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# Body Area Networks: A Survey

**Min Chen · Sergio Gonzalez · Athanasios Vasilakos · Huasong Cao · Victor C. M. Leung**

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**Abstract** Advances in wireless communication technologies, such as wearable and implantable biosensors, along with recent developments in the embedded computing area are enabling the design, development, and implementation of body area networks. This class of networks is paving the way for the deployment of innovative healthcare monitoring applications. In the past few years, much of the research in the area of body area networks has focused on issues related to wireless sensor designs, sensor miniaturization, low-power sensor circuitry, signal processing, and communications protocols. In this paper, we present an overview of body area networks, and a discussion of BAN communications types and their related issues. We provide a detailed investigation of sensor devices, physical layer, data link layer, and radio technology aspects of BAN research. We also present a taxonomy of BAN projects that have been introduced/proposed to date. Finally, we highlight some of the design challenges and open issues that still need to be addressed to make BANs truly ubiquitous for a wide range of applications.

M. Chen · S. Gonzalez · H. Cao · V. C. M. Leung
Department of Electrical and Computer Engineering,
The University of British Columbia, Vancouver, BC, Canada

M. Chen
School of Computer Science and Engineering,
Seoul National University, Seoul, South Korea

A. Vasilakos (✉)
Department of Computer and Telecommunications Engineering, University of Western Macedonia,
Macedonia, Greece
e-mail: vasilako@ath.forthnet.gr

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## 1 Introduction

Recently, there has been increasing interest from researchers, system designers, and application developers on a new type of network architecture generally known as body sensor networks (BSNs) or body area networks (BANs),[1] made feasible by novel advances on lightweight, small-size, ultra-low-power, and intelligent monitoring wearable sensors [6]. In BANs, sensors continuously monitor human's physiological activities and actions, such as health status and motion pattern.

Although many protocols and algorithms have been proposed for traditional wireless sensor networks (WSNs) [1], they are not well suited to the unique features and application requirements of BAN. To illustrate this point, the differences between BAN and WSNs are listed as follows:

– Deployment and Density: The number of sensor/actuator nodes deployed by the user depends on different factors. Typically, BAN nodes are placed strategically on the human body, or are hidden under clothing. In addition, BANs do not employ redundant nodes to cope with diverse types of failures—an otherwise common design provision in conventional WSNs. Consequently, BANs are not node-dense. WSNs however, are often deployed in

[1] There are some variations that include the word "Wireless" and/or the word "Sensor". Therefore, WBAN and WBASN are widely accepted too.

places that may not be easily accessible by operators, which requires that more nodes be placed to compensate for node failures.
- Data Rate: Most WSNs are employed for event-based monitoring, where events can happen at irregular intervals. By comparison, BANs are employed for registering human's physiological activities and actions, which may occur in a more periodic manner, and may result in the applications' data streams exhibiting relatively stable rates.
- Latency: This requirement is dictated by the applications, and may be traded for improved reliability and energy consumption. However, while energy conservation is definitely beneficial, replacement of batteries in BAN nodes is much easier done than in WSNs, whose nodes can be physically unreachable after deployment. Therefore, it may be necessary to maximize battery life-time in a WSN at the expense of higher latency.
- Mobility: BAN users may move around. Therefore, BAN nodes share the same mobility pattern, unlike WSN nodes that are usually considered stationary.

There are several advantages introduced by using wireless BANs which include:

- Flexibility: Non-invasive sensors can be used to automatically monitor physiological readings, which can be forwarded to nearby devices, such as a cell phone, a wrist watch, a headset, a PDA, a laptop, or a robot, based on the application needs.
- Effectiveness and efficiency: the signals that body sensors provide can be effectively processed to obtain reliable and accurate physiological estimations. In addition, their ultra-low power consumption makes their batteries long-lasting due to their ultra-low power consumption.
- Cost-effective: With the increasing demand of body sensors in the consumer electronics market, more sensors will be mass-produced at a relatively low cost, especially in gaming and medical environments.

In addition to the above, BANs may interface with other wireless technologies, such as WSNs, radio frequency identification (RFID) technology [41], Zigbee [56], Bluetooth, Bluetooth Low Energy (previously called WiBree) [5], video surveillance systems, wireless personal area network (WPAN), wireless local area networks (WLAN), internet, and cellular networks. In this case, the marketing opportunities for advanced consumer electronics and services will expand extensively, and more autonomous and intelligent applications that can be deemed essential to improving people's quality of life will be generated.

According to World Health Organization, aging population is becoming a significant problem at the same time that sedentary lifestyle is causing millions of people to suffer from obesity or chronic diseases everyday. It is thus reasonable to expect that this circumstance will only contribute to an ongoing decline in the quality of services provided by an already overloaded healthcare system [36]. In summary, several key applications will benefit from the advanced integration of BANs and emerging wireless technologies:

- Remote health/fitness monitoring: Health and motion information are monitored in real-time, and delivered to nearby diagnosis or storage devices, through which data can be forwarded to off-site doctors for further processing.
- Military and sports training: For example, motion sensors can be worn at both hands and elbows, for accurate feature extraction of sports players' movements.
- Interactive gaming: Body sensors enable game players to perform actual body movements, such as boxing and shooting, that can be fedback to the corresponding gaming console, thereby enhancing their entertainment experiences.
- Personal information sharing: Private or business information can be stored in body sensors for many daily life applications such as shopping and information exchange.
- Secure authentication: This application involves resorting to both physiological and behavioral biometrics schemes, such as facial patterns, finger prints and iris recognition. The potential problems, e.g., proneness to forgery and duplicability, however, have motivated the investigations into new physical/behavioral characteristics of the human body, e.g., Electroencephalography (EEG) and gait, and multimodal biometric systems.

Several design issues must be addressed in order to enable the deployment and adoption of BANs. At the hardware level, body sensors must be small, thin, non-invasive, wireless-enabled, and must be able to operate at a very low power level. From the communications perspective, it is imperative to design appropriate medium access control (MAC) protocols to ensure higher network capacity, energy efficiency, and adequate quality of service (QoS). At the application level, innovative architectures should be implemented for the corresponding applications.

The remainder of this article is organized as follows. We discuss the communications architecture of BANs in Section 2. In Section 3, we review body sensor devices, as well as sensor board hardware and platforms. We provide a detailed investigation of current proposals in the physical and data link layers in Sections 4 and 5. Section 6 reviews several candidate wireless technologies that are leading contenders in the emerging market of BANs. Section 7 provides a survey and taxonomy of various application architectures for BANs. Section 8 outlines some future research issues and trends, and Section 9 concludes this paper.

