# Low Power Medium Access Control for Body-Coupled Communication Networks

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***Abstract*—Body-coupled communication (BCC) is a promising technology that enables wireless communication around and limited to the human body. It consists in generating low-power electric fields at the surface of the human body for transmiting signals. Its physical (PHY) layer has several advantages over classical radio frequency (RF) PHY layers, e.g., IEEE 802.15.4, for body-area networks (BANs), like a better robustness to body shadowing and a greater energy efficiency. From the medium access control (MAC) point of view, BCC BAN networks are a sub-class of wireless sensor networks (WSNs). Because WSN nodes are battery-powered device with limited energy capacity, energy efficiency is a key requirement for many applications. A low power MAC protocol is one of the component that enables to fulfill such a requirement. However current solutions developed so far by the scientific community are solely targeting RF systems. The properties of the BCC PHY layer are such that using those solutions would lead to inefficient energy usage. Therefore we developed and present in this paper AdaMAC a new MAC protocol that takes into account the specific properties of the BCC PHY layer. Compared to state-of-the-art protocols AdaMAC performs better in terms of reliability, latency and energy efficiency when applied to BCC systems.**

## I. Introduction

Energy efficiency is a significant requirement in the field of wireless sensor networks (WSNs). Indeed WSN nodes are battery powered device with limited lifetime due to limited battery capacity. This implies restrictions on available resources, e.g., computation and communication capabilities or memory size. Therefore optimizing energy usage does not only increase the operational time of a WSN node but can also be used to extend its capabilities. Among all power consumption factors of a WSN node, wireless data communication represents an important part of the power budget. In order to optimize this aspect one can address two different, separated problems which are optimizing the physical (PHY) or the medium access control (MAC) layer.

In this paper we focus on body-area networks (BANs) which are a sub-class of WSNs where nodes operate in the near vicinity of the human body. BAN nodes usually use a RF PHY layer operating in the industrial, scientific and medical (ISM) radio band. They suffer of mainly two problems which are body shadowing and poor energy efficiency. First the human body shadows high frequency RF signals [1] in a highly variable way [2] with respect to human movement, making communication among nodes on one body unreliable. Second, RF signal propagates far from the human body, e.g., more than ten meters for IEEE 802.15.4, which is a loss of energy when it comes to let two nodes on one body communicate with each other. For comparison purpose, a IEEE 802.15.4 CC2420 [3] transceiver from Texas Instrument consumes about 0.2 $\mu$J/b at 250 kb/s.

Body-coupled communication (BCC) [4] on the contrary, by using the human body as the communication channel is more reliable and energy efficient. In [5] it is shown that the propagation loss is well below 80 dB for almost all node locations and that body movements only result in small variations in channel attenuation. In their work [6] and [7] respectively achieve an energy efficiency of 0.37 nJ/b at 10 Mb/s and 0.32 nJ/b at 8.5 Mb/s, which is three orders of magnitude more efficient than IEEE 802.15.4. We believe that BCC is an interesting approach for improving energy-efficiency of the PHY layer in BANs.

With respect to the MAC layer, there has been extensive work on low power protocols for WSNs. The basic principle of these protocols is that all nodes in the network periodically alternate between active and sleep mode in order to save energy. We can differentiate two categories of low power MAC protocols. First synchronous protocols, e.g., S-MAC [8] or T-MAC [9], are based on the fact that all nodes wake-up at the same time. Transmissions only occur when the network is active. This concept requires all nodes to be synchronized. Second asynchronous protocols, e.g., B-MAC [10], WiseMAC [11], X-MAC [12] or TrawMAC [13], are using a long preamble packet, which is longer than the sleep period of all nodes, to signal upcoming data packet. In the paper on B-MAC, [10] first proposed the idea of low power listening (LPL) and long preamble. WiseMAC uses *local synchronization*, i.e., nodes that communicate among each other piggy-back their wake-up schedules so that they can stay synchronized and use short preambles. X-MAC employs the idea of a *strobed preamble* consisting of multiple micro-preambles which enables a potential receiver to signal that it is

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ready to receive data, by interrupting the preamble. TrawMAC applies the features of WiseMAC and X-MAC and provides further improvement with respect to broadcast communication. Recently [14] proposed RI-MAC, which is an asynchronous protocol but does not use long preambles. Instead of that a transmitter listens for a long time while potential receivers signal there availability with small beacon packets.

