Paper

Wearable biosensing: signal processing and communication architectures issues

Patrick Celka, Rolf Vetter, Philippe Renevey, Christophe Verjus, Victor Neuman,
Jean Luprano, Jean-Dominique Decotignie, and Christian Piguet

Abstract—Long-term monitoring of human vital signs is becoming one of the most important fields of research of biomedical engineering. In order to achieve weeks to months of monitoring, new strategies for sensing, conditioning, processing and communication have to be developed. Several strategies are emerging and show different possible architectures. This paper essentially focuses on issues in wearable biosignal processing and communication architecture currently running at the Swiss Center for Electronics and Microtechnology (CSEM) in the framework of several European projects.

Keywords— wearable sensors, wireless BAN, biosignal processing, low-power DSP.

1. Introduction

Wearable sensing of human physiological signals is becoming an essential part of nowadays monitoring systems [1–3] (see references in the same issue of the IEEE EMB Magazine), [4–8]. These revolutionary systems should allow clinicians, physiologists, psychologists, social institutions and people themselves to have access to a lot more information on the human body function than ever before. Long-term monitoring, from days to months, is envisaged in these systems. Several questions arose then from psychological, clinicians and technical views and should be addressed carefully in order to obtain a useful, reliable system. Social implications and psychological impacts of such systems will not be discussed in this paper, but should be kept in mind. Rather, this paper will focus on the technological aspects of such wearable biosensing systems, from the low-level physiological signal sensors to the highest level of interpretation of the extracted information and possible biofeedback to the user, and power delivery and management issues.

Figure 1 shows a generic platform for monitoring patients. Thanks to the transmission of data over mobile communication (GSM and GPRS), full mobility is offered to the patient. The system comprises sensors, processing and communication functions worn by the user, interconnected with a portable base station, which is the gateway to the Internet where the collected data are made available to the authorized professionals, i.e., doctors, nurses, etc. The portable system includes local pre-processing close to the physiological signal collection nodes and global processing which takes benefit of the availability of various types of physiological (electrocardiogram (ECG), partial oxygen blood saturation (SpO_2), skin temperature, etc.) and physical activity signals (acceleration, position, etc.) to perform efficient denoising and classification of the biosignals.

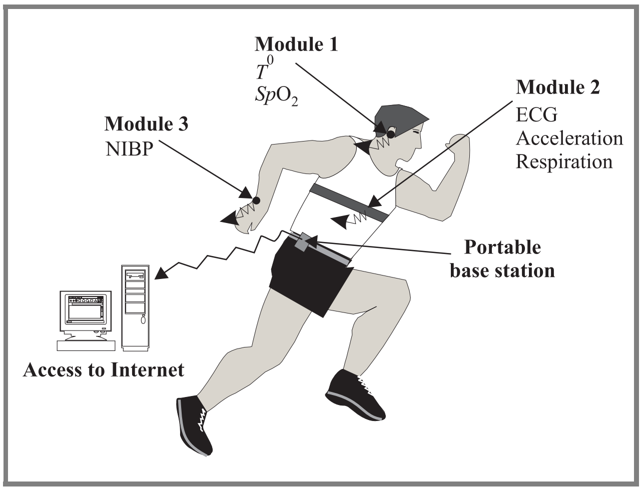


Fig. 1. Overview of a possible architecture comprising, sensors, processors and communication units (© CSEM).

The use of discrete units interfacing groups and family of sensors (e.g., electrocardiogram, respiration belts) is not practical for continuous use due to volumes, sensor placement and consequent discomfort. To make the sensors and processing really wearable, they have to be embedded in the clothes or worn in natural units such as watch earring, finger rings, headset; which are tailored for the specific heath monitoring needs of the users (sickness, professional, sports).

The architecture of the system may be described as a number of discrete layers. Distribution of functions in the layers and communication between the layers must be done in such a way that the relevant information is always properly extracted and transferred at the appropriate rate. If simultaneous recording of the signals is necessary, synchronization issues between the different sensing units have to be addressed. Figure 2 shows the different possible layers and the interconnections. The low-level *sensing* layer is divided into three localized sub-layers: sensors, signal conditioning and signal processing. The highest-level *processing* layer is divided into two global sub-layers: feature extraction layer and the personalized application layer. The processed signals are then fed to the therapists and/or the user himself.

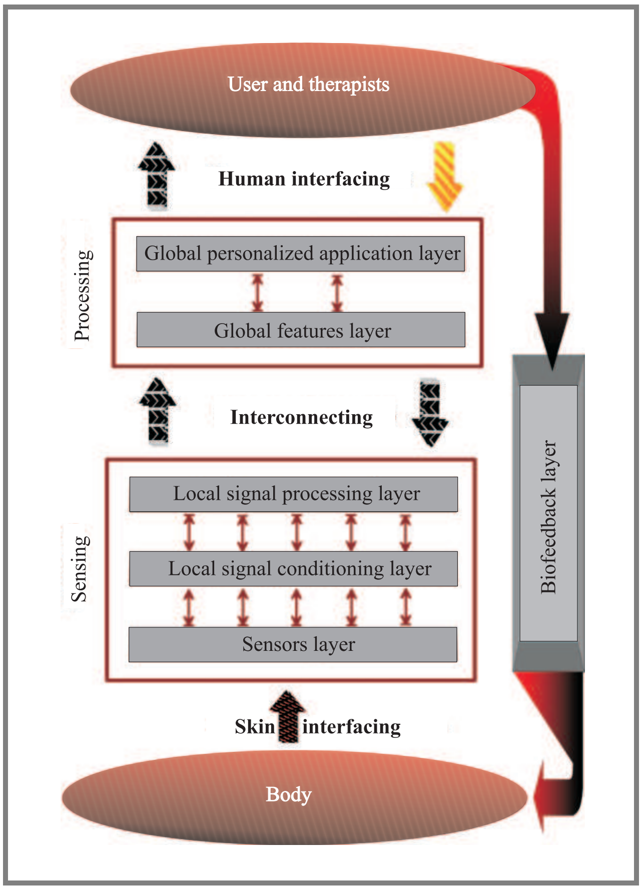


Fig. 2. Different layers appearing in the architecture of Fig. 1.

In the low-level sensor layer, new fiber materials and soft electronics technologies allowing convenient long-term monitoring are required. Textile sensors, integrated into garments, are very well suited for long-term monitoring solutions, but also provide lower quality signals implying an increase in the complexity of the analog and digital processing of the signals [5]. Typical textile sensors include: ECG, breathing, galvanic skin response, and actuators for biofeedback. Soft electronic sensors are for instance scalp electroencephalogram (EEG), accelerometers, temperature, heart rate, and SpO_2. Integrating sensors and electronics into garments in a convenient and reliable way is not an easy task and requires a high degree of miniaturization requesting the development of ASICS for mixed analog and digital techniques. Unobtrusive integration of sensors and actuators also includes the provision of adequate connector solutions to interface the electronics and the interconnection (textile or wired) of sensors and connectors. Low-level signal processing in this layer includes noise cancellation algorithms. This close-to-sensor DSP strategy is essential with low-amplitude physiological signals, to increase the signal-to-noise ratio and the channel-coding algorithm, which depends upon it. Algorithms with minimal complexity should be used due to the restriction in computing resources, i.e., memory and instructions flow rate. Packaging problems in terms of soft and wearable electronics with user-friendly power supply solutions is also to be tackled. Bi-directional flow of information in the sensing layer is meant for possible re-adjustment of the sensing device for optimal performance.

The sensing layer is then interconnected to the processing layer. Textile wiring or wireless connection is possible. The processing layer consists in high-level signal processing: feature extraction and personalized algorithm parts. The personal profile algorithm determines the current health condition and compares it to the personal reference profile, which also contains personal standard values for the collected parameters. The reference personal profile can be supported by data from external resources. If strong deviations occur, the respective therapy or biofeedback is given. Observable output variables are collected by the application layer and are used to derive the therapy recommendations.

Fig. 3. Prototype of shirt with electrodes for movement measurement at shoulders and respiration bands (plethysmography) from the IST European project WEALTHY (wearable health care system).

Target users of the intelligent biomedical clothes include patients during rehabilitation and early release from hospitals, professional personnel at risk and people during sport activities (professional or leisure). Sensing biomedical wearable can for instance:

- provide an integrated view of normal and abnormal patterns of activity, which would be otherwise difficult to detect and in situations that are usually uncontrollable by physicians;

- improve the quality of care for patients by monitoring health status during rehabilitation activities, allowing them to perform their everyday activities;
- monitor professional workers operating in extreme environmental conditions;
- support citizen and athletes by providing monitoring and processing of physiological parameters while they are performing sport activities.

