A low power wireless node for contact and contactless heart monitoring

M. Magno, C. Spagnol, L. Benini, E. Popovici

* Dipartimento Elettrica e dell'Informazione (DEI) Università di Bologna, Bologna, Italy
† ETH Zurich, Switzerland
‡ Electrical and Electronic Department, University College Cork, Cork, Ireland

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Ubiquitous vital signs sensing and processing are promising alternatives to conventional clinical and ambulatory healthcare. Novel sensors, low power solutions for processing and wireless connectivity are creating new opportunities for wearable devices which allow continuous and long term monitoring, while maintaining freedom of movement for the users. This paper presents a low-power embedded platform with novel high sensitivity electric potential dry surface sensors that can be used in either contact or non-contact mode to measure biomedical signals. The proposed low power system is optimized to compute the heart rate and respiratory rate close to the sensors. This approach reduces the amount of data that needs to be transmitted to a host device. It allows also the platform to be autonomous and wearable or even be used in cars for applications such as driver drowsiness detection. Experimental measurements show the acquisition and the processing of data from sensors and the low power consumption achieved with the node in different modes of operation.

1. Introduction

Technology advancements of sensors, low power mixed-signal/RF circuits, wireless communication and embedded systems have enabled the design of compact, low power, high performance and low cost distributed sensing solutions better known as Wireless Sensor Networks (WSNs). WSN are covering an ever-increasing range of applications, such as surveillance, building monitoring, sports/fitness and, of particular interest, applications for health care. Wireless wearable health-monitoring systems have enjoyed increased interest from industry and research community alike during recent years [1–3]. As the world elderly population is increasing, governments are spending on healthcare significant amounts of money. This has created the need to monitor patients health status while they are out of the hospital to decrease the cost and at the same time increase the comfort and wellbeing of the patients which can be in a familiar environment. Wearable devices are also very attractive for sports, fitness and wellness and entertainment market to measure sports performance, daily activity, sleep patterns, and other related parameters. To address this demand, recent research efforts focus on wireless, unobtrusive, mobile, and easy to wear solutions to make the monitoring process more user-friendly and hence easier to be accepted. Wearability and wireless communication are important factors for any application that aims to achieve real-time, continuous and unobtrusive monitoring since the presence of wires may limit the user activities and level of comfort and also influence significantly the measurements. These systems are perfectly suited to be integrated within a telemedicine platform and wearable monitoring providing information technology that will be able to support early warning of abnormal conditions, prevention of serious consequences and in general health and body information [1,13,14]. As stated above, wireless wearable systems bring several advantages when compared to traditional wired health monitoring systems. The freedom of movement due to the wireless connectivity is the most obvious and important advantage for the users. In fact, the system can unobtrusively sense and process the vital signs of the person anywhere and anytime for as long as it is needed (often limited to a number of days of continuous monitoring). Another important advantage for the users is the tracking of their health conditions without frequent visits to the clinician, and to have alerts in case of a critical situation. As an example, patients that suffer from conditions where the symptoms present themselves in the form of seizures (i.e. epilepsy) can now avoid to be hospitalized for days for continuous monitoring [4]. For this reason a large number of novel body sensors are proposed by several companies [5,6]. These sensors can meet the requirements of a

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wireless sensors node especially in terms of high accuracy, small-scale factor, high integration, multisensory versatility and low-power consumption.

Common sensing biomedical parameters includes skin temperature, body motion, heart rate, blood pressure, respiration rate, electrocardiography (ECG) for the heart health, Electromyography (EMG) for the muscles control, Electroencephalography (EEG) for the brain signals, oxygenation signals, and internal temperature [8–16].

The most widely used sensors to detect vital sign and health monitoring are the Electrocardiography (ECG) which provide useful information about the cardiovascular system. High sensitivity electric field sensors in this domain are starting to be used for detection of ECG-like signals to cover different types of applications ranging from forensics and healthcare to IC inspection and automotive safety systems [6]. These sensors can work without any skin preparation or the use of conductive gels required when using conventional wet electrodes, moreover can work also in contactless manner where the skin contact is not possible, for example in-car application where the electrodes are embedded in the driver’s seat. Finally, these sensors can work attached/deployed in more wearable parts on the body such as on the arms, fingers and legs. These features together with the high sensitivity and high quality of the signal and low power consumption make these sensors the most promising candidates to be used in wearable biomedical parameters.

