From Handheld Devices to Near-invisible Sensors: The Road to Pervasive e-Health

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Abstract. Pervasive computing refers to the increasing integration of information and communication technologies into people's lives and environments. In particular, pervasive technologies have been identified as a strong asset for achieving the vision of user-centred preventive healthcare. However, there are engineering problems to be solved before many of the envisioned applications in healthcare can become a reality. The objective of this chapter is to present future research demands in pervasive sensing by means of miniaturised wearable and implantable sensors featuring ultra-low power consumption, high portability, and robustness. At the same time, since many emerging non-invasive measurement techniques related to monitoring physiological and psychological status of individuals rely on bioelectrical impedance spectroscopy (BIS), we also consider the perspectives for bioimpedance applications, referring in particular to the use of CMOS technology for chip-scale integration of BIS readout electronics.

Keywords: bioelectrical impedance spectroscopy, CMOS technology, body sensor networks.

1 Introduction

Current economic, social, and demographic trends are demanding healthcare systems focused on prevention and early detection of illnesses, which should be able to provide an optimized medical response as well as a reduction in the number of visits to the hospital [1, 2]. eHealth – the beneficial application of information and communication technology (ICT) to the healthcare sector – stands out as a way to improve the operational efficiency of all the supporting processes involved in the delivery of healthcare. eHealth is not just about converting paper records to electronic ones, but also about making these electronic records available, as and when required, to healthcare providers across the chain. eHealth covers the interaction between patients and health-service providers, institution-to-institution data transmission, peer-to-peer communication between patients or health professionals, health information networks, electronic health records, telemedicine services, and personal wearable and portable systems for monitoring and supporting patients [3]. Therefore, eHealth systems can deliver high-quality information in real

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time and in a manner that is easily accessible everywhere, while at the same time they have the power if not to reduce, at least to manage this complexity. For instance, doctors can access patients' medical records more easily, get immediate access to test results from the laboratory, and deliver prescriptions directly to pharmacists. Patients with chronic conditions can carry monitoring devices which alert their doctor if their condition changes, yet being allowed to continue with their daily life activities.

Since its inception in the early 1990s, eHealth has shown a lot of successful examples [4, 5]. Wireless communication technology came to encourage different strategies of mobile and ubiquitous eHealth initiatives, ranging from doctor mobility, i.e., remote access to medical data, to patient mobility, e.g., remote monitoring of vital signals and wearable medical sensors, up to web based medical data access. By introducing pervasive computing systems that reason intelligently, act autonomously, and respond to the needs of individuals in a context- and situation-aware manner, 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 ICT [6, 7].

Although there is no univocal description in the current literature, pervasive healthcare may be defined from two perspectives: i) as the application of pervasive computing technologies for healthcare and ii) as making healthcare available everywhere, anytime, and to anyone [8]. Accordingly, pervasive healthcare offers opportunities for future healthcare provision, both for detecting, treating, and managing disease and for patient administration [9]. For instance, remote sensors and monitoring technology might allow the continuous capture and analysis of patients' physiological data. Medical staff could be immediately alerted to any detected irregularities. Data collection on this scale could also provide for more accurate pattern/trend analysis of long-term health conditions. Wearable sensors may offer greater patient mobility and freedom within and even outside hospitals and save both time and money by reducing the need for repeated and intrusive testing. At the same time, sensors embedded in items of clothing, for example, might allow constant monitoring of heart rate, body-mass index, and other physiological variables.

Pervasive healthcare addresses a set of technologies and concepts that help integrate healthcare more seamlessly to our everyday lives, regardless of space and time. While there has been significant progress toward this vision, most research has focused on the development of small-scale systems, tested by a handful of users, interacting with a limited number of devices. The simple truth is that, in order to implement sustainable eHealth programs, pervasive eHealth must move from being simply an innovation in healthcare through a sustainable change process to ultimately transform healthcare delivery. Moreover, future pervasive systems need to encompass a large number of computational platforms, users, devices, and applications dealing with massive amounts of data. Diverse devices such as smart phones, tablets, laptops, desktops, wearable sensors, radio frequency identification tags, and embedded wireless sensors on the order of thousands, millions, and even billions of units, as envisioned in the future Internet, will enable a wide spectrum of applications, including those of pervasive eHealth [10].

Consequently, the research community needs to address the issue of scale, i.e., it is essential to consider the ability of eHealth services to maintain an adequate level of efficiency as they scale to entire national populations. In this context, ubiquitous health monitoring systems based on tiny wireless medical sensors are going to play a key role for pervasive healthcare. These systems will allow healthcare service givers to early detect and act on signs of patients' clinical deterioration, thus improving the quality of care in a reliable, unobtrusive, and cost effective way [11].

A pervasive health system will ultimately need information about individuals and their surrondings, which will be delivered by embedded sensors, thus integrating pervasive sensing with pervasive computing. 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 measurement of physiological signals [12]. Unlike wired monitoring systems, BSNs provide long-term continuous monitoring of patients under their natural physiological state even when they move [13]. The successful realization of this vision requires innovative solutions able to remove the critical technological obstacles to implement wireless sensor nodes for biomedical applications. This chapter presents future research demands in pervasive sensing by means of wearable and implantable miniaturised sensors featuring ultra-low power consumption, high portability, and robustness. The rest of the chapter is organized as follows. Section 2 gives an overview of wireless technologies that have fundamental importance in supporting continuous and reliable long-term monitoring systems. The major design challenges of miniaturised, autonomous, and wireless medical sensors are discussed in Section 3. Since many emerging non-invasive measurement techniques related to the physiological status of individuals rely on bioelectrical impedance spectroscopy (BIS), perspectives for medical applications are highlighted in Section 4, referring in particular to the use of CMOS technology for chip-scale integration of BIS readout electronics. Finally, conclusions are drawn in Section 5.

