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Energy-Efficient Context Aware Power Management with Asynchronous Protocol for Body Sensor Network

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Abstract MEMS sensor technology and advances in electronics, low-power processors and communication have enabled ubiquitous monitoring, providing significant opportunities for a wide range of applications including wearable devices for fitness and health tracking. However, due to the limited form factor required, there remains a challenging issue that limits even more the success of wearable devices: the limited lifetime due to the small energy storages that supply the devices. This limitation affects usability and forces the data processing to keep low-complexity to match the power constraints. As wireless communication is typically the most power hungry activity in wearable sensors devices, many techniques focus on reducing the communication power consumption. For this reason, advanced power management can be exploited to increase the lifetime of the devices. In this work, we present a wireless body area network with an adaptive power management strategy combining an ultra-low power wake up radio with context awareness. The context aware power manager is based on activity recognition, which is evaluated to decide which other nodes must be activated. The nano-power wake up receiver is used to reduce the idle listening power of the main radio and enable an asynchronous ultra-low power protocol. In order to evaluate the benefit, we present a real world application to assist elderly people in gait rehabilitation through a closed loop feedback. Experimental results demonstrate the benefit of the proposed power management in terms of energy efficiency. We evaluate the overall power consumption of the system and the lifetime extension, which can increase up to a factor of 4 depending on the amount of time the system can be placed in sleep mode.

Keywords Body area networks · Power management · Wake-up receiver · Energy efficiency · Context recognition · Asynchronous communication

1 Introduction

Due to the rapid development of wearable technology, Wireless Body Area Network (WBAN) is, today, 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]. WBAN devices have led to increased power requirements due to more and more functionalities, while the trend towards smaller devices and slimmer/lighter form factors continues [1]. As a result, many power and energy-aware techniques have been proposed to address these conflicting goals. In particular, in rehabilitation applications, the WBAN is also used

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for real time processing and feedback provisioning. Furthermore, the application imposes strict requirements in quality of service, i.e. accuracy of the measurements, timing, avoidance of data loss, etc.

Hardware and software approaches focus on node–level power management techniques such as dynamic voltage and frequency scaling, power-aware scheduling, dynamic power management, etc. Alternative approaches are based on hardware choices such as use of low-power radios or custom ultra-low power hardware components or subsystems [2]. In fact, 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. To address power management challenges in WBAN, the development of activity aware power management approaches that can be generalized to other contextual information (from which the name CAPM – context aware power management). Depending on user activities and application goals, the device switches between different power management policies corresponding to different setup of the unit components (i.e. sensor sampling rate, microcontroller configuration or transceiver power states, etc.). In another work [4], CAPM is tested at node level. However, the knowledge of the context can influence more than one node in a WBAN and in particular, we focus on the possibilities offered in a multi-node scenario, augmenting our previous work. In this work a software strategy based on CAPM is combined with the availability of an ultra-low power hardware component, the radio trigger [5] enabling to selectively wake-up nodes at the best convenience. The use of the wake up radio in WBAN has been proposed in previous works [7] [8], but the combination with an activity aware power manager in a rehabilitation scenario has not yet been attempted.

The highest benefits can be reached by combining hardware and software techniques and this is the approach followed in the present paper. We analyze the benefits of using the combination of power management with on-board activity recognition and a wake-up radio in a gait rehabilitation scenarios, where the user wears a wireless sensor system comprised by 3 inertial nodes developed around a dual core heterogeneous processor from NXP. In one system two nodes are deployed on the feet and a third is placed on the trunk and perform the activity classification. The feet nodes are equipped with a wearable wake up radio, which consumes around 2 μW@3 V, and they are switched on and off from the node on the trunk according to the activity detected by the power management. With this approach the system can increase the energy efficiency; in fact, in the selected rehabilitation scenario nodes can be activated only when the user is walking for periods longer than 1 minute and remain in a low power state for the rest of the time with only the wake up radio activated. We compared the power consumption with the use of the Context Aware Power Management (CAPM) alone and with the combination of CAPM and wake up radio. We demonstrate that we can significantly enhance the lifetime of the WBAN for a typical usage scenario. 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.

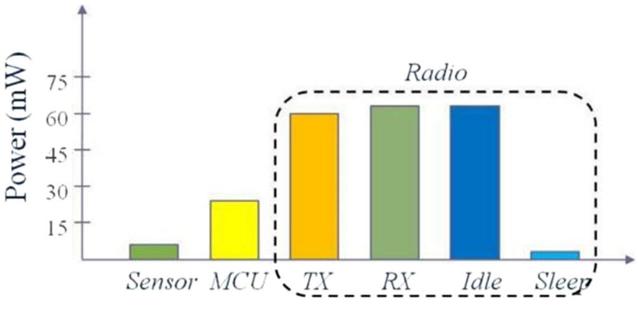


Fig. 1 Typical power consumption in wearable nodes [3]

The reminder of the paper is as follow: after introduction in Section 1, in Section 2 the state of the art in the field is briefly introduced, and our work is compared with it. Section 3 describes the architecture of the system from hardware and software point of view. In Section 4 results of measurements performed on the system are presented, and conclusions are drawn in Section 5.

