Adaptive MAC Protocol for IEEE 802.15.6-based Wireless Body Area Networks: Postprint

Authors: Yuan Deying, Guoqiang Zheng, Ma Huahong, Wu Honghai, Jishun Li

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Abstract

To address the issues of low adaptability and poor energy efficiency in wireless body area network MAC protocols, this paper proposes an adaptive MAC protocol (A-MAC) for wireless body area networks based on IEEE 802.15.6. The protocol enhances the superframe structure of IEEE 802.15.6, wherein the durations of the contention access phase and contention-free access phase are adjusted according to the proportion of nodes generating various priority data. The contention access phase is further partitioned into three sub-phases, with the duration of each sub-phase dynamically adapted based on data priority conditions. All nodes compete for channel access during the contention access phase in accordance with a channel access strategy. Simulation results demonstrate that the network performance achieved with the A-MAC protocol significantly outperforms that of the IEEE 802.15.6 MAC protocol and the CA-MAC protocol in terms of throughput, energy consumption, and network latency.

Full Text

Preamble

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Adaptive MAC Protocol Based on IEEE 802.15.6 for Wireless Body Area Networks

Yuan Deying[1], Zheng Guoqiang[1,2], Ma Huahong[1], Wu Honghai[1], Li Jishun[1,2,3]

[1]School of Information Engineering, Henan University of Science & Technology, Luoyang, Henan 471023, China;
[2]Henan Key Laboratory for Machinery Design & Transmission System, Henan University of Science & Technology, Luoyang, Henan 471003, China;
[3]State Key Laboratory of Mining Heavy Equipment, Luoyang, Henan 471039, China

Abstract: To address the problems of low adaptability and poor energy efficiency in wireless body area network (WBAN) MAC protocols, this paper proposes an adaptive MAC protocol based on IEEE 802.15.6 for wireless body area networks (A-MAC). The protocol improves the superframe structure of IEEE 802.15.6, where the lengths of the contention access phase and the contention-free access phase are adjusted according to the proportion of nodes generating data of each priority. The contention access phase is further divided into three sub-phases, with the length of each sub-phase dynamically adjusted based on data priority conditions. All nodes compete for channel access during the contention access phase following the channel access strategy. Simulation results demonstrate that networks using the A-MAC protocol achieve significantly better performance than those using the IEEE 802.15.6 MAC protocol and the CA-MAC protocol in terms of throughput, energy consumption, and network delay.

Key words: wireless body area network; IEEE 802.15.6; adaptive; MAC protocol

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0 Introduction

Wireless Body Area Networks (WBANs) are communication networks centered on the human body, formed by interconnecting specialized sensors attached to or implanted inside the human body with devices surrounding the body (such as mobile phones and PDAs). These networks continuously monitor various physiological parameters (such as heart rate, body temperature, blood pressure, electroencephalogram (EEG), electrocardiogram (ECG), etc.) as well as body movement status and environmental information. This monitored information can be collected by personal electronic devices or mobile phones and forwarded to remote monitoring centers, with applications spanning remote healthcare, entertainment, emergency response, sports training, and wellness services.

In WBANs, the Medium Access Control (MAC) protocol determines how the wireless channel is used, handling collision detection and resolution, priority control, slot allocation, and node transmission sequencing. Therefore, MAC protocol design plays a primary role in the reliability and energy efficiency of WBANs. Situated between the physical layer and network layer, the MAC protocol has a decisive impact on WBAN performance and is one of the key technologies ensuring effective communication. Network performance metrics such as throughput, transmission delay, reliability, and energy consumption are all closely related to the MAC protocol employed.

Compared with traditional wireless sensor networks, WBANs have many unique characteristics: the application carrier is the human body, node sizes are very small; communication distances are short and network scale is small; sensor nodes have limited energy; data transmission requires security and real-time performance. Additionally, since WBANs are human-centric and many devices operate on or inside the human body, network topology can easily change due to human movement, and network traffic can fluctuate significantly due to health conditions, requiring strong adaptability. Consequently, traditional wireless sensor network MAC protocols cannot be directly applied to WBANs, and new MAC protocols must be designed to meet the specific characteristics and requirements of WBANs. This paper investigates an adaptive MAC protocol based on IEEE 802.15.6 for wireless body area networks, which aims to improve network performance in terms of throughput, energy consumption, and delay.

1 Related Work

1.1 IEEE 802.15.6 Protocol Overview

IEEE 802.15.6 is a communication standard specifically designed for body area networks. It defines three main access modes: beacon mode with beacon periods (superframes), non-beacon mode with beacon periods, and non-beacon mode without beacon periods. This paper focuses on the beacon mode with beacon periods, whose superframe structure is divided into nine phases as shown in [Figure 1: see original paper]: Beacon period (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 (RAP2), Managed Access Phase 2 (MAP2), Beacon2 period (B2), and Contention Access Phase (CAP).