Although those protocols enable substantial gains in terms of energy efficiency for WSNs, they do all use a RF PHY layer has basis hypothesis. When looking at low power BANs, we would like to use a BCC PHY layer. The properties of this technology are such that applying previously cited protocols would lead to inefficient energy usage. Indeed RF systems have a transmission (TX) power which is about the same as their receiving (RX) power. On the contrary BCC technology implies a RX power which is one order of magnitude higher than the TX power. Because receiving is expensive, it should be avoided, maybe at the expense of transmitting more. While [10] and [11] rely on contention (which involves long listen times) for collision mitigation, [12] introduces many listen slots inside its preamble frame and [14] even shifts the *good* TX time of the preamble into costly long RX time. Therefore a new MAC protocol is required to exploit this characteristic and provide energy efficiency to BCC networks.

In this paper we first give insights on MAC requirements of BCC networks. We present AdaMAC, a contention-free, low power MAC protocol, which takes into account BCC PHY layer specific characteristics and exploit them to achieve good reliability, low latency and energy efficiency for BCC networks. We implemented AdaMAC on the network simulator ns-2 and simulated it as well as B-MAC, WiseMAC, X-MAC and TrawMAC. We show here the results of these experimentations, compare AdaMAC to other MAC protocols when applied to BCC networks and give insights about the impact of our new algorithms.

The rest of the paper is organized as follow: Section II describes AdaMAC, the specific requirements of BCC networks and the algorithms we developed to fullfil them. Section III presents simulation results as well as comparison among AdaMAC and other low power procols. Section IV concludes this paper and outlines future works.

## II. Contention-free, low power MAC protocol for BCC networks

This section presents the algorithms developed for AdaMAC in order to achieve an energy-efficient MAC protocol for BCC networks. There exists majors differences between BCC BANs compared to classical RF WSNs. A BCC network is composed of nodes that are either worn by the user on his body or touched by the user (generally for a short time). The number of nodes that are part of the network is small. Any node in contact with the body of a user shall be capable to communicate with any other node as well in contact with the same user. A major design choice of [7] is to consider a BCC network as a single-hop mesh. In order to fulfill full body coverage requirement, the PHY layer was designed so that any node on the body can reach directly any other one. It was decided not to rely on relay nodes to forward data from one part of the body to another. The rationale behind that is that the topology of the network might be very dynamic, thus relay nodes could disappear, preventing full body coverage. We illustrate the dynamic behavior of the topology with the following example: a user wears a BCC identifier in order to be identified at a BCC-capable door, the network is composed of a single node most of the day and of two nodes for very short periods of time. Another example could be a user wearing many BCC-enabled multimedia devices which continuously guard themselves against theft. In that case the user may decide to take or let specific devices at any time modifying the topology of the network although the theft protection application still needs to be performed. Another major advantage of BCC technology is that it enables to use very low frequency in comparison to standard RF systems (O(MHz) instead of O(GHz)), enabling low energy consumption while still providing high data rate. Obviously such a system has unique characteristics with respect to channel access, e.g. at comparable energy consumption a BCC system will provide a much better latency or reliability than a typical RF system.

The most fundamental characteristic of the PHY layer with respect to the MAC layer is the asymmetry between RX power and TX power. We have

$$P_{RX} = kP_{TX} \tag{1}$$

with $k$ an integer. As BCC transceiver are limited in TX power (for body exposure reasons) and as the incoming power at the receiver is very low, the RX power required to achieve full body coverage is higher than the TX power. Our current BCC solution [7] has a factor of four between RX power and TX power and upcoming solutions shall use a factor around ten.

### A. Protocol Architecture

As mentioned previously, for some applications BCC devices might be worn all day and transmitting few times a day to an external BCC device. Therefore a synchronous MAC protocol is not our preferred option as it would cost energy for useless synchronization. AdaMAC uses the approach of [10], it is an asynchronous MAC protocol. It incorporates local synchronization from [11] and strobed preamble from [12]. Unlike [10], [11] and [12], AdaMAC does not use contention to mitigate collision, and unlike [12], it uses an energy-wise optimal micro-preamble size calculated based on $k$ and on the size of the sleep period.

The sequence of packets which are exchanged is illustrated in Figure 1.

