Implantable Body Sensor Network MAC Protocols Using Wake-up Radio – Evaluation in Animal Tissue

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***Abstract*—Applications of implantable sensor networks in the health-care industry have increased tremendously over the last decade. There are different types of medium access control (MAC) protocols that are designed for implantable body sensor networks, using different physical layer technologies such as narrow band, ultra wide-band, human body communication, and ultrasound with an innovative low power access technology called wake-up radio (WuR). The WuR operates alongside the main radio either in the same frequency or different frequency, with much lower power and reduced hardware components than main radio. In this article we analyze the impact of WuR on commonly used MAC protocols and evaluate three MAC protocols with WuR using real hardware implanted in animal tissue and compare them with three other MAC protocols without WuR. The hardware implantable board is embedded with a micro-processor, wireless communication unit and is subcutaneously implanted under the skin of the animal tissue. Five nodes with one of them being the central controller connected in star topology are used for evaluation. Energy efficiency, reliability in terms of packet loss ratio, and end-to-end delay for each node are considered as the evaluation criteria.**

I. Introduction

Application of wireless sensor networks in monitoring patients' health has increased tremendously in recent years [1][2]. One of the technologies enabling such applications is the implantable body sensor network (IBSN), in which sensor nodes are placed *inside* the human body for continuously monitoring the vital signs of patients with life-critical diseases, the elderly, and infants. Monitored vital signs include electro-cardiogram (ECG), electro-encephalogram (EEG), heart rate, blood pressure, and blood glucose levels. Another technology also used for health-monitoring is the wearable body sensor network, in which the sensor nodes are placed *on* the human body [9]-[12]. The main disadvantage of this type of sensor network is the unreliability and lower data quality. This is due to disturbances caused by the dynamic human behavior and motion artifacts [1]. IBSN limits the movement of sensor nodes as they are placed inside the body. Another advantage of IBSN is its support for closed-loop control, in which a patient's response to a certain therapy is collected in real time to control the therapy. Examples of such controls include controlling pace-makers, neural stimulators, and drug delivery devices. Communication between sensor nodes in IBSN has to be energy efficient and reliable for long-term operation and to prevent any fatal failures [2]. In order to standardize the wireless communication in, on, and around the body (not limited to humans), IEEE 802.15 task group 6 has been set in 2007 [3]. The task group aims to standardize wireless communication with a dedicated radio spectrum, ultra-sound, and ultra-wide-band communication, and an in-body communication channel. The immediate use of ultra-sound, ultra-wide-band and in-body communication channel in IBSN is not feasible due to the lack of reliable technology to have it implanted inside the body.

One of the important considerations of the IEEE 802.15.6 design was to have Medium Access Control (MAC) protocols for low-power and short-range radios in three different physical (PHY) layers [3]. To this end, access mechanisms with different priorities for different types of data, such as emergency data, non-emergency data, and data that require Quality of Service (QoS), have been introduced. Beacon mode with beacon periods, non-beacon mode with and without super-frames are types of access mechanisms proposed in the standard [3]. The MAC protocol proposed in the standard supports low peak current for wireless radio, thereby allowing more flexibility for sensing and local processing. It is clear from the standard that MAC protocols for implantable networks have to be energy efficient.

A. Operation and advantages of wake-up radio in IBSN

In the last decade, the concept of ultra-low power wake-up radio (WuR) was introduced. It operates together with the main radio with much lower power consumption than the main radio [13]. The WuR reduces the energy consumption by switching the main radio to deep sleep mode when no data is transmitted or received. The WuR is operated with different duty cycles. This also yields a good power budget for the sensor nodes. The WuR can either operate in the same band of the main radio or in a different band. Different innovative WuR designs already exist which operate in the power range of nanowatts [15]. It has been shown that WuR reduces the overall power consumption of wireless communication in sensor nodes, provided the duty cycle of main radio is carefully tuned with WuR [13].

The main features of WuR to consider it as a suitable candidate for IBSN are low power consumption, reliable performance in short-range networks, ability to operate out-of-band with main radio, and not requiring complex hardware [28]. The high power consumption of the main radio is due to idle-listening, over-hearing, data collision and state-switching (on state to off state and vice-versa). The WuR is used to only turn the main radio on when it is really needed. By doing so, the power consumed by the main radio for idle listening is eliminated, along with the over-hearing problems preventing data collision to occur. The data communication is then initiated and completed using the main radio, reducing the total amount of time that the main radio is turned on. The WuR of the transmitter broadcasts a node-id encoded wake-up

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signal, which is acknowledged by the WuR of the destined node, indicating that the main radio of the receiver node is actively listening. The main radio of the transmitter is turned on only when the acknowledgement is received for the wake-up signal, hence reducing energy consumption and increasing reliability.

