Energy Harvesting Aware Hybrid MAC Protocol for WBANs

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Abstract—In this paper, we propose a hybrid polling Medium Access Control (MAC) protocol with Human Energy Harvesting capabilities, called HEH-BMAC, designed for Wireless Body Area Networks (WBANs). The proposed protocol uses a dynamic schedule algorithm to combine User Identification polling (ID) and Probabilistic Contention (PC) random access, adapting the network operation to the random, time-varying nature of the human energy harvesting sources. HEH-BMAC offers different levels of node priorities (high and normal), energy-awareness and flexibility. Extensive simulations have been conducted in order to evaluate the energy efficiency and throughput of our scheme compared to IEEE 802.15.6 standard in energy harvesting conditions.

Index Terms — Energy efficiency, 802.15.6, Energy harvesting, Medium Access Control (MAC).

I. INTRODUCTION

Wireless Body Area Networks (WBANs) are composed of small and intelligent body sensor nodes (BNs). The BNs form a heterogeneous group of devices with different tasks (sensors and/or actuators), priorities, available energy and wireless communication capabilities, among others. Each BN usually performs a unique and irreplaceable role in the network, mainly due to its highly specialized function, its potentially high cost and the space restrictions that impose a small number of nodes in the WBAN. The main goal of a medical WBAN is to manage the communication of important clinical data for the monitoring, diagnosis and/or treatment of diseases. BNs can be placed inside or on the human body depending on the function and the physiological signal to be monitored. One of the main requirements of the WBAN is energy efficiency. The power available to the BNs is often restricted, as they are typically powered by batteries. Hence, energy efficiency is essential to maximize the lifetime of the node’s battery. The problem of the energy supply is further complicated in the case of sensors implanted in the body, since the removal and replacement of the nodes is not always feasible (because it could cause damage to the node and put at risk the patient’s health).

An infinite source of energy harvesting (EH) would be the ideal solution to prolong the lifetime of WBANs [1]. In general, the network operation is affected by the type of the power source, i.e., the battery or the EH source. The battery is a known power supply that allows planning and administration of the energy stored in it. EH sources, on the other hand, deliver only small amounts of energy compared to batteries and are more time dependent. In most cases, the harvested energy is not sufficient for the direct operation of the BNs and hence a rechargeable storage device (e.g., a supercapacitor or a battery) must often be employed until the energy required for the performance of the BNs’ functions has been acquired. The energy collected by a harvester in the human body depends on factors such as the location of the node, as well as the harvester characteristics and dimensions. The EH sources in the human environment can be classified into two main types: i) predictable sources (e.g., heart contractions, chest movement from breathing, etc.), and ii) unpredictable sources (e.g., the motion of walking, the body temperature difference, etc.). As an energy harvester uses a particular phenomenon to produce electricity, the availability of the energy source defines the rate at which energy is obtained. The EH rate is the amount of energy obtained per time unit when the energy source is available. The EH rate also defines the time needed to reach the energy levels required for the proper operation of the node.

The wireless interface consumes a considerable part of the available energy during the node operation. Therefore, the Medium Access Control (MAC) layer is the most appropriate level to address the energy efficiency issues, since it performs functions related to packet transmissions, flow control and energy management [2]. The application of EH introduces an extra variable to the network, related to the availability and the magnitude of the collected energy, and the responsiveness of a BN at any given time. A node can perform a successful transmission if and only if the energy consumed during its operation does not exceed the amount of harvested energy [3]. Hence, both the throughput and the energy efficiency of the network are affected by the EH rate.

A WBAN powered by human EH may be a heterogeneous network with respect to the application requirements of the BNs, as well as the types of energy harvesters attached to them. The performance of the energy harvester can directly affect the node’s operation. For example, the energy availability may restrict the nodes’ access to the medium, since it is possible that the BNs do not have the energy required for the data communication over a certain period of time. Hence, the design of a MAC protocol must take into account the types and characteristics of the human EH sources. On the other hand, it should exploit the fact that the area of network activity is always the same, i.e., the human body [4]. Building on the above, a BN placed on a specific area of the body may be attached to a respective energy harvester (e.g., a pacemaker attached to an energy harvester that uses heartbeats to produce energy).

