Extending Body Sensor Nodes' Lifetime Using a Wearable Wake-up Radio

Andres Gomez*, Xin Wen*, Michele Magno*† and Luca Benini*†

*D-ITET, ETH Zurich
Gloriastrasse 35, 8092 Zurich, Switzerland
{firstname.lastname}@ee.ethz.ch

†DEI, University of Bologna
Viale del Resorgimento 2, 40132 Bologna, Italy
{firstname.lastname}@unibo.it

Abstract. Body Area Networks (BAN) have received significant attention in recent years and have found a wide range of applications, including wearable devices for fitness and health tracking, mobile communications, among others. Energy storage devices such as batteries continue to be a bottleneck in these small form factor devices, thus requiring advanced power management techniques to sustain devices' increasing power and lifetime demands. As radio transceivers are typically the most power hungry subsystem in wearable sensors devices, many techniques focus to reduce the communication power consumption. In this work, we focus on wake-up radios as a novel technology which can be in listening mode consuming only few nW, significantly reducing the overall power consumption of communication. We evaluate the performance of state-of-the-art wake-up receivers (WUR) in the BAN context, and the tradeoffs between its addressing capabilities, range, and sensitivity. Using in-field measurements, we quantify energy savings and estimate the resulting prolongation of the sensor node's lifetime in a wearable gait-detection application, where nodes communicate via a Bluetooth main radio.

Keywords: Body Area Networks, Wake-Up Receiver, Energy Efficiency.

1 Introduction

With the rapid development of technology, increasing functionality is being integrated into wearable devices. Wearable technology is strategic in healthcare, where smart electronic devices can continuously monitor patient's vital signs and enable doctors to identify possible diseases earlier and to provide optimal treatment [1]. These new capabilities have led to increased power requirements, while wearable devices continue to trend to smaller, slimmer and lighter form factors [1]. As a result, many power and energy-aware techniques have been proposed to address these conflicting goals.

Reducing the power consumed in communication by wireless sensor nodes can be very effective, since the radio transceiver is one of the components with the highest power consumption, as shown in Fig. 1. One common way of reducing the energy consumed by the radio is duty-cycling. The node can switch the radio between active

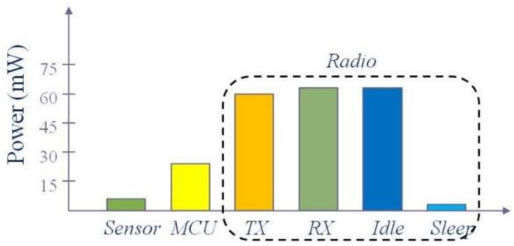


Fig. 1. Typical power consumption in wearable nodes [11]

and sleep mode with predefined intervals. Low-power states are programmed to take place only when no communication is supposed to happen. However, there are some limitations to duty-cycling. First, devices still have to stay in idle listening during certain periods. Second, overhearing communications destined to other devices will also cost a considerable amount of energy. Third, radios have to be synchronized in order to guarantee proper communication among devices. Synchronization implies that transmitters have to wait for a sufficient amount of time before sending any meaningful data. Since receivers cannot successfully receive a message in sleep mode, they must kept ON even when no information is being sent or received. Another approach is to use asynchronous schemes, which are generally considered to be the most power efficient ones, since they practically eliminate the costly idle listening [1],[5]. Here, an ultra-low power wake-up radio receiver (WUR), usually coupled with another (main) radio, listens continuously to the transmission medium and wakes up the main radio only after a wake-up signal is detected. Naturally, there are clear trade-offs between cost (an additional receiver is needed), and the potential energy savings.

In this work, we implement a state-of-the-art WUR architecture in the context of BAN applications, perform a thorough evaluation of the WUR's range/addressing capabilities and their impact on the energy savings. To this end, a gait detection application for Parkinson's disease (PD) with one sink node and two sensor nodes is studied. Using real-world measurements of the implemented system, we calculate the prolongation of the sensor nodes' lifetimes and demonstrate the savings introduced by the WUR.