In this paper, we will evaluate different MAC protocols with and without WuR to asses their suitability to be used in IBSNs. The evaluation is carried out by characterizing the radio channel using real hardware in the animal tissue (Section III) and in simulations of network parameters in MATLAB (Section IV). This evaluation will help to identify the bottlenecks of access mechanisms in the real world. As a result, the advantages and disadvantages of WuR in IBSN are described. The results are compared with software simulation results obtained from a human body channel model reported in [27].

II. MAC PROTOCOLS WITH AND WITHOUT WAKE-UP RADIO FOR IMPLANTABLE BODY SENSOR NETWORKS

IBSNs are life critical. Therefore, nodes must neither fail due to energy deficiency nor report unreliable data at any point in time within the lifespan of the network. Every single access to the wireless medium is expensive in terms of energy. Therefore, access protocols need to be designed carefully meeting the communication reliability and energy efficiency requirements of the network. In this section we briefly describe six MAC protocols with and without WuR in three different categories, i.e., contention-free, contention-based, and hybrid. These protocols will be used in our experimental analysis being reported in Section III.

Contention-based access mechanism

The contention-based access mechanism investigated in this study is Berkeley MAC (B-MAC) for low-power sensor networks [25]. It features low-power listening (LPL) and two random back-off periods without control packets such as receive to send (RTS), clear to send (CTS) and acknowledgment (ACK). One drawback of CSMA is the delay: the sensor node has to wait to occupy the channel with a random back-off, thereby eliminating any real-time guarantee. The main disadvantage of B-MAC is the preamble, which creates large overheads. The effect of WuR can be studied by implementing a wake-up feature in B-MAC, reducing the delay by shortening the LPL mode and preambles.

Effect of WuR: The channel can be pre-occupied by a node of the same network or by an external interferer sharing the same spectrum. By using WuR, the main radio can sleep if it is not communicating, allowing the channel to be free of internal interference. The WuR will eliminate the idle listening by waking up only the intended receiver with encoded wake-up signals [14]. As a result, the main radio can transmit without waiting for the free channel and receiver can sleep without over hearing. The implementation of CSMA with WuR follows the Sub Carrier Modulated MAC protocol as reported in [14].

Contention-free access mechanism

The contention-free access mechanism or time division multiple access (TDMA) enables the access to communication channel with guaranteed time slots (GTS). The real-time guarantee can only be achieved by time synchronization between the nodes with large and regular beacons shared within the network. These beacons consume additional bandwidth and power before any data is communicated. The implementation of TDMA protocol in our paper follows Preamble-Based MAC as reported in [8]. The analysis of this protocol will explicitly show the efficiency of WuR in reducing the overheads of TDMA and thereby reduce the duty cycle of the main radio of [8].

Effect of WuR: The use of WuR reduces the overheads in TDMA by reducing the large preambles prior to the transmission of the useful data. GTS for the main radio communication can still be achieved with shorter beacons containing synchronization, priority, and slot information as shown in [29]. The idle listening period of the main radio can be largely reduced with the use of WuR in TDMA mechanisms as well, which again decreases the power consumption. In order to evaluate the effect of WuR in TDMA, the implementation in this study follows On-Demand MAC as reported in [29].

Hybrid access mechanism

The hybrid access mechanism uses CSMA for non-real-time data communication and TDMA for real-time data. The data is sent based on priority and the GTS can be set depending on the application. One such hybrid MAC protocol which meets the requirements of IBSN is PNP-MAC [6]. The disadvantages of [6] are resource exhaustion in client nodes, high energy consumption and longer beacons, as it is not optimized for energy efficient performance.

Effect of WuR: The effect of WuR in the hybrid access mechanism in terms of energy consumption, delay and reliability will be studied by comparing the PNP-MAC [6] with the Power-Efficient MAC which reduces the power consumption by shorter beacons in TDMA and shorter delay in the CSMA-based protocol reported in [7].

