The Design and Software Implementation of a MAC Protocol for Body-Coupled Communication Systems

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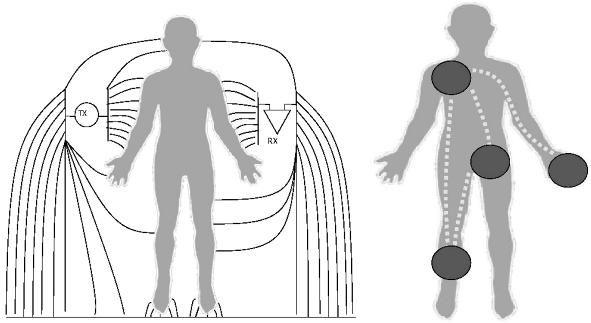
***Abstract*—Body-coupled communication (BCC) is a technology that is based on the use of capacitively-coupled electric fields over the human body. In this paper we highlight the design and implementation of a medium access control (MAC) protocol specifically designed to meet the requirements of BCC-enabled body area networks (BANs). We propose a set of specific protocol enhancements over well-known MAC protocols that are based on the concept of *low-power listening*. We present the proposed protocol in conjunction with the embedded software implementation for the prototype hardware platform. The purpose of this approach is to demonstrate that several protocol enhancements were motivated by observations on the actual BCC hardware and its intricacies. Finally, we present a series of experiments under real conditions.**

***Index Terms*—MAC protocol, body coupled communication, low energy consumption.**



(a) (b)

Fig. 1. Body-coupled communication consists of modulating capacitively induced electric fields through the human body (a), while our system model considers multiple on-body sensor nodes (b).

I. INTRODUCTION

Health care and personal entertainment applications that require the presence of devices on the human body (or in close proximity to it), need to be supported by body area networks (BANs). The reason is that more and more of these devices need to be connected either between them or between an external device. BAN nodes typically use an RF PHY layer operating in the industrial, scientific and medical (ISM) radio band. However, RF technologies suffer mainly from three problems in the case of BANs that are: body shadowing, interference, and poor energy efficiency. The first problem is well-known since the human body shadows high frequency RF signals in a highly variable way with respect to human movement, making communication among nodes on one body unreliable [1]. Second, an increasing number of interconnected devices that operate in the RF spectrum create significant problems in terms of interference with the surrounding devices. Finally, RF signals propagate far from the human body, e.g., more than ten meters for IEEE 802.15.4, which is a considerable loss of energy even when two nodes on one body communicate with each other.

One technology that has the potential to address the aforementioned problems related to the emergence of BANs, is the body-coupled communication (BCC) [2],[3]. BCC is a communication technology that uses the human body as the communication channel. BCC transmitters generate low power electric fields on the surface of the human body, and the variations of the field are sensed from any attached receiver in the same human body (see Fig. 1(a)). Hence, this is a communication technique that does not use EM radiation and thus it does not interfere with other BCC or RF systems. One of its advantages is that for nearly every location on the human body the propagation loss is well below 80 dB [4]. It was also shown in the previous work that body movement results only in small variations of the channel attenuation [4]. Another advantage of the BCC technology is that hardware transceivers can be designed to be very efficient. The work in [5] presented a solution which has an energy efficiency of 0.37 nJ/bit at 10 Mbps, i.e. three orders of magnitude more efficient than IEEE 802.15.4. In this paper we consider a system model where all nodes on the human body are equipped with BCC transceivers and it is depicted in Fig. 1(b). The BCC hardware technology is the one presented at [5], [6]. Our contribution is a new MAC protocol that meets the particular requirements that BCC-based body-sensor networks set. We demonstrate the protocol design decisions together with the design of the embedded software and we show how a real-life implementation might change decisions about the protocol behavior itself.