2 Related works

Many works on WBAN focus on reducing power consumption and extend battery life time on both software and hardware. However, nearly all the major techniques try to reduce communication power consumption. Software strategies includes Dynamic Power Management, achieved by reducing the activities of a node, by changing the duty cycle and by waking up the system from deep sleep modalities. Duty-cycling is a common technique to reduce the idle mode energy consumption which consists of switching from listening mode to sleep mode [11]. 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. There are other reasons why duty-cycling can be detrimental in our application scenario. 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 be kept ON, even when no information is being sent or received. Several techniques have been proposed for lowering or eliminating the power wasted for idle listening of the transceiver [11, 12]. Other software techniques are trying to reduce the amount of data transmitted to a host node. For example, in [23,] the on board processing is optimized to reduce the communication activities and then the power consumption by processing the data directly on board. In [24] compressed sensing is used to reduce the amount of data to be sent via radio and minimize the overall power consumption due to the communication. 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, 9]. Here, an ultra-low power wake-up radio receiver (WUR) [18], usually coupled with another (main) radio [23], listens continuously to the transmission medium and wakes up the main radio only after a wake-up signal is detected [20]. Naturally, there are clear trade-offs between cost (an additional receiver is needed), and the potential energy savings. Asynchronous techniques have also received considerable attention because of their increased energy efficiency [6]. In [13–17], 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 [7], 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 [15, 16], 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 combine context aware power management (CAPM) techniques using on board low power processing and the benefit of wake up radio, to extend the lifetime of body sensor nodes. In field evaluation of the whole system is presented and the benefits of our approach are presented together experimental results and 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 System overview

The purpose of the system is to assist elderly people in gait rehabilitation through a closed loop feedback. To perform such task, it is necessary to have one wearable sensor node on each foot and a central node for coordination, data collection and feedback restitution (Fig. 2). Our system is constituted by the following components: one Master Node (MN), two Slave Nodes (SN) capable to collect inertial data and perform basic data processing to extract gait features.

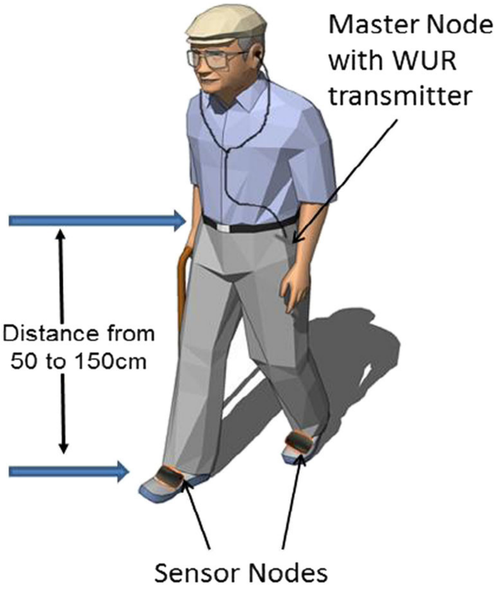


Fig. 2 Nodes worn by user for gait detection. The system is a variant of [10]

The sensors nodes are worn on the shoes whereas the master node is worn on the waist of the subject. Due to its position on the waist, the MN is able to compute subject's trunk posture and to detect subject activity. The algorithms used to compute gait features are derived from OpenShoe Inertial Navigation System [25]. Thanks to these algorithms, it is possible to extract and to compute step features like step duration, step length, step velocity, foot elevation, etc. The system can work in two modes: SN collect sensory data and extract gait features that are sent to MN where results from both feet are combined to generate a feedback. While the MN has to be active to monitor the subject's activity, SN can be turned off when the person is not walking, thus we implemented a context detector on the MN to detect when the subject is walking and a radio wake up to send wake signal to SN also when they are in deep sleep condition. The system is constituted by a processing and sensing unit, and a radio wakeup connected to them through I/O pins and SPI port (Fig. 3).

3.1 Master node

The master node is designed around the NXP LPC54102 microcontroller, which has a heterogeneous multi-core architecture. The chip includes one ARM Cortex-M4F processor core (higher performance) assisted by one ARM Cortex-M0+ coprocessor (lower power). In this way, tasks can be strategically positioned to match the application's performance requirements in an energy efficient way. The node hosts also a motion sensor, the BMC150 from Bosh, which includes a gyroscope and a triaxial accelerometer; however in this work we use only the accelerometer. The LPC54102 microcontroller samples the sensor and processes the data using the Bosch BSXlite library and can send the results over via the wireless communication. As

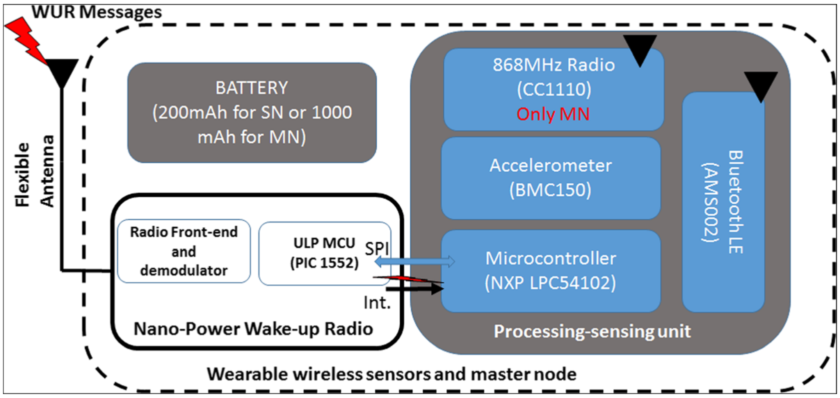


Fig. 3 Wearable wireless sensor node architecture

radio interface there is both a Bluetooth Low Energy (BTLE) module, the AMS002 from AckMe Network, and an 868 MHz transmitter, the PIC 16lf1824t39A from Microchip. The BTLE is used to exchange sensors data between MN and SN, while the 868 MHz transmitter is used to send On-Off-Keying wake up messages detected by the WUR receiver on the sensor node and consumes only around 577nW when in deep sleep and 3 mW when transmitting wake up messages. This double wireless interface is present only on the MN as it is the only node in the network which has the capability to wake up and send commands to the others nodes. The main node has no WUR receiver as this is used only by the sensor node to go in sleep mode and waiting for wireless messages to wake up again.