## 2 BAN communication architecture

Compared with existing technologies such as WLANs, BANs enable wireless communications in or around a human body by means sophisticated pervasive wireless computing devices.

Figure 1 illustrates a general architecture of a BAN-based health monitoring system. ECG, (electroencephalography) EEG, (electromyography) EMG, motion sensors, and blood pressure sensors send data to nearby personal server (PS) devices. Then, through a Bluetooth/WLAN connection, these data are streamed remotely to a medical doctor's site for real time diagnosis, to a medical database for record keeping, or to the corresponding equipment that issues an emergency alert. In this article, we separate the BAN communications architecture into three components: Tier-1-Comm design (i.e., intra-BAN communications), Tier-2-Comm design (i.e., inter-BAN communications), and Tier-3-Comm design (i.e., beyond-BAN communications), as shown in Fig. 1. These components cover multiple aspects that range from low-level to high-level design issues, and facilitates the creation of a component-based, efficient BAN system for a wide range of applications. By customizing each design component, e.g., cost, coverage, efficiency, bandwidth, QoS, etc., specific requirements can be achieved according to specific application contexts and market demands.

### 2.1 Intra-BAN communications

We introduce the term "intra-BAN communications" in reference to radio communications of about 2 meters around the human body, which can be further sub-categorized as: (1) communications between body sensors, and (2) communications between body sensors and the portable PS, as shown in shown in Fig. 1. Due to the direct relationship with body sensors and BANs, the design of intra-BAN communications is critical. Furthermore, the intrinsically battery-operated and low bit-rate features of existing body sensor devices make it a challenging issue to design an energy-efficient MAC protocol with QoS provisioning.

To avoid the challenges of wirelessly interconnecting sensors and a PS, existing schemes, such as MITHril [37] and SMART [12] utilize cables to directly connect multiple commercially available sensors with a PS (i.e., a PDA), as shown in Fig. 2a.

Alternatively, CodeBlue [47] stipulates that sensors directly communicate with APs without a PS, as shown in Fig. 2b. Compared with the previous two approaches, Fig. 2c represents the typical architecture of utilizing a star topology, whereby multiple sensors forward body signals to a PS that in turn forwards the processed physiological data to an access point (e.g., WiMoCa [16]).

Figure 2d and e present an advancement to a two-level BAN. In the first level, multiple wired or wireless sensors connected to a single central processor in order to reduce the amount of raw data, and save energy. After data fusion, the size of data that needs

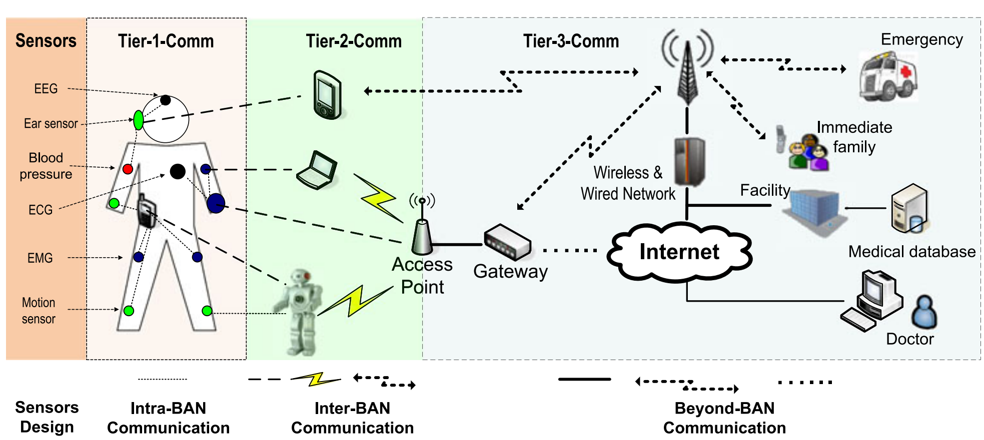


Fig. 1 A three-tier architecture based on a BAN communications system

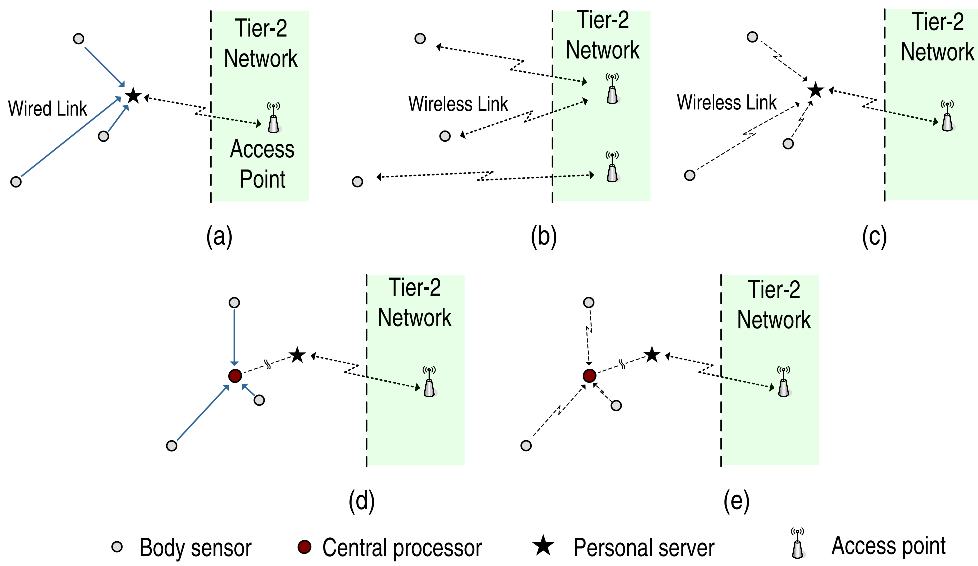


**Fig. 2** Architecture of intra-BAN communication: **a** wired; **b** directly connected to AP; **c** wireless; **d** hybrid; **e** cluster & wireless

to be transmitted from the central processor to a PS is reduced. However, these solutions involve more challenges, such as advanced sensor data processing by considering the specific biomedical communications characteristics. For example, in [3], where a two-level based intra-BAN structure is adopted, one node receives a signal from sensors, and forwards it to another that is connected to the base station as shown in Fig. 2e. It is evident that the system complexity increases when adopting architecture Fig. 2e from Fig. 2a.