III. EXPERIMENTAL CHARACTERIZATION

A. Experimental set-up

Animal tissue was obtained from a slaughterhouse and the ethical codes [5] in using animal tissues were carefully followed. The animal tissue was approximately 4 kg of meat taken from a pig's thigh, consisting of layers of skin, muscles and thigh bone as shown in Fig. 1. The choice of excerpting animal tissue from a pig is because of its close resemblance to anatomy and physiology of the human tissue [4]. The hardware is a custom-made platform, whose specifications are given in Table I. In order to prevent any short-circuit on the board during experiments, the hardware is covered with paraffin coating as shown in Fig. 2. The experiment was carried out in a controlled biological environment. The channel model is obtained by characterizing the radio channel using the node implanted inside the animal tissue. The parameters of the wake-up radio were obtained from Microsemi's ZL70102

Fig. 1: Dissected part of pig

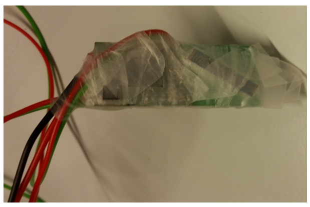

Fig. 2: Paraffin coated node

datasheet [16]. The wake-up radio transceiver consumes a very small amount of energy (a few nW), whereas the main transceiver usually operates in the order of μW [15][14]. These models were used for further analysis of network parameters in MATLAB.

Parameter	Value
CPU	MSP430
Main radio	CC430
Antenna	Ceramic, 433 MHz
Peripherals	UART, SPI
Dimensions	$30 \times 7 \times 5$ mm

TABLE I: Hardware specifications

Parameter	Value
Tx power	-10 dBm
Tx distance	100 cm
Packet length	20 bytes
Data rate	40 kbps
Modulation	BPSK

TABLE II: PHY layer

B. *Characterization of the radio channel*

The designed hardware supports different configurations for the narrow band PHY layer. The configurations of the PHY layer should follow the IEEE 802.15.6 communication standard with parameters such as communication range, transmission power, data rates and interference mitigation. In order to evaluate the physical settings of the hardware, we placed the battery-powered hardware subcutaneously in the animal tissue. The choice of placing the node subcutaneously is to eliminate the complex propagation losses due to varying conductivity of deep tissues. Two nodes were used for characterizing the radio channel: one placed inside and the other one placed outside the tissue. Different configurations of transmission power and transmission distance were selected and the received signal strength (RSS) was measured between the two nodes. Upon selecting transmission power and transmission range, the data rate and packet length were fixed for the given hardware. Table II shows the obtained results of the optimal physical settings of the node and the PHY layer parameters which were used to obtain the RSS-based model of the radio channel.

IV. Simulation of network performance

A. *Network setup*

After characterization of the hardware, we formed a network to evaluate the performance of the communication between the sensor nodes using software simulation. We used a star topology network composed of a central coordinating node and five client nodes. We used discrete event simulation with the models obtained from characterization of radio channel. Simulation was repeated for different values of inter-packet arrival time (IPAT), while observing parameters such as delay, power consumption, packet drop ratio and duty cycle. IPAT is defined as the time between adjacent packets to arrive at the receiver. It is a commonly used parameter to evaluate network performance, as it is directly affected by dynamic wireless channel.

B. *Evaluation by theoretical analysis and simulations*

In order to evaluate the performance of MAC protocols with wake-up radio, three important parameters are considered: *delay*, *packet loss ratio*, and *power consumption*. The operation of the MAC protocol with wake-up radio is shown schematically in Fig. 3. The sensor node is assumed to have a main radio and a wake-up radio allowing parallel radio transmissions. A MAC protocol with wake-up radio is expected to reduce the delay of communication in the main radio, the packet loss ratio, and the energy consumption of the wireless communication. In this section we formalize these assumptions and analyze the performance based on them. We verify the validity of the formulas with simulations performed using the channel model developed from the characterization.

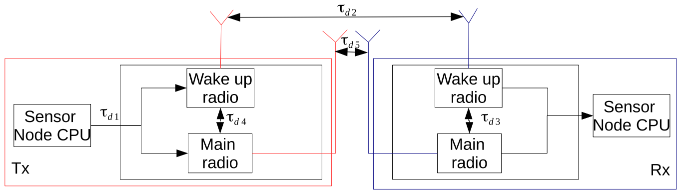

Fig. 3: Overview of delays for dual radio communication

1) Delay: The delay in a sensor network is defined as the time taken for a set of data to travel from the source to the destination without any errors. Let $D_{\text{data-wur}}$ be the overall delay for communicating the data packet using the access mechanism with wake-up radio as shown in Equation (1). Fig. 3 gives an overview of delays in data communication, where

- τ_{d_1} is the time taken for communication between the CPU of the sensor node to the wireless module,
- τ_{d_2} is the time taken for successfully waking up the destined node by the transmitter,
- τ_{d_3} is the time taken to wake up the main radio after receiving the appropriate wake-up signal,
- τ_{d_4} occurs after receiving acknowledgement for the wake-up signal from the receiving node, and
- τ_{d_5} is the time taken for the main radio communication including the time taken for the mechanisms prior to accessing the channel such as random back-off, clear channel assessment, and synchronization.

