

Ultra-Low Power Sensor Design for Wireless Body Area Networks: Challenges, Potential Solutions, and Applications

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Abstract

This paper addresses the design challenges in wireless body area networks and gives an overview of recent technological achievements to tackle these challenges. It covers the areas of wireless communication, digital signal processing, sensing and read-out, and energy harvesting. In addition, this paper presents research platforms developed at IMEC/Holst Centre to illustrate how technological breakthroughs in these areas lead to the realization of ultra-low power wireless body area networks. It also demonstrates how the developed platform may help researchers to investigate emerging applications relying on wireless body area networks.

Keywords

Wireless body area networks, ultra low power, sensor nodes.

1. Introduction

The wireless body area network (WBAN) is a wireless network used for communication among sensor nodes operating on, in or around the human body in order to monitor vital body parameters and movements. For example, as illustrated in Figure 1, a patient has a number of sensor nodes attached to his body surface or implanted into tissues. These nodes transmit various sensed signals from the body, such as electroencephalography (EEG), electrocardiography (ECG), electromyography (EMG), skin temperature, skin conductance, and electrooculography (EOG), to a home base station, from where the signal can be forwarded to a hospital, clinic or elsewhere, through a wireless local area network (WLAN), cellular network or public switched telephone network. Besides these medical applications, the WBAN also enables its user

with lifestyle, assisted living, sports or entertainment functions [1].

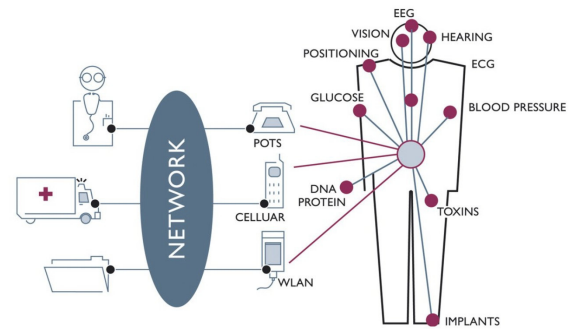


Figure 1. Diagram of wireless body area network and its seamless connection with hospital environments.

A typical sensor node in WBAN should ensure the accurate sensing of the signal from the body, carry out low level processing of the sensed signal, and wireless transmit the processed signal to a local processing unit [2]. The main challenges for successful realization of the sensor nodes can be summarized as follows:

1. The overall size and weight of sensor nodes should be tailored to the human body. It is expected that the sensor nodes could become invisible in order to avoid activity restriction or behavior modification. This requires new integration and packaging technologies.
2. The total energy consumption of sensor needs to be drastically reduced to allow energy autonomy. This is especially important for implantable sensors. As the energy autonomy of current battery-powered sensors is limited, the energy harvesting technology could be integrated to significantly extend the operating life of sensor nodes.
3. The security of WBAN should be guaranteed to protect the patient's privacy. The sensed signal from the body should have secure and

limited access. It should be very important that the sensed signal from one person cannot be mixed up with that from another person.

4. The reliability needs to be paid special attention. An undetected life critical signal could lead to fatal consequences. The improvement of reliability requires minimizing not only wireless communication errors but also sensing and read-out errors.
5. The intelligence should be added to sensors so that each one is capable of storing, processing and transferring signal continuously or on an event-triggered basis. Intelligence could also be introduced at the network level to deal with issues such as network management, data integration and data interpretation.

To address the above challenges, the successful design of WBAN requires expertise in wireless communication, digital signal processing, sensing and read-out, energy harvesting, and packaging and integration. Advances in the above key areas facilitate the rapid development of WBAN [2]-[4]. Now the IEEE 802.15 task group 6 is developing a low-power wireless communication standard to guide the future deployment of WBAN [5].

In this paper, we will introduce the recent progress in the areas of energy harvesting, ultra low power wireless communication, digital signal processing, sensing and read-out, which could tackle the main technological obstacles in WBAN. These areas will be discussed in Section 2, Section 3, Section 4, and Section 5, respectively. In Section 6, we will highlight recently developed research platforms to illustrate how technological advances enable the emerging WBAN. Finally, we will conclude the paper in Section 7.

2. Energy Harvesting

One of the key considerations in WBAN design is the energy supply of sensor nodes. The size of the energy supply increases with the required store energy and is typically the largest contributor to the size of the sensor node. Thus, the overall power consumption of the sensor nodes is expected to achieve below 1 mW [6]. This expected power demand is sufficiently low such that the harvested energy technology could start to be integrated in the sensor node to partly or fully replace the battery.

Energy harvesting is a relatively young research field and has been developed for about 10 years [7]. It takes the energy – mechanical, thermal, or light - from the ambient environment and converts this into electrical energy, which is stored in an energy storage system (ESS). The energy storage system balances the energy generation and consumption. Subsequently, if the mean

generated energy is at least equal to the mean consumed energy, there is no more need to replace or externally recharge and monitor the energy storage system during the complete operational lifetime of the device. In Table 1, the harvested power is listed for different sources, considering a 1cm^2 area for the device [7]. It suggests that energy harvesters can be used effectively in the $10\ \mu\text{W} - 1\text{mW}$ range, which is typical of sensor nodes in WBAN.

