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Hybrid Medium Access Control Protocol Based on IEEE 802.15.6 for Wireless Body Area Network

***Abstract**. The reliability and efficiency of a Wireless Body Area Network (WBAN) rely on the Media Access Control (MAC) protocol design. This paper proposed an efficient method, namely, the Hybrid MAC (HB-MAC) protocol, to enhance the reliability and maximize the performance of WBAN using a hybrid superframe structure according to IEEE 802.15.6 standard requirements. The HB-MAC consists of a contention access period and a scheduled access period. The proposed protocol is compared to the C-MAC and IEEE 802.15.6 MAC protocols based on the performance metrics of Packet Delivery Ratio (PDR), throughput, energy consumption, and average delay. The simulation results show that the HB-MAC outperforms its competitors as it could achieve up to 95% PDR, 10% enhanced throughput, 20% energy optimization, and 30% improvement in average delay. Therefore, it can be concluded that the HB-MAC protocol is an efficient method for WBAN application.*

***Streszczenie.** Niezawodność i wydajność bezprzewodowej sieci komputerowej (WBAN) opiera się na protokole Media Access Control (MAC). W artykule zaproponowano skuteczną metodę, a mianowicie protokół Hybrid MAC (HB-MAC), w celu zwiększenia niezawodności i maksymalizacji wydajności sieci WBAN przy użyciu hybrydowej struktury superramki zgodnie z wymaganiami normy IEEE 802.15.6. HB-MAC składa się z okresu rywalizacji i zaplanowanego okresu dostępu. Proponowany protokół porównuje się z protokołami C-MAC i IEEE 802.15.6 MAC w oparciu o metryki wydajności, takie jak współczynnik dostarczania pakietów (PDR), przepustowość, zużycie energii i średnie opóźnienie. Wyniki symulacji pokazują, że HB-MAC przewyższa swoich konkurentów, ponieważ może osiągnąć do 95% PDR, 10% większą przepustowość, 20% optymalizację zużycia energii i 30% poprawę średniego opóźnienia. Można zatem stwierdzić, że protokół HB-MAC jest efektywną metodą aplikacji sieci WBAN. (**Hybrydowy protokół kontroli dostępu do nośnika oparty na IEEE 802.15.6 dla bezprzewodowej sieci komputerowej**)*

Keywords: Reliability, Efficiency, Hybrid, Scheduled access
Słowa kluczowe: Niezawodność, wydajność, hybryda, dostęp zaplanowany

Introduction

The IEEE 802.15.6 standard is specifically designed for Wireless Body Area Network (WBAN), enabling the monitoring of physical conditions, including blood pressure and heart rate. It also enables the recording of Electromyography (EMG), Electrocardiogram (ECG), and Electroencephalogram (EEG), with data transmission to the network coordinator, often called the hub [1]. It aims to create an international standard for reliable, low-power communication within or near the human body, unlike power-intensive IEEE 802.15.4-based low-rate Wireless Personal Area Network (WPAN) [2]. The strict requirements and rules of WBAN require complete compliance with the IEEE 802.15.6 standard [3].

The IEEE 802.15.6 Media Access Control (MAC) layer offers three distinct communication modes, namely: (1) beacon mode with beacon period superframe boundaries, (2) non-beacon mode with superframe boundaries, and (3) non-beacon mode without superframe boundaries [4]. In the context of this paper, our focus centres on the beacon mode with beacon period superframe boundaries, as illustrated in Figure 1. In this operational mode, the superframe is divided into nine access phases: beacon (B, B2), Exclusive Access Phase (EAP1, EAP 2), Random Access Phase (RAP1, RAP2), Managed Access Phase (MAP1, MAP2), and Contention Access Phase (CAP), with a total of 256 slots [5, 6]. In each beacon period, the hub transmits a beacon frame to achieve clock synchronization among all sensor nodes. The beginning and end of the superframe are determined by the beacon frames, unless it is an inactive superframe [7].