In the last years, several major sport and leisure electronics companies have developed alliances with clothes industries to combine electronic functions and fashion into the clothes as shown in Fig. 3, where respiration and shoulder movements are captured by sensors in the fabric [5].
This paper is organized as follows: Section 2 will describes a selection of textile and soft electronic systems, parts of the sensing layer, including the analog processing of the signals; Section 3 will focus on one possible architecture for the processing layer. Section 4 will address the communication issues in the wearable biosensing paradigm. Section 5 will conclude this paper.

2. Sensing and analog electronics

As mentioned in the introduction, many different biosensors can be implemented depending on the type of applications. We will focus in this paper on ECG, activity and *Sp*O$_2$ sensors. As most of the biosensors have an interface to the skin of the subject, artifact originating from the movement of the body is of major implications for the overall system robustness from the quality of the data to the transmission flow rate and coding strategies. As such, artefacts have to be reduced to a minimum. Analog filtering is the second step in the sensing layer (Fig. 2), and is to be designed with great care to minimize as much as possible these artefacts, typically by limiting the bandwidth of the measured signals to their frequency band of interest, by notching unwanted frequencies and by amplifying the useful signals. Other noise sources have also to be taken into account in the design of the signal conditioning layer. This section will introduce some concepts related to fiber sensors and soft electronics sensors.

2.1. ECG sensors in the garment

Electrocardiogram is a signal of primary importance in biomedical monitoring. Integrating the electrodes into a garment, miniaturizing and eventually distributing the electronics in the clothes are challenging goals which aim at strongly increase user comfort, and therefore ease and enhance the long-term monitoring of ECG signal (longer than 24–48 hours). The classical electrode patches are very efficient but not suited for integration into a garment. An innovative solution consists in alternating normal yarns and metallic yarns in the fabric at the location of the electrodes. Optimization of this technique has led to sufficiently good

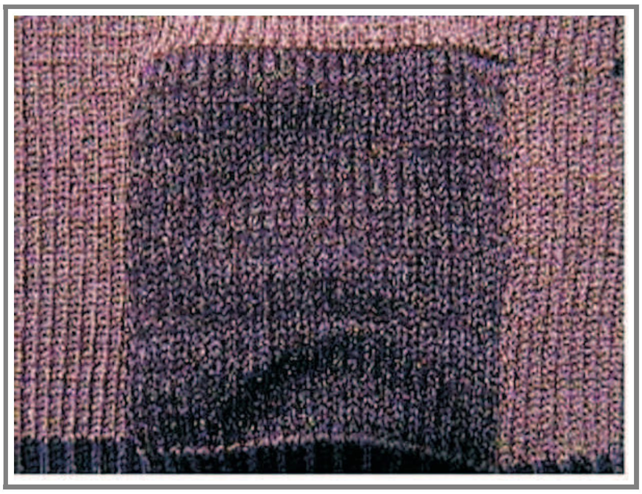


Fig. 4. ECG electrode woven in the fabric, as implemented in the IST European project WEALTHY.

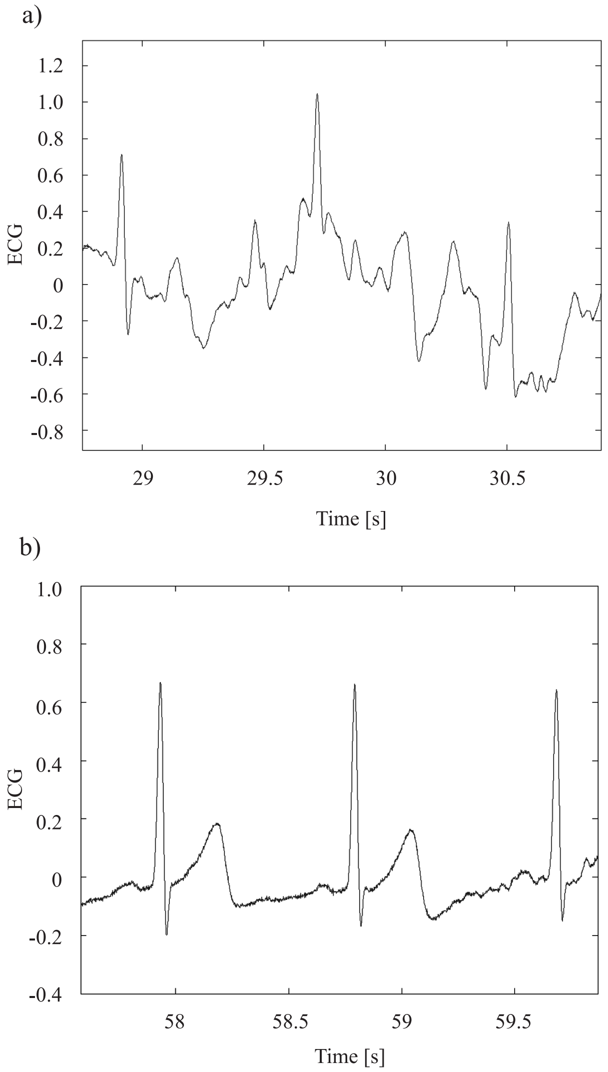


Fig. 5. ECG signal as recorded at rest with torsion artifacts: (a) without the membrane and (b) with the membrane. Signals have been recorded at Smartex in the IST European project WEALTHY framework.

signal quality, compared to classical electrode patches. Figure 4 shows an example of ECG electrode woven in the fabric [2, 5].

Two major problems have to be solved in addition to make the acquired signal useable:

- the signal acquisition must be performed while the subject is moving;
- good contact with the body skin is necessary.

Since it is not possible or wanted to ask the user to remain quiet during the measurements, signal processing has to be used to remove signal artefacts due to movements during the acquisition. Information about the activity and movements of the persons can of course be very efficiently used to really enhance the ECG signals (refer to Subsection 3.1.1). Their acquisition requires additional tissue and non-tissue sensors. Furthermore, the contact between the body skin and the fabric electrodes can be strongly improved by using a hydrophilic membrane during the measurements [5].

The ECG measurements obtained are of satisfactory quality under mild movement as seen in Fig. 5.

2.2. Activity and posture sensors in soft electronics

Two types of sensors can be used, depending of the required accuracy versus the power consumption and their location:

- piezoelectric sensors are directly woven in the fabric (fabric sensors);
- non-tissue sensors are monolithic integrated circuit such as solid-state accelerometers.

The former ones are completely buried in the fabric, and represent a good solution when activity measurement includes not only the activity of the body as a whole, but also and separately, the measurement of the movements of the arms, shoulders, legs, knees and other body areas. The drawback is a lower signal quality compared to those obtained with more complex solid-state devices, which often directly include also signal conditioning, power supply decoupling, etc. Sensor chips and very small sensors have to be encapsulated in special packages that are affixed to the textile fabrics.

In both cases, fine conductive materials woven into the fabric provide the necessary electrical connections for the signals, sensor control and power supply. The interconnection between the sensors, the electronics and the textile is still a challenge. Several solutions have been proposed in the literature. The Georgia tech wearable motherboard (GTWM) has represented a significant step in the connection of sensors and the communication modules [6, 7]. The routing of data communication and power supply was for instance further addressed in [8]. The electrical impedance of the yarns is much higher than standard wires making more difficult the acquisition of sensor signals and the transfer of data with limited sensitivity to the electromagnetic environment. Two technologies are summarized in [1]:

- conductive yarns of the fabric are prepared for contact with the electronic circuit by soldering tiny metal contacts to wire-bond the circuit. The module and the wires are then molded for mechanical protection;
- thin flexible circuit board with electrodes is glued to the textile before being molded.

2.3. SpO_2 sensors embedded in an earphone

To measure SaO_2 optically, two light-emitting diodes are used to illuminate the tissue, such as a fingertip. One light is red (e.g., 660 nm) and the other is infrared (e.g., 940 nm). The absorption of the infrared light is very dependent on the SaO_2, and the red light is less dependent of this value. Therefore the ratio of the light intensity as detected on corresponding photodetectors can be used to drive an output display calibrated to give the SaO_2 value. This method is referred to pulse oximetry and is nowadays the standard non-invasive way of estimating the SaO_2, which we refer as SpO_2 for saturation pulsed oximeters. The emitter (LED) and receiver (photodiode) can be placed either side by side on the surface of the skin tissue, or on each sides of it leading to the two techniques: reflectance and transmittance. The transcutaneous reflectance oximeter has the advantage to allow monitoring of SaO_2 transcutaneously at various locations on the body surface, including more central locations such chest, forehead, limbs, that are not accessible via trans-illumination oximetry.

Fig. 6. Earphone-based sensor together with a recorder (© CSEM).

Oximeters present important errors due to light attenuation by absorption, refraction, and multiple scattering from undesirable organs. And because of differences in the properties of skin and tissue, variation from individual to individual in attenuation of light causes calibration problems. Problems with both transmission and reflectance oximetry include poor signal with body movement [30, 31]. These artifacts can be generated in different ways: when the subject is performing body movements, hence modifying the physiology of the tissue under gravity and probe pressure on the skin, when the different layer of the sensed tissues are modified by small muscle or nerve activities induced by strain or stress, and when the light probe-tissue coupling is modified through the time by displacements of the probe on the surface of the sensed tissue. Also, a reduced perfusion (hypoxemia) of the tissue leads to wrong estimates of the SpO_2 value. A new sensor encapsulated in a standard earphone system (see Fig. 6), which can improve the reliability of such sensor under daily activities, is under development [28, 29] (see Subsection 3.1.1).