Nodes periodically listen to the channel for a time $3L_L$, then go to sleep for a time $L_S$ if the channel is idle and they do not have a packet to send. The time $L_L$ represents the minimum time required by the receiver to detect the preamble and read control data embedded in it. Nodes wake-up for $3L_L$ to insure that in case they wake-up at the end of a micro-preamble and fail to detect it, they can still receive the next one. If a node

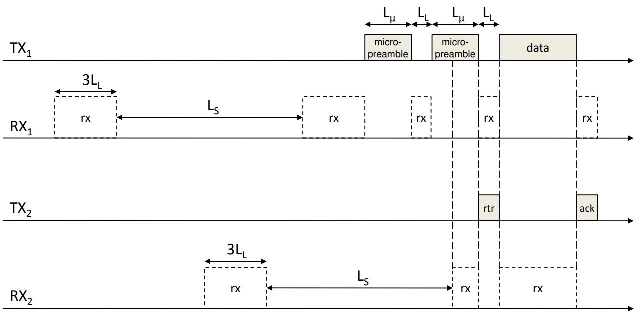


Fig. 1. Packet exchange sequence in AdaMAC

wants to start a data exchange, it first transmits a preamble of size $L_{preamble}$

$$L_{preamble} = L_S + 2L_L \tag{2}$$

which is composed of $n$ micro-preambles of size $L_\mu$ and $n-1$ listen slots of size $L_L$

$$L_{preamble} = nL_\mu + (n-1)L_L \tag{3}$$

with $n$ an integer strictly bigger than 1. Each micro-preamble contains the address of the destination node. When a node wakes-up and listens to a micro-preamble, if it is not the destination node, it goes back to sleep. On the contrary it sends a ready-to-receive (RTR) packet to the source node in order to interrupt the long preamble. When the source node receives the RTR packet, it sends a data packet. When the destination node receives the data packet, it sends an acknowledgement (ACK) packet. Then both nodes go back to sleep.

In the following we describe how the energy-wise optimal micro-preamble size is derived, how we remove contention from the protocol and finally how these features enable efficient quality of service (QoS). Our guideline through all this work is to let nodes in RX mode as few as possible, while still providing good reliability (efficient collision mitigation).

### *B. Optimal micro-preamble size*

For a RF system where the RX power is about the same as the TX power (i.e., $k = 1$), e.g., using a low power MAC protocol like X-MAC [12], the energy-wise optimal size for $L_\mu$ is the sum of the time required for the receiver to synchronize on the preamble plus the time to read the destination address (i.e., $L_\mu = L_L$).

$$L_{preamble} = (2n-1)L_L \tag{4}$$

and

$$n = \frac{L_S + 3L_L}{2L_L}. \tag{5}$$

In that case we calculate the average size of the preamble $\overline{L_{preamble}}$, which represents how long will the preamble really be in average. Assuming that the wake-up time of the destination node is uniformlly distributed over the preamble size and that it is independent of the preamble transmission time we find

$$\overline{L_{preamble}} = \sum_{i=0}^{i=n-1} \frac{1}{n} \cdot (2i+1)L_L \tag{6}$$

$$= \frac{L_S + 3L_L}{2}. \tag{7}$$

This represents a considerable decrease in the size of the preamble (compared to $L_S + 2L_L$) and therefore an improvement of the latency. With $k = 1$ we find following average energy consumption for the preamble

$$\overline{E_{preamble}} = \left(\frac{L_S + 3L_L}{2}\right) \cdot P_{TX} \tag{8}$$

which is better than the original $(L_S + 2L_L)P_{TX}$ without strobed preamble. Now we calculate again these parameters, but this time for a BCC network ($k > 1$) in order to evaluate the performance of the choice $L_\mu = L_L$ for such networks. We first compute $n'$, the average number of micro-preambles contained in the average size of the preamble

$$\overline{L_{preamble}} = (2n'-1)L_L \tag{9}$$

with

$$n' = \frac{n+1}{2} = \frac{L_S + 5L_L}{4L_L}. \tag{10}$$

Second we derive the average energy consumption cost of the preamble for $k > 1$

$$\overline{E_{preamble}} = (n' + (n'-1)k)L_L P_{TX} \tag{11}$$

$$= \left(\frac{(k+1)L_S + (k+5)L_L}{4}\right) \cdot P_{TX}. \tag{12}$$

We find that it is greater than $(L_S + 2L_L)P_{TX}$ for all $k > 3$, (note that for $k = 3$, $\overline{E_{preamble}} = (L_S + 2L_L)P_{TX}$). Our goal from now on is to find the value of $L_\mu$ which minimizes the average energy consumption of the preamble. We call it the optimal micro-preamble size. For that we assume

$$L_\mu = pL_L \tag{13}$$

with $p$ an integer and from Equation (5) it comes

$$n = \frac{L_S + 3L_L}{(p+1)L_L}. \tag{14}$$

We calculate again the average size of the preamble but this time with $L_\mu > L_L$

$$\overline{L_{preamble}} = \sum_{i=1}^{i=n} \frac{1}{n} \cdot ((p+1)i - 1)L_L \tag{15}$$

$$= \frac{L_S + (p+2)L_L}{2}. \tag{16}$$

We also derive the average energy consumption for the preamble $\overline{E_{preamble}}$

$$\overline{E_{preamble}} = \left(\frac{(k+p)L_S + (p^2 + (4-k)p + 2k)L_L}{2(p+1)}\right) \cdot P_{TX}. \tag{17}$$

