Body area network for wireless patient monitoring

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Abstract: Patient data monitoring is a key issue for health and disease management. The use of wireless sensors within a body area network (BAN) makes this task seamless and easy. A BAN system is presented, which allows the connectivity of a wide range of heterogeneous body sensors to a portable hub device that is connectable to external networks (IEEE 802.11, GPRS). This BAN is based on the use of Zigbee/IEEE 802.15.4 standard technology and off-the-shelf modules. It is currently being used at the European level for the detection and the prediction of the human physiological state in relation to wakefulness, fatigue, and stress applications in which users carrying out daily activities are monitored in an unobtrusive and comfortable way. Characterised by its low power consumption, low cost, and ability to connect a wide range of heterogeneous sensors, this system can substantially improve the performance of different services, especially those that are health related.

1 Introduction

Patient monitoring systems can be used to collect health data at home and, in some cases, in outdoor scenarios, facilitate disease management, diagnosis, prediction and follow-up [1–4]. Recent advances in the development of smaller and more precise sensors, which do not require gels, have made it possible to apply a wide range of wireless patient monitoring systems in natural environments (i.e. at work, at home and so on) [5, 6]. The monitoring of people in their natural environments is not practical when it is necessary to use cables to connect the sensors with the processing and communication units. However, the increased performance, availability, and miniaturisation of wireless communication technologies are major factors in the increasing deployment of home health care services [7, 8].

One of the goals of the current e-health approach is to empower citizens to fight diseases by promoting a preventative lifestyle and early diagnosis. The starting point is to obtain a thorough knowledge of a citizen's current state of health and to obtain this information through continuous monitoring; therefore, analysis of the vital signs is mandatory. Research and development (R&D) in Europe is playing a very active role in achieving this goal and includes initiatives based on integrated textile sensors (wearable devices) [9], new ways to measure typical parameters in an unobtrusive way [10] and grid computing [11, 12].

However, there are still major problems that must be resolved and improvements in battery power, usability and size of the sensors are not enough. There is also a need for a body area network (BAN) [13, 14] that assures connectivity, standardisation, transmission of heterogeneous signals, and multipurpose applications in order to reach the mass market. This BAN is mostly wireless and personal, and is also known as the Wireless Personal Area Network [15]. Sensor connectivity with processing units is not a new topic; it is common to use radio frequency (RF) technologies, mainly Bluetooth. This communication is usually handled through a point-to-point connection between the sensor and the monitoring unit. However, the development of new systems with several sensors that are connected simultaneously to the processing unit through wireless communications is necessary. Systems of this type allow the creation of a BAN, as shown in Fig. 1, with several sensors located on different parts of a person's body in order to monitor different parameters and that connect to a central processing unit (e.g. a personal digital assistant (PDA)), which makes use of the available communication standards [16].

The first BAN developments were based on Bluetooth, as in the Mobihealth project [17], but capacity and power consumption makes other incipient wireless technologies more suitable. IEEE 802.15.4 is the base for current developments such as the Ubimon [18] and Codeblue [19] projects. Another option is the ultrawideband (UWB) as used in the Basuma project [20].

The BAN presented in this paper is based on the IEEE 802.15.4 protocol and takes into account the necessities of providing general interfaces for the integration of a great variety of sensors and the synchronisation of the acquired data, and achieving a usable and comfortable system for the final user.

2 Materials and methods

2.1 User requirements

The BAN presented here has been designed and developed to fulfil two major requirements: usability and comfort, and the capacity to integrate a great variety of sensors.

The system is to be used by people carrying out their daily tasks in their normal environment. With this in mind, the key design parameters were as follows: to keep the size of the modules small, to avoid the use of

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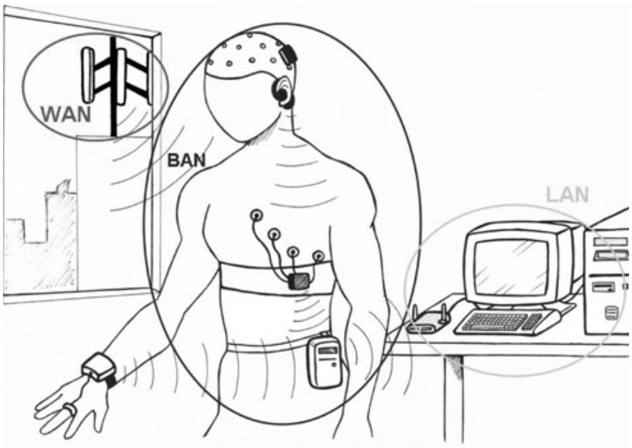

Fig. 1 *BAN with external connection*

cables, to keep the power consumption low in order to avoid the frequent changing of batteries, and to provide system autonomy. In other words, the system is designed to be discrete, usable, comfortable, and unobtrusive.