2 Why Is a Sensor Network Important?

Sensor networks have been heralded as one of the 21 most important technologies for the 21st century [14]. Most researchers agree on the fact that a sensor network consists of a large number of inexpensive and smart devices with multiple onboard sensors, networked through wired or wireless links and densely deployed, that cooperatively collect information of the physical world in which they are embodied and may control the surrounding environment [15, 16]. The most perceptive reader will observe that this definition is not very specific. In fact, national power grids, with their many sensors, can be considered as a large sensor network although they were developed before the term sensor network came into vogue. Therefore, using a wide enough interpretation, almost anything fits the definition of a sensor network, even humans. When observing human skin on a microscopic scale, we are impressed by the diversity and density of embedded sensors.

This abundance includes sensors for pressure, acceleration, temperature, and so on. Despite their immense variety, all sensor networks have one fundamental feature in common: each sensor is limited in its ability to monitor a situation. The power of a sensor network comes from the fact that even though individual nodes are quite limited, the whole array becomes very powerful when networked. In this Section, we will focus on one of the most common applications of sensor networks in the context of eHealth, namely human vital-sign monitoring.

Let us think about the course of a typical day in a hospital. Lots of medical sensors like thermometers, blood pressure meters, electrocardiography (ECG) monitors, and pulse-oximeters are used to monitor the condition of patients. Some measurements, such as temperature reading, will be taken periodically, whereas others, such as ECG monitoring a patient with a heart disease condition, must be done continually. A significant amount of nurses' time is spent on measuring and recording temperature, blood pressure, and other values for patients' medical records in order to monitor progress and discover relapses. Moreover, one of the most time-consuming problems caused by cables is that when patients are moved, all wires must be unhooked during transport and then reattached when the patient reaches his or her destination. A close study of the intra-hospital transport of ECG monitored patients proposed using wireless ECG sensors to save time and trouble [17]. The same way, the need for removing cables is present when we consider another scenario, where a patient is recovering from a health trouble. Indeed, patients need to get out of bed as early as possible, which implies that cables restraining them to their beds during the recovery are problematic. Thus, clinicians request wireless sensor technology to propose appropriate solutions.

2.1 Wireless Sensor Networks

Traditional sensor networks in the medical sector focus on establishing network communication between mobile devices having great amounts of computational power and energy at their disposal, such as cell phones. These networks, which are referred to as mobile *ad-hoc* networks (MANETs), do not allow a sufficiently dense sampling of physical, physiological, psychological, cognitive, and behavioural processes so as to encompass the pervasive eHealth monitoring vision. Advances in hardware and wireless network technologies have led to low-cost, low-power integrated sensors with onboard processing and wireless data transfer capability, which are the basic components of already existing WSNs. One factor that distinguishes these networks from MANETs is that their end goal is the detection/estimation of some event of interest, and not just medical data communication. WSNs carry the promise of drastically improving and expanding the quality of healthcare across a wide variety of settings for different segments of the population [18].

Despite the interest in the application of WSNs to healthcare, a significant gap remains between existing sensor network designs and the requirements of medical monitoring. Most WSNs are intended for deployments of stationary nodes that transmit data at relatively low data rates, with the focus on best-effort data collection at a central base station. By contrast, medical monitoring requires relatively high data rates, reliable communication, and multiple receivers. Unlike many WSNs, medical monitoring cannot make use of traditional in-network aggregation since it is not generally meaningful to combine data from multiple patients. In fact, if the data from a sensor on one patient would find its way to a sensor on a different patient, it would be considered as a security breach. Moreover, in a medical sensor network, each sensor has a unique task of measuring a given phenomenon of a particular patient—other sensors measure either a different phenomenon on the same patient, or a similar phenomenon on a different patient.

Whilst WSN technology continues to evolve for the broad range of possible applications, it does not specifically tackle the challenges associated with human body monitoring and patient care. The principal reason is that most sensor network applications have very different data, communication, and lifetime requirements. Unlike conventional WSN applications, medical deployments are characterized by mobile nodes with varying data rates and few opportunities for in-network aggregation, as pointed out above. In addition, the human body environment is on a smaller scale and also requires a different type and a different frequency of monitoring. Numerous published research works succeeded in demonstrating how wireless medical sensors can be minimised and how this will be useful in the future eHealth sector. However, the problem of replacing cables with a wireless connection is affected by a rather complex interplay of problems, e.g., power consumption and security. The realisation that proprietary designed WSNs are not ideally suited to monitoring the human body and its internal environment has led to the development of body sensor networks [19].