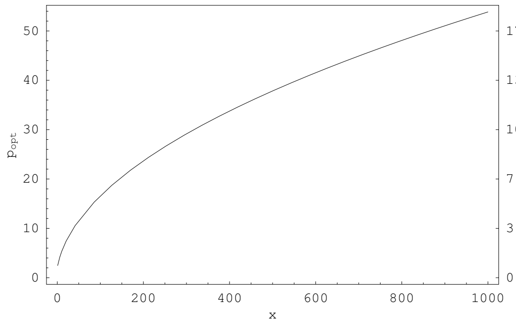


Fig. 2. Optimal micro-preamble size and optimal number of micro-preambles

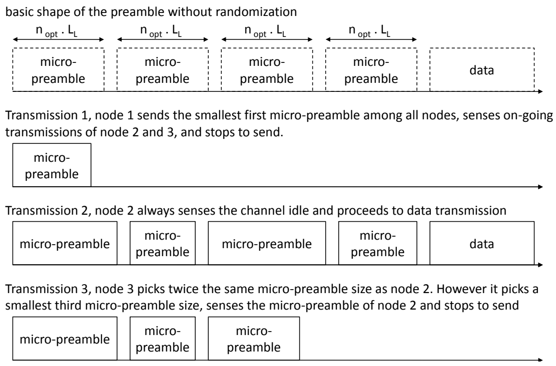


Fig. 3. Randomization of micro-preamble size for collision mitigation

By minimizing $\overline{E_{preamble}}$ with respect to $p$ we can find the optimal value of $p$, $p_{opt}$, which minimizes the average energy consumption of the preamble.

$$p_{opt} = \sqrt{\frac{(k-1)(L_S + 3L_L)}{L_L}} - 1. \tag{18}$$

We illustrate in Figure 2 the optimal size $p_{opt}$ of the micro-preamble and the optimal number of micro-preambles $n_{opt}$, taking $k = 4$, and $L_S = xL_L$ where $x$ is an integer. AdaMAC features that are introduce next are based on micro-preambles size of $L_\mu = p_{opt}L_L$.

### *C. Contention-free collision mitigation*

As explained previously, one source of long channel listening and therefore of high energy consumption for BCC networks is contention. Nodes trying to access the channel listen for a random amount of slots in order to mitigate collisions. AdaMAC does not use contention in this general sense. The preamble packet is sent directly after sensing the channel for $L_L$. To cope with collisions we randomize the size of each of the micro-preamble composing the long preamble around $L_\mu = p_{opt}L_L$. While transmitting its preamble, a node senses the channel between two micro-preambles and can detect other colliding micro-preambles. A node which detects an on-going transmission immediately stops to transmit its own preamble. When a node didn't detect any other communication during all its listen slots it is allowed to transmit its data packet. We illustrate this concept in Figure 3. For each of the first $i \in [1, n_{opt} - 1]$ micro-preambles the transmitter picks a random number $r_i$ uniformly distributed over $[-R, +R]$. It

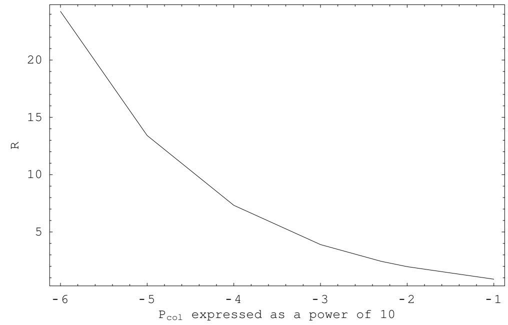


Fig. 4. Required value for R to achieve a specific probability of success

uses the following micro-preamble sizes $L_{\mu i}$

$$L_{\mu i} = \begin{cases} (p_{opt} + r_i)L_L, & \text{for } i < n_{opt} \quad (19) \\ (p_{opt} - \sum_{i=1}^{i=n_{opt}-1} r_i)L_L, & \text{for } i = n_{opt} \quad (20) \end{cases}$$

this way the total size of the preamble stays $L_S + 2L_L$. We use condition

$$R < \frac{p_{opt}}{n-1} \tag{21}$$

in order to prevent any micro-preamble to be of size zero. Now we derive the probability to still have a collision, i.e. that at least two nodes pick the same random numbers. For $j$ concurring nodes and $n$ listen slots, we express this probability $P_{col}$ as follow,

$$P_{col} = 1 - \frac{j!C^j_{(2R+1)^n}}{(2R+1)^{nj}}. \tag{22}$$

Obviously $P_{col}$ decreases as $R$ increases. On the other hand, as $R$ increases, the average energy cost of the preamble does not increase. We calculate the required value for $R$ to achieve a certain probability of collision and illustrate it in Figure 4.