Table 1. Characteristics of various energy sources available in the ambient and harvested power [7].

Source	Source power	Efficiency	Harvested power
Ambient light			
Indoor	$0.1\text{mW}/\text{cm}^2$	5-30%	$10\ \mu\text{W}/\text{cm}^2$
Outdoor	$100\text{mW}/\text{cm}^2$		$10\text{mW}/\text{cm}^2$
Vibration/motion			
Human	$0.5\text{m}@1\text{Hz}$ $1\text{m}/\text{s}^2@50\text{Hz}$ $1\text{m}@5\text{Hz}$ $10\text{m}/\text{s}^2@1\text{kHz}$	1-10%	$4\ \mu\text{W}/\text{cm}^2$
Industrial			$100\ \mu\text{W}/\text{cm}^2$
Thermal Energy			
Human	$20\text{mW}/\text{cm}^2$	$\pm 0.1\%$	$30\ \mu\text{W}/\text{cm}^2$
Industrial	$100\text{mW}/\text{cm}^2$	$\pm 3\%$	$1-10\text{mW}/\text{cm}^2$
RF			
Cell phone	$0.3\ \mu\text{W}/\text{cm}^2$	$\pm 50\%$	$0.1\ \mu\text{W}/\text{cm}^2$

2.1 Energy Source

A) Harvesting Energy from Motion and Vibration

For converting motion or vibration, the principle of inertia has to be used: the transducer is inserted in a frame, one part of it is fixed to the frame itself, and the other can move. The frame is attached to the moving or vibrating object and relative motion of the parts of the transducer is controlled by the law of inertia (see Figure 2). This approach is the most widely used for harvesting energy from vibrations [6]; in most cases the system is made resonant by means of suspending the moveable part to a spring.

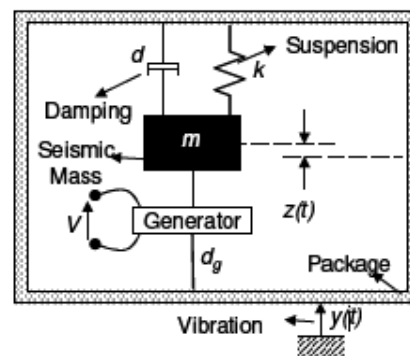


Figure 2. Schematic overview of a vibration harvester (from [8]).

It has been shown in [9] that if z_{max} is the maximum possible displacement, the corresponding power is obtained for a well defined value of the damping and is given by

$$P_{res} = 4\pi^3 m f_{res}^3 Y z_{max}, \quad (1)$$

where f_{res} is the resonance frequency. Harvester performances are frequently benchmarked against this value of the power [6].

B) Harvesting Energy from Temperature Differences

Thermal energy harvesters are based on the Seebeck effect: when two junctions, made of two dissimilar conductors, are kept at a different temperature an open circuit voltage develops between them.

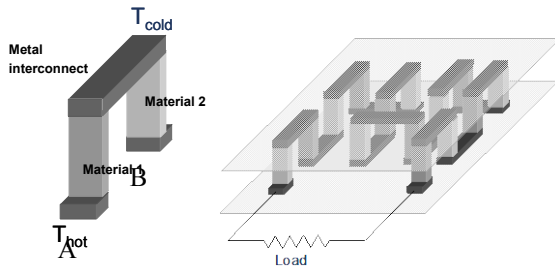


Figure 3. Schematics of a thermocouple (left) and of a thermopile (right).

Figure 3, left, shows the schematics of a thermocouple, the simplest voltage generator based on the Seebeck effect. We distinguish two pillars, or legs, made of two different materials and a metallic interconnect. When a temperature difference $\Delta T = T_h - T_c$ is established between the bottom and the top of the pillars a voltage V develops between the points A and B. This voltage is given by

$$V = \alpha_n \Delta T - \alpha_p \Delta T = \alpha_{np} \Delta T, \quad (2)$$

where α_n and α_p are material dependent quantities, known as Seebeck coefficients.

The core element of a thermal energy harvester is the thermopile, i.e. a device formed by a large number of thermocouples placed between a hot and a cold plate and connected thermally in parallel and electrically in series (see Figure 3, right). The power to be achieved is given by

$$P \propto (\alpha_{np} \Delta T)^2. \quad (3)$$

Apart from improving the material properties, a large effort is ongoing towards thermopile miniaturization through micromachining [10].

C) Photovoltaic Harvesting

Photovoltaic (PV) converts incoming photons into electricity. Outdoor these cells have been used for many years, where power densities are available up to 100 mW/cm². Efficiencies range from 5% to 30%, depending on the material [11]. Indoor the situation is much different, since the illumination levels are much lower than outdoor (100 to 1000 μ W/cm²). Furthermore, at low illumination levels, the efficiency of solar cells will drop considerably. Much research is therefore needed to optimize these cells for low level illuminations.

D) RF Energy Harvesting

Ambient radio frequency (RF) energy, which is available through public telecommunication services e.g. global system for mobile communications (GSM), wireless local area network (WLAN), is also a possible source for energy harvesting.