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II. RELATED WORKS

This section presents an overview of the related works in the area of energy efficient MAC protocols for wireless sensor networks (WSNs) that could also be applied in a BCC-based

BAN. 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. In [7], and further detailed in [8], the authors present the first research work in the area of low power MAC protocols for WSNs. The proposed S-MAC protocol is a synchronous low power MAC. All the nodes periodically transition between the sleep and wake up modes and all nodes wake up at the same time. When a node desires to transmit a packet, it knows when the complete network will be awake and can transmit at this time. This protocol requires the entire network to be synchronized. The work of Polastre described in [9] is probably the most important breakthrough in the field of low power MAC protocols for WSNs. The proposed protocol named B-MAC uses the concept of low power listening (LPL) and long preambles. With this protocol, all nodes in the network can operate asynchronously. Each node wakes up regularly and independently from all other nodes at a given time and senses the channel with a wake up receiver to check if the channel is busy (this action is called LPL). If the channel is busy the node wakes up completely, otherwise the node goes back to sleep. When a transmitter wants to reach another one it sends a long preamble which has a size longer than the maximum time between two wake up times of any receiver. This approach provides the opportunity for any receiver to sense the preamble and receive data packet after a wake up. Shortly after [9], El-Hoiydi, proposed in [10] WiseMAC, a low power MAC protocol that is also using LPL and long preambles. Another important work in the field of low power MAC is the one of Buettner in [11]. The author introduces the concept of micro-preambles where a long preamble is strobed into very short preambles with listen slots in between. When the destination node catches the preamble it can send a ready-to-receive packet to the source to indicate that it is ready to receive the data packet. This feature reduces overhead due to long preamble as well as the latency.

III. BCC Characteristics and MAC Protocol Requirements

A fundamental characteristic of BCC systems is the dissymmetry between RX power and TX power [5], [6]. The reason for this behavior is that a BCC transceiver has to limit the TX power for body exposure reasons [4]. This means that the power at the receiver is limited and the complexity of the receiver hardware circuitry increases. The end result is that the RX power required to achieve full body coverage is higher than the TX power. Consequently, an efficient MAC protocol should tend to minimize the time that a node spends in RX mode, probably at the expense of the time spent in TX mode. This is a very important difference when compared with low power MAC protocols that need to be designed for WSNs. Another important design choice for the hardware BCC system, was that any node in contact with the body of a user should be capable to communicate with any other node attached to the same human body without multi-hop communication [5].

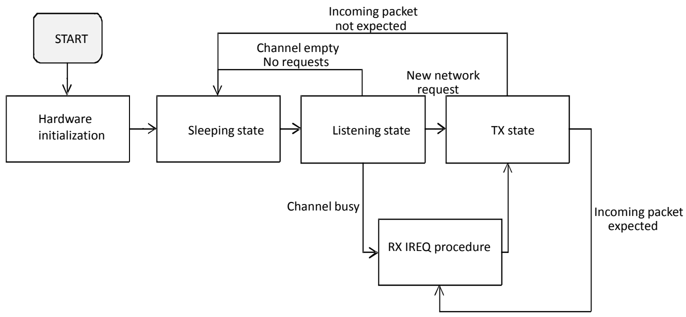


Fig. 2. Generic view of the state machine and interactions with the receiver interrupt service routine (RX_IREQ).

A. MAC Design Requirements

The MAC layer should be able to meet the requirements of typical low power WSNs and in addition the requirements of BCC networks explained before.

1) Energy & Performance: First, in order to be able to control the energy consumption, the MAC protocol should provide a wake up (WUP) and sleep (SLP) mechanism. The traffic in most of BCC-based applications is unpredictable because nodes do not exchange packets at a regular periodic rate. This means that the WUP/SLP mechanism should be asynchronous in order reduce energy consumption for unnecessary synchronization. Therefore, the protocol will need an algorithm to achieve a temporal synchronization when a packet is transmitted. Another important observation is that both the throughput and latency are related to the WUP/SLP mechanism. With a longer sleep time, the latency becomes higher and the throughput is decreased. This means that the period a node is awake or asleep should be adapted dynamically depending on the application demands.

2) Reliability & Fairness: Another important characteristic is the reliability of the MAC protocol that should be again adjustable. Consequently, the MAC should also have a contention mechanism and a retransmission procedure in order to guarantee (or not) the success of a packet transmission. While designing the contention mechanism, it must be ensured fair sharing of the channel. Finally, the channel used is a full body coverage channel, so when a node is transmitting a packet, any other node can receive it and no other can transmit a packet at the same time. This means that the MAC protocol should be designed on the top of a half-duplex channel.

IV. MAC Protocol Design

A. Overview

The main goal is to design a MAC protocol that meets the requirements described in the previous subsection. In order to meet these requirements, we will need a protocol with a set of specific characteristics: 1) An asynchronous wake up and sleep mechanism. 2) An algorithm to obtain temporary synchronization then transmitting packets. 3) A retransmission and contention window (backoff) algorithms for use in unsuccessful communication.

