Asynchronous on Demand MAC Protocol Using Wake-Up Radio in Wireless Body Area Network

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***Abstract*—A fast growing class of sensing technology is wearable, where network nodes are tightly coupled with the human body. Wireless body area networks (WBAN) technology has gained popularity over the last few years, with a wide range of applications covered, in particular in health and rehabilitation. Wearable and pervasive computing are able to sense, monitor and process the data to provide smart assistance and context-aware ambient intelligence environments. However present-day WBAN devices are mainly battery-powered and due to energy issue they need to be recharged every day or even hours and thus they miss the expectations for a truly unobtrusive user experience. This work presents a novel energy-efficient asynchronous MAC protocol using a nano-watt wake up radio with addressing capabilities to reduce the energy consumption of the communication and then extend the WBAN life time. We present the benefits of the wake up radio in a star topology widely used in WBAN where the number of the node is around 5 to 10. The implemented protocol exploiting the low power consumption of the wake up radio, the low latency and the addressing capabilities can increase significantly the energy efficiency of the single node and entire network reducing both idle listening and data collisions. Result based on measured power consumption and OMNET++ simulation demonstrate that by using the wake up radio it is possible to reduce the power consumption up to 150 times compared to related protocols and the lifetime can be significantly increased in a real world scenario.**

I. Introduction

Wireless body sensor network (WBAN) consists of several low-power, intelligent nodes with sensors deployed on the human body to monitor the biometrical data and the environment parameters. WBAN enables many applications in sport and fitness, gaming, human interfaces and e-health by allowing unobtrusive and continuously monitoring. In particular, healthcare systems such as personalized in-person health monitoring and treatment, that provides medical services to citizens, are used to diagnose and treatment of many diseases such as Parkinson, motion issues, asthma, and other diseases [1]. WBANs are demonstrating to be useful in improving health-related habits and reaching fitness goals. Many commercial products as activities tracker have surrounding the electronic market, together with smart phone application to motivate people to take care of their health. In many applications, wireless nodes are used to collect data from different body parts and this is another important scenario where WBAN provides an optimal solution as each single node is placed in several part of interest of the human body collecting data even from different sensors types.

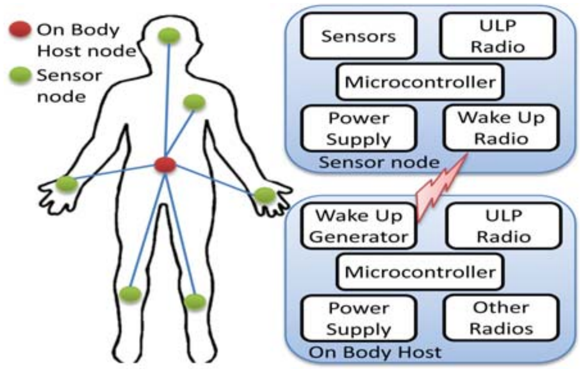


Fig. 1: A typical connection of WBAN network. Each sensor node is equipped with a wake-up radio.

A typical WBAN architecture is depicted Fig. 1. According to the application requirements, the WBAN is comprised by few or several low power sensors (or actuator) nodes which communicate with and on body coordinator/host which is more power hungry device and is in charge of collecting information and acting as a gateway with a remote host or an Internet connection[2] [3]. Although there are many different MAC protocols and radios to enable the communication between the nodes in a WBAN, probably the most used topology is the start topology using MAC protocols initiated by the receiver (host/coordinator in WBAN) such as the traditional Receiver-Initiated Cycled Receiver (RICER) [4]. This is due especially for the low power consumption requirements of this topology and the limited number of sensors/actuator devices possible to deploy in a human body. Moreover start topology in WBAN is demonstrated to facilitate the power management and power saving in combination with wake up radios technology [5] [6]. Due to this combination is possible selectively wake up the sensor node needed during the monitoring time and increase the energy efficiency of the communication. Moreover, the collisions of the transmitted data and the waste of energy due to the idle-listening of the main radio are also reduced.