### *D. Quality of Service*

AdaMAC enables efficient priority mechanisms. We detail here two of them.

1) If different nodes have different values of $R$ they have different priorities. Obviously a smaller value of $R$ means a higher priority, i.e., a lower probability to have a short first preamble and stop to transmit in case of collision.
2) If we code a priority field in the preamble, a node which senses a micro-preamble during the collision mitigation phase might still continue to transmit if it has a higher priority. The other node would later detect a higher priority preamble and stop to transmit.

## III. Simulation Results

We present simulation results performed with ns-2 2.32 [15]. To understand the basic behaviour of the protocol we simulate an application composed of five nodes on a human body. Each node transmits with a constant bit rate (CBR) alternately to each one of its neighboor. Parameters used are illustrated in Table I. Next we show respectively in Figure

TABLE I
SIMULATION PARAMETERS FOR NS-2

| *Parameter* | *Value* |
|---|---|
| Nodes | 5 |
| Packet size | 50 bytes |
| TX power | 0.6 mW[7] |
| RX power | 2.1 mW[7] |
| Sleep power | 0.01 mW |
| $L_L$ | 1 $\mu$s |
| $L_S$ | 10 ms |

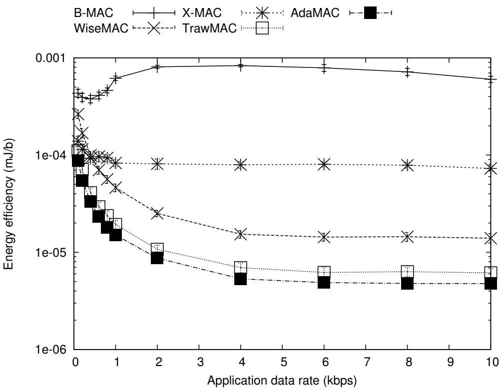


Fig. 5. Energy efficiency [mJ/b]

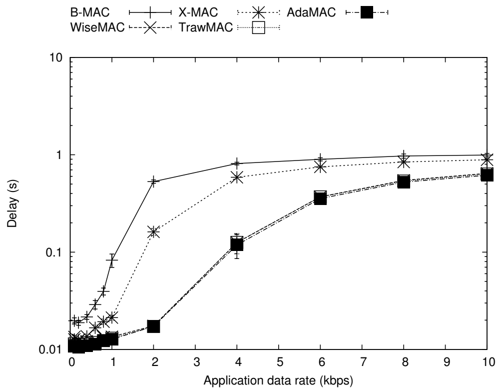


Fig. 6. Delay [s]

5 and in Figure 6 the energy efficiency (in mJ/b) of the communication and the delay (in s) of data packets, with respect to the application data rate, for different protocols. The energy efficiency is better for AdaMAC than for any other MAC protocol at any data rate. The difference with TrawMAC is of the order of the nJ/b while the difference with B-MAC is around $0.1\mu$J. Please note that these results are achieved assuming $k = 3.5$ [7], which is, as seen in Equation 12, just enough so that taking $L_\mu$ as small as possible is not the optimal strategy. Future work on BCC PHY layer should provide a $k$ in the order of 10 which would greatly increase the advanatage of AdaMAC over other protocols. Also the delay encountered by AdaMAC stays about the same than the other protocols although it uses longer micro-preambles than X-MAC or TrawMAC. It can be explained by a higher robustness to collisions.

## IV. CONCLUSION

In this paper we introduced specific requirements for BCC networks with respect to MAC protocols. We presented AdaMAC, a low power MAC protocol targeted to BCC networks. AdaMAC uses the new concepts of energy-optimal micro-preamble size and contention-free collision mitigation through randomized micro-preamble size around the optimal size. We show with simulations that AdaMAC is more energy-efficient for BCC networks than other low power MAC protocols originally developed for RF WSNs. In the future, AdaMAC will be implemented on the BCC solution described in [7] to verify our simulation results.

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