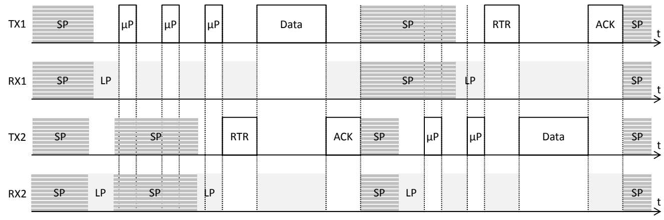


Fig. 3. Representative packet transmission procedure between two nodes.

The design that was selected for the basic packet transmission scheme (PTS) is described below:

- The transmitter wakes up from the sleeping period and senses the channel. If the channel is busy, it waits for a contention window and tries again.
- If the channel is empty, the transmitter sends a series of micro-preambles (uPs) with listen slots in between.
- When the destination wakes up and listens to a uP, it sends a ready-to-receive packet (RTR) to the source in order to signal its presence.
- As soon as the source receives a RTR, it stops sending uPs and sends the data packet (DATA).
- If the destination receives the data successfully, it sends an acknowledgment packet (ACK).
- The data exchange is finished when the source receives the ACK.

B. Protocol State Machine

The MAC protocol has been designed as a state machine that runs continuously in a micro-controller. There are three main different states that their interactions can be seen in Fig. 2. *Sleeping state:* Here, the node sleeps for a random time between the listening period (LP) and the sleeping period (SP). *Listening state:* At this state, the node wakes up from the sleeping period and senses the channel for possible incoming packets. If the channel is empty, it checks for new network requests. *TX state:* At this point, the node creates the packet that needs to be transmitted and sends it on the channel. Then, if an incoming packet is expected, it enables its receiver. There is also a receiver interrupt procedure named RX_IREQ, where the node saves the packet received and checks if it is a correct packet or not. Every time a packet is received, this procedure is executed.

C. Asynchronous Wake Up/Sleep Mechanism

The PTS presented is based on the assumption that when a node is not transmitting it can receive data. While this is a very reliable approach, it is highly inefficient in terms of energy consumption. Indeed a node will turn off its receiver when there is nothing to receive on the channel. In our protocol, the node will wake up randomly and will be awake during another time instant. The time period that network nodes are either awake or asleep is determined by the SP and the LP. These two parameters are the ones that affect the throughput the most. When the transceiver is asleep, it is not able to receive

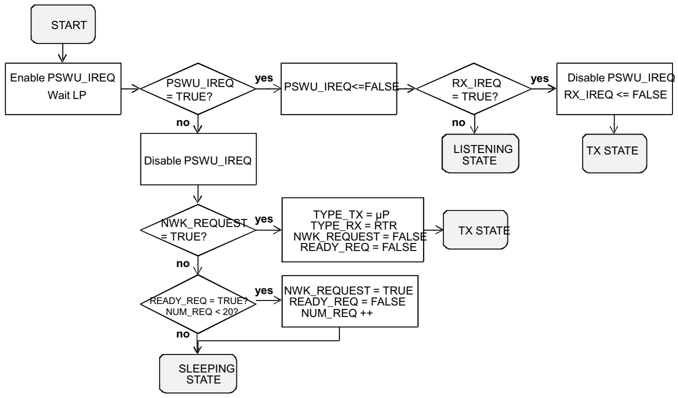


Fig. 4. A small part of the MAC protocol state machine.

a packet or to deal with a new request from the network layer for a new transmission. The node chooses randomly a time between LP and SP and it remains asleep for that time. Then the node wakes up and listens for channel activity, just in case any other node is trying to send a uP. If not, it can either go to sleep again or if there is a new network request it can begin a new communication round. In Fig. 3 we see how two nodes sleep (SP) and listen (LP) independently. First, N_1 needs to send message and so it uses the PTS explained before. At the end of that communication, and after the SP, N_2 does exactly the same. Details follow in the next subsections.