2.2 Body Sensor Networks

Professor Guang-Zhong Yang was the first researcher who specifically defined the term body sensor network (BSN) [19]. BSN technology represents the lower end of power and bandwidth in the body area network (BAN) scenario [19]. A BAN is formally defined as a system of wireless devices in close proximity to or inside a person body that cooperate to enable monitoring for the benefit of the user [20]. When compared to conventional WSNs, BANs consist of a lower amount of smaller nodes, typically from 20 to 50 nodes, and provide less space coverage [21]. Figure 1 shows average power consumption and data rate for a number of popular wireless technologies. Notice that the range of BAN devices can vary significantly in terms of bandwidth and power consumption in order to support a great variety of medical and non-medical applications and, hence, data rates vary from few kbit/s for simple data to several Mbit/s in video streams.

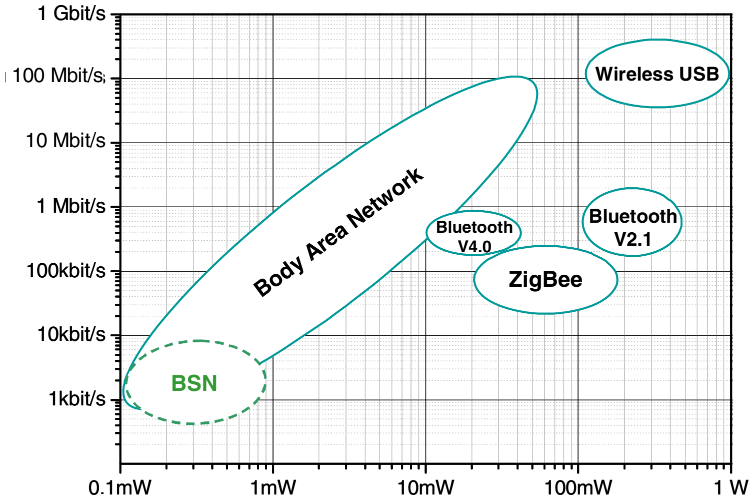


Fig. 1. Average power consumption *vs* data rate of available wireless technologies

As the application of BANs have been extended from connecting personal electronic consumer goods to implementing medical and healthcare applications, BAN has become a key element in the infrastructure for pervasive eHealth applications. The use of BANs in the medical area consists of wearable and implantable sensor nodes that sense biological information from the human body and transmit it wirelessly over a short distance to a control device worn on the body or placed in an accessible location. As shown in Table 1, the data rates needed for vital-sign monitoring are usually low for the individual sensor. Recently, several transceivers for BANs have been developed [23, 24]. However, their working distance and power consumption are beyond the optimal choice for monitoring health status. Moreover, due to the energy absorption in the human tissue, their transmitted signals around the human body significantly suffer from huge path loss [25]. The pursuit of long-term and continuous monitoring without human activity restriction has promoted the concept of BSNs. This specialized family of WSN has the potential to facilitate patient-centric healthcare.

Table 1. Human biopotential and biophysical signals [22] and their typical data rate, bandwidth, and accuracy

	Data rate	**Bandwidth**	**Accuracy**
ECG (12 leads)	288 kbit/s	0.1 – 1000 Hz	12 bits
Electromyogram	320 kbit/s	5 – 10000 Hz	16 bits
EEG (12 leads)	50 kbit/s	0.1 – 100 Hz	12 bits
Movement	35 kbit/s	0 – 500 Hz	12 bits
Temperature	120 bit/s	0 – 1 Hz	8 bits
Blood saturation	16 bit/s	0 – 1 Hz	8 bits

