocol in Section 4. Finally, the article is summarized in Section 5.

2. Related Work

IEEE802.15.6 is a communication standard specially developed for body area network [6]. There are three types of access modes: beacon mode with beacon period (superframe), nonbeacon mode with beacon period, and nonbeacon mode with no beacon period. This paper mainly studies the beacon mode with beacon period, and its superframe structure is divided into 9 stages, as shown in Figure 1, which are beacon phase (B), exclusive access phase 1 (EAP1), random access phase 1 (RAP1), managed access phase 1 (MAP1), exclusive access phase 2 (EAP2), random access phase 2 (EAP2), managed access phase 2 (MAP2), beacon phase 2 (B2), and contention access phase (CAP) [7].

In these nine phases, except for beacon phases (B and B2), the other phases mainly adopt two access mechanisms. The slot allocation in the exclusive access phase, the random access phase, and the contention access phase adopts the contention-based access mechanism, while the managed access phase uses the scheduling-based access mechanism.

User priority (UP) is also defined to reduce the probability of collision in IEEE 802.15.6. Eight priority levels are defined in IEEE802.15.6, numbered 0, 1. . .7. In the CSMA/CA contention access mechanism, the node mainly maintains three parameters, that is, back-off counter (BC), contention window (CW), and retransmission times R. When the node has data to send, the back-off counter is uniformly distributed over the interval [1, CW] as an initial value. BC is the number of times used to record the back-off. When BC is 0, the node sends data. CW is the size of the current contention window. In order to avoid collision, when the node detects that channel is idle, it does not send data immediately and waits for a random time. The length of the waiting time is determined by the value of CW, and its value range is [CWmin, CWmax].

The emergence of the IEEE802.15.6 standard has promoted the rapid development of the WBAN, and there has been an upsurge of research on WBAN at home and abroad. Many enterprises and research institutions are actively engaged in the research of WBAN. Therefore, many MAC protocols based on IEEE 802.15.6 have been proposed for WBAN in recent years.

In [8], the author introduces a context-aware MAC protocol to meet time-varying requirements of WBAN based on the traffic nature and channel status, which adopts a hybrid superframe structure, allocates timeslots based on traffic awareness, and allocates access policies according to channel sensing. However, in the contention access phase, different data types of different nodes are not considered to be treated differently. In [9], the proposed MAC protocol increases the data rate of the nodes by allocating the resources according to the condition of the network, and an efficient and energy-saving MAC protocol (HE-MAC) was designed to reduce energy consumption and improve network reliability. An adaptive MAC protocol is proposed in [10], which uses the TDMA method to access the channel and synchronization scheme is defined to avoid collision. In [11], a hybrid MAC protocol based on priority is proposed by French scholars based on the superframe structure of IEEE802.15.6. It divides the channel into data channel and control channel and gives priority to the life-critical service. At the same time, sleep mode is used to save the energy of wireless sensor and increase the network life. The protocol can guarantee the minimum transmission delay of emergency services, but it ignores the problem of the transmission of periodic data with a large amount of traffic in the body area network. In [12], a priority-based MAC protocol is proposed, in which nonemergency data is transmitted during the contention access period and the emergency data is transmitted during the noncontention access period. The central node allocates time slots for ordinary nodes according to priority, which can reduce the transmission conflict rate of emergency data and reduce the probability of collision, thereby reducing energy consumption and reducing the transmission delay of emergency data. The Medical Emergency Agencies MAC Protocol (MEB MAC) balances the contradictory requirements of energy efficiency and service quality, using idle time slots to insert additional listening window opportunities for emergency services without affecting network throughput, by providing long superframe for emergency data access to reduce its delay [13].