When harvesting energy in the GSM or WLAN band, one has to deal with very low power density levels. For distances ranging from 25 m to 100 m from a GSM base station, power density levels that range only from 0.1 mW/m² to 1.0 mW/m² may be expected [12]. For WLAN environments, power density levels that are at least one order of magnitude lower are found [13]. Therefore, neither GSM nor WLAN are likely to produce enough ambient RF energy for wirelessly powering miniature sensors, unless a large area is used for harvesting.

Alternatively, the total antenna surface can be minimized if one uses a dedicated RF source, which can be positioned close (a few meters) to the sensor node, thereby limiting the transmission power to levels accepted by international regulations.

2.2 Proof-of-Concept Demonstration

Several demonstrations have been developed recently to prove the concept of energy harvesting. For example, a thermoelectric generator (TEG) integrated into a T-shirt and powering an ECG system was demonstrated in [14]. The system, illustrated on Figure 4, does not require any technical assistance: the user just puts it on and the device starts automatically. When taken off, the system switches back to a standby regime. The TEG modules are made of commercial BiTe thermopiles designed to reach a near-maximum

power-to-thickness ratio. Each module has a size of $30 \times 40 \times 6.5 \text{ mm}^3$. Fourteen modules are integrated in the front side of the shirt. Under an ambient temperature of 23°C and under sedentary activity, the whole thermoelectric generator typically provides power within $0.8 - 1 \text{ mW}$ range at about 1 V on the matched load. Furthermore, two amorphous silicon PV cell modules of $2.5 \times 4 \text{ cm}^2$ size each are integrated in the shirt on its shoulders. They provide additional power during use or during storage of the shirt, where light energy may be used to compensate for the self-discharge of the battery.

There are other two energy harvesting examples based on PV. The first one measures the real-time EMG signal on a human body (see Figure 5a). The second one is the sensor cube (Figure 5b) measuring the temperature [14]. Both are intended to be used for indoor applications, with a typical light intensity of around 400 lux . A large effort has been devoted to decrease the original power usage by a factor of 10. Despite applying power optimization and integrating 'off-the-shelf' low-power electronics still a large area PV is needed ($\sim 140\text{cm}^2$) for the high duty-cycled EMG application (1 mW , $\sim 300 \text{ bps}$). For the sensor cube, the mean power consumption has been reduced to about $10 \mu\text{W}$, at the expense of the data rate reduction (1 bps).



Figure 4. (a) Thermoelectric module for integration in clothing; (b) electrocardiography shirt with integrated thermoelectric generator.

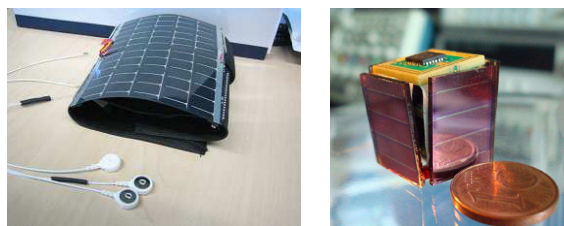


Figure 5. Illustration of the EMG WBAN application powered by the flexible PV harvester (a) and sensor cube application integrating PV harvesters as packaging (b).

2.3 Future Work

The main focus of our IMEC/Holst Centre in the area of energy harvesting is in the development of devices based on micromachining. Being able to fabricate energy harvesters in a batch mode will enable to decrease the cost considerably. In general, progress in micromachined embodiments is clearly visible but these systems still need to demonstrate reliability and cost-effective production. Each of the aforementioned harvesting principles has its own specific issues. In the case of the vibration harvesters, choice of material, packaging and reliability is a concern. Furthermore, much research is devoted in designing devices which can tap into multiple frequencies instead of one specific. For the thermal devices, the thermo-electric material is a hot topic of researched. Materials with an improved efficiency are being developed, but there are not yet suited to be incorporated into micromachined devices. The PV world has only recently started to work on specifically indoor applications, so a lot is to gain in terms of efficiency. RF devices can gain from advances in antenna design and ultra-low power high-frequency alternating current to direct current (AC-DC) converters.

3. Wireless Communication

The name of WBAN clearly indicates that wireless communication is one of the most important aspects in the design of WBAN. The presence of human body poses many new wireless communication challenges.

3.1 Propagation Environments

In general, the human body is not a friendly environment for wireless communication. It is partially conductive and consists of materials of different dielectric constants, thickness, and characteristic impedance. Therefore, the human body can significantly influence the behavior of propagation and lead to high losses. Furthermore, the movement of the body when combined with wave obstruction can lead to significant signal fluctuations.

Thus, a good understanding of the characteristics of propagation environments on, in, or around the body is critical to the design of wireless communication for WBAN. However, for propagation inside the human body, physical measurement and experimental study is hardly to be feasible. One alternative in the current stage is to use a three-dimensional (3D) simulation and visualization scheme [16]. Simulated results in this study have shown that the path loss attenuates much faster with longer distance compared with a free-space

transmission scenario as expected. However, as the human body is too complicated and composed of varied components that are non-predictable and will change with a person's age, weight, postures, etc., further validated results are expected in the future.