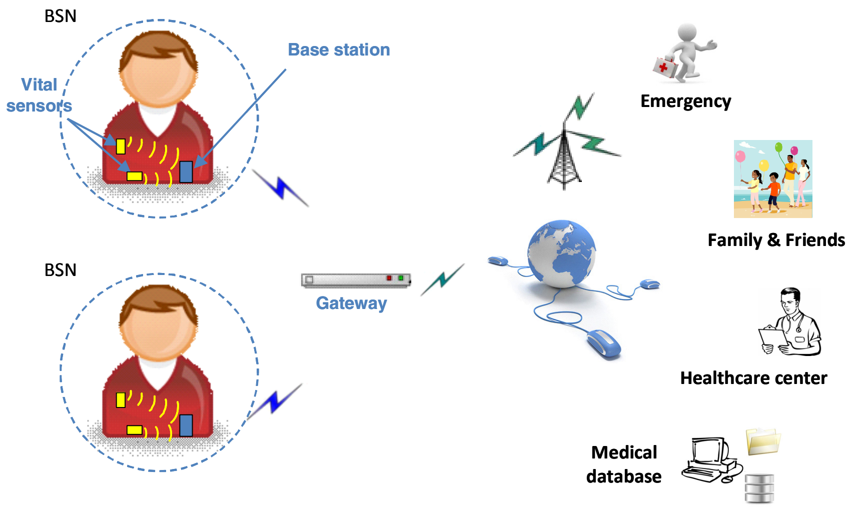


Fig. 2. Architecture of a BSN in a pervasive e-Health scenario

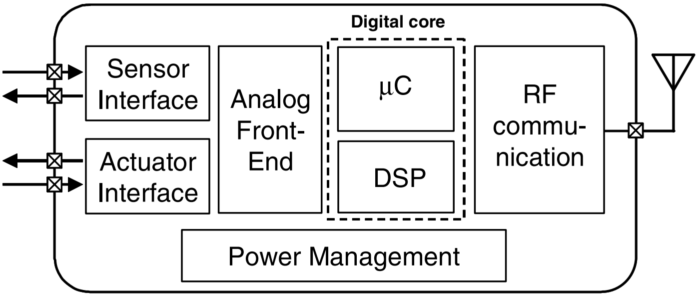
A BSN results from the fusion of sensing and wireless technologies, as it consists of a series of miniaturized low-power sensors wholly or partially covering the body area that collect, process, and communicate physiological information from the body [19], [26]. These sensors can be either wearable or implantable. As illustrated in Fig. 2, one of the sensor acts as a master node, i.e., as a base station, for central control, and a number of vital-sign sensors act as slave nodes. The base station thus plays a different role from the slave nodes in the network and has more resources in terms of physical size, available energy, radio-frequency (RF) communication range, and computing power. Although the challenges faced by BSNs are in many ways similar to those that are typical for BANs, there are several important differences between the very small low-power sensors of BSNs and their BAN counterparts. First, the body itself prevents the reuse of the same node across many roles due to the particular characteristics of physiological data measurements. Second, the close proximity of the base station makes node-to-node communication largely unnecessary. BSNs therefore tend to use star topology, with each sensor node communicating only with the master node. Third, sensor nodes have limited energy resources available as they have very small form factor. Finally, for most sensors it is not possible to recharge or replace batteries although a long lifetime of the node is required.

Most proposed prototypes of BSNs are largely based on commercially available off-the-shelf technologies [19], [27], [28], [29], which employ Bluetooth, ZigBee, or other RF communication protocols commonly used in BANs and WSNs.

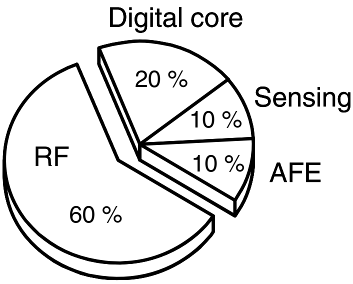
However, there are great obstacles that prevent such solutions from gaining wide acceptance from its intended end users. One major obstacle is the physical implementation of the proposed sensor nodes, as all components are packed into a double-side printed circuit board reaching an area of several hundreds mm^2 [27], [28]. In addition, the typical power consumption is on the order of tens milliwatts [19], [29]. It should be pointed out that these sensor nodes support complex architectures in which many available resources are rarely or even never used. Therefore, a long-term continuous monitoring with wearable sensors is not yet feasible by using commercial off-the-shelf technologies. Nowadays, ASIC-based BSN sensors have been proposed for medical applications [30]. Custom BSN integrated circuit design is an emerging field. Despite intensive research efforts, few implementation works have been published so far. One reason may be that these custom nodes are heavily tailored to a specific application instead of being flexible and generic. BSN technology is not mature and there are several constraints limiting clinical possibilities. Moreover, sensor nodes will not be adopted if they are too inconvenient or uncomfortable. In next Section, the major challenges to be faced when designing miniaturized, autonomous, and wireless wearable sensors are discussed.

3 What Does a Medical Pervasive Sensor Look Like?

The purpose of a medical sensor is to provide information to a physician as to the function and performance of an organ, a group of organs, or system within the body of a patient. In the context of pervasive eHealth, the acquisition of biomedical signals, such as those for measuring vital signals, can be performed through BSN sensors attached on the patient's body or through special wearable sensors. Very often, the acquisition of a biomedical signal is not sufficient and it is required to process the acquired signal to get the relevant information buried in it. The transmission of the collected information to the base station is performed through an appropriate wireless technology. As shown in Fig. 3a, a BSN sensor can be divided into five major functional blocks: 1) the stimulating/sensing components for biomedical stimulation and sensing (sensor and actuator interfaces), 2) an analog front-end (AFE) for signal acquisition, 3) a digital core for control and local processing, 4) an active RF transceiver for data link, and 5) a power-management unit. Although power consumption depends on the specific nature of the application, energy is mainly spent on processing sampled data by the microcontroller and forwarding the data out via a wireless link. Fig. 3b highlights the power breakdown of a BSN sensor illustrating this statement, where in general communication accounts for the majority of the energy expenditure of a sensor.



(a)



(b)

Fig. 3. (**a**) Conceptual block diagram of a BSN sensor and (**b**) its power breakdown

At a first glance, a BSN sensor can be identified as an integrated smart sensor for human body monitoring with wireless communication capabilities. Nowadays, technological developments in materials and electronics have led to the miniaturisation and integration of sensors into intelligent devices and systems that not only measure and analyse, but also act on the resultant information. The size and the cost of smart sensors have decreased with time, and the improvement in the technologies for other important components, such as memory and radio transmitters, will allow more capable and long lasting devices, thus reducing their maintenance cost [31]. For example, a smart temperature sensor will convert the raw data signal to temperature information, e.g., Celsius degree, and automatically establish a network connection to pass on the information. Therefore, just an integrated smart sensor in the technology arena is a candidate for having the prefix *ubiquitous* or *pervasive* added to it. However, the wearable nature of the BSN sensor places unique constraints on its specification and design. Although it is rather difficult to draw general indications because of the wide variety of sensors in medical applications [32], some trends about present and future technical barriers can be highlighted.

3.1 Major Design Challenges

The nodes that constitute a BSN must meet certain requirements in order to minimize the adverse impact of the wireless network over the patient. There are three key challenges, namely extreme reliability, small size/weight, and very low power consumption, which can become a design complexity nightmare (Fig. 4).