2 Related Works

To reduce communication power consumption, several techniques have been proposed for lowering or eliminating the power wasted for idle listening of the transceiver [7], [8]. Duty-cycling is a common technique to reduce the idle mode energy consumption which consists of switching from listening mode to sleep mode [7]. However, even though duty-cycling helps saving power, it can severely limit the reactivity of the devices, since radios cannot receive messages when they are off or in sleep. Asynchronous techniques have also received considerable attention because of their increased energy efficiency. In [9]-[11], several different architectures for ultra-low-power WURs for wireless sensor network devices are presented. These works all reduce the idle listening and significantly reduce the overall network energy consumption. In [3], a novel solution consuming only 98nW is presented. This solution uses a comparator, and a custom CMOS rectifier designed to achieve sensitivity of -41 dBm. In [13] and [18], the authors present a thorough survey of various wake-up schemes and their advantages over duty-cycling schemes. Addressing capability, though costlier in terms of power, is the only way to achieve selectivity, which can be an important parameter for certain applications.

In this work, we focus on a state-of-the-art WUR, presented in [15], and evaluate the impact of its operating modes (with and without addressing) and its performance in the context of a wearable application. Furthermore, we calculate the energy savings introduced by the WUR, by estimating the sensor node's lifetime in the gait-detection application.

3 Wake Up Radio Overview

In this section, we present an overview of the communication with wake up radios in a wearable application scenario. Fig. 2 shows two main wireless devices of a typical wearable system: the sink node and the sensor node (which can be also more than one), and their main components. The sensor node, which reads and processes data from a sensor, will transmit the data via the main radio (i.e Bluetooth Low Energy) only after the WUR receives a wake-up signal from the sink node. This work focuses on the battery-based sensor node, and how its lifetime can be significantly extended using a WUR.

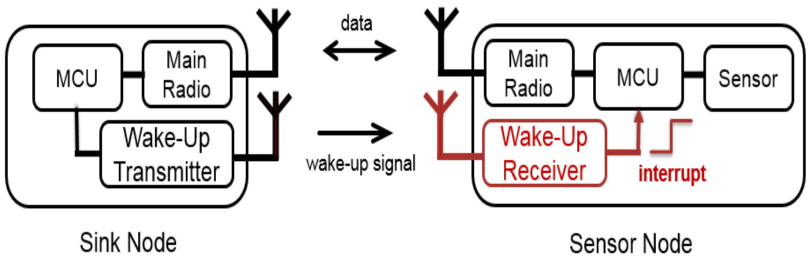


Fig. 2. Block diagram of the proposed system

Sink Node (SN). Usually body area network systems are centered on a sink node which is the node in charge to collect data from the sensor nodes and organize the network. Furthermore, it can request information from the sensor node. When no WUR is used, the communication is done via the main radio, which requires both radios (sender/receiver) to be turned on even when there is no data transmission. With WUR the main radio can be turned off when no data transmission is needed and still listen the channel with an ultra-low power radio (WUR). This is an important feature, in many wearable applications, where activation and deactivation of the main radio can be determined by the context (i.e. if the sink node detects some activity from the sensors). It should be noted that to send the wake-up signal, an additional wake-up transmitter radio is required on the sink node, meaning there is a clear trade-off between the additional cost and energy savings. Later on, in the evaluation section, we will test for two transmitter antennas with different form factors and gains, which will be important parameters for the product's design.

Sensor Node (SEN). The sensor node is usually placed on the human body to collect and process data from sensors. If no WUR is used, then the sensor node has no choice but to keep the main radio on continuously or activate it with duty cycling, dealing with the tradeoff of reactiveness and energy saving. This scenario can be seen in Fig. 3.a. Using the WUR, the sensors node has the capability to be in continuously listening mode, waiting for the sink node messages and activating the main radio only when it is needed. This process can be seen in Fig. 3.b. It is important to notice that as the WUR is an additional, always-on component, its power consumption has to be significant lower than the main radio (in the order or nanoWatts) to be effective. The latency is another critical feature, as the main radio has to be switched on as soon as possible. This work focuses on evaluating this wake-up process with on-the-field measurements of the maximum range and the impact that false negatives, false positives, and packet losses could have in the total energy savings of a BAN application. We will evaluate a WUR presented in [15] which consumes only around 600nW with a latency of few microseconds. The WUR sensitivity is -42dBm which allows to achieve few meters with wearable antennas. The wake up radio provides two modalities with addressing and non-addressing: when using addressing mode the sink node is able to select which sensor node to wake up using an address. In the non-addressing mode, all nodes within the range of the message are woken up. The main difference lies in the length of the packet and the energy required to sample and decode the address.