In addition, the system has been designed to allow the connection of a great variety of sensors that enable the system to be valid for heterogeneous signals and applications. These include:

1. *Interface connection.* Two types of interfaces have been defined to integrate both analogue and digital sensors.
2. *Sampling rate.* The system has been designed taking into account sensors with low sampling rates (accelerometers, pulse, and so on), as well as sensors that acquire signals that are continuous in nature, such as electroencephalograms (EEG), electrocardiograms (ECG), electro-oculograms (EOG) or electromyograms (EMG). Table 1 shows some examples of accepted characteristics for some signals acquired by Holter systems.
3. *Electrodes/Sensors/Monitoring devices*. The sensor concept can be very broad; the system has been designed for the connection of electrodes, sensors, and monitoring devices. These devices can be a set of electrodes plus the amplification and filtering chain for the acquisition of analogue signals, or a complete system that provides digitised data.

2.2 Proposed BAN

The BAN is a wireless sensor network that follows a star topology (see Figs. 2 and 3), and is formed by two main types of module.

Table 1: Acquisition characteristics in Holter systems

	EEG	EOG	EMG	ECG
Amplitude range (μV)	$\pm$1000	$\pm$2000	$\pm$1000	$\pm$2000
Frequency range (Hz)	0.001–90	0.001–90	15–200	0.1–250
Gain	1000	500	1000	500
Precision in 16 bits (μV)	0.015	0.030	0.015	0.030

1. *Sensor communication module (SCM).* A small device (34×48 mm) that can be connected to or integrated with one or several sensors, and allowing wireless communication with a central processing unit.
2. *Personal data processing unit (PDPU).* A central processing unit ($73 \times 110 \times 25$ mm) that coordinates the BAN, controls the communication with all the SCMs of the network, and the communication with external networks.

One important consideration is also that all communication technologies used in the BAN are based on communication standards.

1. The wireless communication between the PDPU and the sensors (SCM) is based on a proprietary network protocol that is compatible with IEEE 802.15.4 [21] and Zigbee [22]. This means that, although the protocol between the PDPU and the SCM is proprietary, future sensors will be able to connect to the BAN by using the Zigbee standard. IEEE 802.15.4/Zigbee has been chosen because of its low power consumption when compared with the other options such as Bluetooth [23, 24].
2. The PDPU has been designed to connect to local external systems through several standard connection technologies: USB (to connect individual devices such as PCs or personal digital assistants (PDAs)), and Wi-Fi (to connect with local area networks).
3. PDPU can also connect to with wide area networks (WAN) using standard GPRS (general packet radio service).

Another important issue is the connection of the sensors to the SCM. To develop a BAN that connects to a wide range of heterogeneous sensors, a sensor interface between the sensors and the SCMs has been defined to enable the connection of both analogue and digital sensors with the SCM. Therefore, it is possible to connect up to four analogue sensors/electrodes or up to four digital sensors.

2.3 Association of a SCM to a BAN

The BAN is based on a beaconed system defined by IEEE 802.15.4. This means that a central device, the PDPU, coordinates the BAN by sending a special frame, called a beacon, every second. A beacon is a special frame composed of several fields: the BAN identifier number, the address of the BAN coordinator, a beacon sequence number, some characteristics of the BAN related to synchronisation issues, and the interval of time in which a new beacon will be sent. Fig. 4 shows the generic frame format of an IEEE 802.15.4 frame. Fig. 5 shows the fields that compose the Bacon frame.