The energy consumption at the 2.4GHz Narrowband (NB) Physical (PHY) layer of the IEEE 802.15.6 standard is examined by using two modulation techniques: Differential Binary Phase Shift Keying (DBPSK) and Differential Quadrature Phase Shift Keying (DQPSK) [8]. The evaluation of MAC configurations involves analysing the scheduled access mode facilitated by Time-Division Multiple Access (TDMA) and the contention access mode facilitated by Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). A hybrid mechanism can be achieved by combining any of these techniques. In CSMA/CA, sensor nodes are prohibited from broadcasting until the channel is detected as idle, a process managed by the Back-off Counter (BC) and Contention Window (CW) [9, 10]. The BC value is confined within the [1, CWmin] range, determined by the User Priority (UP) level. When the CSMA/CA slot is idle, the BC decreases by one, and upon reaching zero, sensor nodes can commence transmission. In contrast, TDMA temporally divides the bandwidth to allocate time slots among sensor nodes, enabling them to transmit frames without overlap [11].

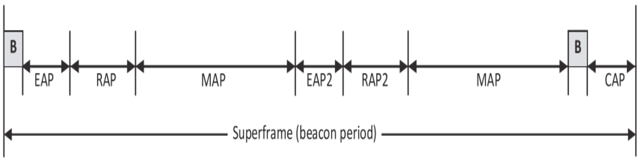

Fig. 1. Beacon Mode with Beacon Period Superframe [5]

This study presents a reliable and energy-efficient MAC protocol called the Hybrid-MAC (HB-MAC). The HB-MAC protocol utilizes a hybrid scheme that includes a contention access method in the RAP phase and a scheduled access method in the MAP phase. In the contention access period, sensor nodes use CSMA/CA to compete for time slots for data transmission, while in the scheduled access period, the TDMA access mechanism is used. The performance of the HB-MAC protocol in the WBAN application is evaluated using the Castalia Simulator in the OMNeT++ environment.

Literature Review

Many research analyses the WBAN MAC mechanism by examining the IEEE 802.15.4 and IEEE 802.15.6 standards. [12] proposed the IEEE 802.15.4 standard-based priority-guaranteed MAC protocol, which uses a contention access method to prioritize heterogeneous traffic. Three types are used to categorize traffic such as emergency, periodic, and normal. Nevertheless, the proposed protocol exhibits increased rates of packet collision, retransmission, and high energy consumption. Based on the IEEE 802.15.4, contention-based traffic prioritization is presented in [13]. The performance of the proposed protocol is upgraded by suggesting a distinct BC rate for every traffic classification. Still, it increases the energy consumption while decreasing the throughput and Packet Delivery Ratio (PDR). To reduce the contention during channel access in the CAP, a Priority Adaptive (PA-MAC) protocol with low energy consumption is proposed [14]. In CAP, multiple phases are divided to allocate various traffic types. Traffic congestion appears in the network during channel access even though this scheme enhances the throughput and decreases energy consumption. This affects the overall network performance, including delay, throughput, and energy consumption. Similar to [14], the work in [15] uses graded channel access during the CAP to reduce the contention complexity. Unfortunately, a phase-level prioritization mechanism for contended channel access is not provided by the CAP. This leads to traffic delays and increased energy consumption.

In addition, [16] develop a C-MAC protocol to incorporate an asynchronous duty cycling mechanism. It employs an ordering-based communication scheme to eliminate collisions in the CSMA/CA method. However, prioritizing multiple nodes leads to higher collisions during channel access. A non-overlapping BC method that considers the UP level specified in the IEEE 802.15.6 standard has been proposed in [17] to prevent backoff priority collisions. For contended channel access in each backoff period, a distinct range of backoff numbers is assigned to each UP. Nevertheless, the small CW ranges contribute to a higher collision rate, leading to a high increase in delay and energy consumption with a low throughput. In [18], the CSMA/CA scheme is used in CAP, while the TDMA mode is used in the Contention Free Phase (CFP). Regrettably, due to high packet loss probability, throughput is reduced in the presence of heavy traffic or a large number of nodes. This happens because CW ranges are small. The authors [19] propose an IEEE 802.15.6 CSMA/CA integration of the Parameter-based Backoff Counter Regulation (PBCR) approach for BC value selection. Even though UP improves IEEE 802.15.6 CSMA/CA, there is additional overhead introduced by each sensor node computing PBCR during each backoff. Therefore, this causes higher energy consumption, longer packet delivery delay, and reduced throughput [20].