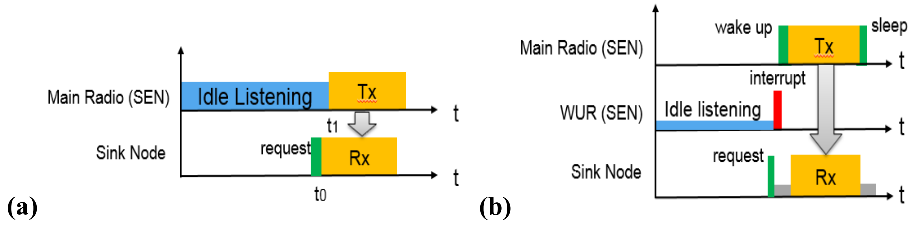


Fig. 3. Sample timeline with (a) only a main radio, and (b) with a main radio and a WUR.

4 Experimental Evaluation

In this section, we will first introduce the experimental set-up used to characterize the range and performance of the implemented WUR. The first range experiment, is done using two antenna on the sink nodes (SN). The first, shown in Fig. 4.a, uses a low gain 0 dBi PCB antenna which uses only 1cm^2 of space. A second SN with a higher gain, 7 centimeter long, 2dBi antenna, shown in Fig. 4b, was also tested. In these experiments the radio was configured with On Off Key modulation for the messages and 868MHz frequency with 1.2 Kbps and +10dBm power output. At the receiving part, we used a WUR with a flexible antenna by Molex [16], with a gain of 2.2 dBi as the sensor nodes have to be placed on the body. The bendable antenna, shown in Fig. 4.c, measures only 1.3 cm x 10.67 cm, and can be placed directly on the node or on the body.

(a) SN with low gain antenna **(b)** SN with high gain antenna **(c)** WUR bendable antenna

Fig. 4. Antennas used for the wake-up transmitter and receiver (not to scale).

4.1 WUR Range & Performance

The first part of the experiment aims at testing the communication range of the system. The distances between the sink and sensor nodes was varied from 10 cm to 315 cm, and 1000 packets where generated 3 seconds apart. Afterwards, it was recorded whether the sensor node detected the wake-up signal and generated the interrupt. The results can be seen in Fig. 5. As expected, the sink node with the high gain antenna has a longer range, over 3.1 meters, which is suitable for many wearable application where few meters are required. It should be noted that the difference in range between the *non-addressing* and *addressing mode* is only noticeable for the low gain antenna, where a gradual decrease in the success rate indicates some decoding errors in the address bits.

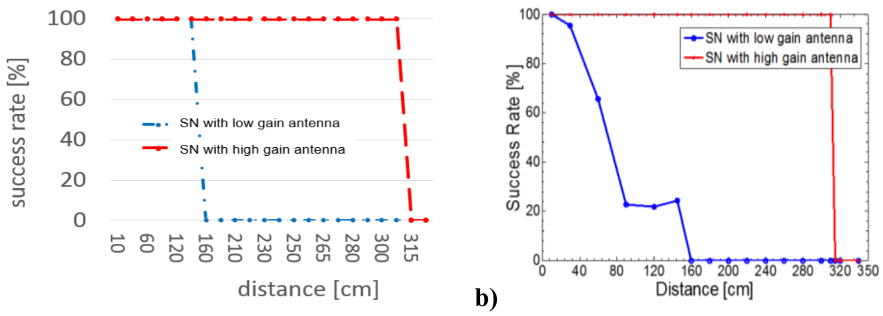


Fig. 5. WUR success rate evaluation in (a) *Non-addressing Mode*; and (b) *Addressing Mode*.

So far, it has been shown that the WUR can have a range from approx. 1.6 to 3.1 meters, depending on the antenna, which is a common communication range for many BAN applications. We will now evaluate the WUR's different performance parameters using the sink node with a high gain antenna, placed at a maximum distance of 85cm from the sensor nodes. This corresponds to the distance between the waist and feet of our test subject in standing position, as shown in Fig. 6.