## 2.2 Inter-BAN communications

Unlike WSNs that normally operate as autonomous systems, a BAN seldom works alone. In this section, we define "inter-BAN communications" as the communications between the PS and one or more access points (APs). The APs can be deployed as part of the infrastructure, or be strategically placed in a dynamic environment for handling emergency situations. Similarly, the functionality of a tier-2-network (as shown in Fig. 1) is used to interconnect BANs with various networks that are easy to access in daily life, such as the Internet and cellular networks.

We divide the paradigms of inter-BAN communications into two categories, infrastructure-based architecture (Fig. 3) and ad hoc-based architecture (Fig. 4). While the infrastructure-based architecture provides larger bandwidth with centralized control and flexibility, the ad hoc-based architecture facilitates fast deployment when encountering a dynamic environment, such as medical emergency care response, or at a disaster site (e.g., AID-N [19]).

### *2.2.1 Infrastructure based architecture*

Most BAN applications use infrastructure-based, inter-BAN communications that assumes an environment with limited space, e.g., a waiting room in hospital, home and office, etc. Compared to its ad-hoc networks counterpart, infrastructure-based networks offer the advantage of centralized management and security control. Due to this centralized structure, the AP also works as the database server in some applications (e.g., SMART [12], CareNet [28]).

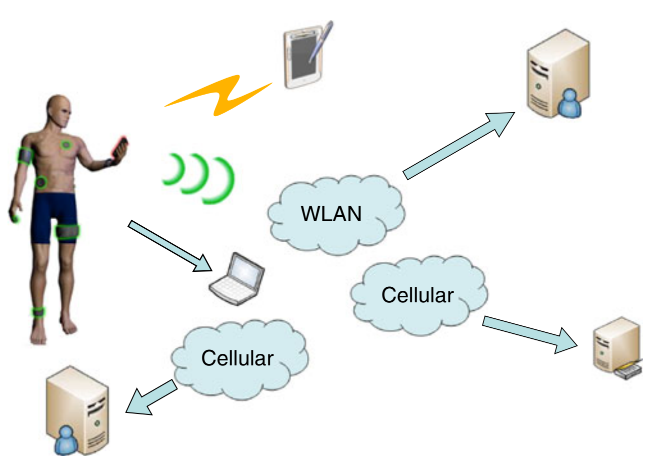


**Fig. 3** Inter-BAN communication architecture: infrastructure-based mode

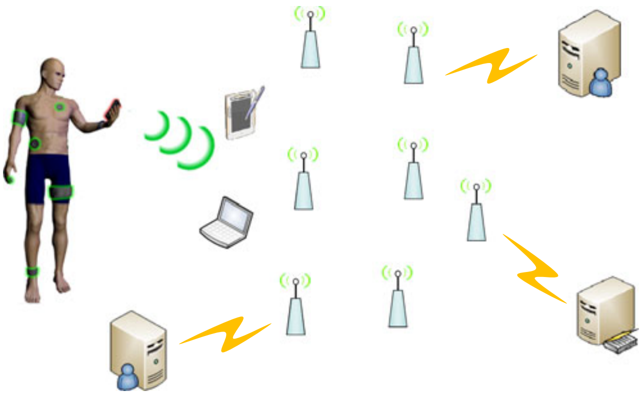

**Fig. 4** Inter-BAN communication architecture: ad hoc-based mode

### 2.2.2 Ad hoc based architecture

In the ad hoc based architecture, multiple APs are deployed to help the body sensors transmit information within medical centers. Thus, the service coverage is larger than in the infrastructure-based architecture, facilitating users to move around in a building, playground, or in an emergency rescue spot. While the coverage of a BAN is limited to about two meters, this way of interconnection extends the system to approximately one-hundred meters, which suits both in a short-term setup, and in a long-term setup (e.g., at home).

Two categories of nodes exist in this architecture setup, i.e., sensor/actuator nodes in or around a human body, and router nodes around a BAN, both of which have the same radio hardware to facilitate multi-hop routing. This architecture setup is similar to that of a traditional WSN, and both of them often employ a gateway to interface with the outside world. In WSNs, however, every node functions as a sensor node and a router node.

Since there is only one radio, all communications share the same bandwidth, and thus collisions can easily occur, given that the number of routers and sensor/actuator nodes is larger in certain area. Normally, an asynchronous MAC mechanism, such as carrier sense multiple access with collision avoidance (CSMA/CA) in ZigBee/IEEE 802.15.4, is used to deal with collisions.

The various APs of this system form a mesh structure, which has the following features: (1) radio coverage is larger as a result of multihop data dissemination, making it possible to better support patient's mobility, though bandwidth is reduced during multi-hop data forwarding; (2) fast and flexible wireless deployment can be achieved to rapidly install emergency response systems. For example, multiple router nodes can be deployed on the wall [47] or along the emergency route [19]; and (3) the network can be easily extended without affecting the entire network. To this end, APs may be added whenever needed.

### 2.2.3 Inter-BAN communication technology

Compared to intra-BAN communications, wireless technologies for inter-BAN communication are mature, and include: WLAN, Bluetooth, Zigbee, cellular, and 3G, etc. The more technologies that a personal server supports, the easier for a BAN to be integrated with other applications. Bluetooth is a popular wireless protocol for short range communications, but BANs need protocols that support low energy consumption and the self-organizing feature seen in ad-hoc networks. Even though Bluetooth has a very good communications mechanism over a short range, it is not a very feasible solution for BANs. To overcome these problems, most of the BAN applications use the ZigBee protocol. A key component of the ZigBee protocol is the ability to support mesh networks. ZigBee is used nowadays for communications between sensors in a network. There are many reasons why it has become as popular. Some of them are: (1) it incurs low energy consumption for communications between the nodes, (2) it has a low duty cycle that enables it to provide longer battery life, (3) its communications primitives enable low-latency communications, (4) and it supports 128-bit security [69]. In addition, it has all the basic features required for communications between the sensors in wireless nodes. ZigBee also enables broad-based deployment of these types of sensor networks in a cost-effective manner. Most of these applications use WLAN to communicate to the AP because it is much faster than cellular networks. By comparison, cellular network has a unique advantage in that many people carry cellphones using this technology, which provides a friendly user-interface, and communicates with peripheral devices conveniently.

## 2.3 Beyond-BAN communication

Compared to the Tier-2-Comm's design, Tier-3-Comm design is intended for use in metropolitan areas. In order to bridge the two networks for inter-BAN and beyond-BAN communications, a gateway device, such as a PDA can be employed to create a wireless link between these two networks.