In this paper we present an Asynchronous Wake-up on Demand MAC protocol (AWD-MAC) and therefore we analyze the benefits using a wake up radio with addressing capabilities with a star topology based wireless body area network scenario, where the sensors nodes are collecting their data and the host/coordinator is managing the communication as receiver of the data/information. We provide a complete OMNET++ model and simulation evolution of the benefits using a developed nano-watt wake up radio and comparison with or without addressing mechanisms. Due the presence of the wake up radio, the sensors nodes can selectively be activated by the remote host (according to a specific application) to reduce the power consumption and transmission collisions. We compared the power consumption with three different scenario in absence of wake up radio, with the use of the Wake radio and addressing done by the main micro-controller, and with the addressing performed directly by the on board low power wake up radio. We demonstrate that we can augment the lifetime of the WBAN up to 150 times for a typical usage scenario where a data sensor is sampled and sent to the remote host.

The reminder of this paper is as follow: after introduction in chapter I, in Section II the state of the art in the field is briefly introduced, and our work is compared with it. Section III describes the architecture of the system from hardware and software point of view. In Section IV results of measurements performed on the system are presented, and conclusions are drawn in Section V.

II. RELATED WORK

Research on reducing power consumption and improving energy efficiency in WBAN has been prolific in recent years. A wide variety of methods and techniques to extend the lifetime of networked nodes have been proposed [7]. This confirms the notion that extending a sensor node's lifetime is crucial to enable the success of a high number of applications. This is particularly critical in WBAN, where nodes are supplied by small form factor batteries and where the energy availability is limited. For this reason, energy efficiency and power management [8], [9] are key aspects when designing WBAN sensors, and can increase significantly the lifetime of the devices [2].

Radio devices typically consume a significant amount of available energy when they are active, since they are the most power hungry subsystem of the sensor nodes. Thus, it is advantageous to switch it off whenever possible and wake it up only when there are data to be transmitted or received [1]. However, a big part of the energy consumed in communication is attributed to idle listening. To be reactive, the radio must be active, though it only listens on the communication channel, without sending or receiving data. Collisions also cause power inefficiency as the message needs to be re-transmitted. The power consumption in idle listening is comparable with the transmitting/receiving power. As a result, several energy efficient approaches aim to reduce or eliminate idle listening with low latency[10]. Energy efficient communication protocols for WBAN can be classified into two main approaches: software (i.e. MAC with collisions avoidance and duty cycle optimization approaches) and hardware software using novel hardware (e.g. WUR) [7], [10] .

In the pure software approach, many MAC protocols have been proposed to achieve adaptive duty cycling in an attempt to reduce the idle listening time and avoid collisions [11]. However, the main drawback of these approaches is that lower duty cycles will increase communication delay, which does not match the application requirements in terms of fast reactivity and immediate communication. In this direction successful energy efficient protocol have been presented as for example traditional Receiver-Initiated Cycled Receiver (RICER) [4] and

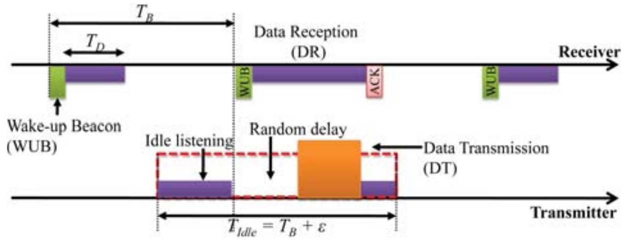


Fig. 2: Receiver Initiated CyclEd Receiver (RICER) protocol.

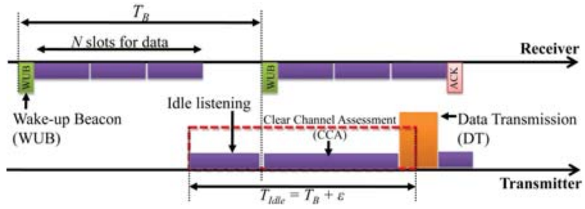


Fig. 3: RICER3 protocol. Monitoring the channel by CCA process is performed before sending a data packet.

its extended protocol, RICER3 [12]. Hardware wake up radio technology promises to eliminate idle listening by using the ability to continuously listen the channel with reduced power consumption (order or μW or less) and generate events with negligible latency. WURs are enabling MAC protocols with a reduced power consumption and low latency compared with the traditional low duty cycling MAC protocols. [14].