Equations (2) and (3) represent the delay in TDMA and CSMA respectively, where $\tau_{d_{csma}}$ and $\tau_{d_{tdma}}$ are the time taken for the backing-off procedure in CSMA and the time taken for synchronization in TDMA.

$$D_{\text{data-wur}} = \left(\tau_{d_1} + \tau_{d_2} + \tau_{d_3} + \tau_{d_4} + \tau_{d_5} \right) \tag{1}$$

$$D_{\text{data-csma}} = \left(\tau_{d_1} + \tau_{d_{csma}} + \tau_{d_5} \right) \tag{2}$$

$$D_{\text{data-tdma}} = \left(\tau_{d_1} + \tau_{d_{tdma}} + \tau_{d_5} \right) \tag{3}$$

For a MAC protocol with wake-up radio to have less total delay than a MAC protocol without wake-up radio, $(\tau_{d_2} + \tau_{d_3} + \tau_{d_4})$ must be less than $(\tau_{d_{csma}}, \tau_{d_{tdma}})$. From literature [29][28][14], it is found that the above condition is met for different access mechanisms in body sensor networks. The time taken for the wake-up radio to wake-up the main radio and acknowledge the sender is less than the back-off period in CSMA and the beacon interval in TDMA, given the fact that internal interference and overheads are higher for the main radio. In our evaluation, experiments will be conducted to measure the delay in the network and verify the validity of the condition for the given IBSN scenario. Measured values of the parameters τ_{D_1}, τ_{D_5} correspond to the values found in the hardware's datasheet [16]. Values for the rest of the delay parameters could not be measured directly and were therefore taken from the datasheet. The graph in Fig. 5 confirms that $(\tau_{d_2} + \tau_{d_3} + \tau_{d_4}) < (\tau_{d_{csma}}, \tau_{d_{tdma}})$, i.e, the delay of the main radio without wake-up radio is higher than that of the main radio with wake-up radio. Furthermore the results show that the CSMA mechanism without wake-up radio has the highest delay and hybrid access mechanism with wake-up radio has the lowest delay. Even though the network size is smaller, the nodes suffered from collision in CSMA access mechanism without wake-up radio. The delay in TDMA access mechanism is almost the same for MAC protocols with and without wake-up radio, since there is no change is time schedule. However, the effect of longer and continuous beacons in TDMA is reduced, increasing the effective throughput. There were few missed emergency data communications from high priority nodes during the experiment which is not encouraged in IBSN. Hybrid access mechanism with wake-up radio has no issues in delay and has better delay performance than CSMA and TDMA without missing any emergency data from high priority nodes and no collisions. In terms of delay, TDMA has a higher performance but due to the limitation in handling high priority data, the hybrid access mechanism with wake-up radio has a lower delay as shown in Fig. 6.

2) Duty cycle and power consumption: Duty cycle is the proportional duration for which the radio is turned on for useful data communication. The power consumption can be predicted using the duty cycle and the values of current and voltage of the radio hardware according to the data sheet of the radio hardware used. The duty cycle of the main radio is reduced by introducing the wake-up radio, which detects the wake-up packet and lets the main radio turn on from deep sleep state. This makes the main radio to remain turned off for a longer period of time without losing any useful data from being transmitted or received. Let C_{M_0} be the duty cycle of the main radio without wake-up radio, C_{M_1} the duty cycle of the main radio with wake-up radio, and C_W the duty cycle of the wake-up radio. In order to relate the power consumption with the duty cycles, let P_0 be the power consumed for wireless communication with wake-up radio and P_1 the power consumed for wireless communication without wake-up radio. Similarly, let $P_{M_{on}}$ be the power consumption of the main radio when turned on, and $P_{M_{off}}$ the power consumption of the main radio when turned off. We then have

$$P_0 = C_{M_0} \cdot P_{M_{on}} + (1 - C_{M_0}) \cdot P_{M_{off}} \tag{4}$$

$$\begin{aligned} P_1 = C_{M_1} \cdot P_{M_{on}} + (1 - C_{M_1}) \cdot P_{M_{off}} + \\ C_W \cdot P_{W_{on}} + (1 - C_W) \cdot P_{W_{off}} \end{aligned} \tag{5}$$

This power calculation is to show that the longer the sleep mode, the shorter the duty cycle and hence the lower the power consumption. The power consumed by the main radio is higher than that of the wake-up radio. Hence for a system without wake-up radio to be power efficient, $P_1 < P_0$ has to be achieved. Applying the condition to Equations (4) and (5), we obtain

$$C_{M_1} < C_{M_0} - \frac{C_W \cdot P_{W_{on}} + (1 - C_W) \cdot P_{M_{off}}}{P_{M_{on}} - P_{M_{off}}} \tag{6}$$

From Equation (6), we observe that the duty cycle of the main radio with wake-up radio is always less than the duty cycle of the main radio without wake-up radio, considering (by design) that the power consumption of the main radio is much higher than that of the wake-up radio.