In order to overcome the constraints inherent in contention-based MAC protocols, the contribution of this paper is to achieve high reliability and energy-efficient MAC protocol through the implementation of a hybrid mechanism based on the combination of CSMA/CA mode and TDMA mode.

Hybrid MAC (HB-MAC) Protocol

Detailed explanations of the HB-MAC protocol, encompassing discussions on the proposed superframe structure and slot allocation algorithm, are provided in this section. The HB-MAC protocol operates in a beacon-enabled mode, where beacons are transmitted after each superframe. The HB-MAC protocol adopts a hybrid superframe structure comprising a beacon, RAP, and MAP encapsulated within a superframe consisting of 32-time slots, as depicted in Fig. 2. The RAP length is 12-time slots and functions as a contention access period. Meanwhile, the MAP length is 20-time slots and operates as a scheduled access period. Before initiating the data transmission process, the sensor nodes perform connection requests and connection assignment procedures to integrate into the communication network during the RAP slots. Therefore, the HB-MAC protocol allocates RAP slots to handle the connection procedure process. The data transmission begins when the sensor nodes connect to the network. Initially, sensor nodes transmit data during the RAP slots using the CSMA/CA procedure. After completing the RAP slots, the sensor nodes utilize the TDMA mechanism to send their data during the MAP slots.

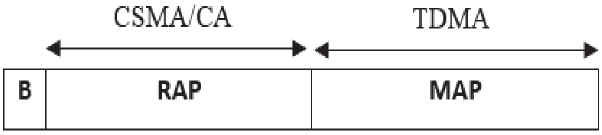

Fig. 2. HB-MAC superframe structure

The proposed algorithm for slot allocation of the hub is presented in Algorithm 1. Initially, the BC value is assigned randomly from the range [1, CWmin]. Before transmission, the sensor nodes conduct a Clear Channel Assessment (CCA) and randomly initialize the BC value. If CCA indicates a busy channel, the connection establishment fails, and the BC value is locked. With a clear channel and successful connection establishment, the system checks if the current time allows frame transmission. In the case of an affirmative response, the BC value is reduced by one, enabling sensor nodes to transmit data to the hub during RAP slots and wait for an Acknowledgment (ACK). Upon receiving the ACK, the MAC state transitions to sleep mode. If the scheduled access length is greater than zero, it signifies the availability of the MAP phase for slot allocation. In this situation, the channel allocates the MAC state to enable scheduled time access, allowing the sensor nodes to transmit data freely without contention during the MAP slots. When the hub successfully receives the scheduled request packet, it allocates the scheduled slots to the sensor nodes accordingly. Subsequently, the nodes await ACK, fostering a controlled and efficient communication environment within the designated time slots.

```
Algorithm 1: Slots Allocation
Initialization: BC = rand [1, CWmin]
Data frame ready for transmission
Step 1: Data frame transmission in RAP
if (MAC_STATE = = MAC_RAP), then
    if (CCA = = CLEAR), then
        BC = BC – 1
        if (BC = = 0), then
            Transmit data frame
            if ACK received, then
                Data frame transmission success
            else
                ACK time-out
        else
        Count the BC
    else (CCA = = BUSY)
else go to setup phase
Step 2: Data frame transmission in MAP
if (Scheduled access node), then
    if (MAC_STATE = = MAC_FREE_TX (scheduled)), then
        Transmit data frame
        if ACK received, then
            Data frame transmission success
        else
            ACK time-out
    else (MAC_STATE = = MAC_SLEEP)
        Nodes go to sleeping mode
end
```