In this paper we propose a combination of an asynchronous, energy-efficient MAC protocol for WBAN combining the benefits of the wake up radio the benefits with a Receiver-Initiated Cycled Receiver RICER MAC protocol to increase the energy efficiency eliminating the idle listening power consumption and reducing the data collisions rate.

III. BACKGROUND ON RICER AND WAKE UP RADIO

In this section, we focus on the idle listening and the packet collision, which are the main issues on communications using receiver-initiated protocols as RICER or RICER3. In the first one, which is shown in Fig. 2, a communication is initiated by a broadcast Wake-Up Beacon (WUB) from a receiver. Meanwhile, the transmitter opens an idle listening window to receive the WUB. To guarantee a beacon can be received, the idle listening time (T_{Idle}) must be a threshold ε longer than the beacon period (T_B). Once the WUB is received, a data packet can be sent to the receiver. However, a data collision can occur at the receiver if multiple nodes receive a same WUB. Therefore, before sending a data packet, each node waits for a short random delay. If the receiver successfully receives a data packet within a period T_D, an Acknowledgment (ACK) will be confirmed. Otherwise, it turns into sleep mode and wakes-up again for sending another beacon.

In RICER3 protocol depicted in Fig. 3, the transmitter replaces a random delay in RICER by a Clear Channel Assessment (CCA) process, lasting for a random number of slots from 1 to N. Therefore, the receiver has to wait a data packet for a maximum N slots after sending the beacon. Although collision probability is reduced compared to RICER, multiple transmitters can sent their data in the same slot. Increasing the value of N can reduce the collision probability but more

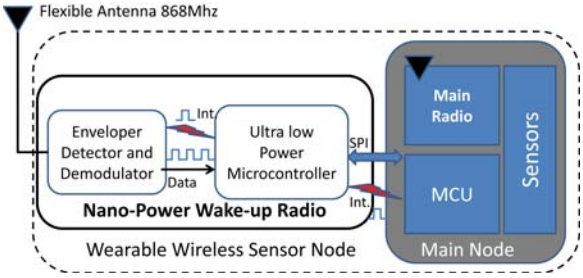


Fig. 4: Nano-watt wake-up radio based WBAN node.

energy is required at the receiver for waiting a data packet and also at the transmitter for the CCA process.

In those protocols, the first issue is that the transmitter has to perform an idle listening for a wake-up beacon, which is a dominant consumed energy in wireless communications [15]. Therefore, removing the idle listening brings a breakthrough to reduce the total consumed energy at the transmitter, leading to a great improvement of the system lifetime. Secondly, beacons are broadcasted by the receiver, leading to packet collision when multiple transmitters receive the same beacon. Moreover, it also reduces the data rate at the receiver since only one transmitter is able to send its packet. Other nodes have to postpone their packet transmissions until the next wake-up.

By using a nano-watt wake-up radio (WUR), the idle listening can be fully removed and communications among the nodes are completely asynchronous. A WUR is always active to monitor the channel and sends an interrupt signal to wake-up the main radio of the transmitter as soon as there is a request from a receiver. A brief description of the WUR using in a wireless node is presented in the next subsection.

A. Wake-Up Radio

The radio wake up is an ultra low power hardware receiver able to detect wake up signals which can be either data (i.e. addresses) or commands. In this work we used state-of-the-art nanowatt-power wake up radio with addressing capabilities (the wake up can receive and process data as well) presented in[16] activated by an On Off Keying (OOK) message at 868Mhz. Fig. 4 shows the main architecture blocks of the wake up radio. The first block is the RF front-end which is maximized to achieve -42dBm of sensitivity with a power consumption of around 390nW when it is listening the channel, due to an ultra-low-power comparator (AS1976 from Austrian Microsystem) which is the sole active component of this block. The interrupt is generate with a low latency of only few μ (8μs minimal 8μs) tuneable to few hundreds of μs to avoid false positive. Moreover an addressing mechanism is implemented to further avoid false positive and wake up only the node it is intended to activate. In fact, the second block is used to generate the final wake up signal for the main microcontroller only if the first byte received is the correct address. The main microcontroller can set its address dynamically during run-time through the SPI port and also send and receive commands. This task is done by an 8-bit ultra low power microcontroller from Microchip (PIC12LF1552) which has only 40nW of sleep power. So the overall power consumption in listening mode, when no data are received, only around 430nW. The PIC can be also bypassed, and in this case the interrupt and data after the first block can be also sent directly to the main microcontroller. In this case, it possible to eliminate the PIC's 40nW, however the main microcontroller will increase the addressing activities. In following we will evaluate the benefits of an ultra low power device to process the addressing. Addressing has also an impact on the latency to wake up the node. This latency is strongly dependent from message data rate and length of the address. For example for a 10kbps data rate and 8 bits address this will be only around 800uS and for 1Kbps data rate will be 8ms. So it is important according to the application select the right trade off between latency and addressing capabilities. For most of WBAN monitoring applications a 10ms delay to start the communication and transmit the data it is more then reasonable. Moreover this latency is orders of magnitude lower than the duty cycling protocols where usually is in the order of [4].