In this paper, taking into account the latest developments in the areas of WBANs and EH, we propose a hybrid polling MAC protocol, called HEH-BMAC, designed for WBANs in conditions of human EH. Our contribution is summarized in the following:
1. HEH-BMAC is adapted to different energy levels acquired by human EH sources. In particular, our protocol has the following features: i) it offers priority differentiation by combining two different access methods, i.e., User Identification (ID) polling reserved access and Probabilistic Contention (PC) random access for nodes of high and normal priority, respectively, ii) it dynamically adjusts the ID/PC periods according to the energy levels of the BNs, and iii) it provides flexibility by allowing the dynamic addition or removal of BNs from the network.

2. We evaluate the performance and energy efficiency of HEH-BMAC and we compare it with the IEEE 802.15.6 standard under the same EH conditions.

The rest of the paper is organized as follows. In Section II, we describe the related work on MAC protocols for WBANs. In Section III, we introduce the HEH-BMAC. In Section IV, we evaluate the performance of HEH-BMAC by extensive simulations and, finally, Section V concludes the paper.

II. RELATED WORK

WBANs are specified in the IEEE 802.15.6 standard for short-range wireless communications in the vicinity of (on-body), or inside (in-body), a human body [4]. In IEEE 802.15.6, time is divided into superframes. This structure allows three types of access mechanisms: 1) random access (contention-based), which uses either CSMA/CA or slotted ALOHA for resource allocation, 2) improvised and unscheduled access, which uses unscheduled polling/posting for resource allocation, and 3) scheduled access, which schedules the allocation of slots in one (1-periodic) or multiple (m-periodic) time allocations.

The main advantages of contention-based MAC schemes are: good scalability, adaptation to traffic load fluctuations, low complexity, lower delay, and reliable transmission of packets. However, their transmission efficiency is reduced due to the packet retransmissions, while the power consumption is relatively high due to the overhearing, idle listening and packet collisions. In addition, an analytical study of MAC protocols for WBAN by Ullah et al. [2] shows that the CSMA/CA-based protocols present problems such as heavy collisions and unreliable Clear Channel Assessment (CCA). Instead, TDMA has high transmission efficiency, low power consumption and no packet collisions. In the same study [2], the authors considered the TDMA-based protocols as the most reliable and power-efficient protocols for WBANs. The main disadvantages of the TDMA-based protocols are that they are not adaptive, flexible, and scalable, while they require precise synchronization.

The study of Boulis and Tselishchev [5] on MAC design for WBANs indicates that polling-based channel access offers significant energy gains compared to contention-based access. Regarding the latency (end-to-end delay), the combination of short contention periods with long polling periods provides the most stable performance with respect to packet transmissions. Khan et al. [6] claim that the combination of a polling protocol and CSMA/CA could be a good mechanism for power saving and reliable communication of critical medical data. Moreover, Ameen et al. [7] proposed a MAC protocol using TDMA combined with out of band (on-demand) wakeup radio through a centralized and coordinated external wakeup mechanism. The authors proved through simulations that their method outperforms other MAC protocols in terms of energy efficiency and delay.

In a WBAN powered by human EH, each BN is connected to an energy harvester which harnesses energy from the human environment. In a battery powered network, nodes reach a permanent dead state when their batteries are empty. On the contrary, in a network operated by EH, nodes can have dead states in intermittent form. In [8], Eu et al. proposed EH-MAC, a MAC protocol based on probabilistic polling that adapts its operation to the energy harvesting rates and the number of nodes in wireless sensor networks powered by ambient EH to achieve high throughput, fairness and scalability. However, EH-MAC does not assign different levels of priorities to the nodes according to their service requirements, since the access for all nodes is probabilistic.

Actually, most MAC protocols designed for WBANs have been mainly devised to save energy in BNs powered by batteries (known power supply), thus not being compatible with EH (unknown power supply). Hence, the challenge in EH-based WBANs is to design protocols that provide access depending on the priority of each node, taking into consideration its energy supply. Therefore, we propose HEH-BMAC as an efficient solution to this problem. The operation of our protocol is described in detail in the next section.