As shown in Fig. 1, the beyond-BAN tier communications can enhance the application and coverage range of an E-healthare system a step further by enabling authorized healthcare personnel (e.g., doctor or nurse) to remotely access a patient's medical information by means of cellular network or the Internet.

A database is also an important component of the "beyond-BAN" tier. This database maintains the user's profile and medical history. According to user's service priority and/or doctor's availability, the doctor may access the user's information as needed. At the same time, automated notifications can be issued to his/her relatives based on this data via various means of telecommunications.

The design of beyond-BAN communication is application-specific, and should adapt to the requirements of user-specific services. For example, if any abnormalities are found based on the up-to-date body signal transmitted to the database, an alarm can be notified to the patient or the doctor through email or short message service (SMS). If necessary, doctors or other care-givers can communicate with patients directly by video conference via the Internet. In fact, it might be possible for the doctor to remotely diagnose a problem by relying on both video communications with the patient and the patient's physiological data information stored in the database or retrieved by a BAN worn by the patient.

An ambulatory patient travelling to a location outside his/her hometown might experience a critical situation if a medical condition requiring immediate attention is triggered. With the help of BAN communications using the architecture described above, emergency personnel could retrieve all of the necessary medical information from the healthcare database to treat the patient based on the awareness of the existing medical condition.

## 3 Hardware and devices

A body sensor node mainly consists of two parts: the physiological signal sensor(s) and the radio platform, to which multiple body sensors can be connected. The general functionality of body sensors is to collect analog signals that correspond to human's physiological activities or body actions. Such an analog signal can be acquired by the corresponding radio-equipped board in a wired fashion, where the analog signal is digitized. Finally, the digital signal is forwarded by the radio transceiver. In this section, we first introduce some typical body sensors, followed by a survey of currently available radio platforms.

### 3.1 Body sensors

Sensors and actuators are the key components of a BANs. They bridge the physical world and electronic systems. Because these sensors/actuators are in direct contact with persons or even implanted, their size and physical compatibility to human tissues are crucial. This motivates the search and synthesis of novel materials.

As data sources of the BAN system, body sensors are used for collecting the vital signals of a user or patient. Based on these body signals, an accurate diagnosis can be obtained to give the patient correct and timely treatments. Traditionally, measurements via body sensors involve human intervention by medical staff. With the continuous advances in circuit design, signal processing, and Micro-Electro Mechanical Systems (MEMS), body sensory data can be collected in a non-invasive fashion. Body sensor devices are also becoming smaller and wearable, which make BANs more likely to be deployed in a highly dynamic and pervasive environment, compared to previous medical systems. As a result, medical costs and the dependence on the medical facilities can be significantly reduced, while improving the quality of medical services and healthcare. In this section, we introduce some commercially available sensor devices for BANs, such as accelerometer, blood glucose, blood pressure, carbon dioxide ($CO_2$) gas sensor, ECG, EEG, EMG, gyroscope, pulse oximetry, as well as some sensors typically used in WSNs.

With the advances in MEMS, sensors/actuators are increasingly smaller, in the range of 1 to 100 micrometers. Accelerometers and gyroscopes are good examples of this advancement, as they are widely used for motion sensing. With accelerometers/gyroscopes mounted on certain part of a human body, the system can effectively register the subject's movement. Also, it is reported that MEMS devices are being manufactured for automated drug delivery. By fabricating little spikes on silicon or polymers, the liquid drug can be injected through the epidermis under pre-defined instructions, or by remote control.

As mentioned above, ECG monitoring is a typical application in BANs that can help identify the user's health status. It measures potential differences across electrodes attached to corresponding parts of the torso. For bed-side monitoring, disposable electrodes, traditionally made of silver chloride (AgCl), are widely used. However, long-term usage of these types of electrodes may cause failure of electrical contacts, as well as skin problems. A recently developed solution is to use textile-structured electrodes, which are embedded inside clothes, such as fiber, yarn and fabric structure. These textile-structure electrodes, possibly woven into clothes, are free from skin problems and thus comfortable and suitable for long-term monitoring. Compared to AgCl electrodes, they are also much more flexible since their shape can be adapted to human motion. The same kind of electrodes can be also employed for ambulatory EEG and EMG systems.

Thanks to the advancement of both charge-coupled devices (CCD) and complementary metal-oxide-semiconductor (CMOS) active-pixel sensors, cameras can be made so tiny so as to be embedded in eye glasses. The captured images can be mapped to audible outputs, to assist people who have eyesight problems. The images can even be translated to other kinds of formats, e.g., gentle electrical impulses on the tongue. Together with a lollipop-sized electrode array in their mouths, blind peopled can also be trained to regain "vision".

As all BAN nodes require an energy source for data collection, processing and transmission, development of suitable power supplies becomes paramount. One solution to this problem is energy harvesting, e.g. based on body movements or temperature difference. Another solution reported recently is to utilize wireless energy transmission over the short range, i.e., several meters, using evanescent waves. Both approaches require appropriate energy conversion and storage devices. The types of commercially available sensors are listed as follows (Table 1):

– *Accelerometer/Gyroscope*: Accelerometer is used to recognize and monitor body posture, such as sitting, kneeling, crawling, laying, standing, walking and running. Such ability is essential to many applications, including virtual reality, healthcare, sports and electronic games. The accelerometer-based posture monitoring for BANs typically consists of 3-axis accelerometers (or tri-axial accelerometers) which are placed on some strategical location on a human body. They can also be used to measure the vibration, as well as acceleration due to the gravity. Gyroscope is used for measuring or maintaining orientation, based on the principle of conservation of angular momentum. Gyroscopes can be used together with accelerometers for physical movement monitoring.
– *Blood glucose*: It is also called blood sugar and is the amount of glucose circulating in the blood. Traditionally, glucose measurements are done by pricking a finger and extracting a drop of blood, which is applied to a test strip composed of chemicals sensitive to the glucose in the blood sample (http://www.healthopedia.com/). An optical meter (glucometer) is used to analyze the blood sample and gives a numerical glucose reading. Recently, non-invasive glucose monitoring is available through infrared technology and optical sensing.
– *Blood pressure*: The blood pressure sensor is a non-invasive sensor designed to measure systolic and diastolic human blood pressure, utilizing the oscillometric technique.
– *$CO_2$ gas sensor*: It measures gaseous carbon dioxide levels to monitor changes in $CO_2$ levels, as well as to monitor oxygen concentration during human respiration.
– *ECG sensor*: ECG is a graphic record of the heart's electrical activity. Healthcare providers use it to help diagnose a heart disease. They can also use it to monitor how well different heart medications are working. In order to obtain an ECG signal, several electrodes are attached at specific sites on the skin (e.g., arms, and chest), and the potential differences between these electrodes are measured.
– *EEG sensor*: It measures the electrical activity within the brain by attaching small electrodes to the human's scalp at multiple locations. Then, information of the brain's electrical activities sensed by the electrodes is forwarded to an amplifier for producing a pattern of tracings. Synchronous electrical activities in different brain regions are generally assumed to imply functional relationships between these regions. In a hospital, the patient may be asked to breathe deeply or to look at a flashing light during the recording of EEG.
– *EMG sensor*: It measures electrical signals produced by muscles during contractions or at rest. Nerve conduction studies are often done together while measuring the electrical activity in muscles, since nerves control the muscles in the body by