For propagation on the surface of the human body, or propagation from the surface of the human body to the external device, the physical measurement and experimental study is easier to be performed. In [16], a set of channel models were included for the evaluation of different proposals in the IEEE 802.15 task group 6. These channels cover the frequency bands in 13.5, 50, 400, 600, 900 MHz, and 2.4, 3.1-10.6 GHz, and correspond to several measurement settings.

3.2 Power Consumption

The wireless communication is often a major power consumer in the sensor node of WBAN. Table 2 gives an overview of main parameters in current commercial low-power chipsets [17]-[22]. It shows that typical commercial chipsets consume in the order of 10 to 100 mW for data rates of 200 to 2000 kbps, leading to a power efficiency of roughly 50 to 400 nJ/bit. The Nordic nRF24L01 [20] achieves less than 20 nJ/bit, but to the expense of a limited set of functionalities.

Table 2. Overview of commercial chipsets and their main parameters.

Standard Company	Propr. Nordic	IEEE 802.15.4		Bluetooth Wibree	
		Chipcon	Freescall	Skyworks	
Part number	RF24L01	CC2420	MC13192	CX72303	
RX power [mW]	33.3	33.8	99.9	43.2	11.5
TX power [mW]	33.9	31.3	82.0	34.2	12.0
max data-rate [kbps]	2000	250	250	1000	200

Consider the chipset with the lowest achievable transmission power of 10 mW, a typical battery with a capacity of 1250 mAh and a voltage of 1.5 V could only continuously supply it for around 1 week. The need for replacing or recharging batteries in such a high frequency is normally undesirable for wearable WBAN and unacceptable for implantable WBAN. Thus, the current available wireless technology is already a major bottleneck to impede the further development of WBAN whose expected overall power budget is below 1 mW [6]. For this reason, new ultra low power wireless technologies are required, which could consume one to two orders of magnitude less than today's wireless technologies. In our IMEC/Holst Centre, the target is to reach an energy efficiency of 1 nJ/bit, which, at a nominal rate of 200 kbps, translates

into an average power consumption of 200 μ W. Complemented with novel network and protocol schemes, these ultra-low-power transceivers have the potential to virtually eliminate standby power while still providing the robustness and reliability required for WBAN applications.

One of the widely known solutions to achieve low power consumption is the duty cycling, which means that the signal is transmitted only at a fraction of total transmission time. The duty cycling allows switching on the radio front-ends only for the instants where signals must be transmitted or received, and could thus significantly reduce the average power consumption. In principle, the duty cycling requires that the bandwidth should be larger than the symbol rate. The larger ratio of the bandwidth over the symbol rate could result in the more significant power consumption reduction. Thus, the impulse radio (IR) based ultra-wideband (IR-UWB) is one of the suitable choices. The first full integration of a carrier based IR-UWB transmitter in a standard logic 180 nm complementary metal-oxide-semiconductor (CMOS) technology is shown in [4]. The developed transmitter can realize triangular baseband pulses that meet the federal communications commission (FCC) mask. The bandwidth of the generated UWB pulses can be tuned from 500 MHz to 2 GHz. This transmitter can deliver a pulse rate up to 40 MHz with a measured power consumption of 2 mW. Furthermore, a low-complexity analog-based receiver has been reported in [24]. The total power consumption of the chip is 30 mW at 20 MHz, which is comparable to those narrowband receivers in Table 2. This asymmetric power consumption between transmitter and receiver is suitable for those WBAN applications where the transmitter is only located in the power constrained sensor node, while the receiver is located in the local processing unit requiring slightly more relaxed power budget.

Another possible solution is to select suitable system architectures that have the potential to minimize power consumption. One example is the super-regenerative receiver [25], which is one of the oldest receiver technologies still in use today. As shown in Figure 6, the main block is the RF oscillator which periodically starts up and shuts off oscillation controlled by a quench oscillator. The start up time of the RF oscillator is exponentially dependent on the magnitude of the input signal and could thus determine the presence of the signal. The main advantage of the super-regenerative receiver is the use of far fewer components than the commonly used receivers to achieve low-power and low-cost circuit design. Further, the use of the quench oscillator is inherently to exploit the concept of duty-cycling.

Table 3 overviews different chip implementation of super-regenerative receiver based on CMOS technologies. As shown, the power consumption could achieve as low as 380 μ W. The main challenges in the super-regenerative receiver design are summarized as follows. First, a good isolation is needed to avoid RF oscillations from being radiated by the antenna. Second, the use of envelop detector makes the receiver sensitive to interferences. Third, the supported modulation is quite limited, e.g. amplitude or frequency modulation. The use of relatively new radio frequency microelectro mechanical system (RF-MEMS) technologies [27] could improve performance and decrease power consumption of oscillators. Thus, they could be used to facilitate the super-regenerative receiver design in the future.

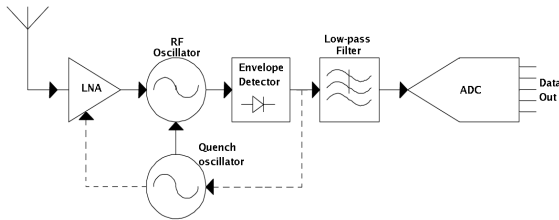


Figure 6. Architecture of a super-regenerative

Table 3. Comparison of the state of the art in super-regenerative receivers.

