A wireless, compact, and scalable bioimpedance measurement system for energy-efficient multichannel body sensor solutions

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Abstract. In this paper, we present the design, realization and evaluation of a multichannel measurement system based on a cost-effective high-performance integrated circuit for electrical bioimpedance (EBI) measurements in the frequency range from 1 kHz to 1 MHz, and a low-cost commercially available radio frequency transceiver device, which provides reliable wireless communication*. The resulting on-chip spectrometer provides high measuring EBI capabilities and constitutes the basic node to built EBI wireless sensor networks (EBI-WSNs). The proposed EBI-WSN behaves as a high-performance wireless multichannel EBI spectrometer where the number of nodes, i.e., number of channels, is completely scalable to satisfy specific requirements of body sensor networks. One of its main advantages is its versatility, since each EBI node is independently configurable and capable of working simultaneously. A prototype of the EBI node leads to a very small printed circuit board of approximately 8 cm² including chip-antenna, which can operate several years on one 3-V coin cell battery. A specifically tailored graphical user interface (GUI) for EBI-WSN has been also designed and implemented in order to configure the operation of EBI nodes and the network topology. EBI analysis parameters, e.g., single-frequency or spectroscopy, time interval, analysis by EBI events, frequency and amplitude ranges of the excitation current, etc., are defined by the GUI.

1. Introduction
The shifting of eHealth from desktop platforms to wireless and mobile configurations enables a distributed and pervasive care model for health and wellness management through the use of miniaturized information and communication technologies [1]. A pervasive health system will ultimately need information about individuals and their surroundings, which will be delivered by embedded sensors. In this sense, wireless sensor network (WSN), which has settled as a leading technology for various applications, exhibits one of its potential uses in the form of body sensor networks (BSNs) for remote monitoring of patients under their natural physiological state [2].

Despite the high degree of development achieved by present solutions that ensure rigorous and reliable monitoring of certain vital signs, e.g., ECG, heart rate, etc., there is still lack of solutions designed to meet the demand of sensors which can be adapted to the particular characteristics of each individual for accurate and noninvasive monitoring of physiological parameters, emotional states as well as for reducing the impact of medical therapies in chronic patients. Bioelectrical impedance analysis has qualities very attractive for personalized monitoring of the physical and mental state of patients and citizens, besides being a noninvasive preventive diagnosis technique [3].
2. Wearable bioimpedance-based body sensor network

The term electrical bioimpedance (EBI), or simply bioimpedance, is used to describe the response of a biological material to the flow of an applied alternating electrical current with given amplitude and frequency [4]. Although EBI technology can be applied in many fields, the detection of physiological events and anatomical structures is one of its major working areas. In certain cases, the information provided by a single EBI measurement may not be enough to resolve complex problems or reliably produce physiological parameters. An alternative approach where multiple EBI signals are recorded in various locations might provide more reliable information. Most of the actual multielectrode methods for measuring bioimpedances aim to the design of fixed-frequency electrical impedance tomography (EIT) systems. Unfortunately, EIT solutions are unsuitable or excessively complex for other purposes such as the time-domain analysis of EBI magnitude [5] and the knowledge of spectral information for tissue characterization [6]. In addition, the difficulty associated with constructing high-fidelity multi-channel, multi-frequency data acquisition instruments has limited widespread development of multiple spectroscopic electrical impedance measurements in different locations. Conventional multichannel systems utilize multiple single-lead EBI measurement systems connected to the same organism, whose excitation signals may overlap, rendering it difficult to extract specific and reliable information.

In this work, we present a wireless multichannel spectroscopy measurement system based on a high-performance EBI sensor. This solution facilitates the measurement of separated bioimpedances in a human body with maximum accuracy. As shown in Figure 1, wireless EBI nodes are placed over the patient’s areas of interest in order to carry out independent bioimpedance measurements and transfer the records to the BSN coordinator. The coordinator is, in turn, wirelessly connected to the patient’s end device, where data are processed. The collected records are available to be transferred to a PC for further analysis. To follow the skin surface, the node can be fixed over a patch or over a strap.