A receiver indicates a specific transmitter by sending a beacon including its address. When there are multiple transmitters, the receiver simply sends beacons with different addresses in a sequence to achieve successful communications with all the nodes. The details of the protocol using the wake-up radio are presented in the next section.

IV. Asynchronous Wake-Up on Demand MAC Protocol (AWD-MAC)

Our proposed MAC protocol is based on the RICER scheme. However, to further increase the energy efficiency, the idle listening process is carried on by a nano-watt wake-up radio (WUR). Due to WUR, the main radio (MR) is kept in low power mode while the WUR is always active to monitor the channel. Whenever the address in a WUB received by the WUR matches its own address, the MR is activated for data packets exchange. However, when the network is deployed, the receiver is not aware of the addresses of its neighbors. Therefore, there are two phases in our protocol: the neighbor discovery phase and the asynchronous communication phase. The strategy in each phase is explained in the following sub-sections.

A. Neighbor Discovery Phase

In this phase, the receiver sends a beacon containing the broadcast address every period T_B using its main radio to achieve the addresses of its neighbors. When a transmitter is deployed, it has to reply when a broadcast beacon (BCB) is received. As soon as the BCB is detected by the WUR, the main radio is woken-up to start the first communication. The receiver confirms this communication by an Acknowledgment (ACK) packet.

As multiple transmitters can reply to the BCB in their first communication with the receiver, packet collisions can occur. Therefore, an avoidance collision scheme is required in this phase. In this work, a strategy similar to RICER3 (depicted in Fig. 3) has been used. After sending a BCB, the receiver opens N slots, waiting for data packets from its transmitters. As soon as a BCB is received by a transmitter, a random slot within N slots is selected to send a data packet to the receiver. The address of the transmitter is embedded in this data packet. When the receiver responses an ACK to confirm a successful communication, the transmitter no longer reply to

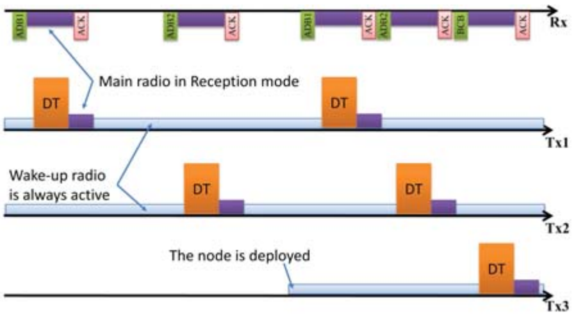


Fig. 5: Asynchronous communication phase. The receiver sends an address beacon (ADB) to the desired transmitter. It also randomly sends a broadcast beacon (BCB) to detect a new deployed node.

the BCB. It turns into asynchronous communication phase and only wakes-up when a beacon containing a correct address is received. Moreover, the transmitter data rate is also included in the packet sent to the receiver. A look-up table is constructed at the receiver to store the address as well as the data rate of each transmitter. Using this information, the receiver is able to wake-up a specific transmitter at a right time.