3.2 Sensor nodes

The sensor node architecture is similar to the MN, but the node includes also a nano-power wake up radio, instead of the 868 MHz transmitter, together with the Bluetooth module, which is able to detect wake up messages and generate interrupts for the microcontroller and does not include the 868 MHz transmitter, as peripheral nodes do not need to wake up other nodes. Due to the presence of the wake up radio receiver, the Bluetooth radio on the SN can be completely switched off when the communication is not needed. In this state, the node is in listening mode only on the wake up radio channel, thus saving a huge amount of power while keeping the wireless wake up capability. In fact, the wakeup radio can be seen as a stand-alone receiver, which always listens to the medium and wake up the processing and sensing unit only when the MN sends a wake up message. The two subsystems WUR and Processing-sensing units together comprise the whole sensor node.

Thus, SN and MN are different: the SN can be powered with a battery with a capacity reduced of a factor 5 w.r.t. the battery of the MN (i.e. 200mAh w.r.t. 1000mAh); thus SN can be optimized in terms of wearability reducing overall weight and size. Furthermore, the MN is equipped with a radio wakeup transmitter whereas an SN mounts a receiver.

3.3 Wake up radio communication and architecture

In this section, we present an overview of the communication with wake up radios in a wearable application scenario. Figure 4 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.

As mentioned before, the main role of the wake up radio receiver is the detection of radio wake-up messages when the main radio, or in our specific system the BLE, is switched off. The primary aim of the wake up radio subsystem is the reduction of the overall power consumption, exploiting the idle listening mode of Bluetooth, which is in the order of milliwatts. In fact, usually the Bluetooth radio wastes energy even in low power mode. Due to the wake up radio, this idle energy can be completely avoided. However, the wake up radio needs to be always on not to miss important messages and allow fully asynchronous communication. Thus, it is important that the power consumption of the wake up radio be order of magnitude smaller than the power consumption of the main radio. In typical WBAN's, the main radio power consumption is around few milliwatts, therefore the power budget of the wake up radio should be in the order of microwatts. Another important feature of wake up radio is the capability to receive data as short messages, which can be parsed directly on-board. This feature enables the addressing capability, so that we can wake up specific nodes using addresses. Furthermore, it enables the possibility to receive short commands without switching on the main radio. The addressing capability reduces also significantly the false positive of the main radio, as the wake up radio can detect wrong messages, and then the overall power consumption is reduced.

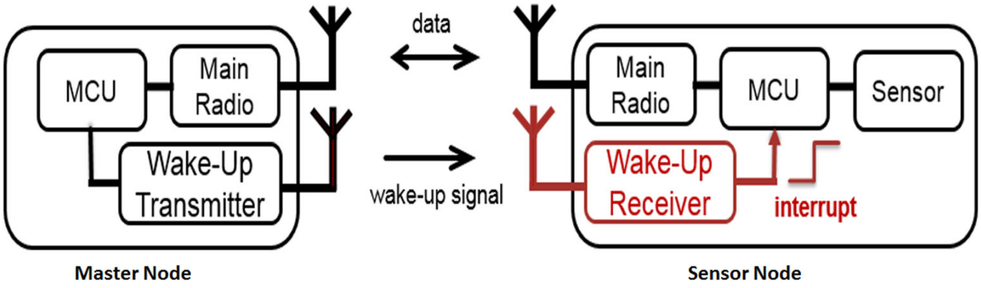


Fig. 4 Block diagram of the proposed system

In this work we used a novel architecture shown in Fig. 5, with a flexible antenna by Molex [20]. The messages are sent using the On-Off Keying (OOK) modulation at a frequency of 868 MHz. The wake up radio includes a passive radio frequency front-end, a data generator made with an active comparator and an ultra-low power 8-bit microcontroller, which can parse the data received by the antenna. Due to low power design the wake up radio consumes only 2 μW in sleep mode, and 165 μW when is receiving the data.

3.4 Context / activity power manager

To extend the lifetime of the whole system, a power management strategy is presented. Typically, if SNs are always active their battery duration is limited to few hours. However, as the SNs need to compute gait parameters, they need to be in active-mode only when the subject is walking. To benefit from this knowledge, we developed and implemented a Context Aware Power Manager (CAPM) on the MN. In the context of gait monitoring, a centralized power manager is desirable since both SN must use the same power management policy. The CAPM is implemented as a background task on the MN, which continuously analyzes accelerometer data and is able to detect if the subject is: walking, running, going up/down the stairs or is in a rest condition (feet are not moving), and choose proper power management policy accordingly. The CAPM is essentially constituted by an activity detection algorithm and a set of power management policies, one for each context of use. Each policy differs from the other for factors such as sensors sampling frequency, MCU frequency and data transmission rate. The context detection algorithm has been designed so to have a minimal impact on the power consumption of the node; this has been achieved through the optimization of every step in the classification process. The steps are: data collection, segmentation, feature extraction, and classification. The context activity power management proposed in this work is an extension of a previous work [4] where more details can be found.

To reduce power consumption of the data collection, we only use the tri-axial accelerometer data since it utilizes a fraction of the power required by gyroscope, and delivers better accuracy than the magnetometer when determining the activity.