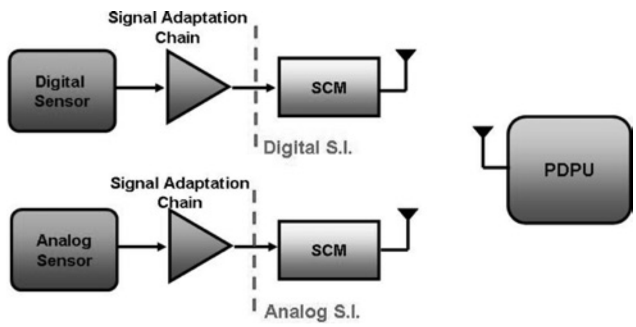

Fig. 2 *BAN schema*

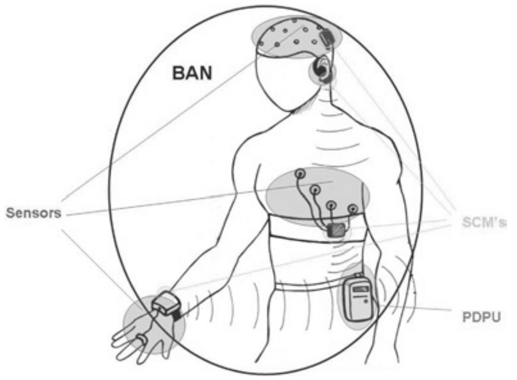

Fig. 3 *BAN architecture*

Frame structure:

Octets:	4	1	1	13 + *n*
PHY Layer	Preamble sequence	Start of frame delimiter	Frame Length	PSDU
	SHR		PHR	MPDU

Fig. 4 *IEEE 802.15.4 generic frame format*

All the sensors in the BAN are attached to SCMs that manage communications with the PDPU. When a SCM is switched on, its first task is to associate itself with a BAN. This association starts with a channel scan from which the results are used to determine the correct BAN. During the scan of each channel, the SCM rejects all frames except the beacon frames, and gathers the channel information contained in the correctly received beacons. The beacon structure in the protocol specified contains a lower number of elements than defined in the IEEE 802.15.4 standard. Beacons that are received with a different format than the defined one are rejected. In the case that no valid beacon has been received in any of the 16 available channels, the device is automatically switched off.

Once all the data from every channel has been gathered, the SCM decides which BAN to associate itself to. From the channels in which valid beacons have been received, the channel with the highest value of link quality (LQ) is chosen. If two channels contain the same value for the LQ, the one with the lower frequency is chosen.

The SCM then sends a command frame requesting an association to the chosen BAN. If the association command frame is received correctly, the BAN coordinator sends an acknowledgment frame, thus confirming the correct reception of the command. The acknowledgment to an association request command does not necessarily mean that the device is associated. The decision of allowing or disallowing a certain SCM is taken according to the BAN configuration. The next beacon from the PDPU informs the SCM whether or not association has been performed, indicating pending data for the SCM with its MAC (media access control) address and later by sending an association response command. However, if, after having received two beacon frames, there is no notification that there are pending data, the SCM repeats the complete process with the next channel with the highest value of LQ. Fig. 6 shows the

Beacon MPDU format:

Octets: 2	1	4	2	1	1	variable	variable	2
Frame control	Sequence number	Addressing fields	Superframe specification	GTS fields	Pending address fields	Address list	Beacon payload	FCS
MHR			MAC payload					MFR

Fig. 5 *Beacon frame (MDPU)*

Octets: 2	1	variable	1	variable	2
Frame control	Sequence number	Addressing fields	Command frame identifier	Command payload	FCS
MHR			MAC payload		MFR

Command Frame (MDPU)

Octets: 17	1	1
MHR fields	Command frame identifier	Capability information
---	0x01	0xC0

Association request command format (MDPU)

Octets: 23	1	2	1
MHR fields	Command frame identifier	Short address	Association status
---	0x02	0xXXXX	0xXX

Association response command format

Fig. 6 *Frames and commands for SCM*

fields of the generic command frame, and the command payload in the cases of the association request and response commands.

When the association response command is received, the SCM processes the command. If the SCM has been associated to the BAN, this command specifies the new short identifier for the new SCM in the BAN and the SCM starts its normal function. If the device has not been associated, the SCM repeats the same process with the channel that has the next highest value of LQ. If none of the BANs detected allows the device to associate, it is automatically switched off. Fig. 7 shows the association process in a graphical way.

2.4 Communication and synchronisation in the BAN

Once the SCM has been associated, it waits for beacons, and enables the receiver in the moment that a beacon indicates the transmission of the next one.

A set of commands is defined for the PDPU to control the sensors that are integrated into the SCM. These are:

1. Sensor configuration. Configures the frequency, gain, and other acquisition parameters.
2. Sensor activation. Starts the acquisition of data.
3. Sensor deactivation. Stops the acquisition of data.
4. Sensor data transmission. Orders the SCM to start sending the acquired data.
5. Reserved. Command reserved to other uses.