III. HYBRID POLLING MAC PROTOCOL OPERATED BY HUMAN ENERGY HARVESTING (HEH-BMAC)

We consider a WBAN with star topology, where a Body Node Coordinator (BNC) is responsible for setting up the network and collecting the information transmitted by the BNs. Each BN is connected to an energy harvester which harnesses energy at a rate of $K_{eff}$. The BNC provides medium access through the execution of the HEH-BMAC protocol rules that will be described in this section.

A. HEH-BMAC Overview

The main feature of the HEH-BMAC protocol is the energy-awareness in EH conditions, since the behavior of each BN dynamically adapts to its energy level. HEH-BMAC combines reserved polling access (ID-polling) and probabilistic contention random access (PC-access) to provide energy-aware and priority-based scheduling. The use of contention-free ID-polling access is provisioned for nodes with predictable energy sources or nodes with high priority (ID-BNs). On the other hand, the use of contention-based PC-access applies to nodes with unpredictable energy sources or nodes with normal priority (PC-BNs). The base of our protocol resides in an algorithm that performs time allocations in a dynamic way. The goal of the dynamic scheduling is to assign time periods for both ID-polling and PC-access. Due to the combination of these two access modes and the dynamic scheduling algorithm, the HEH-BMAC protocol is able to adapt to changes in the network size and the EH rate.

B. ID-polling access mode

A successful communication process in ID-polling mode takes place in three steps: i) the BNC transmits a polling
packet containing the ID of the BN to be polled, ii) the polled BN responds with a data packet transmission, and iii) the BNC sends the acknowledgment (ACK) to confirm the successful reception of the data packet. Each ID-BN remains into the sleep state until its turn to be polled (at known time intervals). Upon its turn, it wakes up and goes into the reception state to receive the polling packet from the BNC. Once polled, the BN checks its energy level. If the level is not sufficient to complete the transmission sequence, the node does not respond to the poll but enters a sleep mode. In this case, the BNC assigns the remaining time reserved for this ID-polling to the PC-access users. Otherwise, if the energy level is high enough, the BN proceeds to the data transmission and after the communication is completed, it turns off its radio again and enters into sleep mode until the next polling round. This sleeping mechanism leads to a considerable decrease in the power consumption of the ID-BNs and enables the collection and storage of significant amounts of energy by the EH process, thus promoting the energy efficiency of our protocol.

C. Probabilistic contention (PC) access mode

PC-access [8] is a probabilistic medium access mechanism based on the transmission of a threshold value sent by the BNC and an algorithm for updating this threshold depending on data packet collisions. The BNC applies the PC-access only when the channel is free and the available time is adequate. In addition, all PC-BNs remain in sleep state during the ID-polling periods.

In PC-access, the BNC broadcasts a control packet called CP-Packet that contains the Contention Probability (CP), i.e., the threshold value that determines the probability of channel access by the PC-BNs. The PC-BNs must check both their energy level and their data packet buffer in order to decide whether to respond to the CP-packet. Only the active nodes with packets to transmit, i.e., the nodes with sufficient energy to complete a transmission sequence, can participate in the PC-access. Otherwise, nodes with low energy levels or no packets to transmit remain inactive until sufficient energy is collected through EH or a new packet arrives. The participating PC-BNs that receive the CP-packet generate a random number “X”, where X ∈ [0, 1]. If the value of X is less than the CP value, the node transmits its data packet; otherwise, the node does not transmit in the current PC-access period and remains idle until the next PC-polling round. The CP value is dynamically adjusted by the BNC according to an updating algorithm that takes into account the number of PC-BNs that respond to the CP-packet. In our model we use the additive-increase multiplicative-decrease (AIMD) technique [8], since it provides higher throughput than other methods. The AIMD is a mechanism to increase the CP gradually (using an additive factor) when polling is unsuccessful or to decrease the CP by a larger amount (using a multiplicative factor) in case of collisions in the network. AIMD technique could be mathematically expressed as:

\[
CP_{(t+1)} = \begin{cases} 
CP_{(t)} + \delta_{\text{add}} & 0 < \delta_{\text{add}} < 1 \quad \text{(case 1. a)} \\
CP_{(t)} \times \delta_{\text{mult}} & 0 < \delta_{\text{mult}} < 1 \quad \text{(case 1. b)} 
\end{cases}
\]  