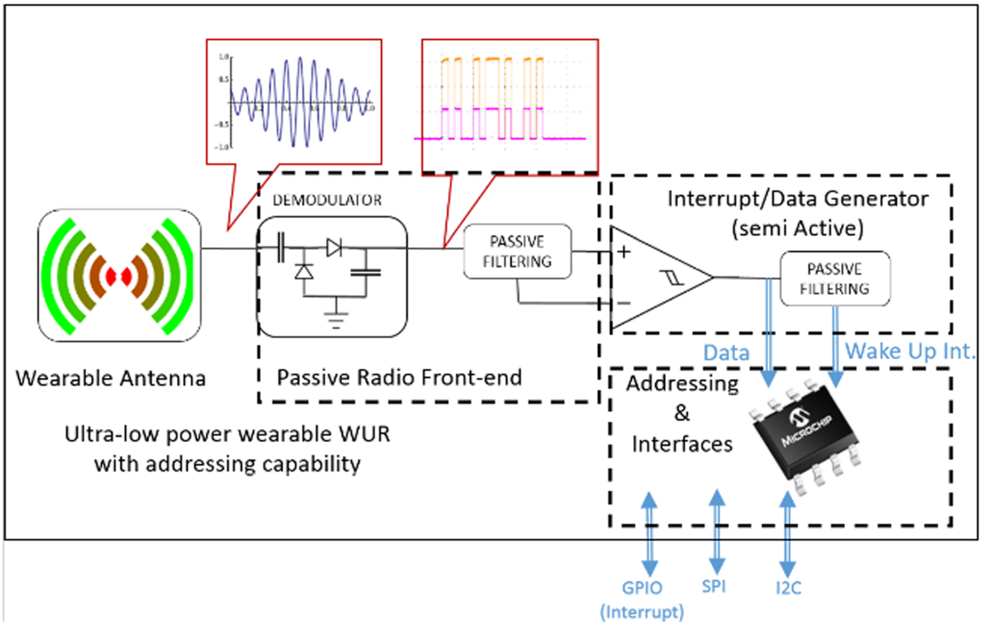


Fig. 5 Wake up radio blocks diagram

We compare the most commonly used classification algorithms for activity recognition [26]:

- K Nearest neighbor with 1,2,10 neighbor (KNN1, KNN2, KNN10)
- Support Vector Machine (SVM with linear kernel)
- Linear Discriminant
- Simple Bayesian approach
- Decision tree

These classifiers have been tested in terms of average time needed to classify an activity when trained with same dataset. Results have been used to decide parameters of the classification algorithm. For the segmentation step we choose windows with 50 % overlapping; the optimal window size resulted to be of 50 samples (Fig. 6), a smaller value would have increased classifier's complexity and computation time (a smaller window resulted for instance in a tree with much more leafs). Whereas a higher value would have decreased classification accuracy, and increased response time [4]. Feature extraction is performed after the data collection to complete the classification; to reduce the MCU load for this task, only time domain features are considered (mean, data range, standard deviation, etc...) since we measured that frequency domain features require on average 8 times more computation time. Also for the classification phase, we tested different classifiers (the most commonly used) [26], we compared them in terms of accuracy and computation complexity. The SVM algorithm has been excluded since the time needed to provide an output was not acceptable in our application. In Fig. 7 we present results of classification error rate when all the classifiers have been trained and tested using 2 different dataset, one for training and one for testing. We measured accuracy (number of not correctly classified activity/total number of classification performed). From results Fig. 7 of it is possible to notice that the classification tree requires very low computation time and has a good accuracy. In our tests with 4 different subjects, the classifier reached an accuracy of 97 %.

We choose to have 3 different power management policies for the SN with the following parameters:

- Running / Stair: Sensors sampling rate 60 Hz, MCU maximum clock @84 MHz
- Walking: Sensors sampling rate 30 Hz MCU maximum clock @ 84Mhz (maximum efficiency)
- Not Walking: Sensor switched off, radio in low power mode, MCU core in sleep mode, only USART active to detect Bluetooth commands

CAPM with WUR The SN on the feet collect and process data from sensors and can be equipped connected with the wake-up radio (WUR). If no WUR is used, then the SN has two options; 1) to keep the main radio (BTLE in this case) on continuously wasting a lot of energy but be ultra-reactive or 2) activate the radio with duty cycling to save energy but losing reactiveness. Figure 8a shows the scenario with the system without any wake up radio where the power of the main radio is similar to the power in transmission (TX) and receiving (RX). Figure 8b shows the scenario when the WUR is placed on the sensors nodes; they can continuously wait for the sink node messages and activate the main radio only when it is needed. In this work we present a CAPM strategy that uses the wake up radio to decide when the sensors node have to be awake and which policies (Sampling a 60 Hz, Sampling a 30 Hz, Sleep mode) must be adopted. The Ultra-low power microcontroller on the wake up radio can detect and parsing the command from the MN and generate an interrupt only when a new policy is detected.