The sensor device comprises standard red and infrared lights working in trans-illumination, and is accompanied by a two dimensional accelerometer for motion compensation using digital signal processing algorithms. The final design of the SpO_2 sensor will include an interconnection layer to transmit the signals to the processing layer. Artefact removal is described in Subsection 3.1.1.

2.4. Signal conditioning and connectors issues

"Non-tissue" sensors are to be conditioned as recommended by their manufacturers, with special care on miniaturization and low-power consumption of the conditioning circuits. The same care must of course also be brought to the conditioning of tissue sensors. The non-idealistic characteristics of the latter, for instance impedance, bandwidth, linearity and passive nature (compared to integrated circuits), make the signal conditioning even more critical: on one side the signal conditioning has to damper the characteristics limitations of the sensors and on the other side it has to allow the extraction of the significant physiological signals from usually weaker acquired signals.

Interconnections, power supply and packaging require very special care, since the garment has to be soft and washable: interconnections have to be very small and robust and packaging should provide temperature, shock and water resistance while remaining small and not incommodious for the user. The problem of interconnection has to our knowledge not been satisfactorily solved yet, while some solutions have been proposed (see [1] and references therein). The main problem is bonding fabric sensors to soft/hard-electronic boards where data path connectors are discrete in space. Wire bonding methods are tedious and are still to be hand made and thus not suitable for production.

3. Digital signal processing

3.1. Noise and artifact reduction, feature extraction and classification

3.1.1. Noise and artefact reduction

Digital signal processing (DSP) algorithms for noise and artefact reduction have been used in many applications. Biomedical engineering uses these techniques more and more often since the data recorded are often corrupted by environmental noise sources (intensive care units) or from undesirable physiological sources, or from the fact that the sensor-tissue interface is not reliable and stable in the time. Such sensor-tissue interface problem is even more dramatic when sensors are embedded in the garment. If the number of signals extracted from the sensors is not too large, DSP algorithms can be implemented in the sensing layer. Otherwise, the DSP should be performed in the processing layer. Advantages of performing the DSP locally are that the information to be transmitted to the processing layer can be amplified and denoised for optimal performance of the transmitter/receiver coding/decoding strategies. Also, the source and channel coding algorithms are performing better when the noises and artefacts are reduced to a minimum. Another reason to perform the noise reduction at the local level is the possibility to reduce the number of signals to be transmitted for further processing, especially when sensors-in-the-garment are used. Indeed, sensors placed in the garment are not reliable by essence but the redundancy is used to compensate for that. An increased number of signals are thus acquired and local digital processing is used to extract a reduced number of enhanced information signals. "Voting"-like algorithms like data fusion are thus used to this purpose.

Noise reduction techniques have always to be adapted to the signals at hand, and also depend on the features to be extracted from them. Well-known techniques are for instance based on Wiener filters (WF) [6], wavelet decomposition (WD) [10] and principal component analysis (PCA) [11]. The use of one or the other depends on the nature of the signal such as the stationarity, the statistics of the information and the noise signal. Figure 7 shows a denoised ECG using WF, WD, and PCA. The WF gives the worst result, while WD and PCA give similar good performances. In most of embedded solutions, recursive or adaptive implementations of the above-mentioned signal processing techniques are necessary. For instance, adaptive PCA algorithms like APEX are quite appropriate for enhancing rhythmical signals [40], as well as other adaptive blind source separation techniques [41, 42].

Artefact reduction techniques are often based on linear filtering algorithms [32]. An artefact-correlated signal is most of the time needed for the removal. The estimation of these filters also depends on the number of signals at hand and the hypothesis of the origins of the information signals. Correlation techniques based on the Gaussian hypothesis leads to the well-known least square solutions, while the non-Gaussianity of the signals can be a good reason to use independent component analysis tools [42]. The resulting filters are anyway always linear. Adaptive implementation of these filters is often used because they require less computing and memory resources than their block-based counterparts (see Subsection 3.2 for details about implementation) [40, 41]. In ambulatory conditions, movement artifact removal can be done using acceleration signals measured close to the sensor. Artifact removal is aimed at recovering the information signal that is masked or distorted due to body movement and resulting in modification of physiological properties of life tissues or organs.

An example of artefact reduction is presented hereafter for heart rate and possibly SpO_2 estimation. Artefact reduction/rejection techniques for robust SpO_2 estimation during

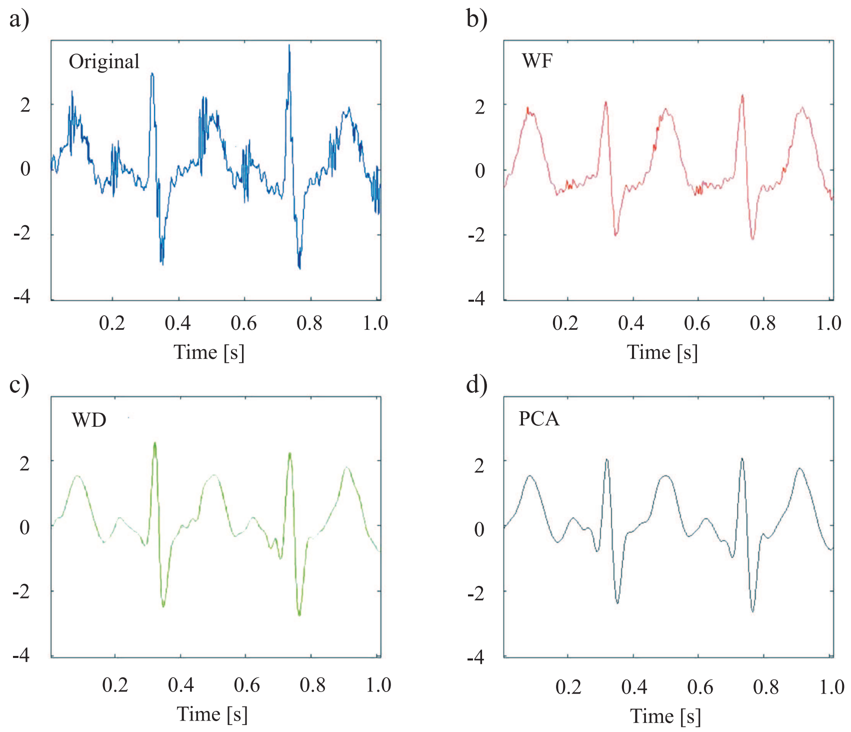


Fig. 7. Example of denoising algorithms: (a) it the noisy ECG; (b) is the WF denoised; (c) is the WD denoised, and (d) is the PCA denoised.

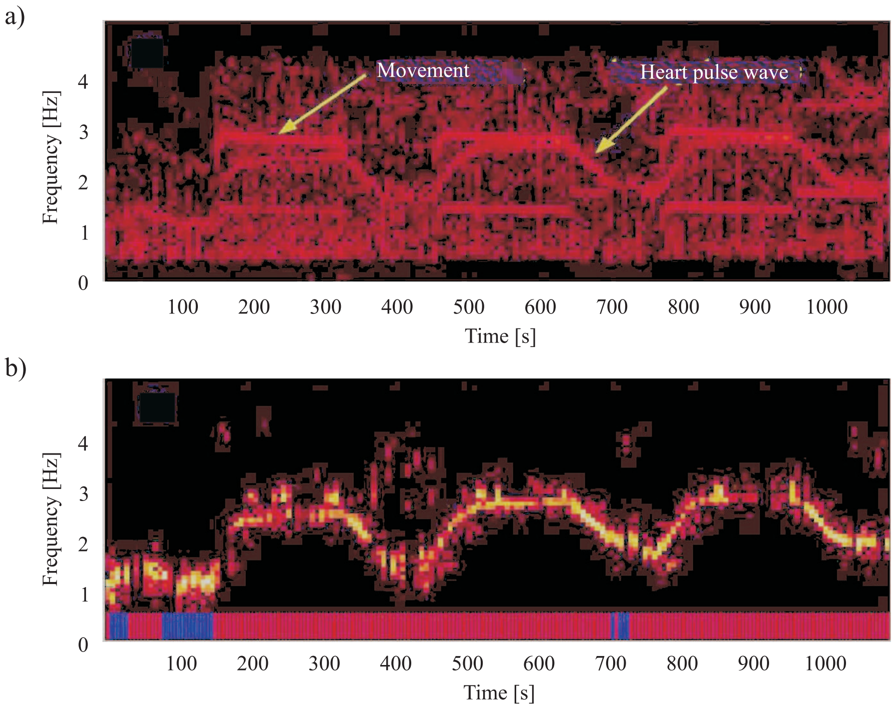


Fig. 8. Spectrograms of the infrared signal: (a) before, and (b) after artifact removal.

low perfusion and movement artefacts have been developed since about 20 years. The first technique dealing with artefacts is the rejection method that use an artefact detection followed by a rejection of the corrupted data. This technique is well suited for short time period but not at all for ambulatory applications where periods of corruption can extend to several minutes. For this reason, signal enhancement techniques have been developed [22, 29, 30, 31]. Figure 8 shows the spectrogram (joint time-frequency representation) of band passed (0.5 Hz – 8 Hz) infrared signals before and after artifact removal, acquired on a subject who was performing alternatively jogging and walking activities. We clearly distinguish the heart pulse wave together with rhythmical movements in Fig. 8a, while only the heart pulse wave can be seen in Fig. 8b after movement artifact have been removed.