The CP updating algorithm changes the value of the CP in two cases: i) if no node responds to the CP-packet, the BNC waits for a predefined time-out period (T_{OUT}) and increases the threshold value to increase the transmission probability of the PC-BNs (i.e., case 1. a); and ii) when there is a collision between two or more nodes, the BNC decreases the value of the threshold to reduce the number of collisions (i.e., case 1. b) and all PC-BNs store the data to their buffer for future retransmission attempts. If only one node transmits in the current PC-polling round, the BNC sends an ACK (successful transmission) and the current value of the threshold is maintained in the next CP-packet (i.e., CP_{(t+1)} = CP_{(t)}).

Summarizing, the CP updating algorithm dynamically adapts the response of the PC-BNs, any node additions or failures as well as changes in the K_{EH} (since the available energy determines the number of participating PC-BNs). Hence, PC-polling offers energy efficiency and network scalability.

D. Dynamic Schedule Algorithm

The BNC is responsible for allocating the ID-polling periods and the PC-access periods. The boundaries of these time periods are defined by the Dynamic Schedule Algorithm. The algorithm performs two main tasks.

The first task is to assign a monitoring time (T_{ai(n)}) and calculate the duration of the data communication process (T_{ri(n)}) for each ID-BN i during the nth access period. The value of T_{ai(n)} for an ID-BN i must be greater or equal to the minimum time required to obtain enough energy to send its data packet. BNC calculates the T_{ai(n)} for each ID-BN using the energy rate K_{EH} of the respective harvester and the inter-arrival time (IAT_{BN}) of the sampled sensor data. Thus, the BNC can estimate when each ID-BN has data to transmit and whether its energy level is sufficient and select an appropriate value for T_{ai(n)}. On the other hand, T_{ri(n)} is defined as the time required for ID-BN i to perform a successful transmission. We also define T_{bi(n)} as the moment of completion of the current communication process, i.e., T_{bi(n)} = T_{ai(n)} + T_{ri(n)}.

The current values of T_{ai(n)} and T_{bi(n)} for all ID-BNs are stored in a dynamic table and are employed by the BNC to coordinate the ID-polling process. When the BNC proceeds to an ID-polling, then the dynamic table is updated with the next values of T_{ai(n+1)} and T_{bi(n+1)} for the next ID-BN to be polled. In this way, we can predict the responsiveness to an ID-polling for a given node, and make the decision to poll it or not (improving the scalability of the system, since the dynamic table is constantly updated). Figure 1(a) presents an example of dynamic calculation of ID-polling and PC-access periods operating together.

The second task of the Dynamic Schedule Algorithm is to calculate the interval between two adjacent ID-polling periods, for example (Figure 1(b)) the T_{bi(n)} of the node ID_{i(n)} and the T_{ai(n)} of the next node ID_{j(n)}. The BNC performs the calculation of this interval using the data provided in the dynamic table. If the time between two consecutive ID-polling periods is sufficient for a successful data transmission of a PC-BN in PC access mode (t ≥ T_{PCmin}), then this time is exploited for probabilistic contention (PC period). Otherwise, if this time is not sufficient (t < T_{PCmin}), the BNC remains idle waiting for the next ID-polling period.
Summarizing, HEH-BMAC offers dynamic operation and energy awareness by combining two access modes: i) **ID-polling using a dynamic schedule**: in ID-polling the responsiveness of a given node to the poll can be predicted (based on its energy levels) and the BNC can adapt the polling interval accordingly, and ii) **PC-access based on probabilistic contention**: the PC-access is performed only when the channel is not occupied by the high priority ID-polling access and the time is sufficient for the communication process.