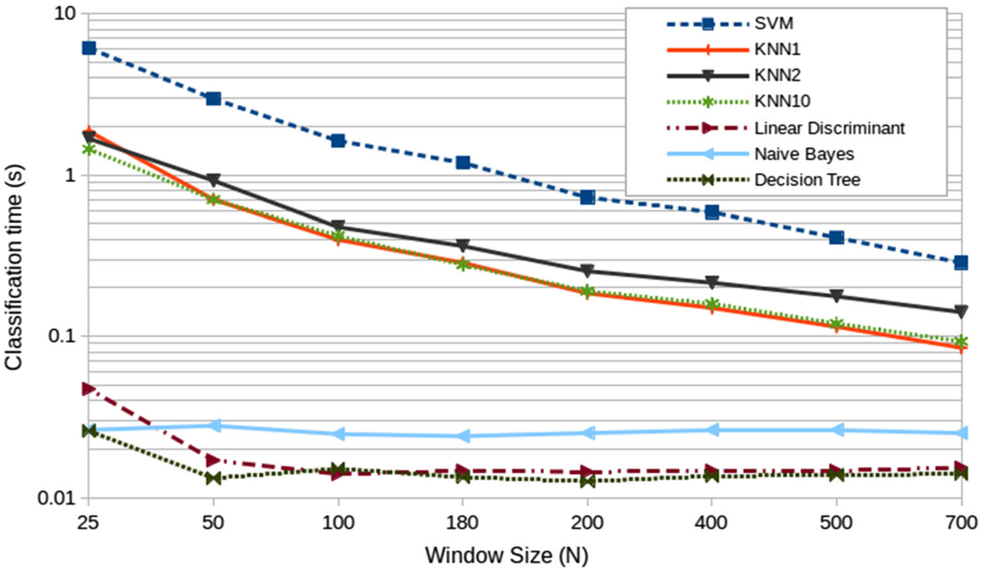


Fig. 6 Classification time using different classifiers and window sizes

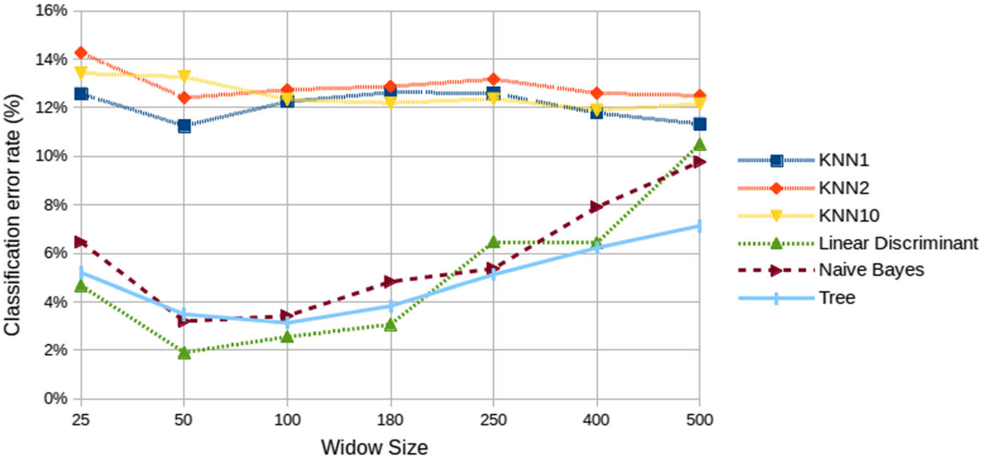


Fig. 7 Classification error rate for different classifiers

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 functionality of the full system has been tested connecting a radio wake up to sensor nodes through general purpose IO of the sensor node on the feet, when we present power measurements on the system nodes in two different configurations: 1) *System without wake up radio, with Power manager* 2) *System with Context Power Management and wake up radio*. The measured power consumption using the gait detection application has been used to evaluate the benefit of the proposed approach in the life time extension. For this purpose we evaluate also the delay due to the wake up radio and the possible error due to the activity recognition accuracy.

4.1 WUR range & performance

The first part of the experiment aims at testing the communication range of the system when using the WUR with the wearable antenna. In order to test the wake up radio the prototype of WUR with wearable antenna has been developed and tested Fig. 9.

The distances between the MN and the SNs were varied from 10 cm to 315 cm, and 1000 packets where generated 3 s 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. 10. The range achieved is over 3.1 m, which is suitable for many wearable application where only a few meters are required.

So far, it has been shown that the WUR can have a range from approx. 3.1 m with 100 % of success rate, which is a common communication range for many BAN applications. We will now evaluate the WUR's different performance parameters using the MN directly on the body, placed at a distance of 150 cm from the sensor nodes. This corresponds to the distance between the waist and feet of our test subject in standing position (max. Distance for 2.2 m tall man). During the experiment, the subject 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-

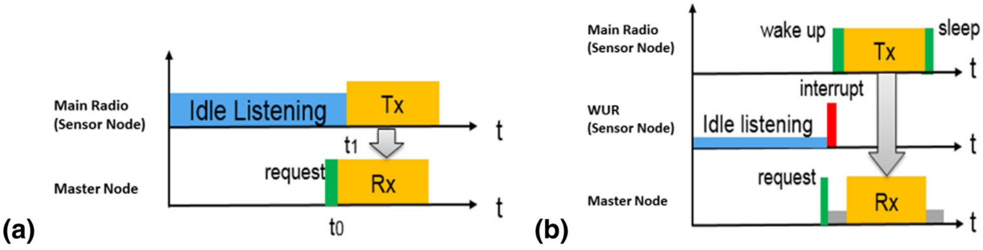


Fig. 8 Sample timeline with **a** only a main radio, and **b** with a main radio and a WUR

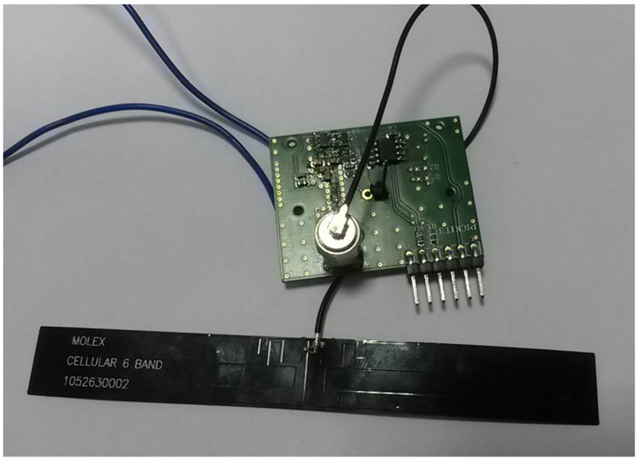


Fig. 9 WUR and flexible Antenna used for in-field performance test

send a second packet in order to wake up the selected sensor node. Consequently, these two parameters are meaningful in evaluating the quality of the wake up radio systems. Figure 11.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. Figure 11.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 expensive wake-up cost only when truly necessary.