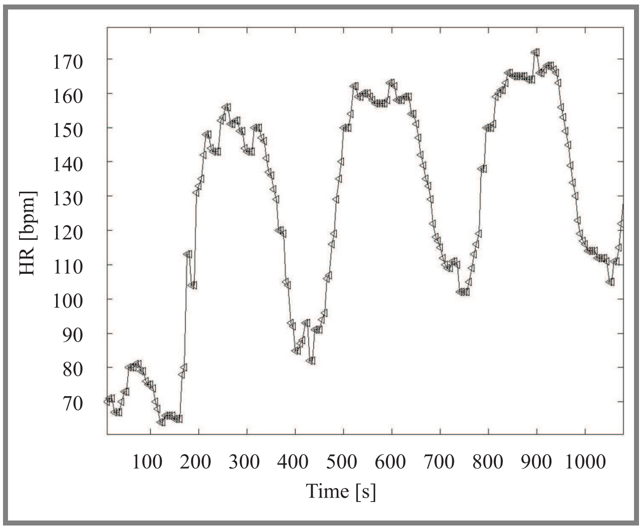


Fig. 9. Estimated heart rate from the enhanced signal who's spectrogram is shown in Fig. 8b.

It is also possible to extract the heart rate from these enhanced signals using robust statistical signal processing [22, 29]. The calculated heart rate is showed in Fig. 9. Note also that the head movements, extracted from accelerometers placed in the earphone, have been recorded and processed to extract some information concerning the type of activity the subject is performing. The color bar at the bottom of Fig. 8 indicates the type of activity: red means that the subject is walking or running, and blue that he is not performing movements. Finer analysis of body movement can be performed and is presented in Subsection 2.2.

3.1.2. Feature extraction and classification

Feature extraction is the essential part of the processing prior to any classification schemes. Features depend on the signals and can be signals variability indices, power densities in physiologically relevant frequency bands, signal model's coefficients (i.e., autoregressive or lumped models), transfer and coherence function, or entropies. The choice of a pertinent small size feature set can improve a lot the personal classifiers task. Many classification algorithms exists such as: linear vector quantization, C-mean, fuzzy C-mean, support vector machine (SVM), hidden Markov models (HMM), self organizing maps (SOM), artificial neural networks (ANN), Bayesian learning (BL), decision trees (DT), discriminant analysis (DA) [37–39]. Some of them are much too complex to be thought of being implemented in DSP processors. Mainly three approaches can be retained for low-power wearable applications: DA, HMM, BL, and ANN.

For instance, if we are interested by cardiovascular dysfunction monitoring, the ECG and its related QRS-T complexes time series such as RR and QT, gives much information on a beat-to-beat basis. Fluctuation analysis of such signals and extraction of features lead to a finer analysis of the behaviour of the cardiovascular system. For instance, so-called HRV indices including power in the very low frequency (VLF: 0 Hz – 0.04 Hz), low frequency (LF: 0.04 Hz – 0.15 Hz) and high frequency bands (HF: 0.15 Hz – 0.4 Hz), and LF/HF ratio have been used for monitoring sympathetic/parasympathetic dysfunction [20], and anesthetic level. Wearable systems have used HRV for monitoring stress level as presented in [21]. Figure 10 gives an example of such indices for RR and QT time series extracted from a subject in walking and running conditions. The cardiovascular response to the physical activity is clearly indicated by all indices. In particular the walking activity from 0 to 10 min and from 25 to 35 min is distinguishable in the LF/HF ratio in the RR time series, while not in the QT ones. The walking activity is also different after the running activity than before it. The running activity from 10 to 25 min gives rise to LF/HF changes in both RR and QT data.

Other stochastic features can be used for HRV analysis such as, renyi, spectral and approximate entropies. Nonlinear features have been shown to be much more sensitive to noise and signal distortions and are not recommended. For most of them, they require lots of computing power and are thus not recommended for online implementation on low-power DSP.

Human movement monitoring is essential because it gives information about body gesture and movement. Acceleration signals gives important information regarding the type of activity the subject is doing.

The aim of the classification of the activity signals is to detect non-stationary segments and to provide information about the physical activity of the subject. Typical activities that can be classified are: static, running, walking, cycling, and non-rhythmical movements. Features are extracted from the acceleration signals using dedicated signal processing and information theory such as variance, spectral frequency power and entropy estimations [24, 29]. Actigraphy is aimed at long-term monitoring of activity. Someren *et al.* have presented such a system in [24] using a single-axis accelerometer. Other approaches have been proposed using three single-axis PCB mounted device for 3D acceleration sensing [25, 26].

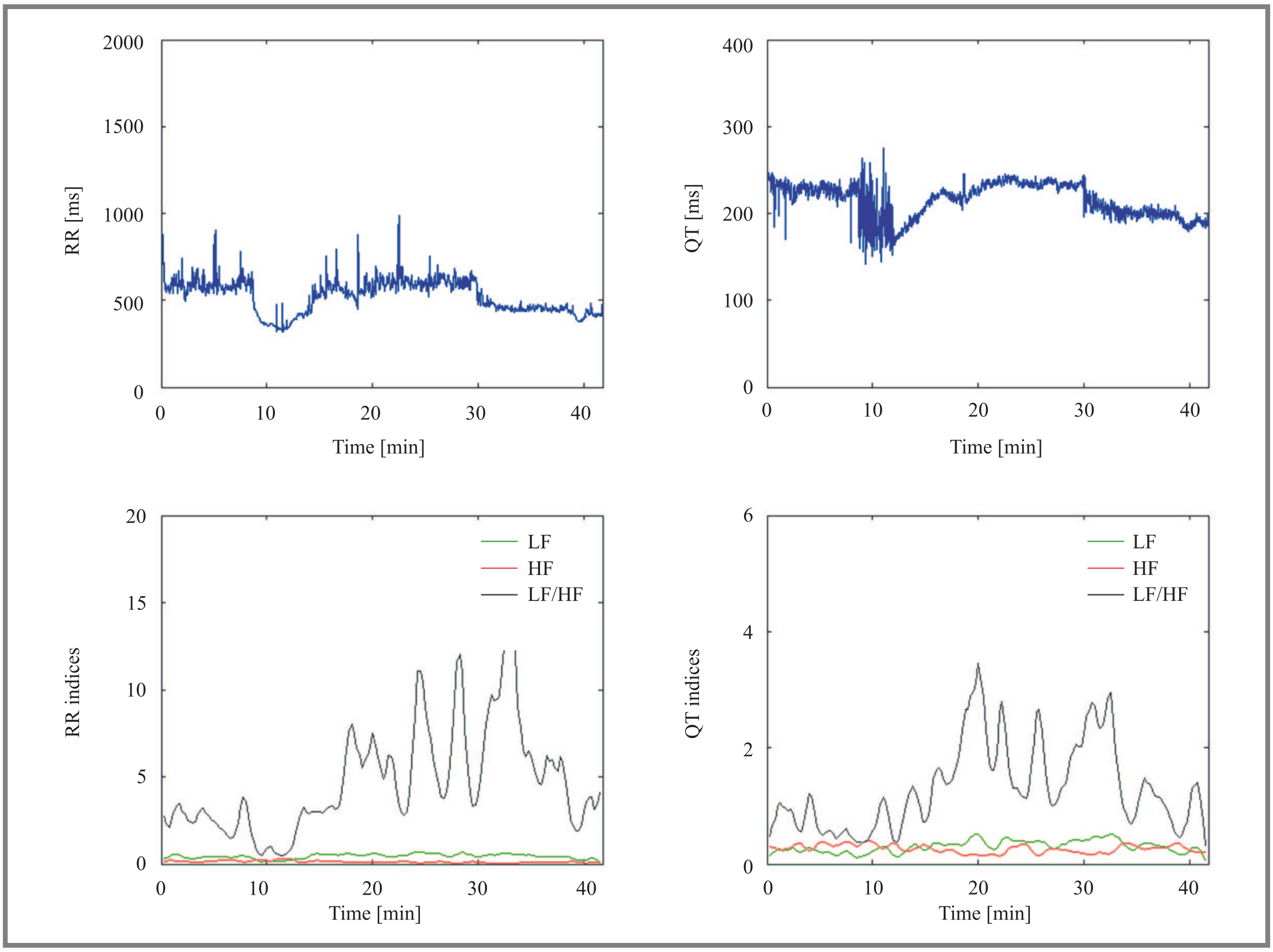


Fig. 10. Online extracted RR and QT time series on a running and walking subject together with the LF, HF and LF/HF features.