### VI. Performances Evaluation

#### A. Simulation Considerations and Setup

In order to analyze and evaluate the performance of HEH-BMAC, we have developed an event-driven MATLAB simulator that executes the rules of the protocol. We adopt a star topology for a network consisting of one BNC, 4 BNs at high priority (ID-BNs) and L BNs at normal priority (PC-BNs). The nodes in our simulation are typical medical sensors, whose traffic characteristics [6] and priorities are shown in Table 1. In the case of the electrocardiogram (ECG) and blood pressure nodes, we adopt a slightly different aggregate traffic model which results to a payload of 120 bits and 96 bits, respectively. We assume that each BN possesses a data buffer, a rechargeable battery and an energy harvester that supplies power at a constant rate $K_{EH} = 1.3\text{mJoule/s}$. This particular value of $K_{EH}$ allows our protocol to reach 100% throughput in the initial setup of the network. We are focusing on the study of energy efficiency of the BNs, so that the energy consumption of the BNC is not taken into account in the calculations. In the beginning of our experiments, the nodes have empty batteries and, consequently, not sufficient energy for transmissions. Through the EH process, they collect energy in order to recover and start transmitting packets. Data packets that remain in the buffer after the simulation are considered lost packets. In our simulation scenario for the HEH-BMAC, the high and normal priorities correspond to ID-polling and PC access mode, respectively. For the AIMD CP updating algorithm, we use $\delta_{add} = 0.01$ and $\delta_{md} = 0.5$, since these values provide high throughput for single-hop scenarios [8]. To evaluate our approach, we compare the performance of HEH-BMAC with the IEEE 802.15.6 Standard. For comparison, we are adopting the non-beacon mode without superframes [4]. We chose this configuration because it offers random and prioritized access through contention window (CW) bounds using CSMA/CA. For the normal priority BNs we will use the CW values that correspond to the user priority (UP) 0 of the IEEE 802.15.6. As for the high priority BNs we examine two different cases, in order to evaluate the IEEE 802.15.6 performance for different CW values and provide a fair comparison with HEH-BMAC. In the first case (Case 1), the CW values of the UP 6 are employed, whereas in the second case (Case 2) the CW values of the UP 3 are selected. The network parameters have been selected for both protocols according to the IEEE 802.15.6 PHY-MAC specification [4]. These system parameters and the values of power used in the simulation models are summarized in Table 2.

#### B. Simulation Results

Initially, the considered setup consists of 4 BNs in high priority and 3 BNs in normal priority. The number of normal priority BNs is gradually increased up to 18 nodes. The metrics for the evaluation of the performance of our protocol are energy efficiency and normalized throughput. Energy efficiency is defined as the total amount of useful data delivered over the total energy consumption [9]. On the other hand, normalized throughput is defined as the number of bits successfully transmitted over the total number of generated bits, within the same period of time.

Simulation results for the energy efficiency for both protocols, HEH-BMAC and IEEE 802.15.6, are shown in Figure 2. Energy efficiency for both schemes decreases as the number of low-priority BNs L grows. For $L=3$, the energy efficiency for the IEEE 802.15.6 protocol reaches 2.36 Mbits/Joule for Case 1 (low CW values) and 1.85 Mbits/Joule for Case 2 (high CW values), while for the HEH-BMAC protocol the energy efficiency is twice higher than the IEEE 802.15.6, for both cases.

Table 1 - BNs characteristics

| No | BN               | IAT (ms) | Payload (bits) | Priority Type | HEH-BMAC | IEEE 802.15.6 |
|----|------------------|----------|----------------|---------------|----------|---------------|
| 1  | ECG SIGNAL       | 20       | 120            | HIGH         | ID-Polling | CSMA/CA       |
| 2  | RESPIRATORY RATE | 50       | 12             | HIGH         | ID-Polling | CSMA/CA       |
| 3  | BLOOD PRESSURE   | 80       | 96             | HIGH         | ID-Polling | CSMA/CA       |
| 4  | BLOOD FLOW       | 25       | 12             | HIGH         | ID-Polling | CSMA/CA       |
| L  | Normal Priority BNs | 65     | 12             | NORMAL       | PC-Access | CSMA/CA       |