**Table 1** Sensors commonly employed in BAN systems and their typical data rates

| Sensor | Topology | Data rate |
|---|---|---|
| Accelerometer/gyroscope | Star | High |
| Blood glucose | Star | High |
| Blood pressure | Star | Low |
| $CO_2$ gas sensor | Star | Very low |
| ECG sensor | Star | High |
| EEG sensor | Star | High |
| EMG sensor | Star | Very high |
| Pulse oximetry | Star | Low |
| Humidity | Star | Very low |
| Temperature | Star | Very low |
| Image/video sensor | P2P | Very high |

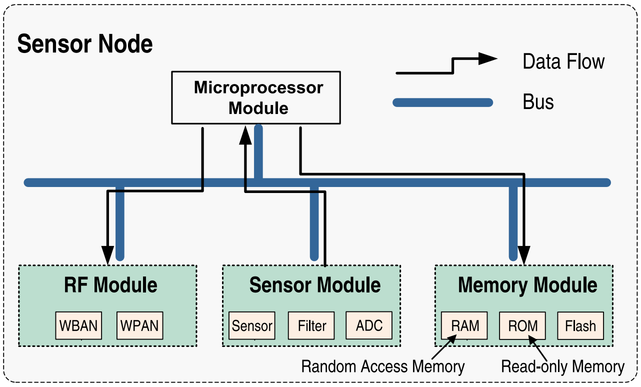


**Fig. 5** Typical modules on a sensor node

electrical signals (impulses), and these impulses make the muscles react in specific ways. Nerve and muscle disorders cause the muscles to react in abnormal ways.

– *Pulse Oximetry*: It measures oxygen saturation using a non-invasive probe. A small clip with a sensor is attached to the person's finger, earlobe, or toe. The sensor gives off a light signal that passes through the skin. According to the light absorption of oxygenated hemoglobin and total hemoglobin in arterial blood, the measurement is expressed as a ratio of oxygenated hemoglobin to the total amount of hemoglobin.
– *Humidity and temperature sensors*: They are used for measuring the temperature of the human body and/or the humidity of the immediate environment around a person. An alarm signal can be issued if a certain amount of changes are measured.

## 3.2 Platform

Figure 5 shows a typical sensor node with sensor, radio and memory modules. The sensor module consists of a sensor, a filter and an analog-to-digital converter (ADC). The sensor converts some form of energy to analog electric signals, which are bandpass-filtered and digitized by the ADC for further processing. We will discuss radio systems for BANs and WPANs used for transmissions of sensed data in the next section.

Table 2 compares the features of various representative sensor platforms in terms of topology and data rate. A complete list and more information can be found in [45]. Although there are additional types of sensors available, we also focus on other important factors, such as operating system support, wireless standard used, maximum data rate, outdoor range, and power level. These systems' features reveal the main characteristics of a sensor from the general application designer's aspect. We can see that all sensors achieve low power consumption, but possess low data rates ranging from 38.4 to 720 kbps, which is insufficient for large scale body sensor networks or applications involving multimedia data traffic such as video streaming.

Overall, a combination of TinyOS [53] as the operating system and IEEE 802.15.4 as the radio interface has been widely adopted. Although some platforms use Bluetooth, it turns out to be energy inefficient compared to IEEE 802.15.4. Thus, the current trend is that more vendors support Zigbee in their new product versions (such as Mulle, http://www.sm.luth.se/~jench/mulle.html). Interference from other radio devices sharing the 2.4 GHz ISM band is another problem that may affect BAN performance.

**Table 2** A comparison of body sensor nodes

| Name | OS support | Wireless standard | Data rate (kbps) | Outdoor range (m) | Power level |
|---|---|---|---|---|---|
| BAN node | TinyOS | IEEE 802.15.4 | 250 | 50 | Low |
| BTNode | TinyOS | Bluetooth | – | – | Low |
| eyesIFX | TinyOS | TDA5250 | 64 | – | Low |
| iMote | TinyOS | Bluetooth | 720 | 30 | Low |
| iMote2 | TinyOS or .NET | IEEE 802.15.4 | 250 | 30 | Low |
| IRIS | TinyOS | IEEE 802.15.4 | 250 | 300 | Low |
| Micaz | TinyOS | IEEE 802.15.4 | 250 | 75–100 | Low |
| Mica2 | TinyOS | IEEE 802.15.4 | 38.4 | >100 | Low |
| Mulle | TCP/IP or TinyOS | Bluetooth or IEEE 802.15.4 | – | >10 | Low |
| TelOS | TinyOS | IEEE 802.15.4 | 250 | 75–100 | Low |
| ZigBit | ZDK | IEEE 802.15.4 | 250 | 3,700 | Low |

## 4 Physical layer

### 4.1 Channel modeling

Channel model is important for the design and evaluation of the signalling techniques employed at the physical layer. In the past few years, researchers have made considerable progress in characterizing the body area propagation environment through both measurement-based and simulation-based studies in order to support:

- Development of more effective antennas with lower specific absorption [36] and better coupling to the dominant propagation modes,
- Evaluation of the performance of PHY layer proposals,
- Prediction of link level performance in alternative sensor deployment configurations;

The studies have been done in various frequency bands, i.e., 402∼405 Hz for implanted sensors, 13.5 MHz, 5∼50 MHz, 400 MHz, 600 MHz, 900 MHz, 2.4 GHz and 3.1∼10.6 GHz for on-body sensors. Different frequency band suits different link types. Studies have showed that three factors contributed to the first-order and second-order characteristics of the channel models of BANs. They are:

- Environment: where the BAN user is located, i.e., indoors, outdoors; whether the user is mobile, and how severe the interference is from other users in proximity.
- Link Class: where the sensor node is located, i.e., in-body, on-body, off-body; whether the participating sensor nodes are located in distinct parts of the body, e.g, between in-body and on-body sensors, and also whether the linked sensors are in direct line-of-sight or not.
- The user's current activity (e.g. walking, running, jumping), as well as how long the activity lasts.