According to the above research background, the current research on the MAC protocol of WBAN mainly has the following problems: the periodic data occupies a large amount

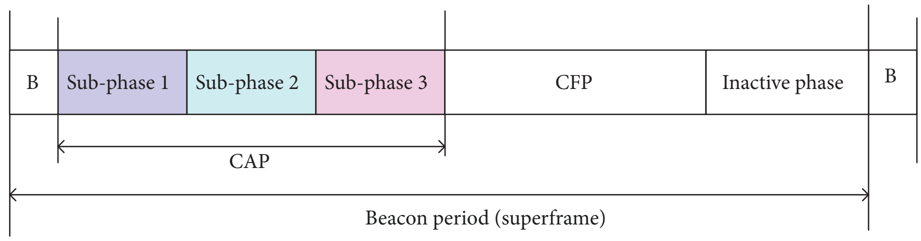

Figure 2: A-MAC superframe structure.

of traffic in WBAN, and the delay of the periodic data is a key factor affecting the network delay. The two access phases in IEEE 802.15.6 are staggered, which increases the control difficulty of the protocol. The length of each access period of the MAC protocol is fixed; when the network traffic changes, it cannot be adaptively adjusted. In the contention access phase, all nodes that need to send data use the CSMA/CA mechanism to compete for access channels, the priority is not differentiated, which leads to large collision probability and long network delay, and the energy consumption is serious. In the noncontention access phase, if the time slot allocation is insufficient or the allocation is too much, this can result in increased delays or wasted time slots.

In order to solve the above problems, this paper studies an adaptive MAC protocol based on IEEE802.15.6 for WBAN (A-MAC). The protocol adjusts the superframe structure based on the IEEE802.15.6 MAC protocol, divides the service type into different priorities, and performs dynamic time slot allocation according to the traffic volume change, thereby reducing network delay, reducing network energy consumption, and improving the network adaptability.

3. A-MAC Protocol Design

Suppose the network adopts a star topology, including one coordinator and N sensor nodes. Due to the limited physical distance, it is assumed that the coordinator and sensor nodes are within the sensing range of each other, so the communication between them is single-hop communication. Sensor nodes are powered by batteries and are located inside or on the body surface, making it inconvenient to recharge or replace the battery. Each node collects only one item of physiological information of the human body, such as blood pressure, body temperature, ECG, sound, and images. The coordinator is used by the mobile phone for easy charging. The initial energy of each sensor node is the same and the energy consumption of the coordinator is not considered.

Based on the above network model and assumptions, this paper studies an adaptive MAC protocol based on IEEE802.15.6 for WBAN (A-MAC). This section discusses the A-MAC protocol in detail, mainly discussing the priority allocation strategy, superframe structure, MAC protocol working process, and channel access process.

3.1. Priority Allocation Strategy. In actual application of the WBAN, there are three main types of data [14]. The first type of data is generated periodically by each sensor node. This data traffic is relatively large and is periodically transmitted to the coordinator. The second type of data is emergent physiological data, user commands, control data, etc. Unlike the first type of data, this type of data is generated only in emergencies, so this type of data is called random data. This type of data has a relatively low volume of business but requires high real-time and reliability. The third category is some audio and video data. This kind of data traffic is not large, and the real-time requirements are not high.

Table 1: Priority of different data.

Priority	Service category
P1 (highest)	Emergency data (e.g. temperature, emergency command, control, etc.)
P2	Periodic data (such as EEG,EMG)
P3 (lowest)	audio/video

According to the characteristics of the data category, it is divided into three priority levels, as shown in Table 1.

In order to reduce the data collision rate and ensure the real-time requirements of high-priority services, different back-off windows (CW) are selected in the protocol for the three priorities. The back-off windows of the P1, P2, and P3 priorities in this protocol correspond to the priorities 7, 6, and 5 in IEEE 802.15.6, respectively.

3.2. Superframe Structure. In order to simplify control difficulty and reduce the control information overhead, the protocol improves the superframe structure of IEEE802.15.6 and reorganizes into four phases, namely, beacon phase (B), contention access phase (CAP), noncontention access phase (CFP), and inactive phase, as shown in Figure 2.

3.2.1. Distribution of the Length of the Two Access Phases. In the contention access phase, the node accesses the channel through the CSMA/CA contention mechanism. The access mechanism is simple to implement and flexible in transmission. However, random access can lead to data collisions, resulting in data packet retransmission and loss, will increase network delay and reduce network reliability.

In the noncontention access phase, node only transmits data in the allocated time slots, and only one node transmits data in each time slot, so collision does not occur, with high reliability and small delay. However, time synchronization is required between the coordinator and sensor nodes, which will result in some additional energy consumption.

The length of the two access phases can be calculated by the following formula:

$$L_{CFP} = \frac{N_2}{(N_1 + N_2 + N_3)} \times L_{sum} \quad (1)$$

$$L_{CAP} = L_{sum} - L_{CFP} \quad (2)$$

where L_{CAP} indicates the length of the contention access phase; L_{CFP} indicates the length of the noncontention access phase; L_{sum} indicates the total length; N_1~ N_3 indicates the number of nodes of each priority.