B. Asynchronous Communication Phase

In this phase, the receiver does not need to send its BCB every period T_B anymore. Based on the look-up table, the receiver is able to determine when its transmitters are available for data transmission. The receiver wakes up and send an address-beacon (ADB) at a given time to active only one transmitter for communication. If many transmitters are able to wake-up at the same time, a set of beacons is sent in sequence, as illustrated in Fig. 5. After each beacon, there is a slot for receiving a data packet. When a packet is successfully received, the transmitter confirms with an ACK before sending another ADB. Once there is no more transmitter to wake-up, the receiver randomly sends a BCB to perform the neighbor discovery phase again. This step is required if there is a new node, which is deployed during the asynchronous communication phase.

Thanks to the nano-watt wake-up radio (WUR), the communications among nodes are purely asynchronous: a transmission request is determined by an ADB, which is initiated by the main radio of the receiver. This approach extremely reduces the average consumed energy at the transmitter for communications. Moreover, only one transmitter, which has the right address, is allowed to wake-up its main radio for sending a data packet to the receiver. It finally means that data collisions can also be removed in the asynchronous communication phase.

Although the WUR brings a solution to remove idle listening and data collision, two issues should be considered:

- Overhearing packets: As the wake-up radio is always active in reception mode, unexpected packets can be received, causing overhearing issue. Let us take the Fig. 5 to explain this overhearing issue. When an address-beacon ADB1 is sent by the receiver to wake-up the node Tx1, it is also received by the WUR of the node Tx2. The wake-up signal is not generated to wake-up the node Tx2 as the address in ADB1 does not match. However, an extra-energy is consumed to process this beacon. Moreover, if the main radio and the WUR use the same frequency, energy due to overhearing becomes more crucial as both data and ACK packets exchanged between Rx and Tx1 are also received by the WUR of the node Tx2.
- False wake-up: This issue only occurs when the main radio and the WUR have the same frequency and modulation. When a data packet is sent from a transmitter to its receiver, (Tx1 to Rx in Fig .5, for instance), this packet may contain a sub-string that matches an address-beacon of another node (Tx2, for instance). In consequence, this node will wake-up, causing the false wake-up issue. Moreover, a data collision also happens at the node Tx1 as it is waiting for an ACK from its receiver but at this time, there is also a data packet sending from Tx2 to the receiver.

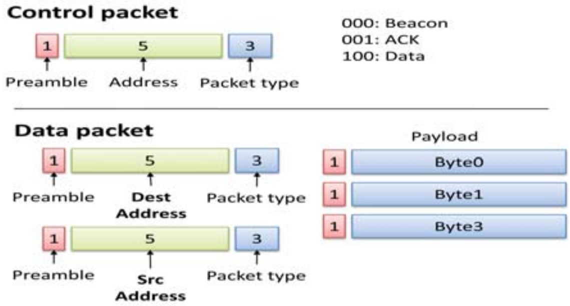


Fig. 6: Format of the packets in OMNET++ simulation.

The advantages and drawbacks when using the WUR are analyzed in a single-hop WBAN network and are described in the next section.

C. Packet Format

The different packet formats used in this paper are shown in Fig 6. There are 9 bits for the control packets, including the beacon and ACK. There is a preamble bit 1 at the beginning, followed by five address bits. The last tree bits are used to indicate the packet type. So far, only tree types have been used. Therefore, three spare values can be used for extra commands, for instance, in a multi-hop network (e.g. forwarding or routing command). Meanwhile, there are five bytes for the data packet: two bytes for the source and destination address and three bytes for the payload. Each byte is followed by a preamble bit to avoid that the WUR starts decoding a packet when there is a bit equal to 1 in the payload. Overall, there are 45 bits for the data packet.

V. SIMULATION ON OMNET++

A. Simulation Setup

To evaluate the proposed protocol a single hop network containing a Base Station (BS) acting as the host node shown in Fig. 1 and several End Devices (ED) sending their sensor data to the BS, has been implemented on OMNET++. In the context of WBAN, the distance between two nodes is less around 2-3m. Each wireless sensor node is based on the PowWow platform [17], which is composed of the MSP430 microcontroller and the CC1101 RF transceiver. This radio

TABLE I: Current profiles of the comparator and the micro-controller using for the wake-up radio model in OMNET++.