Because of the physical architecture of the SCM, the moment that a frame starts being received, an interrupt is activated in the SCM microcontroller. If this interrupt is generated by the reception of a beacon frame, the sequence number of the beacon is captured to be used as

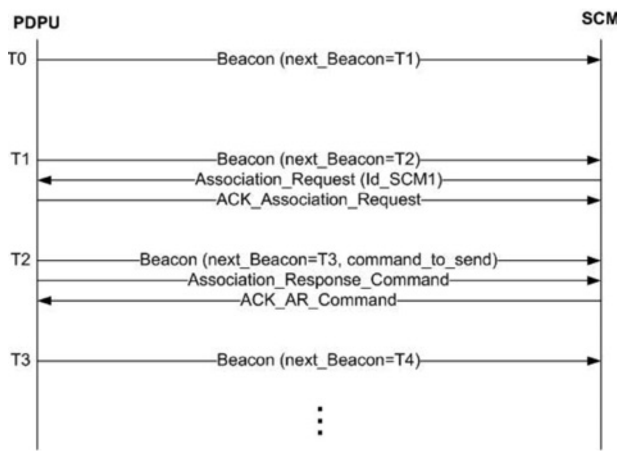

Fig. 7 *SCM association in a BAN*

a synchronisation reference and a timer starts, thus providing the relative time from the reception of this beacon.The precision of this timer is about 1 μs. This error is not significant when dealing with synchronisation of data acquired at sampling rates of up to 500 Hz. When one of the sensors in a SCM is activated by sending a command from the PDPU, the SCM starts acquiring the data until a complete data frame is filled. The SCM sends the data when it receives the sensor data transmission command. But the first frame sent is different from the following ones. The first frame includes the timestamp measured by the timer indicating the time elapsed between the reception of the last beacon and the arrival of the initial data to the SCM.

The PDPU stores the timestamp of the transmission of each beacon. When it receives data frames from the SCM, it reads the information in the initial frame, indicating the time between the transmission of a certain beacon and the first acquisition of data in a certain sensor. With this information, and the information about the sample rate with which data are acquired by the sensor and the SCM, the exact time for each sample is calculated. With this method, the data that are transmitted by several sensors at different sample rates, starting at different times, can be synchronised. Fig. 8 shows the synchronisation mechanism used in the BAN.

2.5 SCM development

All the components that make up the SCM are off-the-shelf. Their main components are:

- MSP430F427 microcontroller;
- Chipcon CC2420 wireless transceiver following the IEEE 802.15.4 standard;
- On-board chip antenna;
- FRAM (ferromagnetic RAM) memory for non-volatile data storage.

The SCM prototype is a four-layer PCB and its microcontroller is programmed in C language.

2.6 PDPU development

The main components that make up the PDPU are off-the-shelf. They are:

- ARM920T™ ARM® Thumb® Processor (AT91RM 9200);
- Chipcon CC2420EM IEEE 802.15.4 transceiver;
- 2 Mbytes of parallel flash memory;
- 32 Mbytes of SDRAM;
- 8 Mbytes of serial DataFlash®;
- Sony-Ericsson GR47 GPRS modem or Digi Connect Wi-EM Wi-Fi module;
- Security Digital (SD) memory card;
- User interfaces: alphabetical two-line LCD display, LED indicators and a five-button based joystick.

The PDPU prototype is a six-layer PCB and the base of the firmware is an embedded Linux O.S. installed in the microprocessor. The firmware is based on the C programming language and has been structured as shown in Fig. 9.

The firmware is composed of a set of modules that allows access to the hardware capacities of the PDPU:

1. *Storage primitives.* To access the PDPU memories (Flash and SD).
2. *Zigbee primitives.* To control the communication in the BAN (with the SCMs).
3. *API external comm.* To control the LAN/WAN communications (USB, Wi-Fi and GPRS).

There is also a set of modules to establish and control the communication with external systems based on a session initiation protocol (SIP).

1. *Communication manager.* This module manages all communications devices through the API external comm.
2. *SIP primitives.* They interpret the SIP and manage the signal protocol.
3. *SIP agent.* An engine that captures all the SIP messages and passes them to the SIP/SIMPLE (session initiation protocol for instant messaging and presence leveraging extensions) module.
4. *SIP/SIMPLE.* Unpackages/packages PDPU commands.
5. *Message manager.* Distributes different messages to different modules.