On the other hand, strict requirements for weight, cost and size, power and functionality became key challenges for every wearable wireless sensor node. To meet the first of these challenges, ultra low power design is required. These systems have to be supplied from batteries which need to last days (typically) or even months. Power restriction impacts on the complete node design, imposing constraints on computational resources, sensors and transceivers. Moreover functionality requirements impact on the biomedical information reliability and eventually on the platform quality. Thus, a hardware/software co-design is required to achieve all the challenges.

This paper presents a wearable wireless sensors node which is able to support medical and health care applications. The node platform is developed to host novel commercial dry-surface electric potential integrated circuit (EPIC) sensors from Plessey Semiconductors optimized for ECG acquisition [7,20]. The proposed analog front end is optimized to reduce the noise of ECG signal in contact and non-contact mode and it is a critical part to have high quality data and algorithms accuracy. The core of the designed node is an ultra low power microcontroller, which samples the signal performing an Analog to Digital Conversion (ADC) and then processes the resulting data into information. The wireless connectivity is provided by two different radios: a Bluetooth Low Energy (BTLE) radio which is used to transmit the information to a remote host or a Smartphone and an ultra low power IEEE 802.15.4 radio (CC2500 by TI/ChipCon). The node is built with energy performance in mind, for these reasons power management in hardware and software is present to avoid any waste of energy. The heart rate (HR) and respiratory rate (RR) algorithms implemented directly on board are presented in this paper.

The remainder of this paper is organized as follows: Section 2 describes recent related work to the wireless body sensors node. Section 3 presents the hardware architecture of the node and its components. Section 4 details the proposed approach, describing the data processing. Section 5 describes the implemented approach, along with measurements, comparative evaluation, and validation. Section 6 concludes the paper.

2. Related works

Wearable wireless devices have recently increased the versatility and popularity of systems designed for monitoring human biomedical parameters to support a wide range of application in healthcare, sports, fitness and entertainment. In this field, research is focused specially on the wearable wireless sensor network (WSN) and Wireless Body Sensor Network (BSN). For the WSN, the sensors nodes are designed to meet the requirements of long term operations and continuous health monitoring and can provide an early warning system or real-time emergency alerting that can be life saving. The small size required for the nodes, the low power resources and limited computing abilities are hard constraints for nodes that are supposed to have long-term life while maintaining continuous sensing.

The most popular runtime data processing in literature are for ECG, EMG, ECG monitoring. The papers [6–17] present different approaches and applications. The nodes architectures are very similar of each other and are comprised mainly of the sensors, the electronic circuit for analog to digital conversion, a microcontroller and a radio. The most used radios for the wireless connectivity with a host (typically a PC or a Smartphone) are usually Bluetooth (or recently Bluetooth Low Energy), Zigbee, or other low power radio, usually in the ISM band and using the IEEE 802.15.4 standard. In previous works researchers focused mainly on the design of sensor nodes for ECG or EEG acquisition and processing. In recent years academic and industrial researchers are proposing wearable devices which can process the data autonomously. Current trends in wireless ECG monitoring systems have produced an innovative and versatile approach to wearable textile-based monitoring systems, ECG data have been collated using smart clothes [18,19,21]. The most important modules of smart wearable monitoring technology are the wearable biomedical sensors which are attached directly on the patient or to electrode-embedded wearable garments. Wireless sensors that measure vital parameters are the most important emerging devices for improving the quality of care whilst reducing costs. In [21] a wearable ad-hoc solution for heart rate is presented. This solution is very interesting and impressive for ultra-low power of only few of μA. The NFC radio is used for the communication to cut further more the power consumption. However it lacks of flexibility and scalability, as it is not possible to modify the firmware and to use another algorithm or radio transceiver. From the analysis of these works it is notable that modern wireless technologies have a very high level of available integrated resources. These resources facilitate data manipulation and processing but on the other hand they bring very high peak power consumption that negatively impacts the well-known issue of lifetime of battery-operated devices. When added to the power consumption of the radio and microcontroller, the body sensor nodes reach quickly very high energy consumption. Nevertheless, any wearable sensing node requires accurate data processing. Many authors have investigated methods to obtain the interested measurements from physiological signals. Possible approaches vary from digital filtering techniques [23–26] to more complex techniques such as continuous wavelet transform (CWT) [28–32] and Variable-Frequency Complex Demodulation (VFCM) [33,34].