We developed a three two-axis accelerometer system and used hidden Markov model to classify the features according to the previously defined classes [23]. This choice was motivated by the fact that hidden Markov models includes temporal information into the model. Figure 11 shows an example of activity classification. Due to discomfort caused by sensors attachment, in certain cases, current kinematic systems are not easy to use during long term monitoring of physical activity. We have worked on a two-axis acceleration sensor located in a headphone for movement artefact heart rate cancellation and also actigraphy [29]. For this reason, we intend to locate the kinematic sensors along with the ECG and respiration sensors in the same wearable (see Subsection 2.2).

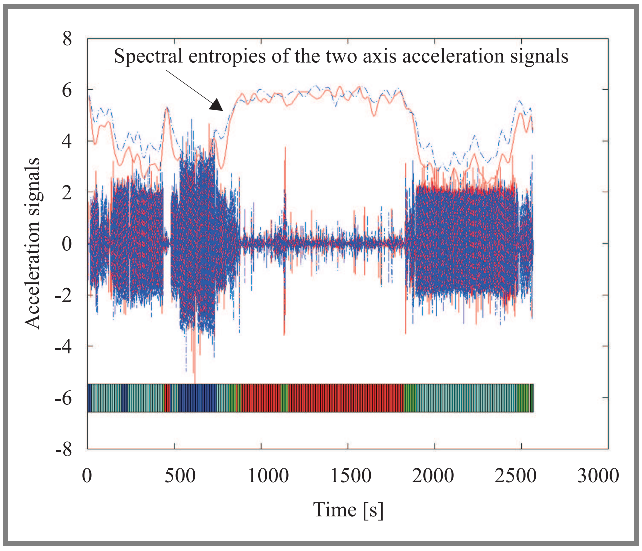


Fig. 11. Example of activity classification together with 3D acceleration signals as measured on the chest with ADXL202.

3.2. System architectures for low-power processing

3.2.1. Energy per operation and energy per transmitted bit

A body area network (BAN) is a collection of nodes that all contain sensors, on body wires or RF link and some digital processing. Some sensors capture the physiological signals. Processing is then performed on the data and transmitted by wires or wirelessly to other nodes or base stations (Fig. 12). The main challenge is the reduction of the power consumption of each node and of the overall system.

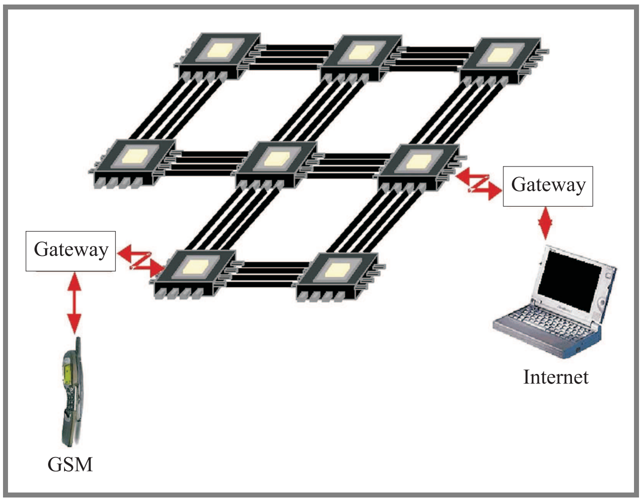


Fig. 12. Sensor array architecture for processing and transmission of biosignals.

The total power has to be optimized by analyzing the tradeoff between the energy cost of computing and transmission. Since the wire or radio transmission per bit is very power hungry, the low-power constraint does not allow transmitting the whole physiological data captured for doing the required processing remotely. This processing has therefore to be done locally and hence requires very low-power techniques for the chip design. This dramatically reduces the energy required for the extraction of the desired information as explained below.

The I/O power is roughly 50% of the total power of a chip. The capacitance of an I/O wire on a board is roughly between 50 to 100 pF. Some low power techniques have to be used, for instance a low voltage swing an a wire; at 200 mV, the power per wire could be 1 mW at 1 Gbit/s while it would be 20 times more at full swing [18]. The peak current is also an issue, as there is no decoupling capacitance to absorb large current spikes. The latter generate a lot of noise and it is a good practice to separate the supply voltages of the I/O and of the chip core [18].

On the wireless communication side, a bluetooth link is assumed to consume 80 mW in sending mode and 10 mW in receiving mode and is therefore not a low-power transceiver. In ISM bands (434 and 868 MHz), low-power RF frontends are reported, consuming about 1.8 mA at 0.9 V in receiving mode and 10 mA in sending mode in a 0.18 μm technology [19].

However, the average power consumption is mainly related to the duty cycle of the transmission process. If the nodes are most of the time in sleeping modes, the average power could be acceptable. So the tradeoff between the numbers of transmitted bits and the possible local computation achieved in the SoC itself has to be defined taken into account the duty cycle.

The energy per transmitted bit compared to energy for processing is an interesting feature:

- roughly about 100 nJ/bit is required for radio transmission (short distance, about 1 m);
- roughly 1 nJ/bit is necessary for wire transmission on a printed circuit board (at full swing);
- it could be more than 1 nJ/bit for wires embedded in clothes;
- the energy per operation in a general purpose processor is roughly 1 nJ/operation;
- 0.25 nJ/operation or less is required for a DSP core;
- 0.001 nJ/operation or less is necessary in specific coprocessors and random logic blocks.

In most of the applications in the e-health domain, the electrocardiogram (ECG), respiratory pattern (RESP) and activity (3DACC) are essential. If we assume that one node capture these signals and that ECG, RESP and 3DACC are sampled at 500, 40 and 40 Hz at 16 bits giving a total of 10.56 kbit/s, and sends these data without processing through 10 nodes and finally by RF link to a base station, the total energy per second or power consumption is:

10 nodes · 10.56 kbit/s · 1 nJ (wires) + 10.56 kbit/s · 100 nJ (radio) = 1 160 000 nJ/s = 1 160 000 nW.

Let us assume now that this given node performs a local processing with a low-power DSP core to extract the heart rate (HR), QT and ST, breath rate (BR), and activity class (4 classes) which represents the information. The number of bits to be transmitted per second is reduced to 100. To perform this parameter extraction, the DSP needs for instance 100 000 operations per second (as well as some operations to receive-send data in each node, i.e., 10 000 operations per second and per node). The total energy per second or power consumption is the following:

100 000 operations/s · 0.25 nJ (operation) + 10 nodes · 10 000 operations/s · 0.25 nJ (receive-send) + 10 nodes · 100 bit/s · 1 nJ (wires) + 100 bit/s · 100 nJ (radio) = 70 000 nJ/s = 70 000 nW.

The power consumption is reduced by a factor of 16 in the second case. The radio energy is generally the largest one, but in the second example, using a DSP core instead of a general purpose processor helps to reduce the total energy from about 3 000 000 nJ to 25 000 nJ (a factor of 120, from 3 000 000 operations at 1 nJ per operation (as a microcontroller, compared to a DSP, requires about 30 times the number of operations for the same task) to 100 000 operations at 0.25 nJ per operation). It is therefore mandatory to design very low-power DSP cores for such applications.

3.2.2. Implementation issues

Digital signal processors implemented in modern submicron CMOS technologies require many transistors. The MACGIC DSP core [16] has 500 000 transistors and up to 1 million with memories. However, in 0.18 μm technology, the silicon area is a few mm^2. The main problem is definitively the power consumption for a given level of performances for battery-powered application. It is why the supply voltage is drastically reduced, as power consumption is proportional to Vdd^2. The MACGIC DSP, at very low supply voltage (0.8 V) but at low speed (5 MHz) consumes about 1 mW executing 60 millions of operations per second (MOPS). It can be translated in 60 000 MOPS/W or 0.02 mW/MOPS.

According to [12], Table 1 shows the evolution of DSP processors. To succeed in the mentioned performances end 2012, very new ideas have to be proposed and tradeoff between performances, power consumption and flexibility.