The PDPU facilitates the integration of simple BAN applications by providing application developers with

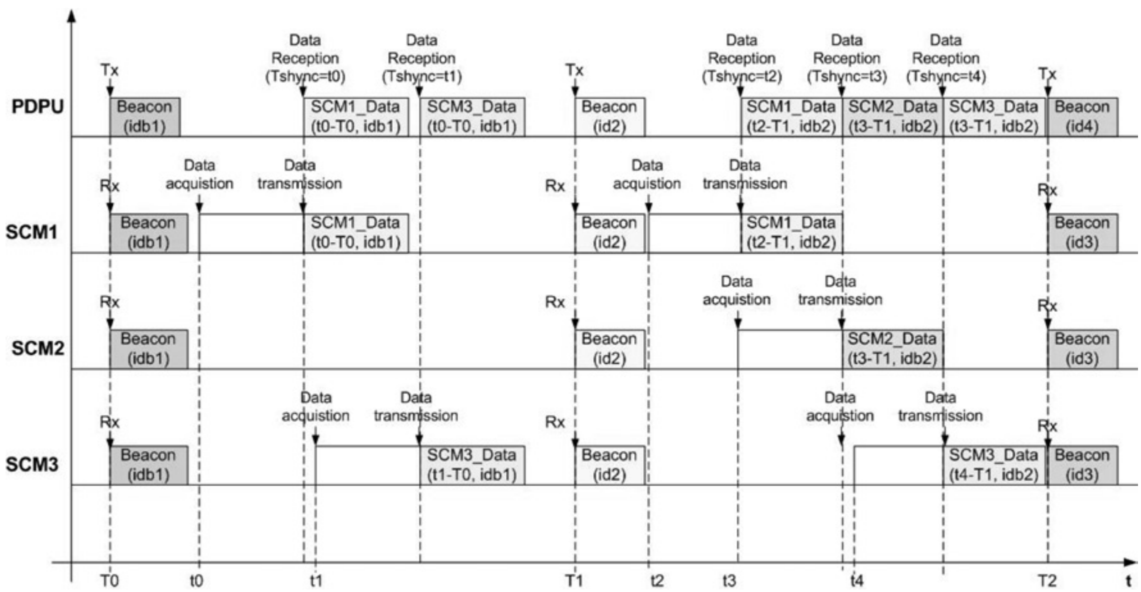

Fig. 8 *Synchronisation in the BAN*

access to a set of C libraries that control the PDPU and BAN capabilities:

1. *API BAN.* Access to BAN communication.
2. *API Capture.* Control of the sensor communication times.
3. *API Store.* Access to BAN memories (Flash and SD).
4. *API PDPU.* Access to different functions of the BAN.
(a) Configuration of BAN (sensors and PDPU).
(b) Request of the configuration of the BAN.
(c) Request of the status of the BAN.
(d) Reset of the BAN.

2.7 Security

In order to secure the communications in the BAN, the AES-CCM-128 security suite provided by IEEE 802.15.4 has been used. This assures access control for the SCMs, data encryption using the standard AES with 128 bit codes, frame integrity using 128 bit codes, and sequential freshness.

The codes are regularly exchanged between the PDPU and the SCM during communication. The protocol is a basic protocol that negotiates and validates the new code. The PDPU periodically sends a command to the SCM that includes the new code. Then, the SCM ciphers an acknowledge command, with the new code and returns it to the PDPU. If the PDPU can decipher the new command, the new code is validated; if not, the PDPU tries a negotiation process one more time. If it fails, the SCM is not valid for the BAN.

There are other mechanisms for protecting the data stored in the PDPU:

1. The data acquired by the sensors are ciphered and stored in a SD memory.
2. The password used to decipher stored data is located in a certain position of the flash memory. Therefore, only programs that know this address can decipher these data. The algorithm used to cipher and decipher data is Blowfish, which is implemented in Linux Kernel.
3. The address of the above-mentioned password is located between the Kernel and the Ramdisk images.
4. In order to protect data from external attacks, the PDPU only uses the requested TCP-ports to establish the communication with external systems. Other services, such as HTTP, FTP, Telnet and so on, are deactivated.

3 Results

3.1 BAN devices

The result of the work performed is the implementation of a real BAN that allows the wireless communication of sensors with a coordinator device using wireless network technologies, and the connection with external systems.

This BAN is composed of two main modules: the SCM and the PDPU (already described). The main task of the SCM is the wireless transmission of the data acquired by sensors to the PDPU. The SCM key characteristics are:

1. Size: 34 mm $\times$ 48 mm.
2. Lithium-ion rechargeable battery.
3. IEEE 802.15.4/Zigbee wireless based.
4. Capability for the secure transmission of data from four analogue or digital sensors.