	Parameter	Value	Unit
Comparator (AS1976)	Receive bit 0	0.33	μA
	Receive bit 1	44	μA
	Sleep	180	nA
MSP430F1612	Processing	3.1	mA
	Wake-up	7.13	μA
	Sleep	19.8	μW
PIC12LF1552	Processing	55	μA
	Wake-up	0.43	μA
	Sleep	20	nA

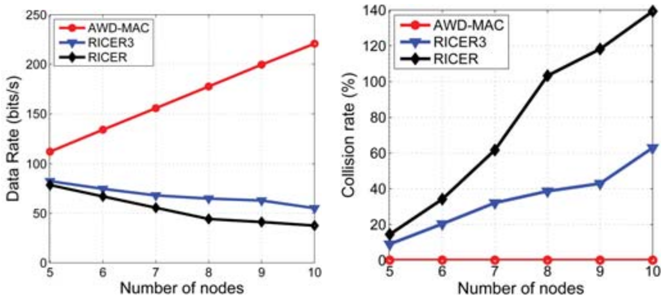
chip is configured to 868Mhz frequency, 1Kbits data rate and OOK modulation, which are compatible with our wake-up radio (WUR) receiver. Except the BS, all EDs are equipped with a WUR and able to generate a packet every 2s. The BS is firstly setup and then, other EDs are randomly deployed. As in this work we are interested to evaluate the energy efficiency of the protocol we used a simple temperature sensor to sample the body temperature, but the protocol can be applied to any other sensors.

When using RICER protocol, the BS sends its beacon every $T_B = 500$ms and the maximum idle listening for the beacon at each ED is $T_{Idle} = 510$ms. After receiving a beacon, an ED waits for a random delay from 1ms to 100ms before sending a data packet. For RICER3, the values of T_B and T_{Idle} are the same but the ED randomly selects one of 3 slots (N=3) to send its data. Each slot lasts for 50ms, which is sufficient to send a 45bits data packet in 1Kbits data rate. When using our AWD-MAC protocol, the same configuration as RICER3 is applied during the neighbor discovery phase. However, if there is no response to the broadcast beacon consecutively three times, the base station switches to asynchronous communication phase.

To evaluate our approach the WUR we modeled the WUR in OMNET++ using measured power consumption. The consumed current profiles of the WUR are summarized in Table I. The consumed current of the wake-up radio is divided into two parts: the comparator and the microcontroller. According to the received bit (0 or 1), the current consumed by the comparator is different. Moreover, our simulation model supports two different configurations for the WUR. In the first one, the WUR does not embedded the on board microcontroller (PIC). Therefore, the address decoding is performed by the MSP430 microcontroller of the wireless node. In the second configuration, this step is carried on by a ultra low power PIC12LF1552 microcontroller. As it can be observed, the PIC12LF only consumed 20nA in sleep mode compared to the MSP430 on Powwow platform, which requires around 20μA. Moreover also in active mode where the PIC can process the addressing data with lower current consumption. Therefore, the overhearing energy can be extremely reduced when using PIC12LF and will be discussed in Section V-C.

B. Base Station Performance

In this subsection we evaluate the benefits in terms of average received data rate and collision rate.The average base station received data rate (R_D) with different number of neighbors is presented in Fig .7a. It can be observed that while R_D is proportionally increased when using AWD-MAC, it is reduced in case of RICER and RICER. The reason is the



(a) (b)

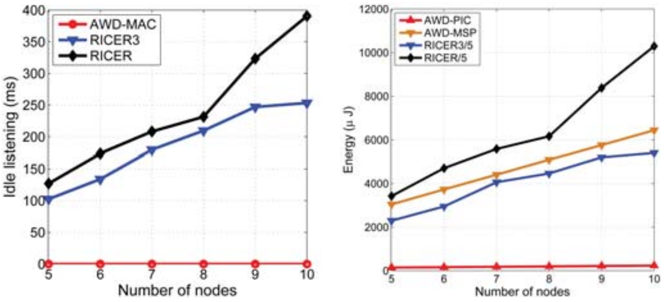
Fig. 7: Average data rate (a) and collision rate (b) at the base station with different number of nodes. AWD-MAC guarantees a high data rate as data collision is removed.