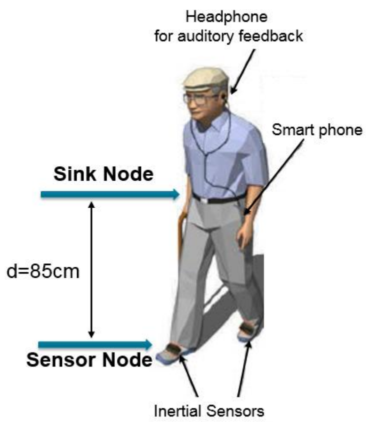
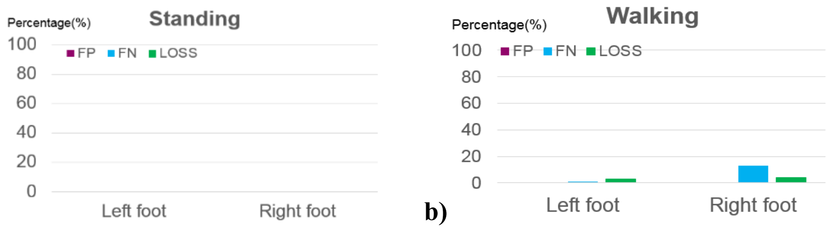


Fig. 6. Nodes worn by user in gait detection application. Modified from [6]

During the experiment, the patient will be either standing or walking, and the performance parameters were recorded. The parameters relevant to this study are:

1. False positive (FP): number of false wake-ups when not needed
2. False negative (FN): number of non-wake-ups when needed
3. Packet loss (LOSS): number of packets lost during transmission process

FPs lead to sensor nodes' unwanted wake-up of the sensors node due to an interrupt by the WUR. The wake-up process using Bluetooth is quite costly and would waste considerable energy if it tries to establish a connection when not needed. FNs occurs when the WUR is not able to detect correctly the wake up messages. FN will generate only a small latency, since the sink node use a timeout mechanism to simply re-send a second packet in order to wake up the selected sensor node. As a consequence, these two parameters are meaningful in evaluating the quality of the wake up radio systems. Fig. 7.a, shows the measurements when the user is standing. Here, there were no losses, false positives or negatives. This means all the messages has been received correctly. Fig. 7.b shows the same test except for the user who is now walking in a building. Due to the movement of the user's legs, the body occlusions, the environmental Radio Frequency noise, FN's and LOSS's now occur. It should be noted that the result is slightly worse on the right foot, because the sink node is mounted to the left side of the user's waist and the human body occlusion is worst. More importantly, even with movement, there were no FP's, so the sensor node will incur the costly wake-up cost only when truly necessary.



a) **b)**

Fig. 7. On the field measurements of WUR with addressing in different conditions.

4.2 Lifetime Analysis

In the last section, evaluation of energy consumption has been done in order to demonstrate quantitatively the improvement of the proposed architecture. We used a gait detection application for Parkinson's disease (PD) presented in [2,6]. The authors of [2,6] have presented a wearable sensor system that can assist patients by detecting gait disturbances using IMU sensors attached to their feet. When an event is detected, it triggers auditory feedback that can help the patient overcome the episode. The gait detection system is composed of three nodes, one sink node and two sensor nodes. The sink node is placed in the waist, and also contains sensors that can recognize the context: whether the patient is walking, or sitting down. The two sensor nodes are placed on the patient's feet. These nodes read the sensor data and do the feature extraction that allows the system to detect gait disturbances. However, since gait anomalies could only occur while the patient is walking, the sensor nodes could potentially enter sleep mode when the patient is sitting down. Patients with advanced Parkinson's disease tend to be seniors who spend most of their time sitting or in bed, which would allow potentially large energy savings. Since the sink node has the ability to detect when the patient is walking, only then will it send a wake-up signal to the sensor node so it can turn on the Bluetooth radio for data transmission.

Table 1. Sensor node's power consumption, with and without WUR.

Radios Used	Idle Listening Power	Transmission Power
Bluetooth	92.4 mW	135.3 mW
Bluetooth and WUR	600 nW	135.3 mW