Simulation Parameter

The simulation is executed using the OMNeT++4.6 simulator along with the Castalia-3.3 module. This simulator is used to evaluate the performance of the HB-MAC protocol and compare it against the C-MAC [16] and IEEE 802.15.6 MAC [5] protocols. The simulation of the HB-MAC protocol utilizes the fixed superframe structure of the conventional IEEE 802.15.6 standard. The specific network simulation parameter settings are presented in Table 1. Five physiological sensor nodes, comprising the Pulse Oximeter (SPO_2), ECG, EEG, EMG, and Motion Sensor, are employed to provide a realistic environment. The sensor nodes randomly send their data during the RAP and MAP phases. The network topology follows a star configuration, with each sensor node establishing a direct connection to the hub, enabling a single-hop data transmission.

Table 1. Simulation parameter

Parameters	Value
Simulation Time (secs)	200
Number of Nodes	1 hub and 5 sensor nodes
Packet Rate (Packet/s)	5
Contention Slot Size (msecs)	0.36
Allocation Slot Size (msecs)	10
Superframe Length (slots)	32
RAP Length (slots)	12
MAP Length (slots)	20

Results and Discussion

This section examines the performance of the HB-MAC protocol in the WBAN, focussing on PDR, throughput, energy consumption, and average delay. The performance of the proposed HB-MAC protocol is evaluated against the C-MAC [16] and IEEE 802.15.6 MAC [5] protocols.

Fig. 3 shows the PDR analysis obtained from the simulation. The PDR is a metric for assessing successful data delivery in a WBAN communication. It can be calculated by dividing the received data packets by the total data packets transmitted by sensor nodes. The HB-MAC protocol demonstrates higher PDR performance compared to the other MAC protocols. The PDR of the HB-MAC protocol consistently exceeds 95% throughout the entire simulation time, in contrast to the C-MAC and IEEE 802.15.6 MAC protocols, which remain below 80%. In the HB-MAC protocol, a hybrid strategy is employed through the integration of contention access and scheduled access methods. This combination optimizes the PDR by providing dedicated time slots for sensor nodes to transmit without contention, thereby minimizing collision probabilities and improving network reliability. Additionally, the contention access of HB-MAC protocol adapts to changing network conditions, optimizing resource utilization. On the other hand, both the C-MAC and IEEE 802.15.6 MAC protocols solely utilize contention access. This can cause multiple sensor nodes to attempt data transmission simultaneously on a shared channel, thereby raising the likelihood of collisions in the network.

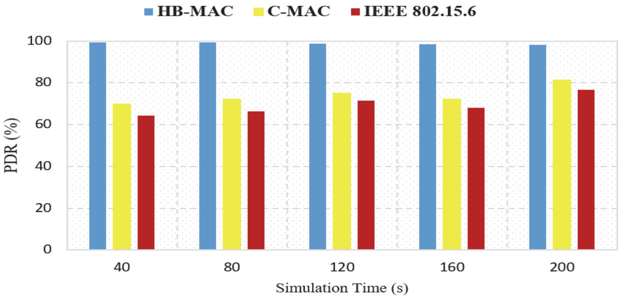

Fig. 3. Packet delivery ratio

The average network throughput is determined by dividing the total number of received packets in bits by the simulation time. Fig. 4 shows the average throughput with the varying simulation time. Among all MAC protocols, the HB-MAC protocol demonstrates higher and more stable throughput, resulting in up to a 10% increase compared to the others. The increased throughput of HB-MAC results in improved PDR and network performance. Meanwhile, the C-MAC and IEEE 802.15.6 MAC protocols maintain the minimum throughput value until the end of simulation time.