Paper	[26]	[27]	[28]	[29]
Technol	CMOS 0.35 μ m	CMOS 0.13 μ m	CMOS 0.13 μ m	CMOS 0.13 μ m
Voltage	1.5 V	1 V	1.2 V	1.2 V
Power	1.2 mW	380 μ W	11.2 mW	2.8 mW
Data Rate	180 kb/s	10 kb/s	110 kb/s	500 kb/s
Energy per bit	6.7 nJ/b	38 nJ/b	101.8 nJ/b	5.6 nJ/b
Quench Freq.	1 MHz	100 kHz	~250 MHz	500 kHz
Carrier freq.	1032 MHz	1.9 GHz	3.5 GHz	2.45 GHz
Modul.	OOK	OOK	2-PPM	OOK

3.3 Quality of Service Differentiation

The versatile applications considered in WBAN should make wireless communication support different quality of service (QoS) requirements [30], and at the same time, to minimize the power consumption. An efficient way to meet this target is the QoS

differentiation, which provides QoS prioritization for a subset of applications.

The QoS differentiation could be performed by modifying parameters of existing medium-access-control (MAC) protocols. For example, in [31], the differentiation of latency and transmission reliability is considered by revising the existing 802.15.4 MAC that specifies a carrier sense multiple access with collision avoidance (CSMA-CA) protocol. In the proposed latency differentiation scheme (LDS), different strategies are used to adjust backoff window sizes to prioritize different types of sensor nodes. In the proposed reliability differentiation scheme (RDS), more transmission attempts are given to the applications having stricter reliability requirement when busy channels and collisions are detected.

The QoS differentiation could also be done by determining whether a separate ultra low power wake-up radio should be used in the receiver. As shown in Figure 7, the wake-up radio continuously monitors the channel, and generates an instantaneous trigger signal when necessary to wakes up the main radio. As the wake-up radio is mainly to wake up the main radio instead of receiving data, its reliability requirement is generally lower than the main radio and thus could be designed very simple. Currently, power consumption of wake up radio is around 50 μ W [32], which is much lower than that of the main radio. In [33], it is shown that the use of wake-up radio is desirable for strict latency requirements applications while the use of the duty-cycled radio only is desirable for loose latency requirements, in terms of power consumption. Thus, by differentiating latency requirements, the power consumption could be optimized.

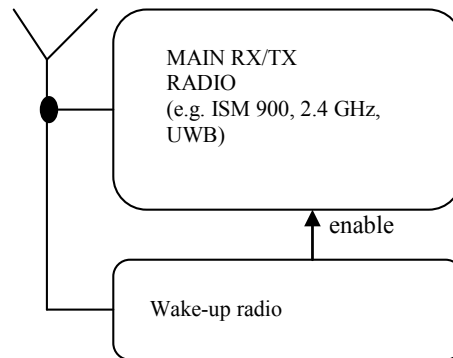


Figure 7. A wake-up radio (WURx) supports the low power operation of a main radio.

3.4 Regulations

The transmission power of the sensor nodes in the WBAN should be kept low in order not to hurt the human body. The specific absorption rate (SAR) is defined as the amount of RF energy absorbed by the human body every second with the unit of W/kg. Local governments have defined safety limits for exposure to RF energy and thus regulated the transmission power. In [34], it is shown that the transmission power below 1.6 mW and 20 mW in US and EU, respectively. In addition, the transmission of WBAN at the selected frequency band should also be regulated by the local governments. An overview of regulations for potential frequency bands in WBAN could be found in [35] and will be not discussed here in detail.

4. Digital Signal Processing

As shown in the previous section, wireless communication is a significant power consuming component in the sensor node of WBAN. Typically, the reduction of data rate could result in the reduction of power consumption of wireless communication. For this reason, the sensor node should be equipped with sufficient intelligence and processing capabilities to extract important features of the raw data sensed, and thus to minimize the amount of data being transferred through wireless communication. Our study showed that for ECG signal monitoring, using ECG delineation algorithm to process the data locally, reduces the data transmission rate and hence the power consumed by the wireless communication by more than 50%.

However, this on-node processing will consume additional power to extract and compress information, and thus create a tradeoff between signal processing and wireless communication. To get a positive net power saving, the on-node processing must be done efficiently. For this reason, one of research directions is to design application specific instruction-set processors (ASIP) for body area network applications. We have recently developed an ASIP that consumes 200 μ W tailored for processing 24-channel EEG signal processing in 90 nm technology. The power breakdown of the ASIP is shown in Figure 8, indicating that after code and architectural optimizations, the memory access energy is dominating. This is an important result highlighting that major power reduction of local processing is possible only by designing power efficient memory circuit and architecture. It is needless to say that transmitting the sampled data from 24 channels is not possible due to power restriction.

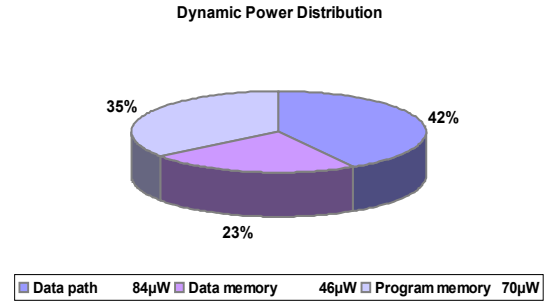


Figure 8. Power breakdown of the ASIP running 24-channel EEG.