Each method has benefits and drawbacks and it is outside the scope of this paper to give a detailed review of them. However, it is of interest to note that the more complex techniques while giving improved estimation have a higher computational complexity that is hard to justify when the interest of the application is to have a generic range and/or to track trends rather that a precise reading. Moreover, the computational cost makes these methods impractical for an implementation on ultra low power sensors. As the previous related works show, the power consumption is the key challenge of the wearable and wireless devices since the stricter constrain is the energy availability.

The node proposed in this paper has been designed to reduce the power consumption through hardware and software co-design.
Moreover, a low power hardware design which makes it possible to provide adaptive power management in order to minimize the power consumption has been devised for the proposed node. Finally, both a heart rate and respiration rate algorithm are implemented directly on the node in order to save communication energy and increase the life-time of the node. The two algorithms are based on [23,25]. These system level choices make the proposed node a flexible, wearable, versatile, low power and reliable wireless node prototype which is suitable for long-term monitoring of a user’s health conditions in unobtrusive matter.

3. Hardware architecture of the node

Fig. 1 shows the architecture of the proposed platform for health monitoring. The wireless connectivity is provided by two commercial chips: one for Bluetooth Low Energy (BTLE) and one for the IEEE 802.15.4. Two novel EPIC sensors by Plessey Semiconductors work both in contactless and in traditional contact modality and they are connected to an ad hoc designed acquisition board in charge to perform the analog filtering and amplification. As the main constraint designing the node is the low power consumption, it includes a hardware design that guarantees the disabling of each component (radios, sensors, Analog board and sensors) by the implemented firmware in the microcontroller. Another key feature is that the signal processing is performed directly on board by the microcontroller which has enough computational resources maintaining low power consumption. Some of the key features for the proposed node include:

- Low power analog board for EPIC Sensor optimized for heart monitoring.
- High accuracy Heart rated and Respiratory rate algorithm on board.
- Contactless and contact less modality.
- Power management to reduce power consumption to achieve long term monitoring.
- Multi radio capabilities (BT, 802.15.4) to increase flexibility connecting to a host.

The following subsections describe in detail the architecture of the platform: A) Epic Sensors and analog circuits, B) Node and Microcontroller, C) Radios.

3.1. Sensors subsystem

The platform was designed to host a pair of EPIC sensors from Plessey. These novel sensors are novel electric potential sensors that have the capability of being used in a number of applications such as proximity sensing, movement sensing and gesture recognition as well as measuring bio-electric signals like ECG, EMG, EOG and EEG. This paper is focused on the possibility to achieve a dry-surface energy efficient wireless node performing ECG data processing with these sensors to exploit their technology together while keeping the low power consumption and power management.

Fig. 1 shows the block diagram of the sensor boards for EMG developed in this paper to achieve the needed analog filtering and amplification. The analog board is one of most important component of the system as it affects the quality of the signal and the further data processing [22]. The board was designed carefully to reduce the noise, filtering the frequency of no interest and to get a signal as clean and clear as possible. Noise reduction in the system is the key to achieve a good ECG signal especially in a contactless application where the noise is very high and can cover the signal. The noise reduction in this approach was achieved in a number of ways. As Fig. 1 shows, the first step in the signal acquisition path is a Low Pass Band filter tuned to 33 Hz. With this it is possible to cut the frequency contribution that does not carry significant information. After the filter, the two signals go through a buffer amplifier which can be configured by software with gain of 1 or 10. The system uses a pair of EPIC sensors to reduce the noise performing differential amplification in order to reject the common noise such as the power line interference that could be present with equal amplitude at each active terminal. Fig. 2 shows how the differential amplifier reduces both the noise and increase the quality of the signal. The signal from both sensors, (A) and (B) in figure, is very noisy and it is hard to see the pick of the heart rate. After the differential amplifier the signal is much less noisy and the peaks more visible and easier to be detected by an embedded system.