According to the formula, the length of the noncontention access phase is related to the ratio of the number of nodes of the P2 priority service to the total number of nodes. The more nodes of the priority P2 service, the longer the length of the noncontention access phase. This is because although the P2 and P3 priority data services are transmitted in the CFP phase, considering the small amount of audio and video data in the wireless body area network, for the convenience of research, we mainly consider the P2 periodic data service here.

3.2.2. Distribution of the Length of the Subphase in the Contention Access Phase. In the contention access phase, the node uses the CSMA/CA mechanism to contend for the access channel. In order to reduce the probability of collision of nodes, we divide it into three subphases according to each data service priority level.

Each specified access phase can be dynamically changed in length and calculated by the algorithm proposed by the coordinator. When a new superframe period comes, the coordinator senses the change in the number of nodes in each class in the current superframe CAP and calculates the number of nodes in each traffic class.

The length of the subphase can be calculated using

$$l_i = L_{CAP} * \left(\frac{N_i}{N_T}\right) \quad (3)$$

where l_i is the length of the subphase (i=1, 2, 3), L_{CAP} is the length of the CAP, N_i is the number of nodes in the service category with priority P_i, N_T is the total number of nodes, and the initial value l_0 is zero. The information of the node priority is controlled by UP (user priority) in IEEE802.15.6.

On the one hand, if nodes are densely deployed in narrow area, then competition will increase and result in high collisions and significant energy consumption. On the other hand, if each priority service only transmits data in a unique subphase, it will result in insufficient time slot allocation or wasted time slots. So in this paper, in order to maximize the utilization of time slots and reduce delay and energy consumption, we set the priority P1 service to access the channel in all subphases; the node delivering service priority P3 can only use subphase 3, and the P2 priority service can access the channels in subphases 2 and 3.

3.3. A-MAC Protocol Work Process. As shown in Figure 3, the working process of the MAC protocol coordinator in a beacon period is presented. First, in the beacon phase, the coordinator broadcasts beacon frames to the entire network to achieve node synchronization. After the node is synchronized, the coordinator receives the request frame of the node that needs to send data, and the coordinator can identify the type of the request frame according to the information of the frame type field and the frame subtype field, thereby the judging priority. The node then contends for the access channel according to the channel access policy. After nodes compete for a successful channel, the coordinator handles differently for different priority data. If it is random data, the coordinator directly feeds back the confirmation information to the node, and the node directs transfer data. If it is not random data, the coordinator sends a beacon with a guaranteed time slot (GTS) to it for transmission in the corresponding time slot of the noncontention access phase. After the coordinator receives the data, it feeds back an ACK frame to the node. After the node data transmission is completed, it enters the sleep state until the superframe ends.

3.4. Channel Access Process. In the beacon phase, the coordinator broadcasts beacon frames to all nodes of the entire network to achieve node clock synchronization. In the contention access phase, according to the data priority, the node that needs to send data sends a request frame to the coordinator in the corresponding subphase. The coordinator allocates time slots for data transmission according to the access channel policy. In the noncontention access phase, the periodic data sends its data to the coordinator by using a dedicated guaranteed time slot (GTS) without competing with other nodes. The specific channel access process is as follows.

Assuming that node A and node B generate random data, node C generates periodic data. In general, the process by which nodes producing different types of data transmit data to the coordinator is shown in Figure 4.

In this case, node A generates random data then first sends a request frame to the coordinator, and after receiving the request frame, the coordinator feeds back confirmation information to the node, allowing it to send data, and node A transmits data to coordinator. When the coordinator receives data successfully, it sends an ACK confirmation frame to node A, so that the data transmission of node A is completed. Node C generates periodic data, which sends a request frame to the coordinator to apply for GTS allocation. After the coordinator successfully receives the request frame, it sends a beacon message containing the GTS allocation to the node. After the assignment is successful, the node transmits data in the corresponding time slot allocated by the CFP. Similarly, after the coordinator successfully receives the data, it feeds back an ACK acknowledgment to node C.