4.2 Power consumption measurements

In this subsection, evaluation of the power 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 using the proposed system and the combination of CAPM and wake up radio. As presented above, the MN is placed in the waist, and also contains sensors that can recognize the context: whether the patient is walking, running, climbing stairs or sitting down. The two sensor nodes are placed on the patient's feet. These nodes read the sensor data and perform the feature extraction that allows the system to detect gait disturbances. However, since gait anomalies can only occur while the patient is walking, the sensor nodes can 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 shows the power consumption of the system for different tasks in different contexts. The first row of the table shows the power consumption when the user is running or climbing stairs it is necessary the sensors are sampled at 60 Hz frequency to perform the gait detection. In this condition the main node and the sensors node consume 52.6 mW and 55.6 mW respectively. As the wake up radio is consuming around 2 μW, its power consumption is negligible, therefore we can consider the consumptions with and without WUR the same. The table shows also the higher power consumption of the main node, due to the reception of sensors' data from 2 SNs. When the users are walking, the sample rate can be reduced to 30 Hz as this frequency is already enough to extract the features for the classification algorithm. In this case the power consumption is reduced to 26 mW for the SN and 30 for the MN. The most significant measurements for the power saving are presented in the last two rows. These data show the benefits of the wake up radio when the data acquisition and the radio is not used. In fact, with the wake up radio the power consumption of the whole SN can be reduced to only 2 μW from the 16.5 mW consumed for the version without the WUR and with the BTLE.

Figure 12 shows the impact of the WUR extra hardware, in term of power consumption, comparing the sensor node with

Fig. 10 WUR success rate vs distance using the wearable flexible antenna

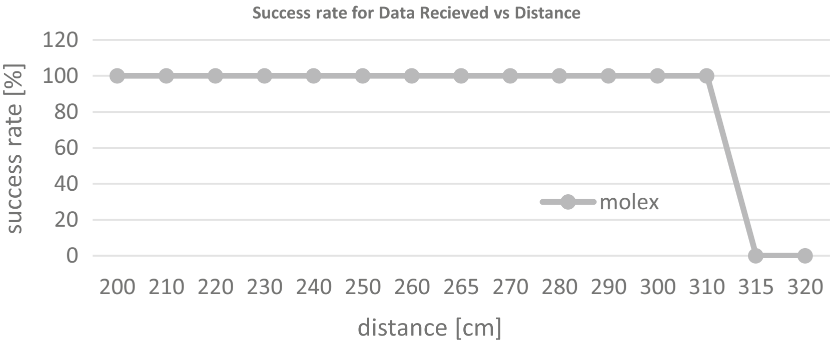
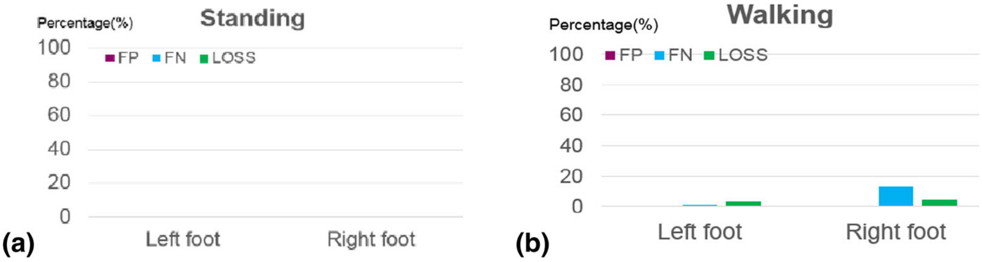


Fig. 11 On the field measurements of WUR with addressing in different conditions



and without WUR. Figure 12a and b show the percentage of power consumption of the sensor node's subsystems when data are acquired, processed and sent. From the Fig. 12a and b, it is possible to notice that the WUR uses less than 1 % of that power of the whole system. Figure 12c and d show the percentage of power used by the BTLE in sleep mode and the one of the WUR. Moreover, as the WUR has an own micro-controller, all processing and sensing unit can be completely switched off. The power consumption of the MN cannot be reduced so much as it has to process the CAPM acquiring data from the on-board sensor, but with the wake up radio the BTLE can be in deep sleep mode reducing the overall power consumption from 18.5 mW to only 6 mW. In the case the MN wants to send wake up messages the 868 MHz transceiver will be used. These data demonstrate that the power consumption reduction in the sleep mode due to the presence of the WIR coupled by the negligible power consumption due to WUR extra hardware in active mode, allow to increase the energy efficiency of the proposed approach and to extend the lifetime of the sensor node as we will show in the next subsection.