Another research direction is to facilitate low power operation of digital part of wireless communication, e.g. MAC protocols and baseband algorithms, by using power management to efficiently control the power distribution of the processors. Previously, we have reported the development of a baseband ASIP for the IEEE 802.15.4a IR-UWB systems [36]. The designed ASIP for UWB reduced the power consumption by a factor 90 in comparison to a 16-bit baseline architecture, while increasing the performance by a factor 122 [37].

Currently, in our IMEC/Holst Centre, we are also working on augmenting the ASIP with security mechanisms such as access control, message integrity, message confidentiality, and reply protection. As indicated in Section 1, security is an essential part of a sensor node in WBAN.

5. Sensing and Read-Out

The sensing and read-out of the signals may draw a significant part of the power budget in today's sensor nodes in WBAN, especially when the number of signals or channels is increasing. Thus, reducing the power required for signal extraction is an important challenge here. In addition, the acquisition of biopotential signals, namely EEG, ECG, EMG and EOG signals, presents an interesting challenge as the signal amplitudes are in the μ V range [39] (see Figure 9). Various noise sources, such as electrode offset voltage and interference from power-lines, requires high-performance readout circuit design that is capable of rejecting such aggressors while amplifying the weak biopotential signals.

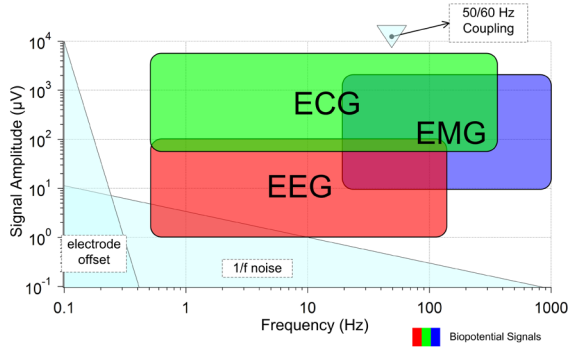


Figure 9. Frequency and Amplitude Characteristics of Biopotential Signals. Aggressors that need to be rejected are also shown.

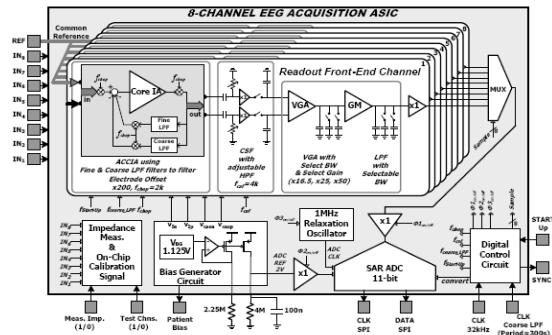
Addressing the above challenges, a family of ultra-low-power front-ends for the read-out of bio-potential signals has been developed [40]. Table 4 summarizes the main characteristics of these application-specific integrated circuits (ASICs). The key achievements in these ASICs are their high performance with ultra-low power dissipation. The prior leads to the extraction of clean biopotential signals while the latter ensures the compatibility with battery operated systems. In addition, an important feature of these readout circuits is their programmable gain and filter characteristics enabling their use for different applications that may require the monitoring of different biopotential signals.

Table 4. Main Characteristics of Ultra-Low-Power Biopotential ASICs.

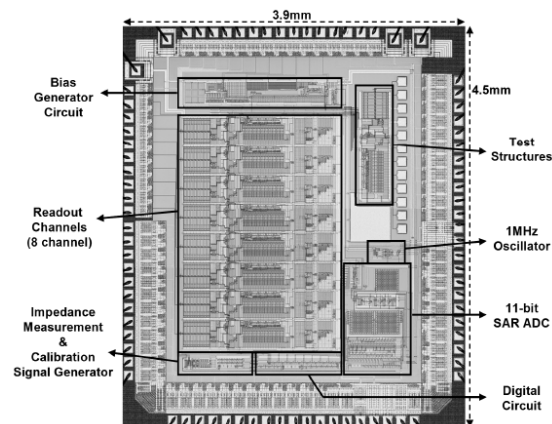
	[41]	[42]	[43]
# channels	24 + 1	1	8
Type of channel	EEG (24), ECG(1)	ExG	EEG
Power consumption	10.5 mW	60 µW	200 µW
Input referred noise	< 1 µVrms	< 0.6µVrms	< 0.6µVrms
CMRR @ 50Hz	> 90dB	> 120dB	> 120dB
Input Impedance	> 100MΩ	> 100MΩ	> 100MΩ

Most recently, we reported the design of a complete low-power EEG acquisition ASIC targeted to miniaturized ambulatory EEG acquisition systems [43]. Figure 10 shows the architecture and the die implementation of the EEG acquisition ASIC, which is implemented in 0.5 µm CMOS process. The ASIC consists of eight readout channels, an 11-bit ADC, a square-wave oscillator and a bias circuit. In addition to the acquisition mode, the ASIC has calibration and

electrode impedance measurement modes. The prior enables the remote testing of circuit operation, where as the latter is useful for remote assessment of biopotential electrode quality. Both of these features are important in terms of the reliability of sensor nodes in WBAN.