Table 1
Performances of DSP processors

Parameters	Years			
	1982	1992	2002	2012
Technology [μm]	3	0.8	0.18	0.02
Nb MOS	50K	500K	5M	50M
Vdd	5.0	5.0	1.0	0.2
MHz	20	80	500	10K
MOPS	5	40	5K	50K
MOPS/W	4	80	10K	1M
mW/MOPS	250	12.5	0.1	0.001

Some interesting implementation techniques can be introduced at power management level. The goal is to provide variable and very low supply voltages and reduced operating frequency for dynamic voltage scaling (DVS) as well as bias voltage to increase transistor threshold voltages (V_{th}) in idle modes. The power management strategy has to take into account many parameters, such as the tasks of the application, task deadlines and the number of cycles of the tasks. It can be implemented on a micro-operating system executed in an embedded micro-controller [17]. It is based on the state transitioning times, i.e., the overhead for turning off (save processor state) and wake-up in a finite (how long) amount of time. This requires predictions about the workload of the tasks that have to be executed.

4. Communication

If we look at Fig. 2, communication takes place between any two adjacent sub-layers. At the lowest layer, between the sensors layer and the local signal conditioning layer signals from the sensors are transported in raw analogue or digital form. Between the local signal conditioning and the local signal processing layers and above the information is likely to be carried in a digital form. This opens the door to communication using local area network technologies such as fieldbusses [33] or wireless sensor networks. In the sequel of this chapter, we will restrict our discussion to networked digital communication and address the issues raised when introducing networks to transport the information at the various levels depicted on Fig. 2. Communication may use wires or be wireless. Both cases will be discussed. Communication may also take place between the person and its environment as in Fig. 1 between the portable based unit and some fixed computer giving access to the Internet. This type of communication that operates in parallel with the communication between the worn units is more conventional and will not be detailed here. We will however discuss its impact on the storage of data within the whole system.

4.1. Advantages of network based solutions

As compared to conventional point to point links, networked based solutions exhibit a number of interesting advantages:

- It is possible to transport control information in addition to the process data. In particular, this permits remote access to diagnosis and calibration functions.
- Cabling costs are reduced. This includes cables, connectors, planning, installation, commissioning and maintenance.
- Acquisition and processing may be easily separated. Changing a sensor will not affect the rest of the system if the interface does not change.
- Extensions may be performed much quicker and at lower cost because few cabling if not no cabling at all is necessary.
- Values from a sensor or any application may be transmitted to any other node. This avoids duplicating sensors and cables.
- Better signal quality as analog values are converted close to their source.

There is however a price to pay. The main drawbacks are:

- Slower data transfers as the medium is shared by all transfers (as compared to a dedicated line for each transfer). This also directly impacts the temporal consistency (see below).
- The network is a single point of failure.

4.2. Requirements

Since the advent of sensor networks in the mid 80 s, a number of studies have addressed the requirements that such networks should fulfill. The work done under the International Standard Organization is a good example of them [34]. The main requirements are the following:

- Handle periodic traffic with different period durations. This is due to the nature of most signal processing applications that are based on periodic sampling of the inputs.
- Handle sporadic traffic with bounded latency. Sporadic traffic, sometimes called aperiodic, corresponds

to transfers on demand of an application. For instance, a number of applications are triggered by events occurring at their inputs. The events should hence be transported as soon as they appear (not a in a periodic manner) whereas the occurrence in time of the event is not known a priori.

- Provide indication for temporal consistency. The fact is that control or acquisition systems expect that different sensed values correspond to sampling instants that should be close to each other (within a few percents of the sampling period). This is very easy to achieve when the inputs are connected directly to the computer on which the application runs. When using networks, latencies are such that this property is lost if no additional mechanism is present. The network should hence provide ways to support this property, named temporal consistency, and to know if a set of values exhibits the property. Note that solutions based on clocks are not sufficient to support the property. Sometimes the age (time elapsed since sampling) of a data, also called absolute temporal consistency, is also important to its users.
- Allow for quasi-simultaneous sampling of a number of inputs. This is a direct consequence of the temporal consistency requirement. This applies most of the time to periodic traffic but may occasionally be required for on demand transfers.
- For sporadic traffic, provide ways to know the order in which events have occurred. An application will take different decisions depending on the order in which events have occurred. As the events are potentially detected on different nodes of the network and may be transported in a different order than the occurrence order, there should be a way to find out the order.
- Transfer data from one node to another or simultaneously from one node to a number of others.
- Be resilient to interference, vibrations, etc.
- Offer a low cost solution. The cost picture includes the devices (nodes, connectors, cables, hubs, switches) as well the planning, installation, commissioning and maintenance expenses.

Although these are not the only requirements, they are the major ones that make sensor networks different from other networks found in the office environment.

4.3. The special case of wireless transmission

Wireless transmission means (optical, radio, induction, etc.) are very appealing because they suppress the interconnection problems caused by wires. The typical example is the SpO_2 sensors at wrist, finger or ear, and blood pressure sensor at the wrist level which preferably would need wireless link. However, they add a number of constraints that should not be underestimated. The properties that have the strongest impact are:

- Compared to cables, radio transmissions suffer from bit error rates (BER) that are some orders of magnitude higher. BER of 10^{-3} to 10^{-4} are usual whereas in cables one may expect BER ranging from 10^{-7} to 10^{-9}. Error detection schemes should hence be enhanced accordingly.
- Radio transmissions suffer from frequency selective multipath fading. Waves may follow different paths that interfere destructively at the receiver site. This results in impossibility of communication at some point in space. Using spread spectrum techniques can mitigate this effect.
- Perturbing systems can easily jam radio transmission. This is especially true in the ISM (instrument, scientific and medical) bands. For instance, in the 2.4 GHz band, high power medical devices are allowed. They may completely suppress all communications for long periods of time.
- The signaling rate is most of the time limited to a few tenths of kilobits per second and seldom exceeds 10 Mbit/s.
- Spatial reuse is low as spectrum is limited. This means that coexistence of several systems in the same area should be either planned (code or frequency allocation) or the medium access control should be designed in a way that takes care of the interference between systems.
- Transmission distances are smaller but this is not a problem in our case.
- Higher cost. Due to its intrinsic complexity, radio transmission is more expensive than cable transmission. However, this cost may be offset by lower installation costs.
- The radio bands cannot be used freely. There are a number of “free” bands, most of them ISM, but their use is governed by a number of rules. For instance, some bands are not allowed to be used 100% of the time. Duty cycles as low as 0.1% can be found. Finally, the number of bands that are available world wide is very restricted. The 2.4 GHz ISM band is among this few.
- While taping a cable requires physical access to the installation, spying radio communication can be done easily. If required, special measures should be added to ensure confidentiality.
- When is wired transmission is used, power can be transported in the same cable. With wireless, nodes may have to operate on batteries. This calls for special battery conserving transmission techniques.

Wireless light transmission may also be used. It is however less common because direct visibility is required. Generally speaking, solutions designed assuming a wired connection cannot be used on wireless transmission without important modifications [35]. In addition, contrary to wired communications, it is wise to design solutions that are able to withstand absence of communication for long periods of time. This is a direct consequence of the first three properties depicted above.

4.4. Communication architecture

Communication takes place on the person (body area network) between all the worn devices and between the person and the external world for instance between the portable base station and a fixed computer that gives access to the Internet (Fig. 1).

In the first case, as mentioned above, a communication network may be inserted between any two adjacent layers (Fig. 2). This suggests that more than a single network may be used. However, in the context of wearable systems, it seems unlikely that multiple networks will coexist on the same person. This means that, either communication may violate the layered approach, or all the connected devices comply with the layered approach in such a way that communication takes place at a single level. A logical solution would hence be to put the network between the sensing layers and the processing layers. Violating the layered approach is also possible. It would however put more constraints on the network.

The above subsections may give the impression that communication must be either wired or wireless. This is by no means implied here. On the contrary, it is perfectly possible to build a solution that combines both types of medias [36].

Communication between the person and the external world may use conventional networks such as wireless LANs provided the application is able to comply with the limitations of such networks in particular in terms of real-time guarantees and consumption. This has strong implications on the presence of local storage on the body worn units as discussed in the next subsection.

4.5. Storage and transfer of data

Generally speaking storage is a necessary evil to compensate for the asynchronisms in the overall system. In other words, would the applications and the communication systems be predictable, storage could be reduce to a minimum if not suppressed. With the use of wireless networks, buffering may also be necessary to cope with the periods of inaccessibility in which the units cannot communicate. In such a case, transfers will occur in bursts when the units can communicate. The normal throughput of the network should hence be larger than the average throughput required by the applications. Between bursts, processed data should be stored locally. An extreme case would be a worn unit that communicates with the care center once a week. Obviously, the local storage should be large enough to retain a week of data. Furthermore, the connection between the patient and the center should provide enough throughputs to transfer the stored data in a reasonable amount of time (a few seconds or minutes).

Even in the case of a permanent connection between the patient and the care center, storage should be planned on the patient to account for the possible losses of connections.

In the context of wearable systems, buffering may occur at different places. It may occur within the sensing layers, within the processing layers or both. The first case is less frequent for at least two reasons:

- Algorithms in the processing layers are executed in a periodic manner. If data is missing, it is not possible to wait until it is retransmitted at a later instant.
- Retransmissions when the first attempt did not succeed create unpredictable behavior and potentially double the necessary network bandwidth. This in its turn increases the cost and should be avoided.