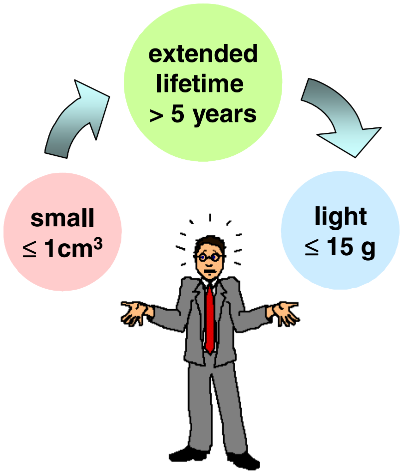


Fig. 4. Key design challenges of a BSN sensor

Reliability is defined as the probability, at a desired confidence level, that a device will perform a specified function, without failure, under stated conditions, for a specified period of time. According to this definition, reliability is a requirement in terms of both product longevity and confidence that the device is working as specified. Well-designed technology allows doctors, nurses, and other healthcare professionals to focus on caregiving functions and promoting the health of patients. This is crucial for the future market of devices used in remote monitoring. Since data need to be reliable and secure, BSNs suffer from the *reliability dilemma*, which means that the higher the reliability desired of data transmission, the higher the data overhead and, hence, the higher the power required.

The second challenge is the sustainable form factor for a BSN sensor. System designers must shrink the size of sensing nodes to the sub cubic centimeter level and give them conformal and wearable shapes that substantially disappear to the point that they are forgettable by the wearer. Size can be reduced by using a small cube or a smart band-aid, which requires new integration and packaging technologies [33]. In particular, chip-on-board assembly, chip-on-chip and, more recently, advanced 2-D and 3-D packaging technologies have improved in such a way that miniaturization is not only possible, but also cost effective while still maintaining adequate reliability.

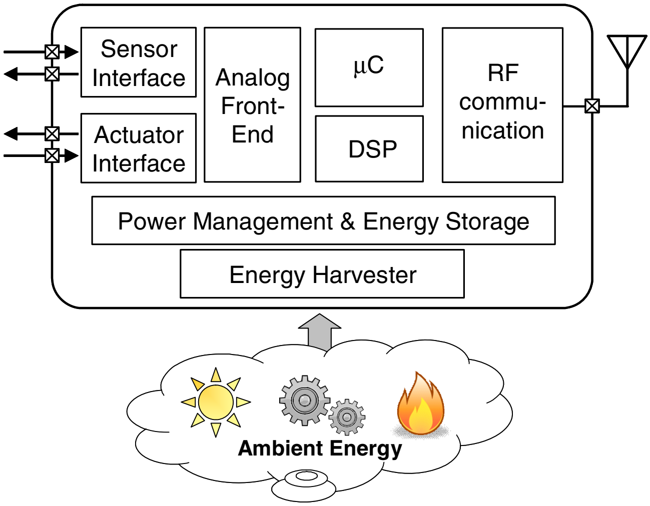


Fig. 5. Simplified block diagram of a self-powered BSN sensor

The third challenge is the sustainable power supply for the sensor. Although the research towards higher energy-density batteries is ongoing and new materials are revolutionizing battery dimensions, their energy density does not scale according to the target size, thus limiting their energy budget to the range of tens to hundreds of joules, i.e., 2 or 3 orders of magnitude less with respect to a cell phone battery [34]. As a result, the minimum required power consumption of sensor nodes often exceeds the rated current capacity of most battery types, thus leading to suboptimal battery lifetime. This drawback precludes the use of many existing solutions based on conventional electrochemical batteries. Moreover, there are also many applications where battery replacement is not practical, such as sensors implanted in the human body. To overcome this shortcoming, another energy paradigm is needed and energy harvesting (also referred to as energy scavenging) from the environment may provide a solution [35].

Energy harvesting is a means of powering sensor nodes by scavenging various low-grade ambient energy sources such as environmental vibrations, human power, thermal sources, solar sources, and wind energy sources and convert the obtained energy into useable electrical energy. Energy harvesting generally suffers from low, variable, and unpredictable levels of available power. Hence, it is likely that the sensor will be powered by a combination of different types of ambient energy sources and the energy thus obtained will be stored in rechargeable microbatteries for later use [35]. This approach is very promising, attracting interest from the scientific community and fostering the creation of new Companies which offer average power densities in the range of tens $\mu W/cm^2$ [36]. In particular, combining both energy storage and energy scavenging sources, the available power of a 1 cm^3 sensor is about 100 μW. This is illustrated in Fig. 5, where the sensor operates by scavenging energy from ambient power sources, e.g., a thermal [36], a vibration, or a solar energy source. The scavenged energy (after buffering on an energy storage element) is then used to power the sensing, computation, storage, and communication modules of the sensor. Since energy harvesters can be used efficiently in the 10 μW to 1 mW range [36], the development of BSNs is linked to a technological leap in the field of integrated-circuit design from low-power electronics (10 – 100 mW) to ultra-low power electronics (0.1 – 1 mW). Accordingly, highly aggressive low-power circuit design and efficient power delivery are required to meet the power constraints set by the sensor.

4 Improved Pervasive Sensing with Wearable Bioimpedance-Based BSN

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, breathing 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 and emotional states as well as for reducing the impact of medical therapies in chronic patients [37]. From the set of available techniques for determining the physical and mental state of a person, bioelectrical impedance analysis (BIA) has qualities very attractive for personalized monitoring of patients and senior citizens during their daily life activity, besides being a non-invasive preventive diagnosis technique [38].