beacon period of the BS is 500ms while the data period of EDs is 2s. Therefore, there are maximum 4 nodes can send their data to the BS without any collision in the best case. However, when there are more than that, at least two nodes will reply to the same beacon, leading to data collision and then, a decrease of R_D. The RICER3 provides a better R_D than RICER protocol since monitoring the channel (CCA) is performed before sending a packet. The CCA process may last from 1 to 3 slots. Therefore, the data collision is reduced when compared to the random delay in RICER. In the other hand, AWD-MAC guarantees R_D linearly increases with the number of nodes. The reason is AWD-MAC sends a set of beacons to wake-up multiple neighbors in a sequence instead of only one common broadcast beacon as in case of RICER and RICER3. This is the first improvement of AWD-MAC compared to related protocols. At a given time, the BS exactly knows which neighbors are able to send their data. Therefore, an appropriate beacon for each neighbor is sent to request its data.

The second improvement of AWD-MAC is that the data collision is almost removed. This is achieved as only one ED is allowed to send its data at a given time. Collisions only occur during neighbor discovery phase or when a broadcast beacon is sent (BCB). However, this phase lasts for a short period (around 30s) compared to the whole simulation time (1 hour). The collision rate (R_C) for the different protocols, which is defined as the ratio between the number of collisions and the number of successfully received packets, is shown in Fig. 7b. When there are 10 nodes, the number of collisions is only 15 times, or R_C = 0.09% . This advantage allows improving the received data rate more than twice, as shown in Fig. 7a.

C. End Device Performance

The impact of our approach is even more important at the ED, which is equipped with a wake-up radio receiver (WUR) where it is possible now eliminate the idle-listening power consumption needed in RICER and RICER3 protocols. In this scenario, only one EP sends the data while remaining nodes have to turn into sleep mode. These nodes waste energy waiting for a beacon but are not able to send their data, leading to the increase of the average idle listening time for a data packet, as shown in Fig .8a. When the number of nodes is increased, this issue becomes more crucial as the idle listening quickly increases with RICER and RICER3. By using the WUR, it is possible solve this issue as shown in fig.



(a) (b)

Fig. 8: Average idle listening (a) and energy consumption (b) for successfully sending a packet at the end device. It is noticed that the energy is scaled 5 times in RICER and RICER3.

Moreover, the average energy required for sending a packet (E_{Tx}) is also significantly reduced as shown in Fig. 8b. The reason is that idle listening is the main power hungry task. In this figure, two different modes of the WUR are considered: the PIC mode (AWD-PIC) and the MSP mode (AWD-MSP). It is noticed that E_{Tx} is scaled by 5 times for RICER and RICER3. In the case of RICER and RICER3, the data collision causes the wasted energy consumption. Meanwhile, overhearing packets are the reason of an increase of E_{Tx} when AWD-MSP is used. However, it seems that E_{Tx} is extremely low and almost constant. Energy consumption using PIC12LF to decode overhearing packets is only in order of nW and therefore, has a low impact on the global energy consumption. Specifically, 95.93% energy is saved compared to MSP430.

To demonstrate the impact of our approach in a real WBAN using the 7 Powwow platforms as sensor node and one as host node. The acquisition data sample for the temperature sensor was every 2s. The host also collected data from the sensor every 2s. In this scenario we evaluate the sensor node lifetime using a 2500mAh battery for each node with our different approaches (addressing on board and MSP430) and the traditional RICER and RICER 3. In this condition the lifetime of the battery was 3years for the proposed AWD-PIC with on board addressing, 44days AWD-MSP, and only 7 and 10 days for the traditional RICER and RICER3.

VI. Conclusion

A novel asynchronous MAC Protocol for WBAN has been presented. The proposed approach exploit a state-of-the-art wake up radio in combination with a RICER protocol to significantly improve the energy efficiecy . The proposed protocol allows to eliminate idle listening and to reduce collision rate. Due to these two important features, it is possible have a high efficient MAC protocol. Experimental results based on the real measured of power consumption, accurate OMNET++ model of the wake up radio and the sensor platform, and simulation demonstrate the benefits of the proposed approaches in terms of power saving, idle listening elimination, collision rate and lifetime extension considering a network up to 10 node. It has been showed the proposed protocol increases the lifetime of the node from only 10 day using a RICER3 protocol to 3 years using a temperature monitoring application. Future works will evaluate the false positive influence of the WUR and the effects of the latency due to the WUR addressing capability.

VII. Acknowledgement

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