The SCM (Fig. 10) is capable of reading data from up to four digital or analogue sensors and relays these data to the BAN coordinator (PDPU) via a 2.4 GHz wireless link based on IEEE 802.15.4/Zigbee protocol. Data are collected with a 16-bit resolution.

In addition, the SCM has a special mode in which it provides a 1 uA test current in order to check the impedance of the analogue sensors connected to it.

Finally, the SCM is equipped with a 32 kbyte FRAM memory that enables it to store readings until the next transmission is requested by the coordinator. The memory also enables it to carry out certain advanced modes of operation.

The PDPU has two basic functions:

1. To coordinate the BAN, receiving the information from the sensors through the SCMs.
2. To bridge the BAN and external systems, retransmitting the data acquired by the sensors to applications existing in external systems.

In addition, the PDPU can process the information before resending it to the local area network (LAN) or WAN levels. The PDPU can therefore obtain more significant information and/or contain simple BAN applications. Its main characteristics are:

1. Secure wireless communication with the SCMs/actuators based on IEEE 802.15.4/Zigbee.
2. Secure wireless communication with external systems using Wi-Fi/GPRS.
3. Wired communication with the LAN using USB.
4. SIP-capable for external connection establishment.
5. LCD screen.
6. Lithium-ion rechargeable battery.
7. SD memory.

The PDPU (Fig. 11) can communicate with the SCM through a wireless protocol based on IEEE 802.15.4/Zigbee. Data received from the sensors through the SCM can be processed by an application, which is stored in a SD memory or forwarded using Wi-Fi or GPRS to external systems.

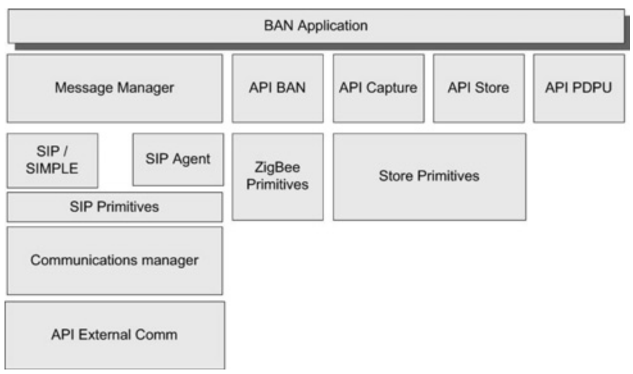

Fig. 9 *PDPU firmware structure*

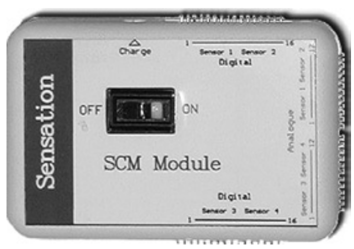

Fig. 10 *SCM picture*

Fig. 11 *PDPU picture*

3.2 Experimental validation

In order to validate the analogue data acquisition via SCM/PDPU, two prototype sensors developed by Microvitae Technologies have been integrated: the Arterorub sensor, which provides continuous recording of arterial blood pressure due to several combined capacitive microsensors, and the Flexelect sensor, which can deliver up to four differential electrophysiological preconditioned signals. Both sensors were connected to two analogue ports of two SCMs. Fig. 12 shows the connection of the Flexelect sensor to the SCM.

Fig. 13 shows the placement of three dry microelectrodes on the chest of a subject. The SCM is connected to the Flexelect prototype active sensor, which is configured with three dry microelectrodes connected to its active wearable system. The differential potential between the two microelectrodes on the subject's right side was measured (the microelectrode on the left side of the subject's chest is the ground electrode). The subject was a young man (28 years old). During data acquisition, he was sitting at rest on a chair. The three micro-electrodes connected to the Flexelect active system were configured as follows:

1. Bandpass filter: 0.1–500 Hz.
2. Active connector gain: 65.

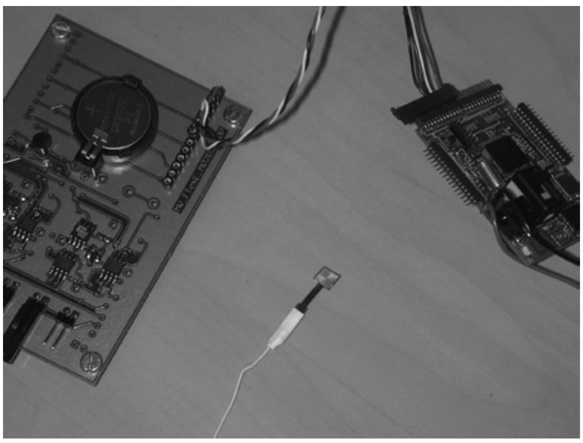

Fig. 12 *SCM + signal adaptation chain + extra-flat electrode (displayed with permission of Microvitae Technologies)*