The analog board has connectors for the two EPIC sensors (PS25101 or PS25102). These sensors work with a positive voltage from 5 to 6 V, thus a step-up DC/DC converter is needed to provide the right voltage. The same voltage is provided for the amplifier, so the TPS61222 from Texas Instruments (TI) was inserted in the analog board to boost the 3.7 V of the battery to 5 V. The choice is driven by the very high conversion efficiency of up to 95%. The low

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quiescent current is only 5 nA and this is very important for the ability to be switched off through the enable pin driven from the microcontroller.

3.2. The microcontroller

To allow quick development of the prototype, in order to evaluate the performance and the benefit of the novel sensors and the proposed architecture, the EZ430-RF2500 kit from TI has been used [27]. The MSP430F2274 microcontroller is the core of the board and it guarantees low power and sufficient computational resource to perform the heart rate monitoring algorithms. The kit incorporates also a CC2500 chip radio from Chipcon which provides the IEEE 802.15.4 communication protocol. In addition, there are a number of free Input Output pins on the board to easily interface the analog board with the sensors and the external BTLE radio board. The microcontroller acquires and processes data from the EPIC sensors via an analog input connected to an internal 10 bits Analog Digital Converter. The dongle kit was modified to allow the switching on/off of the added peripherals and the connection with them. In this way the node can save energy if the application does not require data from the sensors (i.e. in standby mode). In fact, the microcontroller can switch off and on the interface board where the EPIC sensors are driving the enable pin of the DC–DC on the analog board. This is important to save energy in the deep sleep mode when the sensors are not needed. The wireless dongle connected with the analog board supports the data acquisition, processing and RF communication in low power way, requested for most of the biomedical and wearable application.

3.3. Radios

The node is integrated with two types of wireless communication modules. This allows achieving flexibility of communication while keeping standards protocols (Bluetooth and 802.15.4). The two radios are in charge of sending and receiving data which can be both raw or in the form of information (processed data) according with the implemented software on the microcontroller and the application.

Bluetooth: the node hosts the BLE122 module by Bluegiga to allow communication with Bluetooth devices (i.e. Smart Phones, Tablets, PCs). This module is a low energy Bluetooth 4.0 module with an integrated chip antenna and thus, covers very well the WBSN specifications in terms of small factor and range. Moreover it has a very useful feature: the possibility to be controlled in data mode and command mode only with the two pins of the UART. This, together with the high data rate and ultra-low power guaranteed by version 4.0 of Bluetooth justify its use.

Although the current consumption of this Bluetooth device is low with respect to other similar devices, it is still around 3 mA in idle mode (3 μA in ultra-sleep mode). Since the node is designed with low power consumption in mind, an ultra-low power load switch was inserted. The switch is driven from the microcontroller to reduce and almost eliminate the power consumption when the BT is not needed.

802.15.4 Communication: the 802.15.4@2.4 GHz transceiver circuit consists of the radio CC2500 chip and a chip antenna included in the EZ430-RF2500 dongle. The radio of the CC2500 chip can easily be built on top of the IEEE 802.15.4 with the property standard SimplicTI from TI designed for the MSP430. This proprietary stack was chosen for this network because it is much simpler than the one generally used IEEE 802.15.4/ZigBee protocol, requires less memory, can achieve up to 256 Kb/s datarate and enables lower power consumption when the node is in the idle state.

4. Data processing

Low complexity and low power algorithms have been developed for heart rate (HR) calculation and respiratory rate (RR) estimation. The ability to compute physiological parameters on the node allows reduction of the total energy consumption. The benefits on-board data processing are many fold. On one hand it reduces the transmission duty cycle, instead of transmitting raw data hundreds of times per second single bytes for HR and RR can be transmitted once every few seconds. This lowers the energy consumption of the node by switching off the power hungry transceiver, therefore increasing battery life. On the other hand the small size of the processed data enables the user to move away from the base station simply by adding a small memory. These benefits, together with hardware improvement and efficient energy harvesting strategies, allow the development of accurate monitoring systems that can work autonomously for days or weeks.