3. Low-power wireless EBI sensor architecture

A simplified block diagram of the proposed wireless EBI node is outlined in Figure 2a. The EBI sensor comprises four electrodes, which allow tetra-polar impedance measurements in order to eliminate the skin impedance contribution. The EBI sensor, which was designed in 0.35-μm CMOS technology (Figure 2b), injects an ac excitation current into the biological material under test (MUT) which has an unknown impedance $Z_x$, detects the voltage drop across the MUT ($V^+$ and $V^-$), and processes these two signals so as to provide two dc voltages proportional to the magnitude, $V_m$, and the phase, $V_p$, respectively, of the MUT bioelectrical impedance by using a gain/phase detector. Thanks to the EBI sensor architecture, the extraction of the two dc voltages does not depend on the amplitude of the excitation current, which is extremely important at high frequencies where the output impedance of the current source is usually lowered. This reduces the complexity of the circuitry to perform further processing. A microcontroller unit (MCU) supervises the operation of the whole EBI node, controls the amplitude and the frequency of the excitation current, and converts the ensuing dc voltages ($V_m, V_p$) to a digital code by using the inbuilt analog-to-digital converter. Besides, the MCU
supports calibration tasks that aim at avoiding systematic measurement errors. The obtained digital words are transmitted by a radiofrequency section following a short-range wireless protocol (ZigBee).

**4. Experimental results**

Figure 3 is a photograph of the realized wireless EBI node. The heart of the proposed wireless section is the commercial solution CC2430 System-on-Chip from TI/Chipcon. The CC2430 is optimized for long-term battery operation and includes the CC2420 transceiver and an efficient 8051-based microcontroller, which implements the whole digital processing stage. The experimental performance of the developed EBI node is summarized in Table 1. Every EBI node can be independently adjusted (Table 2) so as to optimally measure the electrical properties of the underlying tissue in a given body location. A suitable graphical user interface (GUI), EBI-WSN, was developed in Matlab (7.10.0, The MathWorks Inc., Natick, MA, 2010) to control the operation of the EBI nodes and to show how the BSN works. Along with the sites for EBI measurements, the topology and the complexity of the BSN

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**Table 1.** Experimental performance of the EBI sensor

| Measuring system | Tetrapolar |
|------------------|------------|
| AC current excitation | • 5 µA to 1 mA  |
| Magnitude measurement range | 1 Ω to 3.5 kΩ |
| Phase measurement range | 0º to 90º |
| Analog front-end power consumption | 1.6 mW |

**Table 2.** Programmable parameters of the proposed EBI-BSN node

| Parameter | Options |
|-----------|---------|
| EBI analysis | • Single-frequency (SF-BIA)  |
|           | • Bioimpedance spectroscopy (BIS) |
| Frequency | • Single value (SF-BIA)  |
|           | • Sweep and interval (BIS) |
| Num. of analyses/sweep | • Single (SF-BIA, BIS)  |
|           | • Analysis time interval (SF-BIA, BIS) |
| Amplitude excitation current | • Single value (SF-BIA, BIS)  |
|           | • Automatic tuning (SF-BIA, BIS) |
that result more appropriate for the study of a particular physiological event can be also defined. The effectiveness of the developed GUI environment for time-domain measurement of two independent bioimpedances, i.e., two channels, is shown in Figure 4. The analysis and graphical representation of the measured results transmitted by EBI nodes is also included in the software.

5. Conclusions
The reliability of electrical bioimpedance (EBI) technology for diagnosis may be improved by utilising multiple simultaneous independent measurements. To aid in this, this work presents the design and implementation of a novel energy-efficient wireless multichannel EBI spectrometer, which has the potential to improve the accuracy of actual applications, as well as to develop new ones.

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