There are however cases in which all data should be kept and storage should be performed at the sensory level. Storage in the processing layers is more common because asynchronism is possible (off line processing) and units at this level tend to be in lower numbers making the storage comparatively cheaper.

5. Conclusions

Wearable sensing is far from being mature and needs lots of improvements concerning the power distribution and the ergonomics of the systems. User functionality performances and clinical relevance of the extracted information will impinge on the final market potentials, rather than the individual sensor technical performances.

Communication between wearable units is largely governed by the special needs of signal processing of sensory information. If there are adequate solutions running on wires, existing wireless solutions do not comply with the requirements. Even in the case of wireline solutions, some progresses should be made to reduce further the power consumption and cope with the special nature of fabric embedded connections.

This paper has shown the emerging technological architectures, possibilities and limitations of wearable biosensing. Without doubts, within 5 to 10 years, some of these systems will become available on the market, and CSEM is aimed at playing a central role concerning the electronic and signal processing in wearable biosensors and systems.

Acknowledgements

We are grateful to R. Paradiso from Smartex s.r.l who has provided us with ECG measurements in the framework of the IST European project WEALTHY. At CSEM, this work is currently financially supported by three European projects: U_R_SAFE, WEALTHY and MyHeart.

References

[1] D. Marculescu *et al.*, “Electronic textiles: a platform for pervasive computing”, *Proc. IEEE*, vol. 91, pp. 1995–2016, 2003.

[2] E. Jovanov, T. Martin, and D. Raskovic, “Issues in wearable computing for medical monitoring applications: a case study of a wearable ECG monitoring device”, in *Int. Symp. Wear. Comput.*, Atlanta, USA, 2000.

[3] P. Bonato, “Wearable sensors/systems and their impact on biomedical engineering”, *IEEE EMB Mag.*, vol. 22, pp. 18–20, 2003.

[4] European IST Project Wealthy, http://www.wealthy-ist.com

[5] R. Paradiso, “Wearable systems for vital signs monitoring”, in *Int. Worksh. “New generation of wearable systems for e-health”*, Il Ciocco, Catelvecchio, Pascoli, Lucca, Italy, 2003.

[6] S. Park *et al.*, “The wearable motherboard: an information infrastructure or sensate liner for medical applications”, *Stud. Health Technol. Inform.*, IOS Press, vol. 62, pp. 252–258, 1999.

[7] R. Rajamanickam *et al.*, “A structured methodology for the design and development of textile structures in a concurrent engineering environment”, *J. Textile Inst.*, vol. 89, no. 3, pp. 44–62, 1998.

[8] M. Gorlick, “Electric suspenders: a fabric power bus and data network for wearable digital devices”, in *Int. Symp. Wearable Comput.*, San Francisco, USA, 1999, pp. 114–121.

[9] L. L. Scharf, *Statistical Signal Processing*. Addison-Wesley, 1991.

[10] A. Aldroubi and M. Unser, *Wavelets in Medicine and Biology*. CRC Press, 1996.

[11] I. T. Jollife, *Principal Component Analysis*. Springer-Verlag, 2002.

[12] G. Frantz, “Digital signal processor trends”, *IEEE Micro*, pp. 52–59, Nov.-Dec. 2000.

[13] Ö. Paker, “Low power digital signal processing”. Ph.D. thesis, Informatics and Mathematical Modelling, Technical University of Denmark, June 2002, IMM-PHD-2002-107.

[14] P. Mosch *et al.*, “A 720 mW 50 MOPS 1 V DSP for a hearing aid chip set”, in *IEEE Int. Solid-State Circ. Conf.*, San Francisco, USA, 2000, vol. 461, pp. 238–239.

[15] C. Piguet, “Low-power systems on chips (SoCs)”, in *Conf. CMOS & BiCMOS VLSI DESIGN’01, Adv. Dig. Des., EPFL*, Lausanne, Switzerland, 2003.

[16] F. Rampogna *et al.*, “MACGIC, a low-power, re-configurable DSP”, in *Low Power Electronics Design*, Ed. C. Piguet. CRC Press, 2004, Chapter 21.

[17] A. Sinha and A. Chandrakasan, “Dynamic power management in wireless sensor networks ”, *IEEE Des. Test Comput.*, pp. 62–66, March-Apr. 2001.

[18] C. Svensson, “Low-power and low-voltage communication for SoCs”, in *Low Power Electronics Design*, Ed. C. Piguet. CRC Press, 2004, Chapter 14.

[19] T. Melly *et al.*, “An ultra low-power UHF transceiver integrated in a standard digital CMOS process: transmitter”, *IEEE JSSC*, vol. 36, no. 3, pp. 467–472, 2001.

[20] Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, “Heart rate variability – standards of measurement, physiological interpretation, and clinical use”, *Circulation*, vol. 93, pp. 1043–1063, 1996.

[21] E. Jovanov *et al.*, “Stress monitoring using a distributed wireless intelligent sensor system”, *IEEE EMB Mag.*, vol. 22, pp. 49–55, 2003.

[22] P. Renevey, R. Vetter, J. Krauss, P. Celka, and Y. Depeursinge, “Wrist-located pulse detection using IR signals, activity and nonlinear artifact cancellation”, in *IEEE Ann. Int. Conf. Eng. Med. Biolog. Soc. EMBS*, Istanbul, Turkey, 2001.

[23] P. Renevey, R. Vetter, P. Celka, and J. Krauss, “Activity classification using HMM for improvement of wrist located pulse detection”, in *Biosig2002*, Brno, Czech Republic, 2002.

[24] E. J. W. Someren, B. F. M. Vonk, W. A. Thijssen, J. D. Speelman, P. R. Schuurman, M. Mirmiran, and D. F. Swaab, “A new actigraph for long-term registration of the duration and intensity of tremor and movement,” *IEEE Trans. Biomed. Eng.*, vol. 45, pp. 386–395, 1998.

[25] C. V. C. Bouten, “A triaxial accelerometer and portable data processing unit for the assesment of dayly physical activity”, *IEEE Trans. Biomed. Eng.*, vol. 44, no. 3, pp. 136–147, 1997.

[26] M. Sekine, T. Tamura, M. Ogawa, T. Togawa, and Y. Fukui, “Classification of acceleration waveform in a continuous walking record”, in *Proc. 20th Ann. Int. Conf. IEEE/EMBS*, Hong Kong, 1998, pp. 1523–1526.

[27] R. Vetter, N. Virag, and J. Krauss, “Robust estimation of autonomous nervous profile using non-invasive methods”, in *IEEE Ann. Int. Conf. Eng. Med. Biolog. Soc. EMBS*, Cancun, Mexico, 2003.

[28] C. Verjus *et al.*, Patent Application EP03291464.

[29] P. Celka, C. Verjus, R. Vetter, P. Renevey, and V. Neuman, “Earphone located infrared-based heart rate measurement device”, *Int. Conf. Biomed. Eng. IASTED*, Innsbruck, Austria, 2004.

[30] S. J. Barker *et al.*, “The effects of motion on the performance of pulse oximeters in volunteers”, *Anesthesiology*, vol. 86, pp. 101–108, 1997.

[31] M. J. Hayes and P. R. Smith, “Artifact reduction in photoplethysmography”, *Appl. Opt.*, vol. 37, pp. 7437–7446, 1998.

[32] S. Haykin, *Adaptive Filter Theory*. Prentice-Hall, 1996.

[33] P. Pleinevaux and J.-D. Decotignie, “Time critical communication networks: field busses”, *IEEE Netw. Mag.*, vol. 2, pp. 55–63, 1988.

[34] “Industrial automation. Time-critical communictions architectures – User requirements and network management for time-critical communications systems”, ISO/TR 13283:1998.

[35] J.-D. Decotignie, “Wireless fieldbusses – a survey of issues and solutions”, in *15th Trienn. World Congr. Int. IFAC*, Barcelona, Spain, 2002.

[36] J.-D. Decotignie *et al.*, “Architectures for the interconnection of wireless and wireline fieldbuses”, in *Proc. FeT 2001*, Nancy, France, pp. 313–318, 2001.

[37] R. O. Duda *et al.*, *Pattern Classification*. Wiley, 2000.

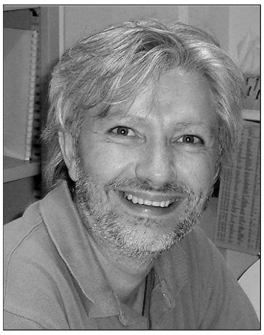
[38] N. Christianini and J. Shawe-Taylor, *An Introduction to Support Vector Machines & Other Kernel-based Learning Methods*. Cambridge: Cambridge University Press, 2000.

[39] C. M. Bishop and C. Bishop, *Neural Networks for Pattern Recognition*. Oxford: Oxford University Press, 1996.