The duty cycle of CSMA without wake-up radio is highest among other access mechanisms indicating higher power consumption due to back-off and higher number of retransmissions. Wake-up radio has reduced the duty cycle of CSMA, however it is still higher than other access mechanisms with and without wake-up radio. TDMA without wake-up radio has higher duty cycle than the CSMA with wake-up radio because of longer and continuous beacons sent for synchronization within the network. The use of WuR reduced the need of continuous beacons and shortened the beacon during the main radio communication. This has significantly reduced the duty cycle of the node when TDMA access mechanism with WuR is used. However, the hybrid access mechanism with WuR overcomes the drawbacks of these access mechanisms by reducing the longer back-offs and numerous retransmissions, shortened beacons and synchronization. As mentioned earlier shorter duty cycles of main radio can save a lot of energy consumption, enabling longer network life and battery-life. The hybrid access mechanism with WuR has the shortest duty cycle of all the access mechanisms as shown in Fig. 4.

3) Packet loss ratio: The packet loss ratio (PLR) is the ratio of the total number of packets failing to reach the receiver to the total number of packets generated at the sender. PLR is an important parameter to analyze the network performance with different physical layer parameters for a specific network topology. In case of IBSN the network topology is fixed, however, the IPAT can vary due to the highly varying physical properties of the human body as a medium. In a delay-senitive network like IBSN, a packet will be considered lost if it has not been received within the threshold time period.

Packet loss ratio is high for CSMA without WuR because of collisions. Emergency data packets were lost when the time threshold for the data packets was exceeded. However, the CSMA with WuR was able to communicate with lower PLR but still not lower than other access mechanisms as shown in Fig. 5. TDMA with WuR has lower PLR at shorter IPAT but was out-performed by the hybrid access mechanism with WuR at higher IPAT. At higher IPAT, TDMA packets were lost due to longer preambles without the use of WuR, whereas TDMA with WuR decreased the PLR considerably benefiting from the shorter beacons. In medical scenarios, the loss of emergency packets is not allowed in any circumstance. From the results there were less packets lost due to collisions when WuR was used. In general, the use of WuR decreased the PLR thereby increasing the reliability of the network.

V. Conclusion

Our results obtained from experiments with animal tissue and from simulations show that the hybrid access mechanism outperforms CSMA and TDMA for IBSN, because it combines the advantages of CSMA and TDMA. The disadvantages of those MACs are mitigated by using WuR. Using WuR has a positive impact on the performance of hybrid access mechanisms for IBSN as it decreases both PLR and latency. The power consumed for duty cycling will also be less when WuR is used, because the power consumed by the WuR is much lower than that of the main radio.

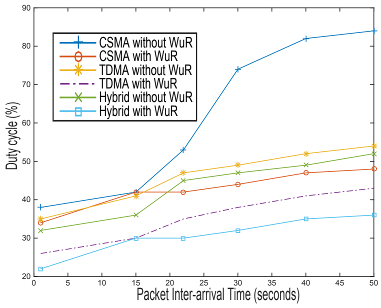

Fig. 4: IPAT vs duty cycle

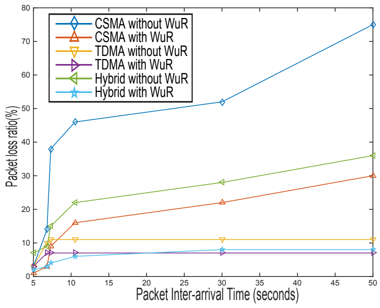

Fig. 5: IPAT vs packet delivery ratio

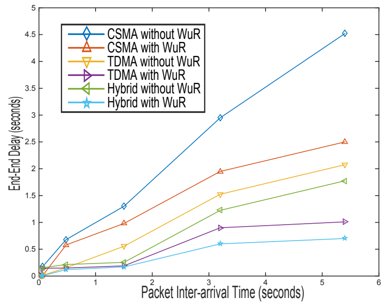

Fig. 6: IPAT vs end-to-end delay

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