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 [39], [40]. According to health issues, the amplitude of the excitation current is so low that EBI technology can be used even in neonates without causing any damage. When a biological material is included as a part of a well-known and well-characterized electrical circuit, valuable information can be derived about the microscopic structure of the material from the study of the behaviour of its electrical parameters, i.e., the magnitude and the phase of its bioimpedance. Needless to say, the knowledge gained about the relationship between the cellular-level structure and the electrical behaviour of living materials, as well as the high degree of maturity reached by silicon microelectronic technology, have allowed the recent progresses in EBI measurement techniques.

Although EBI technology can be applied in many fields, the segment of medical devices is one of its major working areas. In particular, EBI medical applications can be divided in the following three main categories.

- Bioimpedance spectroscopy (BIS), which consists in the study of electrical bioimpedance for tissue characterization and functional monitoring in a determined frequency range of the excitation current signal, typically from 1 kHz to a few MHz [41]. A particular case is the single-frequency bioimpedance analysis (SF-BIA), where a unique input frequency is used (typically 50 kHz). At this frequency, the internal current flows through the extracellular space as well as through the intracellular space, which provides valuable information about the health/integrity of cell walls. Practical applications of BIS and SF-BIA are body composition analysis, early detection of alterations in organs and tissues, assessment of the effectiveness of therapies and treatments, and so on.

- Impedance plethysmography, which consists in recording the instantaneous volume of an object by measurement of electrical bioimpedance [42]. In practice, the term of impedance plethysmography is mostly associated to the assessment of blood volume changes in any part of the body from changes caused in the electrical impedance of such body segment. Thus, typical applications of this method can be found in monitoring the stroke volume of the heart (usually referred to as impedance cardiography or transthoracic impedance cardiography) [43], in assessing peripheral blood flow [44] and arterial stiffness (i.e., the loss of the elastic properties of arteries), in respiration monitoring, and so on.
- Impedance imaging, which is based on multiple impedance measurements by injecting current and recording the voltage with a multiple electrode system located in a cross-section of the body [45], [46]. A reconstruction algorithm applied to the collected data generates an image which provides information about the conductivity inside the body. Depending on the collected data (transimpedance, resistance, or capacitance), the corresponding technique is referred to as electrical impedance tomography, electrical resistance tomography, or electrical capacitance tomography, respectively. In any case, although the resolution of these techniques is poor when compared to other medical image methods [47], impedance imaging is a very promising approach due to the advantages derived from the EBI technology, which are summarized below.

EBI technology presents advantages and drawbacks when compared to other medical diagnosis techniques. As for the first, it should be pointed out that EBI technology is relatively inexpensive, innocuous (non-invasive, non-ionizing, and non-destructive), and easy-to-use. As for drawbacks of EBI technology, it is worth to mention its limited accuracy, mainly when compared to other medical diagnosis techniques such as computer tomography and magnetic resonance, and lack of standardization in the procedures (multiple factors of influence), which makes it not easy to guarantee the repeatability of results.

4.1 Opportunities of Bioimpedance Technology

As a consequence of the demographic trend in the developed countries, the population segment of elderly people needs more and more healthcare services. Moreover, the rest of population segments also demands for higher quality of life (i.e., healthy lifestyle), which also calls for the availability of healthcare preventive programs. These considerations have an adverse impact, in principle, over the financial resources required by National Health Systems which, very often, must provide adequate response to citizens' demands in a social scenario characterized by a shortage of available resources.

The above circumstances are strongly promoting the development of new healthcare structures and strategies, whose success necessarily relies on the availability of diagnosis and assessment medical techniques with some of the following features:

- Medical techniques suited to be incorporated in Primary Healthcare Centres (ambulatory services) instead of being limited for use in specialized hospital services as a consequence of high cost and/or the need for bulky equipment and the necessity to be manipulated by skilled operators;
- Medical diagnosis (and even prognosis) techniques addressed to the detection of diseases as early as possible, which assures the effectiveness of the treatments and therapies at a lower cost;
- Medical techniques to be manipulated by patients with possibility of remote supervision, which also reduces the number of visits to Healthcare Centres.

In summary, there is an increasing interest in the development of medical devices featuring low-cost, light weight, and small size and being innocuous, autonomous, wireless, easy-to-use even by the own patient, and able to early detect alterations in the structure and functionality of organs and tissues as well as to assess the effectiveness of therapies and treatments. Consequently, terms such as Personal Healthcare (p-health), Home Monitoring, Wearable Medical Devices, Non-invasive Medical Technologies, etc. are currently associated to good business chances for healthcare providers and EBI technology occupies a privileged position for contributing to provide a satisfactory response to most of technological challenges.

4.2 EBI-BSN: New Perspectives for Bioimpedance Applications

In order to take advantage of the described social scenario for medical devices, a technology platform for a number of BSN applications based on EBI technology has been developed. In particular, a cost-effective CMOS silicon-chip implementation of a flexible high-performance EBI sensor has been considered as the only feasible way to fulfil the above objectives. Of course, appropriate low-power low-voltage CMOS circuit techniques were adopted in the design phase.