4.3 Lifetime analysis

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 3.3 V, can be seen in Table 1. As the bottleneck of the life time is the sensor node, we evaluate the lifetime extension of these nodes. We evaluated the energy consumed with the two versions, with and without the wake up radio. The energy consumed in one idle to active cycle is calculated as follows:

$$E_{ET}[J] = P_{\text{idle},BT}[W]{*}t_{\text{idle}}[S] + P_{\text{active}}[W]{*}t_{\text{active}}[S] \tag{1}$$

$$E_{BT\_WUR}[J] = P_{\text{idle},BT_{WUR}}[W]{*}t_{\text{idle}}[S] + P_{\text{active}}[W] {*}\left(t_{\text{active}} + t_{\text{wake}_{up}}\right)[S] \tag{2}$$

Equation (1) represents the energy consumed by the Bluetooth-only system, which is the sum of the idle and active energies based on their respective power consumptions, taken from Table 1, when we assume the patient is in walking activity for the 80 % of time and running/stairs activity for the 20 % of time. 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:

$$\text{Lifetime}_{BT}[h] = \frac{C_{\text{batt}}[mAh]{*}V_{cc}[V]{*}3600[s]}{E_{BT}[J]} {*}(t_{\text{idle}} + t_{\text{active}})[h] \tag{3}$$

$$\text{Lifetime}_{BT\_WUR} = \frac{C_{\text{batt}}[mAh]{*}V_{cc}[V]{*}3600[s]}{E_{BT\_WUR}[J]} {*}\left(t_{\text{idle}} + t_{\text{active}} + t_{wake_{up}}\right)[h] \tag{4}$$

Table 1 Power consumption for different policies

Activity	Sensor sampling rate	SN power	MN power
Run / stair (with or without WUR)	60 Hz	52.6 mW	55.6 mW
Walking (with or without WUR)	30 Hz	26 mW	31 mW
Not walking CAPM (BTLE)	0 Hz	16.5 mW	18.5 mW
Not walking CAPM (Wake up Radio)	0 Hz	2 μW	6 mW

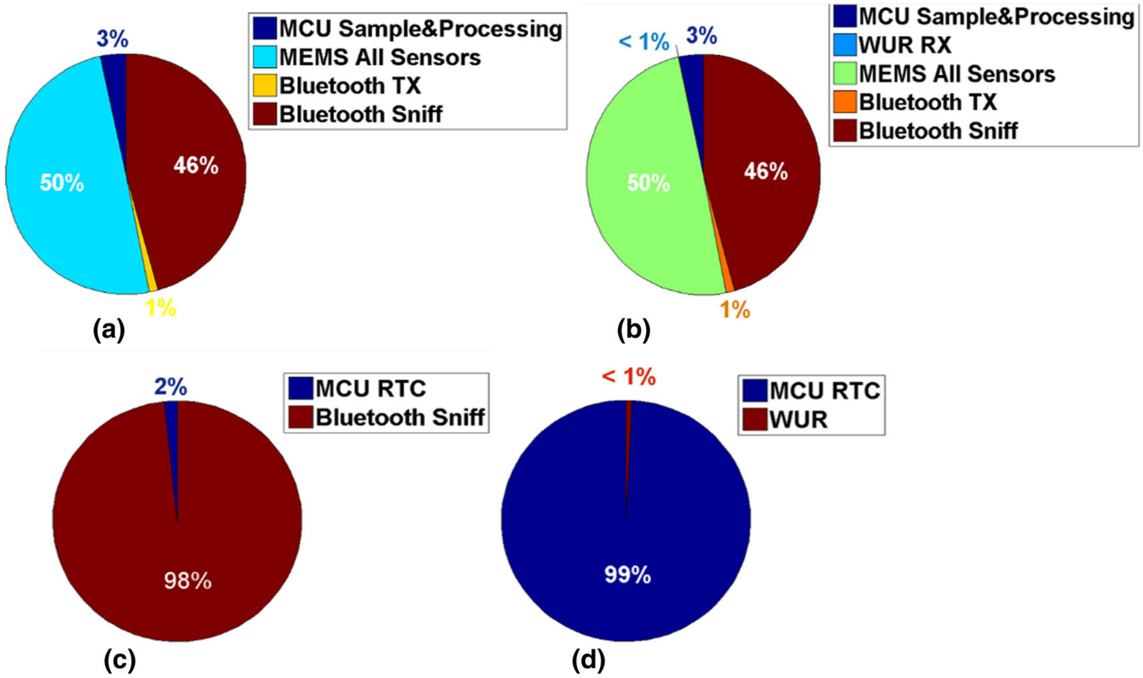


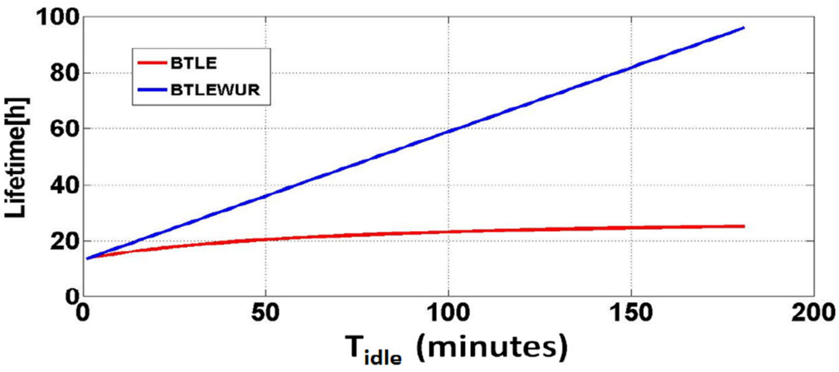
Fig. 12 Nodes' power consumption breakdown for different configurations

Equations (3) and (4) represents the lifetimes of the Bluetooth Low Energy (BTLE) and BTLE + 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 180 min and Vcc was 3 V. Figure 13 shows the estimated lifetimes, in hours, as a function of the idle to active time ratio. When this ratio tends to 1, it means that 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 the CAPM and the Bluetooth Low Energy coupled with the WUR as radio subsystem, and the red shows the same system with only the BTLE. 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.