Figure 5 illustrates a channel access procedure in which two nodes generating random data simultaneously transmit data to the coordinator. Node A and node B simultaneously send request frames to the coordinator, resulting in conflicts. According to the CSMA/CA mechanism, the nodes randomly back off for a period of time. It is assumed that the BC of node A is 1 and the BC of the node B is 2, and after node A returns one time slot, the idle channel assessment (CCA) is performed, and it is detected that the channel is idle at the

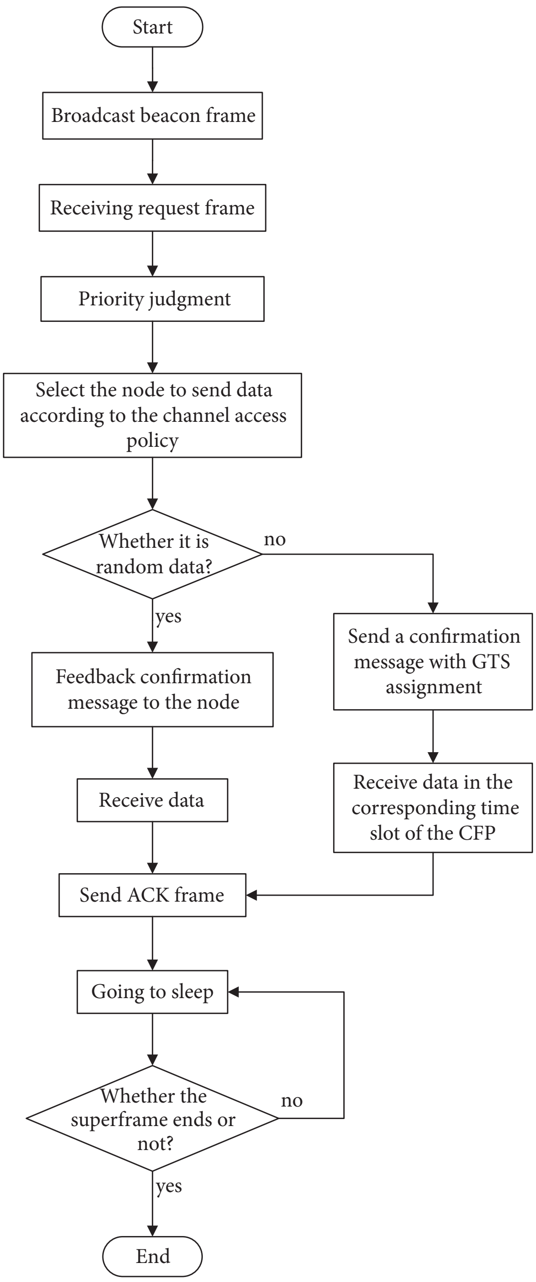

Figure 3: Coordinator work process.

moment, the request frame is sent to the coordinator, and the data is transmitted after receiving the confirmation message from the coordinator. After node B backs off a time slot, it detects that the channel is busy, locks the back-off counter until node A completes its data transmission and continues to back off a time slot, and then sends a request to the coordinator, and after receiving the feedback confirmation from the coordinator, the data is transmitted.

Figure 6 illustrates a channel access process in which two nodes generating different priority data simultaneously transmit data to the coordinator. When both node A and node C have data to transmit at the same time, they send a request frame to the coordinator simultaneously, and the coordinator determines that node A transmits data with a higher priority than node C by identifying the information of the request frame. Then the coordinator sends an acknowledgment message to node A, which sends the data directly to the coordinator during the contention access phase. After the coordinator successfully receives the data, it sends an acknowledgment frame to node A, thereby completing the data transmission. After that, the coordinator sends a beacon containing the GTS allocation to node C, which transmits the data in the corresponding time slot of the noncontention access phase. Similarly, after the coordinator successfully receives the data, it feeds back an ACK to node C.