The analogue signal from the EPIC electric potential sensors is related to ECG after adequate filtering mentioned before. However, the signal presents still some noise and it is subject to marked drifting in particular due to movement [Fig. 3]. Moreover, different
positions of the sensors on the body can lead to significant
differences in the quality on the signal, as shown in Fig. 4. Never-
theless, as long as the peaks can be identified correctly the HR can
be computed correctly. To isolate and enhance the peaks a drift
estimator (block architecture presented in Fig. 5) followed by a
high gain low pass filter has been developed. The combined effect
of the two can be seen in Fig. 6

Several algorithms exist for detecting peaks on a signal, from
Pole-Zero modeling [30] to Hilbert transform [31]. However not all
algorithms fare well in the proposed application due to the EPIC
signals and to their non-stationary property. Other algorithms are
not suitable due to their complexity that makes them non optimal
given the computational speed and energy profile available.
For these reasons a low power, low complexity threshold based
algorithm is proposed and implemented. A screenshot of the
oscilloscope is reported in Fig. 7 to show the action of the peak
detector. Track one is the raw EPIC data while track two is a GPIO
that is toggled by the peak detector every time the threshold is
crossed.

The HR is computed over a time window of 30 s divided in 15
bins of two seconds. Every two second data from the oldest bin is
discharged and the new bin containing the count of the number of
peaks occurred in the last two seconds is inserted. This procedure
ensures to smooth out any false negative and false positive. All
parameters of the algorithm are programmable to allow it to be
customized for different constraints (i.e. Power, performance,
smoothness, etc.). The second part of the proposed on board data
processing software deals with the problem of evaluating respira-
tory rate as an indirect measurement. The fundamental idea here
is to measure the secondary effect that respiration has on ECG (and
ECG related) signals. There are three such effects, namely peak
height modulation, peak-to-peak time modulation and signal bias
modulation. All three effects have been investigated.

Two aspects have been evaluated: a) are these effects traceable
in an EPIC raw signal, and b) at what computational cost can these
be retrieved? The second aspect is of particular interest for the
proposed system, since the implemented algorithm must guaran-
tee to consume less energy than transmitting all the raw data.
Moreover the execution time on the MSP430 in use needs to be
compatible with the sampling rate. Our research pointed to the

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conclusion that the peak height modulation is not clearly traceable in the EPIC signal. This is due to the presence of in-band noise that makes the height of the peaks too variable. Analysis of the peak-to-peak time has proven more successful however to increase time resolution a higher sampling frequency was required. This came at the cost of increased energy consumption (Fig. 7).

The third physical effect has proven more successful. Drift estimation is already present in the HR calculation flow. For HR calculation the estimated drift was removed from the main signal, for RR this estimation became the main signal of interest. To isolate the respiration component from other components, due to the sensors or movements, the drift signal is filtered with an IIR filter. To reduce energy consumption the signal is down sampled to 16 Hz before filtering. The implemented filter has a bandpass of 0.1–0.5 Hz (6–30 breaths per minute). To isolate the signal from other interferences the filter needs to have a steep roll off. For this reason a 34th order IIR bandpass filter has been implemented. Frequency response of the filter is presented in Fig. 8. To avoid discrepancies between simulation and realization, the filter has been designed using MATLAB DSP toolbox using fixed 16-bit arithmetic. The filter has been implemented in the microcontroller as a cascade of Second-Order Sections architecture to reduce sensitivity to coefficient quantization and hence quantization errors. To determine the main frequency present at the output of the IIR filter a second peak to peak detector is used. Due to the fact that the signal is now much smoother as a result to the IIR filtering, the peak detection is done by derivative and zero-cross detection. Finally the RR is computed using the same sliding window process used for HR.