(a)



(b)

Figure 10. Architecture (a) and the die implementation (b) of the EEG acquisition ASIC [43].

6. Research Platforms

The technologies discussed in previous sections have enabled the growth of sensor node platforms in WBAN in recent years for the monitoring of various biological and physiological signals [45]. These sensor nodes differ by their form-factor, their autonomy, the inherent building-blocks (micro-controller, radio, sensors) and their portability. Hardware systems have usually been developed for specific applications with reduced flexibility for adding or subtracting sensors. At the opposite, a platform approach shall provide a generic backbone common to any WBAN, while

allowing to easily interchange the sensors based on the demands of the target application. In this section, we briefly present the generic wireless node platform developed within the Human++ program in IMEC/Holst Centre, and give an overview of the current state of sensor front-end boards available. As new achievements arise from the research on wireless autonomous sensors, the Human++ body area network (BAN) platform will be enhanced by integrating ultra-low-power building blocks, such as new radio chip-sets, digital signal processors, and sensors. Meanwhile, the platform already allows application researchers to investigate emerging applications relying on body area network technology. In particular, the case of emotion monitoring will be discussed to conclude this section.

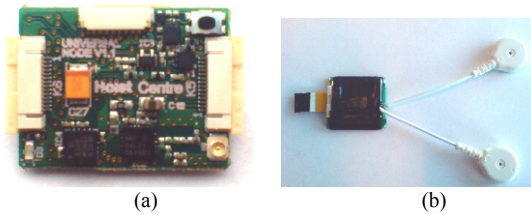


Figure 11 Human++ BAN platform, examples of hardware boards: (a) Generic wireless node, (b) ExG front-end.

6.1 Generic Wireless Node

Typically, sensor nodes in WBAN consist of one or more sensor front-ends, a microcontroller to sample and process data, a power supply and a radio to transmit the data. While the type of sensor might differ from sensor node to sensor node, the microcontrollers and radios are normally the same across a single WBAN. A generic wireless node has been developed to provide embedded processing and wireless transmission functionality. Commercial off-the-shelf elements are used, namely the TI MSP430f1611 microcontroller and Nordic nRF24L01 radio chip-set, selected for their low-power performances. Customized power management circuitry has been developed to optimize power performances of the sensor node, and a Li-ion battery of 160 mAh capacity is connected to the system. The outer dimensions of the generic wireless node are $20 \times 29 \times 8 \text{ mm}^3$, including battery. The average power consumption of the generic wireless node ranges from 28 mA (max current consumption) to less than 1 mA for customized applications, at 3V. Low-power firmware, time division multiple access (TDMA) based MAC protocol

and communication protocol have been implemented to enable several sensor nodes to work within a star-topology network. For a network configuration of three nodes, with 2 data channels per node, and packet retransmission enabled, the average power consumption of the generic wireless node is 2.4 mA at 3V. Average packet losses have been experimentally measured to be less than 1 ppm in static conditions, and shown to stay below 1% in most dynamic environments.

6.2 Sensor Front-End Boards

In Section 5, we reported the design of a set of ultra-low-power front-ends for the read-out of bio-potential signals. In particular, a single-channel read-out front-end has been designed with a variable gain amplifier allowing to electronically adjust the gain of the read-out for varying application needs [42]. Similarly, high cut-off frequency of the readout channel can be electronically adjusted via bandwidth select switches. These features make this single-channel bio-potential read-out ASIC particularly suitable for a wide range of biomedical applications, as its characteristics can be adapted depending on the bio-potential of interest: ECG, EEG, EMG or EOG. Furthermore, its low-power consumption ($21 \mu\text{A}$ at 3V) allows to dramatically reduce the size of the battery, hence of the entire monitoring system. The bio-potential ASIC has been integrated in an ExG sensor board. The outer dimensions of the ExG sensor board are $20 \times 20 \times 5 \text{ mm}^3$. Power consumption is $25 \mu\text{A}$ at 3V.

In addition to bio-potential, other sensor boards have been designed and developed to meet the requirements from various health monitoring applications. In the current state of the Human++ BAN technology platform, sensor boards are available for measurement of bio-potentials, motion (accelerometer and gyroscopes), respiration (based on piezo-electric sensor), skin temperature and skin conductance. This set provides a generic BAN platform from which specific sensor boards can be collected depending on application requirements.

6.3 Emerging Applications

The proposed BAN technology platform can be used to explore new application opportunities in the area of health, wellness and lifestyle, made possible thanks to the recent achievements in wireless autonomous sensor research. Very few studies have so far been reported on the evaluation of enabling technologies in real-life

application cases, and their benchmark against state-of-the-art devices. This is however crucial in assessing the relevance and usability of new technologies for specific applications. Furthermore, such an evaluation process allows capturing and refining specific application requirements, in terms of sensors, processing and networking needs, electronic integration and interface with the body. The proposed platform has been evaluated in the context of wireless sleep monitoring [44], portable cardiac monitoring and real-time arousal monitoring [45]. The later case is highlighted here.