Among these nine phases, except for the beacon periods B and B2, the other phases primarily employ two access mechanisms: contention-based and scheduled mechanisms. Five phases—EAP1, RAP1, EAP2, RAP2, and CAP—use contention-based mechanisms where nodes primarily use CSMA/CA or slotted Aloha to seize the channel for data transmission. MAP1 and MAP2 use scheduled mechanisms where the coordinator allocates transmission slots based on transmission requirements and channel status, allowing nodes to transmit only during their allocated slots and enter sleep mode during other phases.

IEEE 802.15.6 also defines User Priority (UP) to reduce collision probability. In the CSMA/CA contention access mechanism, nodes maintain three parameters: Back-off Counter (BC), Contention Window (CW), and retransmission count R. When a node has data to send, the back-off counter selects a random integer uniformly distributed in the interval [1, CW] as its initial value. BC records the number of back-offs, and when BC reaches 0, the node transmits data. CW represents the current contention window size—when a node detects the channel is idle, it does not transmit immediately but waits for a random period to avoid collisions. The waiting duration is determined by the CW value, which ranges between [CWmin, CWmax], with different priority nodes corresponding to different CWmin and CWmax values as shown in . As evident from , higher user priorities have smaller contention window lengths, resulting in greater probability of channel access.

1.2 Related MAC Protocols

The emergence of the IEEE 802.15.6 standard has accelerated WBAN development, with numerous enterprises and research institutions actively engaged in WBAN research, yielding significant achievements in WBAN MAC protocols. In [8], a context-aware MAC protocol (CA-MAC) was proposed, employing a hybrid superframe structure with slot allocation based on traffic sensing and access strategy allocation based on channel sensing. However, during the contention access phase, it fails to differentiate between different node data types. Reference [9] improved the IEEE 802.15.6 protocol from priority control and slot allocation perspectives, proposing a highly energy-efficient MAC layer protocol (HE-MAC) to reduce energy consumption and improve network reliability. Reference [10] proposed an adaptive MAC protocol using TDMA for channel access while defining appropriate synchronization schemes to avoid collisions. In [11], French scholars proposed a priority-based hybrid MAC protocol (PMAC) based on the IEEE 802.15.6 superframe structure, which separates the channel into data and control channels, prioritizes life-critical traffic, and uses sleep mode to conserve wireless sensor energy and extend network lifetime. While this protocol guarantees minimum transmission delay for emergency traffic, it neglects the transmission of periodic data that constitutes substantial traffic volume in WBANs. Reference [12] proposed a priority-based MAC protocol that transmits non-emergency data during contention access periods and emergency data during contention-free access periods, with the central node allocating slots to ordinary nodes based on priority, thereby reducing transmission collision rates for emergency data, decreasing collision probability, and consequently reducing energy consumption and transmission delay. The Medical Emergency Body-area MAC protocol (MEB MAC) balances the conflicting requirements of energy efficiency and quality of service by utilizing idle slots to insert additional listening window opportunities for emergency traffic without affecting network throughput, and reduces emergency data access delay by providing longer superframe periods for emergency data access [13].

Based on the above research background, current WBAN MAC protocols primarily suffer from the following problems: periodic data constitutes a large portion of traffic volume in WBANs, and the delay of periodic data is one of the key factors affecting network delay; the length ratios of various access phases in MAC protocols are fixed and cannot adaptively adjust when network traffic changes; during the contention access phase, all nodes requiring data transmission use CSMA/CA to compete for channel access without priority differentiation, leading to high collision probability, long network delay, and severe energy consumption; during the contention-free access phase, insufficient or excessive slot allocation results in increased delay or slot waste.

To address these problems, this paper proposes an adaptive MAC protocol (A-MAC) for wireless body area networks based on IEEE 802.15.6. This protocol adjusts the superframe structure based on the IEEE 802.15.6 MAC protocol, classifies traffic types into different priorities, and performs dynamic slot allocation according to traffic volume changes, thereby reducing network delay, decreasing energy consumption, and improving network adaptability.

2 A-MAC Protocol Design

We assume the network employs a star topology consisting of one coordinator and N sensor nodes. Due to limited body distance, all sensor nodes are within the coordinator' s sensing range. Sensor nodes are typically battery-powered and located inside or on the surface of the human body, making it inconvenient to recharge or replace batteries during use. Each node collects only one type of physiological information, such as blood pressure, body temperature, ECG, audio, or video. The coordinator node is implemented by a mobile phone for convenient charging. All sensor nodes have identical initial energy, and the coordinator' s energy consumption is not considered.

Based on this network model and assumptions, we propose an adaptive MAC protocol (A-MAC) for wireless body area networks based on IEEE 802.15.6. This section details the A-MAC protocol, focusing on priority allocation strategy, superframe structure, MAC layer protocol operation process, and channel access procedures.