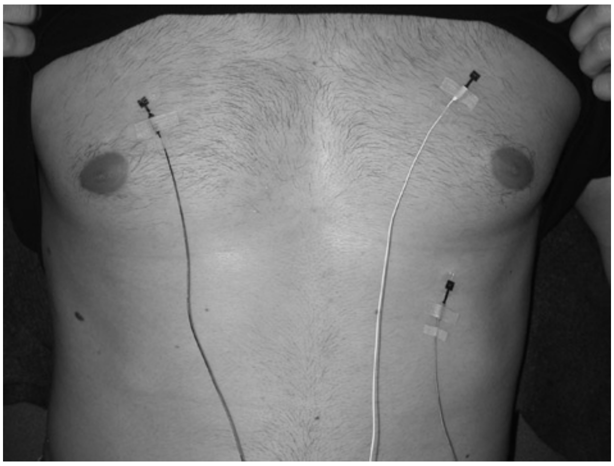

Fig. 13 *Three prototype micro-electrodes placed on the subject's chest for one-lead ECG monitoring (displayed with permission of Microvitae Technologies)*

The Flexelect active system was connected to one SCM, which was configured as follows:

1. SCM gain: 1.
2. Sampling frequency: 100 Hz (10 ms between samples).

The Arterorub sensor was connected to another SCM, which was configured as follows:

1. SCM gain: 1.
2. Sampling frequency: 100 Hz (10 ms between samples).

One-lead ECG signal (Flexelect) and the continuous arterial blood pressure were acquired, digitised, and transmitted by the SCMs and relayed by the PDPU to a PC application through a USB connection. The results are shown in Fig. 14 and indicate significant ECG and continuous blood pressure acquisition.

Other function monitoring devices have been integrated in the same way as for the ECG Flexelect. These include the Actiwrist sensor from the Camntech company for position, the Flexelect sensor for EOG and EMG, and the Textsense respiration sensors from the VTT Institute.

In addition, a synchronisation test is necessary in order to validate the synchronisation mechanism (see Fig. 15). Results were obtained using a test 10 Hz sinewave signal connected to two channels of the two SCMs and using a sampling rate of 236.74 Hz (4.2 ms sampling period).

First analysis of the acquired data involved using a routine that extracts the linearly interpolated zero-crossings of each individual signal and then determines the root mean square (r.m.s.) jitter (delay difference among the samples of the individual acquired signals) in seconds. The results can be seen in Table 2.

The same method was used for carrying out cross-channel measurements. The results were as follows:

1. Mean difference in the interpolated zero crossings between the two channels: 59.5 us.
2. Maximum difference in the interpolated zero crossings between the two channels: 262.3 us.

Finally, a cross-correlation test was carried out using cubic spline interpolation on the acquired channels. The results indicated that the global (average) delay between the two channels is below detectable values.

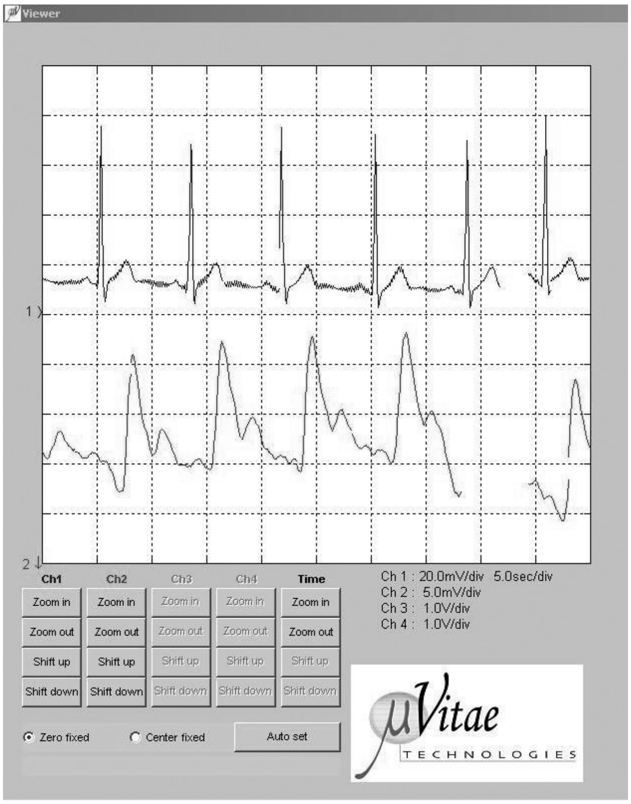

Fig. 14 *One-lead ECG signal and continuous arterial blood pressure acquired and transmitted in the BAN (displayed with permission of Microvitae Technologies)*

The results of the cross-channel errors were significantly lower than the single channel errors, indicating that the single channel jitter values are dominated by the phase noise from the signal generator rather than from the SCM itself.