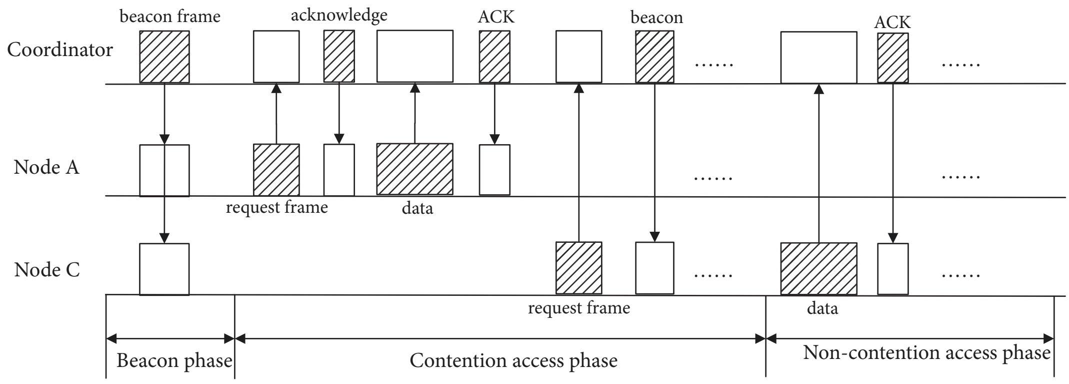

Figure 4: In general (without conflict), node transmits data to coordinator.

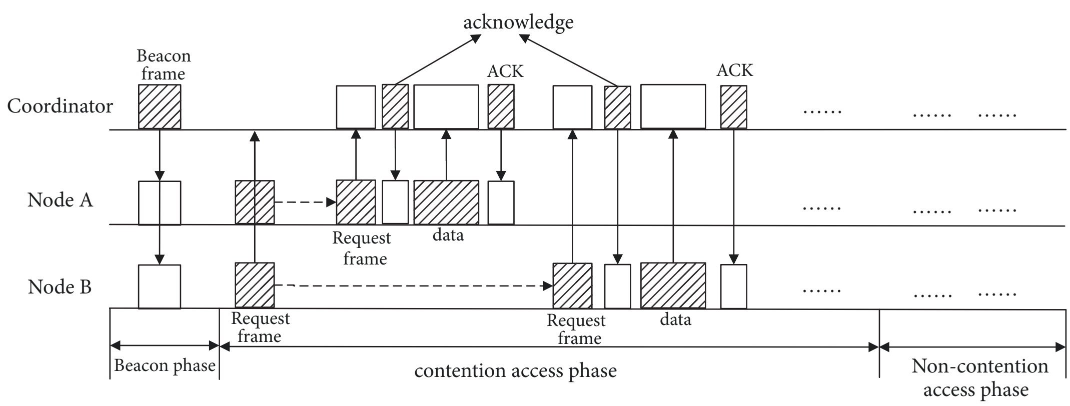

Figure 5: At the same time, two nodes generating random data transmit data to the coordinator.

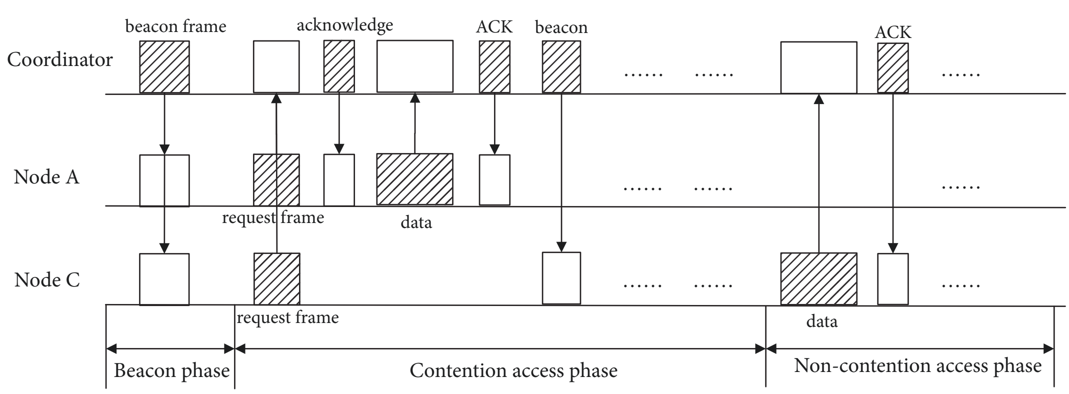

Figure 6: At the same time, two nodes generating different priority data transmit data to the coordinator.

4. A-MAC Protocol Simulation and Performance Evaluation

In this section, the proposed A-MAC protocol is evaluated through Matlab simulation and compared with the IEEE 802.15.6 MAC protocol and the CA-MAC protocol. Three performance metrics are primarily evaluated—network latency, throughput, and energy consumption.