2.1 Priority Allocation Strategy

In practical WBAN applications, three main types of data are generated. The first type is data periodically generated by various sensor nodes. This traffic has relatively large volume and is periodically transmitted to the coordinator. The second type includes emergency physiological data and user commands or control information. Unlike the first type, this data occurs randomly and is therefore called random data. This traffic has relatively low volume but high requirements for real-time performance and reliability. The third type includes audio and video data. This traffic has moderate volume and moderate real-time requirements.

Based on the different characteristics of these data categories, they are divided into three priority levels as shown in . To reduce data collision rates and guarantee real-time requirements for high-priority traffic, different contention windows (CW) are selected for the three priority levels. In this protocol, the contention windows for priorities P1, P2, and P3 correspond to priorities 7, 6, and 5 in IEEE 802.15.6, respectively.

2.2 Superframe Structure

To simplify control complexity and reduce control information overhead, this protocol improves the IEEE 802.15.6 superframe structure by reorganizing it into four phases: Beacon phase (B), Contention Access Phase (CAP), Contention-Free Phase (CFP), and Inactive phase, as shown in [Figure 2: see original paper].

2.2.1 Allocation of Lengths for Two Access Phases In the contention access phase, nodes access the channel through CSMA/CA contention mechanisms. This access mechanism is simple to implement and provides flexible transmission, but random access can lead to data collisions, resulting in packet retransmission and loss, which increases network delay and reduces network reliability.

In the contention-free access phase, nodes transmit data only during their allocated slots, with only one node transmitting per slot, thus preventing collisions and providing high reliability and low delay. However, time synchronization between the coordinator and sensor nodes incurs additional energy consumption.

The length allocation for the two access phases can be calculated using the following formulas:

$$L_{CFP} = \frac{N_2}{N_{sum}} \times L$$

$$L_{CAP} = L_{sum} - L_{CFP}$$

where L_{CAP} represents the length of the contention access phase, L_{CFP} represents the length of the contention-free access phase, L_{sum} represents the total length, and N_2 represents the number of nodes with priority 2 data. According to these formulas, the length of the contention-free access phase is related to the proportion of nodes with priority P2 business among the total nodes—the more nodes with priority P2 business, the longer the contention-free access phase.

2.2.2 Allocation of Sub-phase Lengths in Contention Access Phase In the contention access phase, nodes compete for channel access using the CSMA/CA mechanism. To reduce collision probability, this protocol divides the phase into three sub-phases based on data priority levels.

Each designated access phase can dynamically change its length. When a new superframe period begins, the coordinator senses changes in the number of nodes for each class in the current superframe CAP and calculates the number of nodes in each business class.

The length of sub-phases can be calculated using the equation:

$$l_i = \frac{N_i}{N_{sum}} \times L_{CAP}$$

where l_i is the length of sub-phase i (i=1,2,3), L_{CAP} is the length of CAP, N_i is the number of nodes in business class with priority i, N_{sum} is the total number of nodes, and the initial value is zero. Node priority information is controlled through UP (User Priority) in IEEE 802.15.6.

To maximize slot utilization, this protocol allows priority P1 business to access the channel in all sub-phases; nodes transmitting priority P3 business can only use sub-phase 3; and priority P2 business can access the channel in sub-phases 2 and 3.

2.3 MAC Protocol Operation Process

[Figure 3: see original paper] illustrates the coordinator' s operation process during one beacon period of the MAC protocol. During the beacon phase, the coordinator broadcasts beacon frames containing superframe duration, WBAN timing, and network information to all nodes to achieve synchronization. After network synchronization, nodes with data to transmit prepare their request frames and send them to the coordinator. Request frames differ based on the data business type and are mainly divided into two categories: random data request frames and periodic data request frames. The coordinator can identify the request frame type and determine data priority through information in the frame type and frame subtype fields. Nodes then compete for channel access using the corresponding strategy. After successful contention, if the data is random data, the coordinator directly sends an acknowledgment allowing transmission, and the node immediately transmits data during the contention access phase, which the coordinator directly receives. If the data is periodic, the coordinator sends a beacon with Guaranteed Time Slot (GTS) allocation, and the node transmits during the corresponding slot in the contention-free access phase. After receiving the data, the coordinator sends an ACK frame to the node. After completing data transmission, the node enters sleep mode until the end of the beacon period.

The specific channel access process is as follows: Assume nodes A and B generate random data, while node C generates periodic data. Under normal circumstances, the process of nodes with different data types transmitting to the coordinator is shown in [Figure 4: see original paper].