D. Behavior in the Listening State

After exiting the sleeping state, the node wakes up and enters the listening state. From the hardware point of view, the node enables the interrupt PSWU_IREQ in order to allow the node to sense the channel. If there is a packet in the channel, then the node enables by itself (at the PSWU_IREQ procedure) the RX_IREQ procedure which is responsible for receiving a complete packet. If a correct packet arrives (it should be a uP) to the node, the interrupt PSWU_IREQ is disabled, and the software transitions to the TX state in order to send a RTR to the transmitter node. On the other hand, if the packets at the channel are either incorrect or not successfully received, the node will be awake until the channel becomes idle. Finally, if the node does not sense packets any more, it checks if it there is a new network request. If there is a new request, the node sets the type of packet it is expecting to send (uPs) and to receive (RTR) and it continues to the TX state. If there is no new request, it goes to sleep again. The behavior of this state is represented in Fig. 4.

E. Protocol Enhancements

1) Additional LP after every communication: Every time a communication round ends, the two communicating nodes start to sleep at the same time. This is a way of local synchronization. Although this is not an accurate local synchronization method, since the processing time of the receiver node is not the same with the transmitter, it could be used in order to enforce an extra LP at the receiver. If the transmitter has more than one request with the same destination address in its queue, and an extra LP is enforced to the destination, this allows the transmitter to save a considerable amount of time by not sleeping after every request (i.e. at least one SP per request).

2) Additional data packets per communication: Another optimization is to send multiple DATA packets per request. If a node has more than one DATA packet to send to the same destination, it does not have to establish a new communication round every time. It just has to send, after receiving the RTR packet, the remaining packets back-to-back. When this solution is combined with the previous one, it can improve the throughput in networks which the data rate is high. For implementing this solution, the transmitter indicates at the uP packet the number of data packets it desires to send (up to a maximum value for fairness) and it sets the way to acknowledge the packets. A negative ACK (NACK) packet is used to indicate the incorrectly received DATA packets.

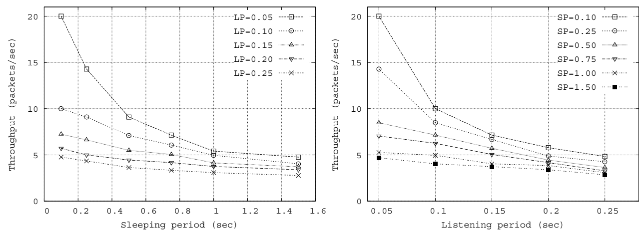
3) Sequence number in requests/uP: The MAC protocols we reviewed use sequence numbers only in DATA packets. However, we observed in our implementation that a problem occurs when more than one node tries to transmit and also when the packet loss rate is high. When a transmitter tries to establish a new communication after a failed one, a third node (not the receiver) may also try to establish a new communication with the same receiver. Because of the other failed communication, the receiver is still expecting a DATA packet. But because the receiver receives a PSWU_IREQ interrupt from the third node, and it is still waiting to finish the previous communication, it does not know that the new interrupt is not from the initial communication. In this case, none of the two communication rounds will succeed because the receiver is blocked due to an expired communication. This problem is solved with a sequence number that is added to all types of packets instead of using lengthy timeout timers.

V. Performance Evaluation

In this section we evaluate the performance of the proposed MAC protocol using a real prototype hardware platform. For our experiments we used hardware development boards that are equipped with the MSP430 micro-controller from Texas Instruments and with a prototype BCC transceiver. Instead of using an actual human body to communicate between two boards, an attenuator was used so that it emulates the path loss induced by a human body. We have also set the values for several systems parameters that can be seen in Table I. Unless specified otherwise, we have chosen the default attenuation to be 30 dB and the packet size 128 bytes. For the application workload we forced the creation of continuous network requests, i.e. the nodes are saturated. A request is created every time the node wakes up. The most important performance metric we desire to measure is the throughput. For the first set of experiments we configured one board as a transmitter and another board as a receiver.

TABLE I
Hardware parameters

Parameter	*Value*	*Parameter*	*Value*
Sleeping period	0.75 sec.	Listening period	0.15 sec.
min. rtx of uPs	7	max. rtx of uPs	17
max. rtx of other packets	4	max. # of backoffs	3



(a) (b)

Fig. 5. Throughput vs. the SP and LP for different LPs and SPs respectively.