To quantify the impact of the WUR on the lifetime of the sensor node, we will compare an initial system with only a Bluetooth 2.0 radio (BLU), and another with Bluetooth and a WUR (BLU+WUR). The former will maintain the Bluetooth radio on (in idle mode) even if the user not walking, while the latter will have it on only when the user is walking. To calculate the lifetimes of these systems, we first estimate the energy they consume with power measurements on our implemented system. These values, measured at 3.3V, can be seen in Table 1. The Idle listening power of the node with only the Bluetooth is around 92.4mW. This value comprises both the Bluetooth power consumption and the idle power consumption of the rest of the node. When the WUR is present the power whole node can be in deep sleep mode as the WUR can act as a wireless switch [17], then the power consumption include only the WUR power consumption (600nW). The energy consumed in one idle to active cycle is calculated as follows:

$$E_{BT} = P_{idle,BT} * t_{idle} + P_{active} * t_{active} \tag{1}$$

$$E_{BT\_WUR} = P_{idle,BT\_WUR} * t_{idle} + P_{active} * (t_{active} + t_{wake\_up}) \tag{2}$$

Equation (1) represents the energy consumed by the Bluetooth-only system, which is simply the sum of the idle and active energies based on their respective power consumptions, from Table 1. The idle time (t_{idle}) is the time the patient spends sitting, when the Bluetooth radio is not transmitting data and t_{active} is the time the patient spends walking, during which there is Bluetooth transmission. Equation (2) represents the energy consumed by the Bluetooth and WUR system. The main difference between these equations is the idle power, as shown in Table 1, and the inclusion of the t_{wake_up} term, which is the amount of time it takes for the Bluetooth radio to turn on and be ready for transmission. Lastly, with these energies per cycle, we can estimate the systems' lifetime when connected to a fully charged, 150mAh Li-Ion battery, using the following equations:

$$Lifetime_{BT} = \frac{C_{batt} * V_{cc}}{E_{BT}} * (t_{idle} + t_{active}) \tag{3}$$

$$Lifetime_{BT\_WUR} = \frac{C_{batt} * V_{cc}}{E_{BT\_WUR}} * (t_{idle} + t_{active} + t_{wake\_up}) \tag{4}$$

Equations (3) and (4) show the lifetimes of the Bluetooth and Bluetooth+WUR systems. These can simply be thought of as the number of cycles that the battery can supply from a given initial capacity (C_{batt}). The calculation is done by assuming $t_{wake\_up} = 3$ seconds, $t_{active} = 30$ minutes, t_{idle} was varied from 0 to 30 minutes and Vcc was 3.3V. Fig. 8 shows the estimated lifetimes, in hours, as a function of the idle to active time ratio. When this ratio tends to 1, it means the device was active mode the entire time. Conversely, as the ratio tends to 0, the device spends more time in idle mode. The figure shows two lines, the blue indicates a system with only a Bluetooth ratio, and the red shows the same system with Bluetooth and WUR. Finally, the more time the patient spends sitting down, the more time the system spends in low-power mode, and the greater the energy savings.

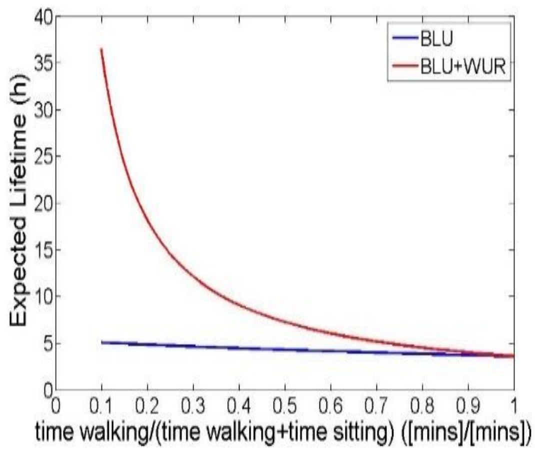


Fig. 8. Expected lifetime with and without the WUR.

5. Conclusions

This work has evaluated the feasibility of WUR for BAN nodes and its potential energy savings in a real BAN application. Thorough testing of the WUR's performance have demonstrated that its range of over 3 meters surpasses the needs of many BAN applications. Furthermore, its addressing capabilities would increase the network's selectivity and the node's lifetime, with only marginal false positives and negatives. In the studied gait detection scenario, two nodes have been attached to the body of an individual and the evaluation has been done in standing state and walking state separately. Lastly, we have calculated the energy savings introduced by the WUR and the resulting prolongation in the node's lifetime of up to 7 times, depending on the amount of time the system can be in sleep mode.

Acknowledgments. This work was supported by "Transient Computing Systems", SNF project (200021_157048), by SCOPES SNF project (IZ74Z0_160481), and ETHZ Grant funding.

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