[40] K. I. Diamantaras and S. Y. Kung, *Principal Component Neural Networks: Theory and Applications*. Wiley, 1996.

[41] J. Karhunen, “Neural approaches to independent component analysis and source separation”, in *Proc. 4th Eur. Symp. Artif. Neur. Netw., ESANN’96*, Bruges, Belgium, 1996, pp. 249–266.

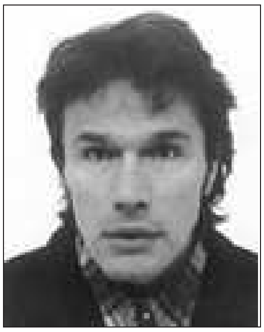
[42] A. Hyvärinen, J. Karhunen, and E. Oja, *Independent Component Analysis*. Wiley, 2001.



Patrick Celka graduated in physical sciences at the Catholic University of Louvain-la-Neuve, Belgium, and obtained his M.Sc. in 1987. He got a master degree in information and signal processing from the Swiss Federal Institute of Technology (EPFL) in 1993 and obtained a Ph.D. degree in 1995 from EPFL at the Circuits and Systems Chair. He has worked as a senior research assistant at the Signal Processing Laboratory at EPFL from 1995 to 1999. He was involved in neuro-cardiovascular system and signal modeling and analysis. From 1999 to 2001, he was leading a biomedical project dealing with the automatic detection/classification of EEG seizures in the newborn at the Signal Processing Research Centre at the Queensland University of Technology, Brisbane, Australia. From 2001 to 2004, he was with the Systems Engineering Division of the Swiss Center for Electronics and Microtechnology, Neuchâtel, Switzerland. He is currently Senior Lecturer in the School of Engineering at Griffith University, Australia. His fields of research include nonlinear dynamical systems theory, nonlinear signal and system modeling and identification, chaos theory and their applications to: neuropsychology, cognitive neuroscience, psychophysics and biomedical engineering.

Swiss Center for Electronics and Microtechnology (CSEM)
Rue Jaquet-Droz 1
CH-2007 Neuchâtel, Switzerland

e-mail: P.Celka@griffith.edu.au
School of Engineering
Gold Coast Campus, Griffith University
PMB 50 Gold Coast Mail Centre
Queensland 9726, Australia

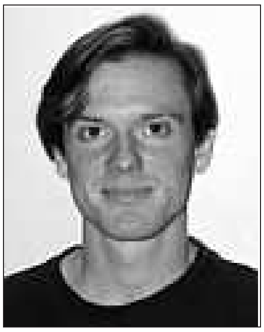


Rolf Vetter was born in Huttwil, Switzerland, in 1965. He received his M.Sc. in electrical engineering and his Ph.D. in biomedical engineering from the Swiss Federal Institute of Technology in Lausanne. Since March 2000 he is working for the Swiss Center of Electronics and Microtechnology (CSEM) in various domains with the following fields of expertise: information and signal processing, algorithmic developments for implantable cardiac rhythm management devices, portable monitoring systems of cardiovascular parameters, development of portable speech processing units and electro-optical embedded signal processing systems. Recently, he became also a part time Professor in advanced signal processing at the University of Applied Science of Western Switzerland.

e-mail: rve@csem.ch
Swiss Center for Electronics and Microtechnology (CSEM)
Rue Jaquet-Droz 1
CH-2007 Neuchâtel, Switzerland

Philippe Renevey received the M.Sc. degree and Ph.D. degree in electrical engineering from the Swiss Institute of Technology, Lausanne, Switzerland, in 1995 and 2000, respectively. He joined CSEM in 2000, where he is involved in the development of signal processing algorithms for industrial partners in the domain of biomedical and speech processing. He also leads projects in the domain of speech processing. His research interests include speech processing (mostly enhancement and recognition) and biomedical signal processing.

e-mail: prv@csem.ch
Swiss Center for Electronics and Microtechnology (CSEM)
Rue Jaquet-Droz 1
CH-2007 Neuchâtel, Switzerland



Christophe Verjus graduated in 1996 as a physics engineer from the Ecole Supérieure de Physique et Chimie Industrielles de la Ville de Paris. After working in Germany as a production engineer for Agilent Technologies, he joined CSEM in 2000 in the control and signal processing group.

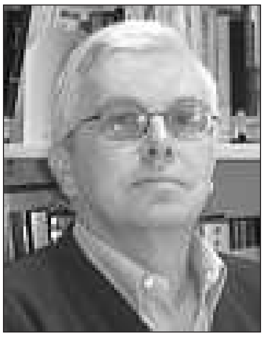
e-mail: cve@csem.ch
Swiss Center for Electronics and Microtechnology (CSEM)
Rue Jaquet-Droz 1
CH-2007 Neuchâtel, Switzerland

Victor Neuman (M.Sc. in 1980 in electrical and electronic enginnering) has worked in an optical fibre company (FOI, later Alcatel) in France on the development of the plasma torch process for silica deposition. He joined CSEM in 1985 as project manager for the development of instruments for singlemode fibre characterisation and consultant for MCVD perform fabrication. From 1988 to 1994, he created and led a small (six people) optical fibre team for the fabrication of special fibres and process development in collaboration with the Swiss fibre producer Cabloptic SA. From 1995 to 2000, he worked on the development of biochemical sensors for diagnostic, as well as the design and commissioning of a RF plasma torch system for fast rate deposition of diamond. He is since 2000 working as a research expert in the control and signal processing group, mainly on signal acquisition and optical problems.

e-mail: vne@csem.ch
Swiss Center for Electronics and Microtechnology (CSEM)
Rue Jaquet-Droz 1
CH-2007 Neuchâtel, Switzerland

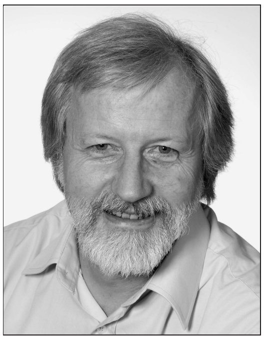
Jean Luprano (M.Sc. in 1987 in electrical engineering) has worked in a biomedical company and was in charge of the electronic development of echographic instruments. He jointed CSEM in 1993, where he was in charge first of electronic developments in the framework of European Space Agency projects. He was then appointed Head of the Application Specific Electronics Section of the Advanced System Engineering Division in 1996. He was responsible of a project for the Home Care of Elderly People and co-responsible for several related projects. He is expert in portable electronics and in the biomedical domain. He is currently responsible for the development and realization of the wearable electronics of intelligent biomedical clothes for heart disease prevention and management, in the framework of an European project comprising 30 partners.

e-mail: jlu@csem.ch
Swiss Center for Electronics and Microtechnology (CSEM)
Rue Jaquet-Droz 1
CH-2007 Neuchâtel, Switzerland



Jean-Dominique Decotignie is Head of the real-time and networking group at the Swiss Center for Electronics and Microtechnology (CSEM) in Neuchâtel. From 1977 to 1982, he has worked at the Swiss Federal Institute of Technology in Lausanne (EPFL) and the University of Tokyo in the area of optical communications. In 1983, he joined the Industrial Computer Engineering Laboratory at EPFL, where he became Assistant Professor in 1992. From 1989 to 1992, he has been the Head of an interdisciplinary project of Computer Integrated Manufacturing at EPFL. Since January 1997, he is with CSEM. Since 1977, he has participated to more than a dozen European projects (COST, Eureka, Esprit, IST). His current research interests include wireless sensor networks, low power and time constrained local area networks, distributed control systems and software engineering for real-time systems. Doctor Decotignie received his M.Sc. in 1977 and Ph.D. in 1982 both in electrical engineering from the EPFL. He is the author or the co-author of more than 100 magazine and conference papers. He is an IEEE fellow.

e-mail: jdd@csem.ch
Swiss Center for Electronics and Microtechnology (CSEM)
Rue Jaquet-Droz 1
CH-2007 Neuchâtel, Switzerland



Christian Piguet received the M.Sc. and Ph.D. degrees in electrical engineering from the Ecole Polytechnique Fédérale de Lausanne, in 1974 and 1981, respectively. He joined the Centre Electronique Horloger S.A., Neuchâtel, Switzerland, in 1974. He is now Head of the Ultra Low Power Circuits Section at the CSEM Centre Suisse d'Electronique et de Microtechnique S.A. He is presently involved in the design of low-power low-voltage integrated circuits in CMOS technology, including design methodologies, microprocessor architectures and logic design. He is Professor at the Ecole Polytechnique Fédérale Lausanne (EPFL), Switzerland, and lectures at the University of Neuchâtel, and at other universities. He holds about 30 patents in digital design, microprocessors and watch systems. He is author and co-author of more than 150 publications in technical journals and of books, and book chapters in low-power digital design.

e-mail: cpi@csem.ch
Swiss Center for Electronics and Microtechnology (CSEM)
Rue Jaquet-Droz 1
CH-2007 Neuchâtel, Switzerland