4 Discussion and future work

There are many papers concerning communication through a BAN but few of them have implemented and tested with heterogeneous signals outside the laboratory environment.

The proposed BAN demonstrates how heterogeneous analogue and digital signals can be managed using off-the-shelf components and existing standards. It offers a platform to run on-body applications or to exchange data with local or wide area networks. The possibility of

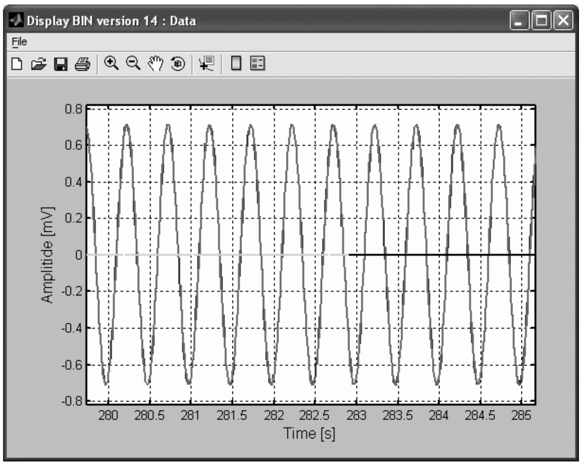

Fig. 15 *Two sinusoidal synchronised signals*

Table 2: Synchronisation results

	Jitter	Maximum deviation in half period for the mean value
Channel 1	169 us	1.02 ms
Channel 2	198 us	1.11 ms

integrating of a great variety of sensors makes this BAN a multipurpose system for the monitoring of body signals and useful in a wide and varied number of application scenarios.

Some fine-tuning work is still ongoing and includes verification of the various communication parameters such as maximum distance between the sensors and the PDPU, the minimum transmission power, and operation when the user is moving. In this way, the minimum power consumption requirement can be assessed and taken into account with regard to the battery design.

Even though wireless technology requires a greater design effort than wired technology, the functional wireless BAN offers great advantages by making the applications unobtrusive and comfortable for the subject. The choice of batteries is a critical issue to be taken into account when designing a BAN. An in-depth study of the relationship between the size of different batteries and their capacities is necessary, as well as the amount of data to be transmitted. In order to implement the BAN system proposed in this work, we have selected the Zigbee standard. This standard is designed for sensor-based platforms intended for very short-range communication, characterised by low power consumption, and having batteries that last for several months or years. The Zigbee standard assumes low duty cycles during transmission. When the amount of data increases, the duty cycle also increases and, consequently, more power is consumed. Thus, an increase in the throughput requirement also means an increase in the power consumption, and an increase in the battery size; this is a problem when developing wireless sensors. Since the objective is to reach the best compromise between data rate capacity, battery size and autonomy, the Zigbee is the best solution for usability, battery life, size and price factors, over other options such as Bluetooth. Use of new incipient technologies like UWB would require an in-depth analysis once the technology is mature.

5 Conclusions

This work has presented a BAN, which is based on the use of the Zigbee/IEEE 802.15.4 standard technology and off-the-shelf modules. It is currently being used in different European research scenarios to manage the monitoring of different heterogeneous vital signs for the detection and prediction of human physiological state. It is being applied to problems of wakefulness, fatigue, and stress within the SENSATION R&D project (1,685,000€ budget with 45 partners, four medical scenarios and 11 transport and industrial applications) [10].

This wireless BAN is a key development for R&D projects. It is also an advance for products and services where applications are framed in scenarios in which monitored users carry out their daily activities in an unobtrusive and comfortable way. This system is characterised by its low power consumption, low cost, and its ability to connect to a wide range of heterogeneous sensors. It substantially improves the performance of different services, especially those related, but not limited, to health.

Finally, even though the recent advances in micro- and nanomanufacturing, new sensing and integration of sensor technologies will revolutionise the new health patient monitoring applications field, this BAN will not require expensive redesign or modification and is likely to remain valid for a good number of years.

6 Acknowledgments

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7 References

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