Fig. 6 illustrates the main circuit sections of an EBI wireless sensor, also referred to as EBI mote. The CMOS analogue front-end section (EBI sensor/spectrometer) injects an ac excitation current into the biological material under test (MUT), detects the voltages in two points of the MUT, and processes these two signals so as to provide two dc voltages proportional to the magnitude and the phase, respectively, of the MUT bioelectrical impedance. A tetrapolar system (two electrodes for current injection and two electrodes for voltage recording) is used so as to reduce measurement errors caused by the electrode/skin interface with respect to the case of its two-electrode counterpart [48]. A microcontroller section supervises the operation of the whole mote, controls the amplitude and the frequency of the excitation current according to the stored program sequence, and convert the ensuing dc voltages representing the magnitude and the phase of the measured EBI to a digital code. At the same time, the microcontroller supports the calibration task that aims at avoiding systematic measurement errors. The obtained digital words are transmitted by an RF section to the coordinator of the BSN following a low-power, short-range wireless protocol, such as ZigBee or Bluetooth low-energy.

The block diagram of the EBI sensor is shown in Fig. 7. Basically, its task consists in measuring the amplitude and the phase of a signal by using a gain phase detector. The excitation current is injected through two electrodes (I^+, I^-) to stimulate the tissue having an unknown impedance Z_x. The excitation current also flows through an integrated reference resistor R_s connected in series with Z_x. Two other electrodes (V^+, V^-) sense the voltage drop across Z_x, which is amplified by an instrumentation amplifier (IA). The voltage signal across R_s is amplified by a second instrumentation amplifier matched to the former. These amplified voltage signals are processed by the phase-gain detector so as to obtain two dc voltages proportional to their magnitude ratio $|K|$ and phase difference θ, respectively. If the two instrumentation amplifiers are identical and have infinite input impedance, it is straightforward to obtain that the unknown impedance Z_x can be expressed as

$$Z_x = R_s \cdot |K| \angle \theta \qquad (1)$$

The excitation current magnitude is chosen to be small enough so as not to be perceived by the subject, but large enough to produce voltage signals that are above interfering noise which might arise from bioelectrical sources such as muscle tissues. In practice, relatively small current magnitudes are involved, i.e., less than 1 mA, which are below the threshold of human perception.

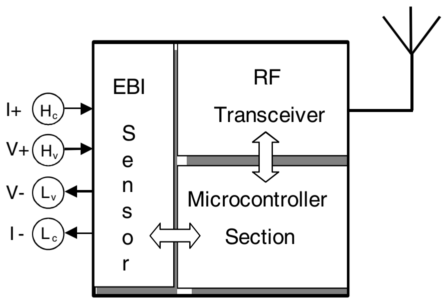


Fig. 6. Functional blocks of an EBI mote

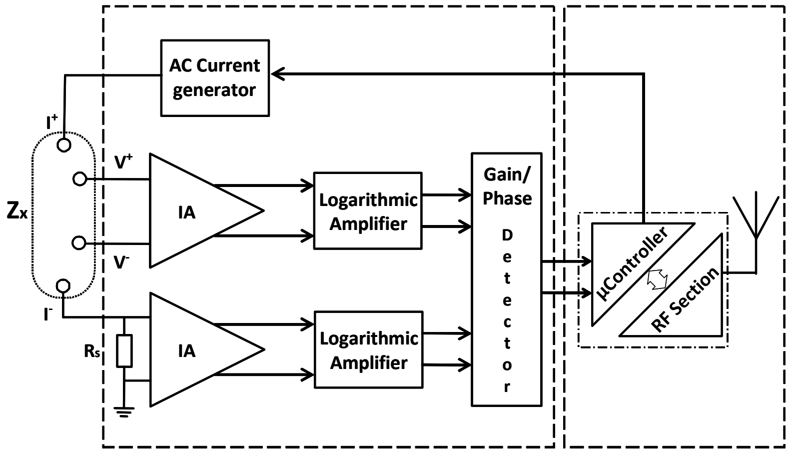


Fig. 7. Block diagram of an EBI-BSN mote (the EBI sensor is enclosed by the left dashed box)

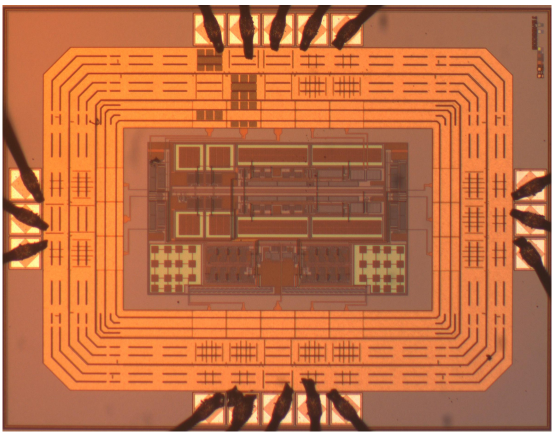


Fig. 8. Chip microphotograph of the high-performance EBI sensor

The EBI sensor was designed and fabricated in standard 0.35-µm CMOS technology. Fig. 8 corresponds to a microphotograph of the fabricated chip. The core 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 mote is summarized in Table 2.