In addition, some important additional findings are summarized as shown below [66]:

- Generally, the propagation wave is more likely to diffract around the human body rather than to pass through it. In addition, the path loss is higher when the transmit and receive antennas are placed at different sides of the body than when they are on the same side of the body [52].
- In the 2.4 GHz band, path loss follows an exponential decay pattern around the perimeter of the body, considering that the multipath components' contribution indoors, flattens out for large distances. Similarly, the Ricean distribution is applied to represeent the small scale fading in this frequency band, while the delay spread is normally-distributed.
- The normal distribution may fit the still posture whereas the log-normal distribution may match still postures and small movements, and the Weibull distribution may represent large movement behaviors in the 4.5 GHz band.
- Implant to implant channels exhibit a path loss between 35 and 40 dB, and a standard deviation between 8 and 9 dB, while implant-to-body surface channels exhibit a path loss between 47 and 49 dB, and a standard deviation between 7 and 8 dB.
- For sensors located over the skin, a channel in the 13.5 MHz band (about 21 KHz wide) exhibits a path loss that is nearly similar to free space.
- In the 900 MHz range, small scale fading is represented by a Ricean distribution with a K factor that decreases as the path loss increases, the average fade duration is described by the Gamma distribution, and the best-fit-to-fade magnitude is the Gamma distribution fitted to a dB scale.

Admittedly, measurement-based modeling for implants and wearable devices is difficult. The complexity of human tissues' structure and body shape should be considered when characterizing the propagation of electromagnetic waves. Moreover, a dynamic environment, body movements, and multipath fading further complicate the empirical validation of channel models. More channel models and relevant references can be found in [59].

### 4.2 Antenna design for in-body sensors

Antenna design in BAN environments is also affected by the user's posture, weight loss/gain, and even his/her aging skin. On the other hand, antenna design should consider the intrinsic on-body environment, restrictions on size, shape and material. Applicable antenna types for BANs can be generally classified into two groups: electrical antennas (e.g. dipole), and magnetic antennas (e.g. loop). For antennas that are placed inside a human body, only non-corrosive and bio-compatible material, such as platinum or titanium can be used for implants. However, these materials yield a poorer performance compared to a copper antenna. The shape and size of an implant antenna depends on its location inside the body, which further limits the freedom of the designer. Heating effects on fat, muscle and skin tissue as a result of the E-field shall also be considered when designing BAN antennas.

The form factor of an antenna, e.g., circular antenna or helix antenna, is restricted to the targeted location of the sensor device, e.g., a pacemaker, stent, or urinary implant.

Also, the maximum power imposed on the antenna is governed by regional and international regulations, e.g., for the Medical Implant Communications Services band, the European Telecommunications Standards Institute requires the output power set to a maximum of 25 μW equivalent isotropically radiated power (EIRP), while the FCC and Radiocommunication Sector (ITU-R) regulates the output power to be a maximum of 25 μW EIRP.

### 4.3 Support for protocol design

From the Physical Layer perspective, support for upper layer BAN protocols gives rise to a design tradeoff between transmission distance, data rate and power consumption. While the distance of intra-BAN communications is limited to about 2 m, and together with the data rate determined by targeted applications, the power consumption depends on body area radio propagation channels and human actions, in addition to the modulation scheme used. Compared to wider area wireless networks, decreasing the distance to 2 m and limiting data rate to 1 Mbps, the current draw of a typical low-power radio will be around 10 mA. The design of physical layer protocols should meet some unique requirements for the case of BANs, such as:

- Seamless connectivity that needs to be maintained in dynamic environments in an attempt to realize the least possible performance degradation in terms of latency, data loss and throughput.
- In unlicensed bands, robust protocol design is needed to mitigate interference issues as induced by surrounding devices operating at a high transmission power.
- Power consumption should scale linearly as the data rate is increased in order to obtain a constant energy-per-bit information signal.

## 5 MAC layer

At the MAC layer, there is a tradeoff between reliability, latency and energy consumption that needs to be resolved. Obviously, the QoS requirements, i.e., reliability and latency, originate from applications, and energy consumption reflects the applicable duty cycle and overall protocol complexity. Compared to wireless networks for wider areas, BANs incur much less energy consumption that translates into longer lifetimes by having a very low duty cycle and a simplified protocol stack. Usually however, body sensors have a very limited battery capacity, especially for those sensors which are placed inside the body. To increase the lifespan of these sensors, energy-efficient MAC protocols will play an important role. On the other hand, some BAN-based applications need highly reliable communication, low energy consumption, and low delays.

### 5.1 Energy efficient MAC protocols

To address the critical issue of extending sensor lifetime, several low power MAC protocols have been proposed for generic WSNs. In these protocols, the radio is turned on/off periodically to save energy. S-MAC [61], T-MAC [13], and TRAMA [40] propose to synchronize their transmission schedule and listening periods to maximize throughput, while reducing energy by turning off radios during much larger sleeping periods. On the other hand, low-power listening (LPL) approaches such as WiseMAC [24] and B-MAC [39] use channel polling to check if a node needs to wake up for data transmitting/receiving, thus reducing the necessity of idle listening. SCP-MAC [60] uses a scheduled channel polling to synchronize polling times of all neighbors and eliminates long preambles in LPL for all transmissions, thereby enabling ultra-low duty cycles. However, all these protocols show inadequate network throughput and delay performance at varying traffic. For example, SCP-MAC assumes a fastest rate of twenty 50-byte long packets for 10 nodes within an average inter-arrival rate of 5 s, which is significantly low in BANs. Furthermore, for low power MAC, how to synchronize the duty cycles of sensors with varying power requirements and traffic characteristics is a challenge.

In recent years, several MAC protocols have also been proposed specifically for BANs.