4.1. Simulation Environment. In this paper, a star WBAN is constructed, including 1 coordinator and N nodes, and up to 20 nodes are set during the experiment. The nodes are randomly deployed in the area of 2 m∗2m, and it is assumed that the nodes are within the sensing range of the coordinator and are transmitted in single hop. In each simulation, 35% of the nodes generate emergency services, 55% of the periodic services, and 10% of the audio and video services. Physical layer parameters are defined in accordance with the IEEE 802.15.6 standard. The arrival of the packet is approximately a Poisson distribution. Small-scale channel fading is ignored and it is assumed that packet loss is only due to collisions. The main simulation parameter settings are shown in Table 2.

Table 2: Simulation parameter settings.

Simulation parameter	Value
Transmission band	2.4GHz
Data transfer rate	250kbps
Simulation time	100s
Packet size	1024byte
Sending energy consumption	414mW
Receiving energy consumption	365mW
Idle energy consumption	275mW
Initial energy of the node	0.5J

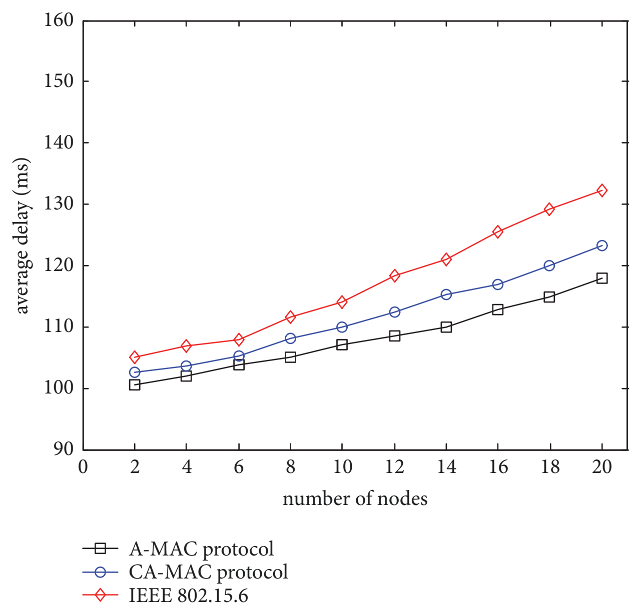

Figure 7: The average delay comparison of the protocol.

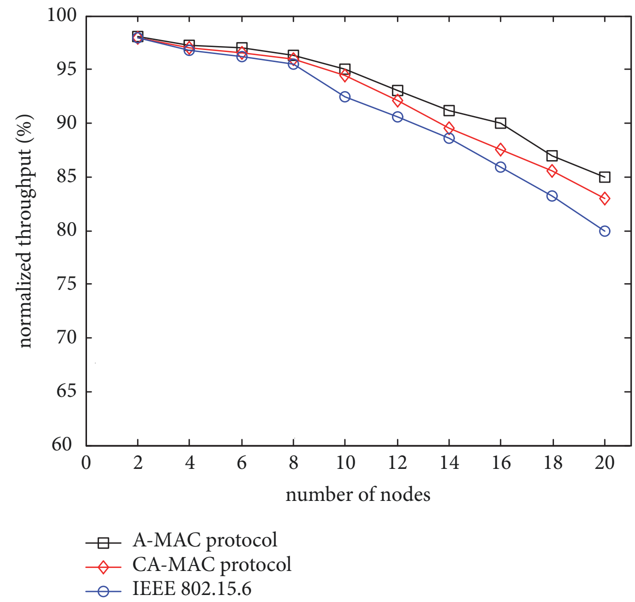

Figure 8: Network normalized throughput contrast diagram.

4.2. Simulation Results and Analysis. The delay is the time difference from the generation of the packet to the successful reception of the coordinator. The average delay of the three protocols varies with the number of nodes as shown in Figure 7. It can be seen from the figure that the average delay of the three MAC protocols increases with the number of nodes, which is due to the increase of the number of nodes, the increase in network traffic, and the increase of probability of node collisions, resulting in the increase of retransmissions and the delay. All three protocols use a priority-based channel access strategy to reduce latency. However, with the increase of the number of nodes, the performance of the proposed A-MAC and CA-MAC protocols is significantly better than that of the IEEE 802.15.6 MAC protocol. This is because the time slots in the superframe structure of the IEEE802.15.6 MAC protocol are fixed, and with the increase of the number of nodes, the collision probability of the nodes increases significantly, resulting in high contention complexity and increased latency. The proposed A-MAC protocol takes full account of node priority, combined with the dynamic time slot allocation and divides the contention access phase into three subphases, which can effectively solve the complex contention problem, reduce the node collision probability, and reduce number of packet retransmission. Therefore, proposed A-MAC shows better performance than the other two MAC protocols.