A. Sleeping Period

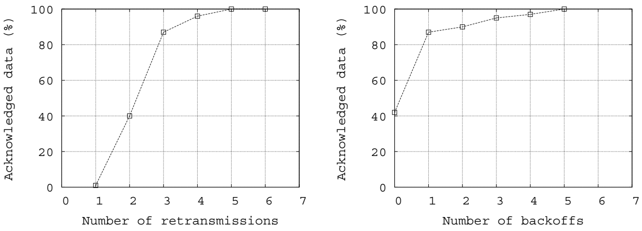
During the SP, the test boards are neither able to transmit nor to receive any packet. Therefore, the shorter the value of SP the higher the throughput since packets can be sent more often. This also means that the node will use more energy, because it sleeps for a reduced amount of time. For these experiments, specific values of the LP were fixed and then we varied the SP. In Fig. 5(a) we can see the obtained results. From the results we can observe that when the configuration is faster with a lower SP, the node can send packets faster. Some of the presented results in this figure might not correspond to realistic configurations, since the SP should be larger than the LP. Because the aim of this protocol is to save energy, this does not happen for example when the SP is smaller than the LP.

B. Listening Period

Another way to evaluate the throughput is to vary the LP. This time period corresponds to the total time that the node uses for receiving an incoming packet. Similar with the previous results the shorter period for LP the better throughput as it can be seen in Fig. 5(b). This is because the node needs less time to get the packet. However, with a shorter SP this also means that the node will have to send more uP packets to establish a communication. We also come across an additional problem when the size of the LP is decreased. If the LP is decreased too much, then the nodes might not be able to receive a packet correctly because they will not have enough time to receive it.

C. Retransmissions and Backoff

Reliability through retransmission for different types of packets (i.e. RTR, DATA or ACK) was one of the most important mechanisms that were embedded in the protocol. We evaluated the performance of the proposed MAC for different number of allowed re-transmissions for any type of packet. In Fig. 6(a) we can see the performance in terms of acknowledged



(a) (b)

Fig. 6. Throughput vs. the allowed number of retransmissions and backoffs.

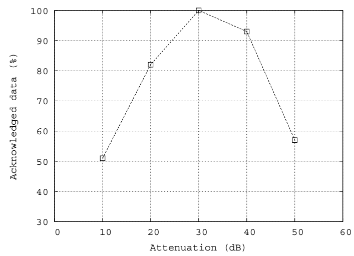


Fig. 7. Throughput vs. channel attenuation.

data packets. We can see that without retransmissions the communication is not possible with the current hardware configuration. However, when we allow the transmitter to re-transmit a packet at least two times, it succeeds almost at the half of the time and if we allow the transmitter to re-transmit at least four times the percentage of success reaches 100%.

One of the most important tasks of the BCC MAC protocol is sharing the channel between competing nodes. Note that this backoff procedure refers to the transmission of the uPs since when a uP is transmitted successfully the remaining nodes remain silent [6]. We present results for different number of allowed backoffs in Fig. 6(b). We see from the results that when the nodes are not allowed to backoff, then they only achieve a 40% successful transmissions. We also observe from the results that for certain percentage of requests, but for a low percentage, there is a need to backoff more than once. This is attributed to significant packet loss that occurs for the relatively high channel attenuation of 40dB.

D. Channel Attenuation

We explained earlier in this section that an attenuator was used between the two development boards in order to emulate the path loss that is introduced by the human body. However, the path loss between two positions in the human body depends on their distance [4] which means that we should also investigate variations of this parameter. For testing the performance of our protocol, we configured the attenuation between 10dB and 50dB and we executed 50 sets of the same test. The results for the percentage of the acknowledged packets can be seen in Fig. 7. We see that on the one hand, a value higher than 30 dB causes higher packet loss so the protocol works as expected and its performance depends only on the data rate that the BCC transceiver can achieve under that attenuation. However, even for low attenuation we observed that the performance decreased. After several tests we observed that this behavior is attributed to the saturation of the receiver due to the amount of power that is received. This observation led to modifications of the hardware board.

VI. Conclusions

In this paper we have presented a new MAC protocol for BCC networks that enables high reliability and low energy consumption. Its main features are: An asynchronous wake up and sleep mechanism in order to control the energy consumption, a preamble transmission procedure to obtain temporary synchronization while sending packets, a preamble contention mechanism, and a retransmission algorithm. We have also proposed three additional algorithmic protocol features in order to improve the initial version of the protocol when it is practically implemented and tested. The results in the real BCC hardware devices demonstrated the behavioral correctness of the protocol. In the future we plan to test the protocol in a larger number of nodes that have smaller form factor and can be easily attached to the human body.

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