- Cascading Information retrieval by Controlling Access with Distributed slot Assignment (CICADA) [31] is a low-energy protocol designed for wireless, multi-hop, mobile BANs. CICADA has been developed to support high-traffic BANs where delays should be low, i.e. all sensors send data often instead of buffering it locally.
- Body sensor network MAC (BAN-MAC [32]) is a dedicated ultra-low-power MAC protocol designed for star topology BANs. BAN-MAC is compatible with IEEE 802.15.4, and accommodates unique requirements of the biosensors in BANs. BAN-MAC

is designed to be an adaptive MAC protocol. By exploiting feedback information from distributed sensors in the network, BAN-MAC adjusts protocol parameters dynamically to achieve best energy conservation on energy critical sensors.
- H-MAC [33], a novel TDMA-based MAC protocol designed for body sensor networks, aims to improve energy efficiency by exploiting heartbeat rhythm information to perform time synchronization. Heartbeat rhythm is in every human body. Biosensors in a BAN can extract the heartbeat rhythm from their own sensory data by detecting waveform peaks. All the rhythms represented by peak sequences are naturally synchronized since they are driven by a same source, the heartbeat. Following the rhythm, biosensors can achieve time synchronization without having to turn on their radio to receive periodic timing information from a central controller, so that energy cost for time synchronization can be completely avoided and the network lifetime can be prolonged.

### 5.2 QoS provisioning at the MAC layer

Similar to the design goals of providing differentiated services according to the traffic type, while considering the optimization of latency, reliability, residual energy, and transmission power, the QoS techniques utilized in WSNs can be leveraged when designing QoS protocols for BANs. However, QoS techniques in BANs have unique requirements. For example, in many scenarios, BANs have to handle real-time communications. With the relatively high sampling rate from some sensors such as ECG, it is important that data are sent out before being dropped due to buffer overflow, considering the limited buffer size of most sensors. In this situation, there are two separate but correlated scheduling schemes: in-node scheduling and channel access coordination. While in-node scheduling tries to send out data as soon as possible based on the locally-available free buffer status, channel access coordination aims at transmitting the data packet of all nodes with the earliest deadline to avoid packet dropping. There are several representative works in this area:

- BodyQoS [67] aims to provide QoS in body sensor networks with prioritized data stream service, asymmetric QoS framework, radio-agnostic QoS, and Adaptive Bandwidth Scheduling. It receives QoS and data transmission requests from the transport layer and uses the underlying MAC protocol to transmit data. BodyQoS consists of three components: Admission Control, QoS Scheduler and Virtual MAC (VMAC). BodyQoS adopts an asymmetric architecture. The Admission Control and Scheduler components are implemented as a master and slave module on the aggregator and sensor nodes, respectively. BodyQoS has an effective mechanism for prioritizing requests to maximize satisfaction.
- The Distributed Queuing Body Area Network (DQBAN [62]) MAC protocol aims at providing better QoS support. It uses a cross-layer fuzzy rule-based scheduling algorithm to optimize MAC layer performance in terms of QoS and energy efficiency. Tests have been performed on the protocol to show that the DQBAN performs better when there are more nodes in a network, and that it provides better QoS support. Using the QoS scheduler along with fuzzy logic rules help in making this protocol more reliable in terms of data transfer and also improves system performance considerably. In addition, end to end delay is measured and it has been shown that there is no delay increase incurred by the QoS scheduler. Less collisions and better transmission techniques also imply that less energy is utilized, which is also proven by experimental results.
- By employing the IEEE 802.15.4 Beacon-enabled mode for QoS provisioning, researchers in [9] propose a QoS provisioning framework for BAN traffic using the corresponding super-frame structure. In addition, a method of prioritizing BANs traffic is proposed, along with algorithms for admission control and scheduling. The framework utilizes both the contention access periods (CAPs) for time-critical traffic, and guaranteed time slots (GTSs) in contention-free periods (CFPs) for periodic traffic. It thus provides a better service differentiation between the timely reporting of rare events, and the continuous transfer of periodic sensor data in a BAN. Maximum compliance to the existing standard is kept to minimize engineering efforts needed for implementation.
- On-going work within the IEEE 802.15.6 Task Group aims at supporting applications with various data rates, where QoS guarantees are crucial in case of life-threatening conditions. User experience with audio/video streaming is also important when designing such kind of networks, although it is much less critical. Some proposals tune the existing IEEE 802.15.4 protocols to better accommodate BANs traffic, while others advance a completely new strategy to utilize new radio technologies, such as Ultra-Wideband (UWB), to deal with new problems (e.g. inter-BAN interference).

## 6 Radio technologies

In this section, we provide a comparative study of emerging and existing radio technologies for BANs and WPANs, including Bluetooth, Bluetooth Low Energy, ZigBee and IEEE 802.15.4, UWB and IEEE 802.15.6, as well as other candidate wireless technologies, which are leading contenders in recent BAN markets, such as ANT, Rubee, RFID, Sensium, Zarlink, Insteon and Z-Wave.

### 6.1 Bluetooth

Bluetooth technology was designed as a short range wireless communication standard, and later widely used for connecting a variety of personally carried devices to support data and voice applications. As a WPAN technology, two or more (up to eight) Bluetooth devices form a short-range network called piconet, where devices are synchronized to a common clock and hopping sequence at the same physical channel. The common piconet clock is identical to the Bluetooth clock of one master device among those in the piconet, while all other synchronized devices are referred to as slaves. This is actually a star topology. Bluetooth devices operate in the 2.4 GHz ISM band, utilizing frequency hopping among 79 1 MHz channels at a nominal rate of 1,600 hops/sec to reduce interference. The standard specifies three classes of devices with different transmission power and corresponding coverage ranging from 1 to 100 m. The current Bluetooth standard, i.e. version 2.0 +EDR, supports a maximum data rate of 3 Mbit/s.

### 6.2 Bluetooth low energy technology

Bluetooth Low Energy technology, formerly known as Bluetooth Low End Extension (LEE), and later Wibree, provides ultra-low power consumption and cost, while minimizing the difference between Bluetooth and itself. Introduced in 2004 by Nokia, Bluetooth LEE was designed to wirelessly connect small devices to mobile terminals. Those devices are often too tiny to bear the power consumption as well as cost associated with a standard Bluetooth radio, but are ideal choices for the health-monitoring applications. Bluetooth LEE was said to be a "hardware-optimized" radio, which means its major difference from Bluetooth resides in the radio transceiver, baseband digital signal processing and data packet format. After further development under the MIMOSA project, which targets use cases including both BANs and WPANs, LEE was released to public with the name Wibree in 2006. One year later, an agreement was reached to include it in future Bluetooth specifications as Bluetooth Low Energy technology.