Based on the BAN platform introduced above, we have developed a customized low-power body area network for monitoring ECG, respiration, skin conductance and skin temperature [46]. Each of these modalities is known to be regulated by the autonomic nervous system, and thus represent interesting candidates to capture emotional responses to external stimuli [46][47]. The system, illustrated on Figure 12, consists of two low-power miniaturized body sensor nodes which communicate with a receiver connected to a pc or to a data logger. The first node is integrated in a wireless chest belt and monitors ECG (lead-I) and respiration. The second node is integrated in a wireless wrist sensor and monitors skin conductance and skin temperature. Each node is composed of a generic wireless node, to which are connected the corresponding sensor front-end boards.



Figure 12. Integrated body area network for ambulatory monitoring of physiological responses from the autonomic nervous system.

Twenty healthy volunteers are involved in the experiment intended to demonstrate the feasibility of using the proposed BAN as a tool to perform real-time measurement of an individual's arousal level [47]. A movie extract is chosen as the arousal stimulus,

characterized by a calm beginning followed by a building-up phase culminating to a frightening event. A reference or target arousal function is defined as being zero during most of the movie, except in a region surrounding the frightening event [47]. Volunteers are asked to watch the movie while their physiological signals are monitored using the wireless system. All tests have been performed in a controlled laboratory environment, in order to minimize the sources of distraction that may eventually lead to unexpected and uncontrolled increases in arousal. A set of features is extracted from the ECG and skin conductance signals, found to be the most responsive parameters to the tests. In a second step, these features are combined in an optimal arousal estimator using linear regression against the target arousal level. The outcome of the regression analysis is a set of coefficients, characterizing the importance of each individual feature in the final estimation of arousal. All algorithms are implemented in real-time, such that the process of feature extraction and arousal estimation can be applied in real-time on any incoming signals.

The resulting estimator has then been used to monitor the arousal level of individuals wearing the system. Several tests have been performed in various environments, varying from laboratory to small public audience. As much as possible, the test subject was isolated from the outside world, for instance using headphones. The test protocol used for these tests consists in four parts: a short movie to get acclimatized, a modified Stroop test, an audio extract and a movie fragment. The Stroop test is modified to induce confusion (and hence mental stress) in the second part of the test. The audio extract is a 3-minute very relaxing piece of classical music abruptly disturbed by noises of several kinds after 120 and 150 seconds, expected to trigger startling responses. The movie clip is identical to the one used to develop the arousal monitor. An example of the estimated arousal level over the test sequence is given in Figure 13 for one of the test subject. In this figure, the solid line gives the estimated arousal over time. The dashed, vertical lines represent the events, as specified by the name shown directly to the right of these lines. It can be seen from this picture that the subject did not show a significant increase in estimated arousal during the modified Stroop test. There was, however, a sharp and large increase in estimated arousal level just after the audio events and the movie event. Apart from the expected responses, there are also some responses that clearly do not origin in any of the events. These false positives can be due to anything that triggers the subject's mind,

such as an arousal triggering thought, or something surprising in the surrounding environment.

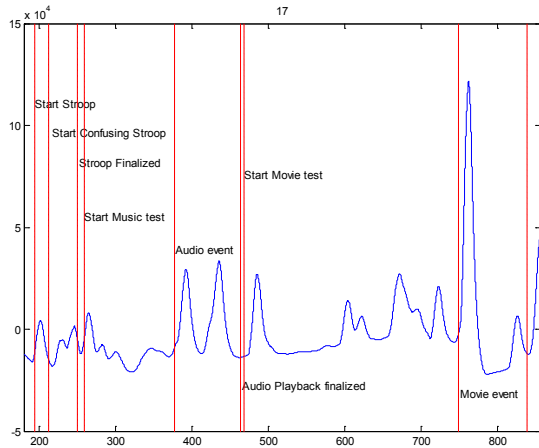


Figure 13. Estimated arousal level over the part of the test protocol: modified Stroop test, audio extract and movie clip. Dashed vertical lines give the timing of the events.

Overall, the arousal monitor has proven to work quite reliably in a controlled environment — that is, in a lab setting where distraction opportunities are minimized. It has also been shown that the conclusions can be generalized from movie to other arousing stimuli, as suggested in Figure 13. However, further experiments are needed before conclusions can be drawn about the extension of the results to non-controlled environments. The low-power monitoring platform presented here certainly will facilitate the transition from lab to real-life environments.

7. Conclusion

In this paper, we overviewed different technologies in the field of energy harvesting, wireless body area networks with the focus on wireless communication, digital signal processing, and sensing and read-out circuits. We addressed challenges, highlighted state-of-the-art solutions, and pointed out future research directions. We also presented integrated research platforms to demonstrate the feasibility of wireless body sensor networks. With the increasing improvement of miniaturization, cost and power consumption of the wireless sensor nodes, we expect that the autonomous, unobstructed, pervasive, and invisible wireless body sensor network could be commercially realized in the future.

8. References

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Ultra-Low Power Sensor Design for Wireless Body Area Networks: Challenges, Potential Solutions, and Applications

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