The network normalized throughput is the ratio of the number of successfully transmitted packets per unit time to the total number of transmitted packets. As the number of nodes increases, the network normalized throughput changes as shown in Figure 8. It can be seen from the figure that as the number of nodes increases, the normalized network throughput of the three protocols decreases, which is due to the increase in the number of nodes and the increase in the number of packets sent, resulting in the increase of the packet loss rate of the sensor nodes. However, compared with the IEEE802.15.6 MAC protocol and the CA-MAC protocol, the proposed A-MAC protocol optimizes the node priority classification, divides the contention access phase into three subphases, and adjusts the time slot allocation policy; thus, it can reduce collisions and it has a significant effect on reducing the rate of packet loss.

The average energy consumption is the average value of the energy consumed by the nodes in the network. Figure 9 shows the relationship between the average energy consumption of the network and the number of nodes. The network energy consumption in WBAN mainly comes from data collision and retransmission. It can be seen from the figure that as the number of nodes increases, the average energy consumption of the three protocols increases. Both the proposed A-MAC protocol and IEEE 802.15.6 MAC protocol schedule access channels based on node priority, which can reduce contention complexity, reduce data collisions and retransmissions, and reduce energy consumption. The proposed A-MAC protocol divides the data type according to the priority and assigns the time slot according to the traffic volume, which greatly reduces the data collision rate and

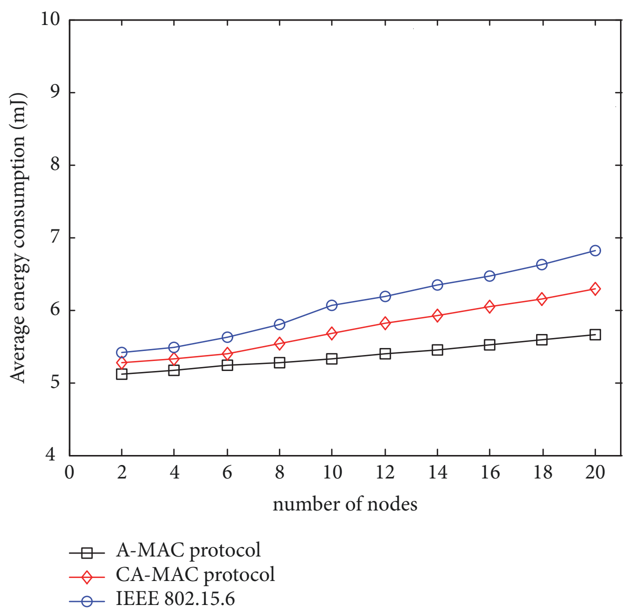

Figure 9: Comparative diagram of average energy consumption of network with increasing number of nodes.

reduces the collision retransmission. Therefore, the average network energy consumption of the proposed protocol is better than that of the other two MAC protocols.

5. Conclusions

In this paper, an adaptive MAC protocol based on IEEE802.15.6 for WBAN (A-MAC) is proposed. Based on the IEEE802.15.6 MAC protocol, this protocol improves the superframe structure and solves the problem that IEEE802.15.6 is interleaved and difficult to control during each access phase. The data service is divided into three priorities according to the service type, and the periodic data is scheduled to be transmitted in the noncontention access phase, which can effectively reduce the collision when the data channel is accessed. The time slot allocation is dynamically adjusted according to the traffic flow condition, which can adapt to the change of service traffic in the network. Through simulation, the performance comparison, and analysis of IEEE802.15.6 protocol, CA-MAC protocol and A-MAC protocol are carried out. The results verify that A-MAC protocol can effectively reduce network delay, reduce network energy consumption, and improve network adaptability.

Data Availability

The data are from previously reported studies and datasets, which have been cited.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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