In this scenario, node A generates random data and first sends a request frame to the coordinator. After receiving the request frame, the coordinator sends back an acknowledgment, allowing node A to begin data transmission. When the coordinator successfully receives the data, it sends an ACK frame to node A, completing node A' s data transmission. Node C generates periodic data and sends a request frame to apply for GTS allocation. After successfully receiving the request frame, the coordinator sends beacon information containing

GTS allocation. Upon successful allocation, this node transmits data during the corresponding slot in the CFP. Similarly, after the coordinator successfully receives the data, it sends an ACK confirmation back to node C.

[Figure 5: see original paper] illustrates the channel access process when two nodes generating random data simultaneously send data to the coordinator. Nodes A and B simultaneously send request frames to the coordinator, causing a collision. According to the CSMA/CA mechanism, nodes will back off for a random period. Assuming node A' s back-off counter BC is 1 and node B' s BC is 2, node A performs Clear Channel Assessment (CCA) after backing off one slot, detects the channel is idle, sends a request frame to the coordinator, and transmits data after receiving the coordinator' s acknowledgment. After backing off one slot, node B detects the channel is busy, locks its back-off counter until node A completes data transmission, continues backing off for another slot, then sends a request to the coordinator and transmits data after receiving acknowledgment.

3 Simulation and Performance Evaluation of A-MAC Protocol

3.1 Simulation Environment

This paper constructs a star-topology wireless body area network consisting of one coordinator and N nodes. Physical layer parameters are defined according to the IEEE 802.15.6 standard. Sensor nodes are randomly deployed in a 2m×2m square area, and all transmissions are assumed to be single-hop. Packet arrivals follow a Poisson distribution. Small-scale channel fading is ignored, and packet loss is assumed to occur only due to collisions. The main simulation parameters are shown in .

3.2 Simulation Results and Analysis

Delay refers to the time difference between packet generation and successful reception by the coordinator. The variation of average delay with node number for the three protocols is shown in [Figure 6: see original paper]. The results indicate that the average delay of all three MAC protocols increases with node number because more nodes increase network traffic and collision probability, leading to more retransmissions and increased delay. All three protocols employ priority-based channel access strategies that effectively reduce delay. However, as node number increases, the performance of A-MAC and CA-MAC protocols becomes significantly better than IEEE 802.15.6 MAC protocol. This is because IEEE 802.15.6 MAC protocol has fixed slot lengths in its superframe structure, and as node number increases, collision probability rises dramatically, resulting in high contention complexity and increased delay. The proposed A-MAC protocol fully considers node priority, combines dynamic slot allocation, divides the contention access phase into three sub-phases, effectively solves node collision problems, reduces collision probability, and decreases packet retransmissions, thus demonstrating better timeliness performance compared to the other two MAC protocols.

Network normalized throughput is the ratio of successfully delivered packets to total transmitted packets per unit time. The variation of normalized throughput with node number is shown in [Figure 7: see original paper]. As node number increases, the normalized throughput of all three protocols decreases because more nodes increase the number of transmitted packets, causing the packet loss rate of sensor nodes to gradually increase and normalized throughput to gradually decrease. However, compared with IEEE 802.15.6 MAC protocol and CA-MAC protocol, the proposed A-MAC protocol optimizes node priority classification, divides the contention access phase into three sub-phases, adjusts slot allocation strategies, and reduces collisions, demonstrating significant effectiveness in reducing packet loss rate.

Average energy consumption refers to the average energy consumed by nodes in the network. The relationship between average energy consumption and node number is shown in [Figure 8: see original paper]. Energy consumption in WBANs primarily originates from data collisions and retransmissions. The results show that average energy consumption of all three protocols increases with node number. Both the proposed A-MAC protocol and IEEE 802.15.6 MAC protocol schedule channel access based on node priority, reducing contention complexity and thereby decreasing data collisions and retransmissions to lower energy consumption. The proposed A-MAC protocol classifies data types according to priority and performs slot allocation based on traffic volume, significantly reducing data collision rates and collision-induced retransmissions. Therefore, the network average energy consumption of the proposed protocol is superior to the other two MAC protocols.

4 Conclusion

This paper proposes an adaptive MAC protocol (A-MAC) for wireless body area networks based on IEEE 802.15.6. Building upon the IEEE 802.15.6 MAC protocol, this protocol improves the superframe structure to solve the problems of interleaved distribution of access phases and high control complexity in IEEE 802.15.6. By classifying data traffic into three priorities based on business type and arranging periodic data transmission in the contention-free access phase, the protocol effectively reduces collisions during channel access. Dynamic slot allocation according to traffic conditions enables adaptation to changing network traffic. Through simulations comparing IEEE 802.15.6 protocol, CA-MAC protocol, and A-MAC protocol, results validate that the A-MAC protocol can effectively reduce network delay, improve network timeliness performance, decrease network energy consumption, and enhance network adaptability.

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Note: Figure translations are in progress. See original paper for figures.