Table 2. Experimental performance of the EBI-mote

Measuring system	Tetrapolar
Ranges of current excitation	• Amplitude: 5 μA to 1 mA • Frequency: 1 kHz, 2 MHz
Magnitude measurement range	1 Ω to 3.5 kΩ
Phase measurement range	0º to 90º
Analog front-end current consumption	0.8 mA
Analog front-end supply voltage	2V (single-supply)

Table 3. Programmable parameters of the proposed EBI-BSN mote

Parameter	Options
Type of EBI analysis	• SF-BIA • BIS
Frequency	• Single value (SF-BIA) • Sweep and interval (BIS)
Num. of analyses/sweeps	• Single (SF-BIA, BIS) • Analysis time interval (SF-BIA, BIS)
Amplitude excitation current	• Single value (SF-BIA, BIS) • Amplitude automatic tuning (SF-BIA, BIS)

Cardiovascular diseases (CVD) represent the leading cause of death in the population of developed countries. They constitute a very attractive application field for multi-channel electrical bioimpedance plethysmography, which allows the measurement of cardiac blood flow (cardiac output) and peripheral blood flow in selected parts of the body [49].

Multi-channel impedance plethysmography based on BSN can provide improved performance in the diagnostic of cardiovascular disorders as well as in other medical applications (it should be noted that two-channel systems represent the most common multi-channel impedance equipment in this area). An EBI-BSN based on the mote architecture of Fig. 7 performs highly flexible and scalable multi-EBI spectrometer architecture. Every mote can be independently adjusted (Table 3) so as to optimally measure the electrical properties of the underlying tissue and, hence, to register the physiological events that occur in a given body location. To follow the skin surface, the mote can be fixed over a patch or over a strap. Along with the sites for EBI measurements, the topology and the complexity of the BSN that result more appropriate for the study of a particular physiological event can be defined. A specifically tailored graphic software interface facilitates the user to program the operation of the motes and the topology of the BSN.

For illustration purposes, Fig. 9 corresponds to a basic and conceptual EBI-wireless BSN (EBI-WBSN) scheme for non-invasive assessment of hemodynamic parameters. Every mote is assumed to be positioned on top of one of the big arteries (carotid, femoral, brachial, etc.) of the arterial tree. Each mote, which carries out a bioimpedance analysis with appropriate values of frequency and amplitude of the excitation current, detects the arrival of the blood pressure pulse which generates a bioimpedance signal. The velocity of a pressure pulse that propagates through the arterial tree is known as Pulse Wave Velocity (PWV) and depends on the properties of the arterial walls. In particular, PWV is indicative of the arterial stiffness. Its clinical relevance consists in the fact that it represents an independent global marker of cardiovascular risk. Also, blood pressure can be measured by tracking the pulse wave transit time in an arterial segment.

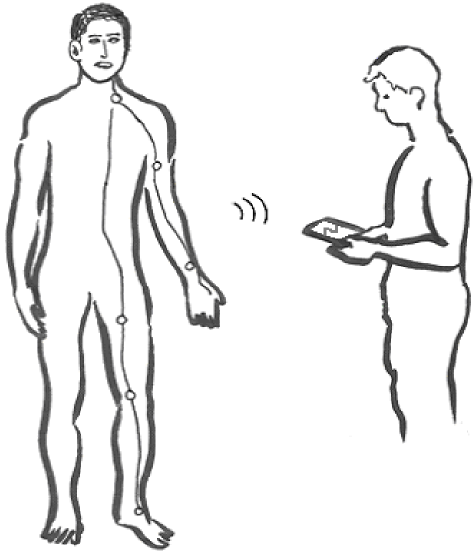


Fig. 9. EBI-BSN scheme for non-invasive assessment of hemodynamic parameters

PWV between the carotid to the femoral artery is accepted as a gold-standard of arterial stiffness in clinical practice [50]. However, PWV in any other arterial segment contains valuable clinical information, since the wall properties are not homogeneous along the whole arterial tree. An EBI-WBSN is able to measure the pulse transient time between any two motes, where pulse transient time refers to the time that a pressure pulse requires to travel through the corresponding arterial segment. All measurements of pulse transient time are carried out over the propagation of the same pressure pulse. The distances between motes can be precisely determined by their respective ZigBee transceivers. This way, the PWV between two any monitored arterial segments, i.e., the ratio of the corresponding distance to the pulse transient time in the considered arterial segment, is accurately derived.

Moreover, changes in cardiac output as well as in peripheral blood flows can be derived from the analysis of the corresponding bioimpedance wave signals and the well-known hemodynamic equations [51].

Finally, from a general point of view, wearable medical systems for pervasive health based on BSNs incorporate technologies that enable continuous and non-invasive monitoring of vital signs and biochemical variables [52], [53]. These systems are also taking advantage of the great improvement in the development of textile-electrode technology [54]. Medical monitoring systems involve monitoring one or more vital signs such as cardiac activity, blood pressure, respiration, blood oxygen saturation (respiration effectiveness), blood glucose level, etc. Electrical bioimpedance is a technology with a suitable potential for playing a leading role in wearable healthcare systems.

5 Conclusions

In this chapter, we have shown why the successful realization of pervasive eHealth can only become reality through innovative solutions able to remove the critical technological obstacles to implement miniaturised wearable sensor nodes for biomedical applications. Three key challenges have been introduced, namely extreme reliability, small size/weight, and very low power consumption. The merits and performance limitations of electrical bioimpedance (EBI) sensors in the pervasive eHealth context have also been discussed. As a case study, an unobtrusive, ubiquitous wireless EBI sensor for real-time monitoring has been proposed.

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