5 Conclusions

This work presented a wearable system for gait detection with Context Aware Power Management (CAPM) in combination with a wake up radio (WUR) for WBAN. The power consumption measurement using the wake up radio are presented as well as the energy savings in a real application. Thorough testing of the WUR's performance have demonstrated that its range of over 3 m surpasses the needs of many BAN applications. 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 4 times, depending on the amount of time the system can be in sleep mode.

Fig. 13 Expected lifetime of the system with CAPM with BTLE and with BTLE plus WUR



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References

1. Magno M, Spagnol C, Benini L, Popovici E (2014) A low power wireless node for contact and contactless heart monitoring. Microelectron J 45(12):1656–1664
2. U Sana, and K. S. Kwak (2012) An ultra low-power and traffic-adaptive medium access control protocol for wireless body area network. J Med Syst 36.3: 1021–1030
3. Hyocheol Jeong, Jeonghyun Kim, and Younghwan Yoo (2011) Adaptive broadcasting method using neighbor type information in wireless sensor networks. Sensors, 11(6), 5952–5967
4. F. Casamassima, E. Farella, and L. Benini (2014) Context aware power management for motion-sensing body area network nodes". In Design, Automation and Test in Europe Conference and Exhibition (DATE), (pp. 1–6). IEEE
5. P. Kamalinejad et al (2014) A high-sensitivity fully passive wake-up radio front-end for wireless sensor nodes. In proc. of Internation Conference on Consumer Electronics (ICCE), Las Vegas. pp. 213–214
6. Kerhet A, Leonardi F, Boni A, Lombardo P, Magno M, Benini L (2007) Distributed video surveillance using hardware-friendly sparse large margin classifiers, *Advanced video and signal based surveillance, 2007. AVSS 2007. IEEE Conference on*, vol., no., pp.87,92
7. Roberts NE, Wentzloff DD (2012) A 98nW wake-up radio for wireless body area networks," Radio Frequency Integrated Circuits Symposium (RFIC), 2012 IEEE, vol., no., pp.373–376
8. Magno M, Jelicic V, Srbinovski B, Bilas V, Popovici E, Benini L (2016) Design, implementation, and performance evaluation of a flexible low-latency Nanowatt wake-up radio receiver. in IEEE Trans Ind Inf 12(2):633–644
9. Groza B, Murvay S (2013) Efficient protocols for secure broadcast in controller area networks. Ind Inf IEEE Trans 9(4):2034–2042
10. Casamassima F et al. (2014) A wearable system for gait training in subjects with Parkinson's disease. Sensors 14(4):6229–6246
11. Jurdak R, Baldi P, Lopes CV (2007) Adaptive low power listening for wireless sensor networks". Mob Comput IEEE Trans, vol. 6, no.8
12. Vodel M, Caspar M, Hardt W (2012) Wake-up-receiver concepts-capabilities and limitations. J Netw. 7.1
13. Nilsson E, Svensson C (2013) Ultra low power wake-up radio using envelope detector and transmission line voltage transformer, emerging and selected topics in circuits and systems. IEEE J 3(1):5,12
14. Spenza Dora et al. (2015) Beyond duty cycling: wake-up radio with selective awakenings for long-lived wireless sensing systems. In proc. IEEE Conf Comput Commun. pp. 522–530.
15. Jelicic V, Magno M, Brunelli D, Bilas V, Benini L (2012, October). Analytic comparison of wake-up receivers for WSNs and benefits over the wake-on radio scheme. In Proceedings of the 7th ACM workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks (pp. 99–106). ACM
16. Jelicic V, Magno M, Brunelli D, Bilas V, Benini L (2014) Benefits of wake-up radio in energy-efficient multimodal surveillance wireless sensor network, IEEE Sensors J
17. Alírio Soares B, Borges Carvalho N (2013) A low-power wakeup radio for application in WSN-based indoor location systems. Int J Wireless Inf Networks 20(1):67–73
18. Takahagi K et al. (2013) Low-power wake-up receiver with subthreshold CMOS circuits for wireless sensor networks. Analog Integr Circ Sig Process 75(2):199–205
19. Magno M, Benini L (2014) An ultra low power high sensitivity wake-up radio receiver with addressing capability, Wireless and Mobile Computing, Networking and Communications (WiMob), 2014 I.E. 10th International Conference on, vol., no., pp. 92,99
20. Molex (2012) Cellular 6-band standalone antenna 105263–002 Datasheet. http://www.symmetron.ru/news/files/pdf/molex/molex_6_band_antenna.pdf
21. Magno Michele et al (2013) Combination of hybrid energy harvesters with MEMS piezoelectric and nano-Watt radio wake up to extend lifetime of system for wireless sensor nodes." Architecture of Computing Systems (ARCS), Proceedings of 2013 26th International Conference on. VDE
22. Anastasi G, Conti M, Di Francesco M (2009) Extending the lifetime of wireless sensor networks through adaptive sleep. Ind Inf IEEE Trans 5(3):351–365
23. W. Wang, V. Srinivasan, and K.C. Chua Extending the life-time of wireless sensor networks through mobile relays, presented at IEEE/ACM Trans Netw, 2008, pp. 1108–1120.
24. Mamaghanian H, Khaled N, Atienza D, Vandergheynst P (2011) Compressed sensing for real-time energy-efficient ECG compression on wireless body sensor nodes. Biom Eng IEEE Trans 58(9): 2456–2466
25. Nilsson J-O et al (2012) Foot-mounted INS for everybody-an open-source embedded implementation. Position location and navigation symposium (PLANS), IEEE/Ion IEEE, 2012.
26. Bulling Andreas, Ulf Blanke, and Bernt Schiele (2014) A tutorial on human activity recognition using body-worn inertial sensors. ACM Computing Surveys (CSUR) 46.3: 33.