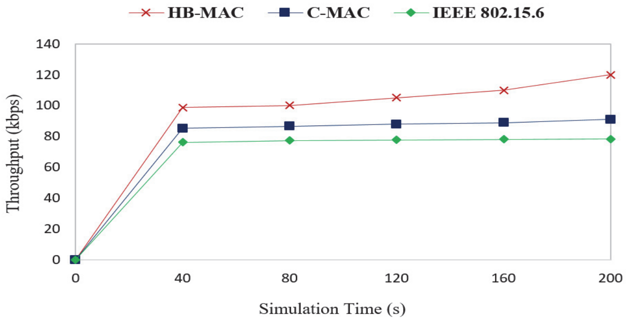

Fig. 4. Throughput

In a comparative analysis, the energy consumption of the HB-MAC protocol is lower than other protocols, as depicted in Fig. 5. The scheduled access mechanism of the HB-MAC protocol effectively reduces idle listening and minimizes energy wastage during inactive periods. During the scheduled access period, sensor nodes have dedicated time slots for data transmission, allowing efficient energy use. On the other hand, the C-MAC and IEEE 802.15.6 MAC protocols utilize a contention-based method, where sensor nodes compete for channel access. This contention process involves sensor nodes sensing for the channel and potentially entering a back-off period before transmission, leading to more energy consumption during contention. In contention-based scenarios, the collisions and retransmission process may contribute to additional energy consumption. The contention process in the C-MAC and IEEE 802.15.6 MAC protocols results in higher energy consumption. The HB-MAC protocol achieves 20% energy optimization by integrating scheduled and contention access methods, resulting in a well-balanced and efficient approach.

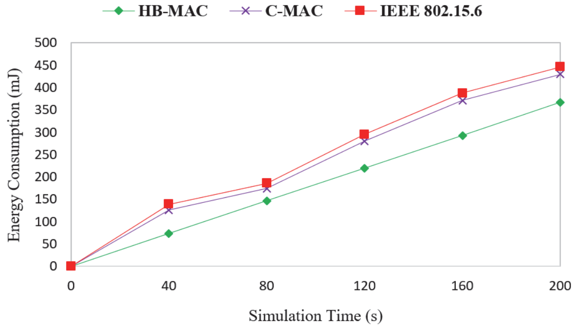

Fig. 5. Energy consumption

Fig. 6 presents the average delay distribution for all MAC protocols, respectively. Notably, the HB-MAC protocol exhibits a lower delay than the other protocol. The 30% improvement in the average delay is attributed to the dedicated time slots provided to sensor nodes during scheduled access periods in the HB-MAC protocol, effectively minimizing contention and potential delays associated with contention. The scheduled access mechanism ensures predictable and deterministic transmission times, reducing average delay. Conversely, in the C-MAC and IEEE 802.15.6 MAC protocols, the contention process is pivotal in influencing average delay as sensor nodes contend for access to the communication channel. The ensuing collisions and retransmission process contribute to an increase in the average delay experienced by the protocol.

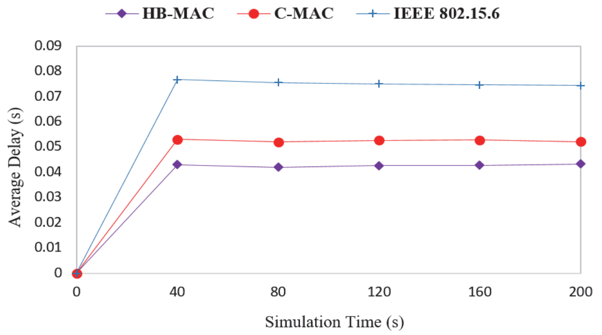

Fig. 6. Average Delay

Conclusion

This paper introduces the HB-MAC protocol, which is a hybrid-based MAC designed to meet diverse requirements in WBAN. The HB-MAC protocol distinguishes between the RAP and MAP access phases in WBAN, with sensor nodes contending for slot allocation in the RAP phase through CSMA/CA, while the TDMA access mechanism is employed in the MAP phase. According to the simulation results, the HB-MAC protocol outperforms the C-MAC and IEEE 802.15.6 MAC protocols in terms of PDR, throughput, energy consumption, and average delay. To achieve further enhancement of the proposed HB-MAC protocol, dynamic slot allocation can be incorporated to accommodate different data types and varying traffic loads. The dynamic adaptation of the superframe structure is suggested as one of the approaches to optimize superframe utilization for reliable data transmission in WBAN communication while ensuring Quality of Service (QoS).

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