Table 2 - System Parameters

| Parameter         | Value   | Parameter         | Value   |
|-------------------|---------|-------------------|---------|
| MAC HEADER        | 56 bits | PLCP Tx RATE     | 91.9 kbps |
| PCS               | 16 bits | $P_{RX}$          | 27 mW   |
| PLCP PREAMBLE     | 90 bits | $P_{TX}$          | 1.8 mW  |
| PLCP HEADER       | 31 bits | $P_{SLEEP}$       | 0.004 mW |
| ACK               | 72 bits | $P_{RX}$          | 0.712 mW |
| T POLL            | 88 bits | $T_{GUE}$         | 0.05 ms  |
| DATA TX RATE      | 485.7 kbps | $p_{GUE}$      | 0.05 ms  |
| CONTROL Tx RATE   | 121.4 kbps | $p_{CSMA Slot}$ | 0.125 ms  |

IEEE 802.15.6 HEH-BMAC

*USER PRIORITY* | *CW min* | *CW max* | CP UPDATING ALGORITHM |
|----------------|----------|----------|------------------------|
| HIGH           | UP 3     | 8        | 16                     | Method: AIMD             |
| HIGH           | UP 6     | 2        | 8                      | $\delta_{add}$ = 0.01   |
| NORMAL         | UP 0     | 16       | 64                     | $\delta_{md}$ = 0.5     |

Figure 1. Dynamic Schedule Algorithm for ID-polling/PC periods access in HEH-BMAC protocol.
CW values). This difference is observed because of the higher number of data collisions in Case 1, caused by the smaller values of CW bounds compared to Case 2. In Figure 2, we can also see how the HEH-BMAC protocol initially (L=3) has similar energy efficiency (1.89Mbits/Joule) to IEEE 802.15.6 Case 1, but lower energy efficiency than IEEE 802.15.6 Case 2. However, as L increases, our protocol gradually outperforms IEEE 802.15.6, regardless of the CW selection. For L=18 (Figure 2), it can be seen HEH-BMAC achieves a gain of approximately 20% in energy efficiency with respect to IEEE 802.15.6.

Figure 3 shows the normalized throughput for the two MAC protocols. We can observe how HEH-BMAC achieves higher throughput as the number of BNs is increasing, compared to the two cases of the IEEE 802.15.6. Looking at L=18, we can see that the normalized throughput of the HEH-BMAC protocol overcomes the Case 1 and Case 2 of the IEEE 802.15.6 by 56% and 45% respectively.

This performance enhancement is explained next. In IEEE 802.15.6, even though high priority nodes have a higher chance to access the medium, they may still suffer collisions with other normal or high priority BNs. On the contrary, in HEH-BMAC, the high priority BNs do not experience packet collisions, since the dynamic scheduling algorithm provides them with contention-free medium access. Packet collisions may only take place among the L normal priority BNs, but they are resolved in a dynamic way through the CP updating algorithm in the PC-access.

In order to highlight the benefits of the dynamic scheduling algorithm of the HEH-BMAC, we compare the normalized throughput per BN of our protocol with Case 1 of the IEEE 802.15.6. Figure 4 shows the normalized throughput of the 4 high priority BNs and the average normalized throughput for L=6, 12 and 18 BNs in normal priority for both HEH-BMAC and IEEE 802.15.6. We can see how through the dynamic schedule algorithm in the HEH-BMAC the normalized throughput of the high priority BNs is maintained to 100%. On the contrary, in IEEE 802.15.6, the normalized throughput of the high priority BNs is gradually reduced because of the increased number of collisions as L increases. The average normalized throughput of the normal priority BNs is decreased for both protocols. However HEH-BMAC obtains a better performance with respect to the standard.

V. CONCLUSION

In this paper, we have presented HEH-BMAC, a novel MAC protocol for WBANs, designed to operate in conditions of human EH. HEH-BMAC provides two levels of well-defined priorities and good flexibility. Our protocol has been proven to outperform the IEEE 802.15.6 standard in terms of normalized throughput under the same conditions of EH. In addition, HEH-BMAC achieves higher energy efficiency when the number of nodes is increasing. In our future work, we plan to design algorithms that exploit EH conditions to enhance quality of service.

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