5. Experimental results

This section shows experimental measurements taken from the developed node to evaluate power consumption for ECG data acquisition, and data processing for HR and RR. Time and energy of the application phases were measured and shown in following tables.

The proposed wireless system provides significant improvements on reliability, latency, flexibility, energy consumption, scalability and distribution. Fig. 9 shows the developed wireless node with the analog board connected with the EZ430-RF2500 board ready to host a pair of EPIC sensor. The experimental setup includes tests in contact and contactless mode to evaluate the performance of the algorithm of heart rate and respiration rate in terms of power and time and functionality. Fig. 9 shows the setup of contactless tests where two sensor were placed in a chair to get ECG data from the back of a person with a cotton t-shirt.
Table 1 shows the very low power consumption of the solution and highlights the big gap between the current consumption in deep sleep mode of our approach, for example BT 2 nA and sensor board 200 nA, compared with the idle mode of 3 mA and 12 mA respectively. Ultra-low power mode is an important feature to increases the long term monitoring capabilities for system supplied by batteries. Table 2 shows the current consumption of the node, in different working modes, in order to give an idea of the low power consumption during listening mode and during data acquisition and processing.

To evaluate the correct filtering, amplification, data acquisition, processing and transmission of the proposed solution, the configuration shown in Fig. 1 has been used. Thus, the EPIC sensors acquire the signals from the human body, then the signals are filtered and amplified in the analog board to reduce the noise and increase the quality, at this point the microcontroller acquires the data via the internal ADC on a free GPIO. After the data is acquired the microcontroller can run the respiration and heart rate algorithms shown in Section 4. The result of the algorithm is sent to a host PC through Bluetooth or 802.15.4 every 5 s to reduce the power consumption due to the communication. In our test the sample rate of the internal ADC was fixed at 256 Hz, and the host PC used a USB dongle with a coordinator with SimpliciTI protocol in the 802.15.4 transmission and a commercial BT dongle.

To evaluate the processing time and the power consumption of the microcontroller while executing the algorithms, the node was

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connected to an oscilloscope to evaluate the time taken and at a shunt resistor was used to measure the power consumption. The measurements were performed for the power consumption of the microcontroller during the algorithm the sensor board was supplied from an external battery and the radio was switched off.

Table 3 shows timing and power profiling for the various subroutines of the data processing algorithm. Fig. 10 shows the measurement of power consumption and timing of the algorithm. Trace 1 (higher one) shows the current passing through the shunt resistor. Trace 2 (lower one) shows the duration of the FIR filter. To obtain the waveforms, a GPIO has been raised at the start of the filtering procedure and then lowered when finished. Each peak is equivalent at the arrival of a new sample from the ADC.

Several aspects of the algorithm can be seen. First it is evident that the FIR filter is activated every time a sample arrives with a frequency of 256 Hz. It is also clear from the comparison of the power profile with the FIR profile that every fourth pick the MSP stays active for longer. This is due to the calculation of the respiratory rate and in particular at the complexity of the IIR filter. The IIR filter is active every fourth sample due to the down sampling to 64 Hz implemented. It was possible to have a stable data of HR and RR in both contact and contactless way.
Performance validation against existing physiological signal databases will be carried on in future work.

6. Conclusion and future works
A low power wireless wearable system for in-situ heart monitoring was presented. The system hosts a pair of novel low power dry-surface sensors capable to work in contactless mode as well as in traditional contact mode. The platform was designed to achieve long term monitoring, performing heart rate and respiration rate algorithms directly on board. The architecture has been engineered with power consumption in mind and the paper shows the performance of a low power design. The versatility and novelty of the node resides in the fact that novel dry surface sensors are used, and the processing is performed on board, close to the sensor in order to have a low power device for heart rate and respiratory rate monitoring. This system is of significant interest in a wide range of application, such as automotive, wearable, sport and fitness and medical application. Performance of power consumption, timing and functionality was performed, tested and evaluated. The experimental results show the low power consumption of the node and very low quiescent current, less than 1 mA in sleep mode and the capability to compute the heart rate and respiratory rate. Future work will include a standalone version of the node and more experimental results in contactless mode and to compare the accuracy with medical approved devices.

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