Bluetooth Low Energy technology is expected to provide a data rate of up to 1 Mbps. Using fewer channels for pairing devices, synchronization can be done in a few milliseconds compared to Bluetooth's seconds. This benefits latency-critical BAN applications, e.g., alarm generation and emergency response, and enhances power saving. Bluetooth Low Energy products can be categorized into two groups: dual-mode chips and stand-alone chips. As the names indicate, stand-alone chips are intended to be equipped with sensors/actuators and to communicate with other stand-alone or dual-mode chips, while dual-mode chips are also able to connect to conventional Bluetooth devices.

Similar to Bluetooth, Bluetooth Low Energy technology will likely operate using a simpler protocol stack and focus on short-range, star-configured networks without complicated routing algorithms. This suits BANs configured in star-topology, and provides better mobility support for them. Inter-BAN communications can be realized through a second radio or using a dual-mode chip; however, the tradeoff is larger power consumption.

### 6.3 ZigBee and IEEE 802.15.4

Currently the most widely used radio standard in BANs is IEEE 802.15.4 (Zigbee) that supports very low power consumption, which is a cost-effective technology. The MAC layer responsibilities of IEEE 802.15.4 are: generating network beacons (coordinator), synchronizing to network beacons, supporting MAC association and disassociation, supporting MAC encryption, employing unslotted/slotted CSMA/CA mechanism for channel access, and handling guaranteed time slot (GTS) allocation and management. IEEE 802.15.4 defines four frame structures: beacon frame, data frame, acknowledgement frame, and MAC command frame. For data transfer, three types of transactions exist: from a coordinator to a device, from a device to a coordinator, and between two peer devices. Data transfers are completely controlled by the devices rather than by the coordinator. A device either transfers data to the coordinator, or polls the coordinator to receive data, both according to the application-defined rate. This provides the energy conservation feature of the ZigBee/IEEE 802.15.4 network, since the device can sleep whenever possible, rather than keeping its receiver continuously active.

Two modes are provided for IEEE 802.15.4 multiple-access scheme: beacon enabled and non-beacon enabled modes. In a beacon enabled mode, a superframe structure is used. A superframe is divided into two portions: active and inactive. During the inactive portion, devices may enter a low-power mode according to the requirement of its application. The active portion consists of contention access period (CAP) and contention free period (CFP). Any device wishing to communicate during the CAP shall compete with other devices using a slotted CSMA/CA mechanism, while the CFP contains guaranteed time slots where no contention exists. However, if a coordinator does not prefer to use the beacon-enabled mode, it may turn off the beacon transmissions, and the unslotted CSMA/CA algorithm is used. Both downlink and uplink compete for the same resources. No duplex scheme is specified.

In [56], it is argued that Zigbee can suffer from interference with WLAN transmissions. BANs operate at 2.4 GHz and suffers from significant and highly variable path loss near the human body [4] causing Zigbee to yield unsatisfactory performance. An additional concern with Zigbee is that the maximum supported data rate is only 250 kbps which is inadequate to support real-time and large-scale BANs. Actually, other issues such as power, data rate, and frequency of Zigbee have led to the effort of the newly formed IEEE 802.15.6 task group [35].

ZigBee/IEEE 802.15.4 targets low-data-rate and low-power-consumption applications. Specifically, the ZigBee Alliance has been working on solutions for smart energy, home automation, building automation and industrial automation. The recently completed ZigBee Health Care public application profile provides a flexible framework to meet Continua Health Alliance requirements for remote health and fitness monitoring. These solutions better suit deployment scenarios in a limited area, e.g., a hospital or a house.

ZigBee/IEEE 802.15.4 devices can operate in three ISM bands, with data rates from 20 Kbps to 250 Kbps. ZigBee supports three types of topologies—star, cluster tree and mesh. ZigBee has the advantage of providing multi-hop routing in either a cluster tree topology or a mesh topology. As a result, BAN network coverage can be expanded. A ZigBee mesh network may include both full-function devices (FFD) and reduced-function devices (RFD), where a RFD is equivalent to a standalone chip in Bluetooth Low Energy, and can only act as an end device, while a FFD is equivalent to a dual mode chip and can also act as a coordinator or a router.

There have been many academic research projects utilizing ZigBee for transporting health-related data. Most prototypes, however, are based on IEEE 802.15.4 chips that do not employ the higher layer ZigBee protocol stack, either because networking capability is not mandatory, or because researchers are interested in devising more appropriate protocols. In our view, ZigBee may have a better chance to be adopted in the area of home automation and industrial automation and control, while in the area of connecting low-power peripheral devices around the human body, e.g., watches, health-related monitors and sports sensors, Bluetooth Low Energy technology possesses a bigger potential to be widely employed, due to its association with Bluetooth as well as lower cost and lower power consumption.

### 6.4 UWB and IEEE 802.15.6

According to the Federal Communications Commission (FCC), UWB refers to any radio technology having a transmission bandwidth exceeding the lesser of 500 MHz or 20% of the arithmetic center frequency. FCC also regulates license-free use of UWB in the 3.1−10.6 GHz band to have a relatively low power spectral density emission. This leads to the suitability of UWB applications in short-range and indoor environments, and in environments sensitive to RF emissions, e.g., in a hospital. Commercial products based on UWB provide extremely high data rates, e.g., "Certified Wireless USB" devices work at up to 480 Mbps, enabling short-range wireless multimedia applications, such as wireless monitors, wireless digital audio and video players. These multimedia devices can be either wirelessly connected with BANs, or are themselves portable as part of a BAN. UWB is also an ideal technology for precise localization, which complements Global Positioning System (GPS) indoors for BAN tracking. At the same time, concerns with electronic and magnetic energy absorbed by human tissue from RF circuits placed in close proximity means that BAN devices need to employ low transmission power and low transmission duty cycles. In this regard UWB outperforms conventional transmission methods and thus attracts much attention.

An emerging BAN standard, IEEE 802.15.6—Body Area Networks (BANs), will likely employ UWB, according to recent proposals and meeting minutes. The standard intends to endow future generation electronics in close proximity to, or inside human body. However, a time frame for product commercialization that incorporates this standard remains unknown.

### 6.5 Other technologies

ANT is a proprietary sensor network technology with the features of a light-weight protocol stack, ultra low power consumption, and a data rate of 1 Mbps. ANT works in the 2.4 GHz ISM band and employs the TDMA access method. With an alliance of up to 200 members, the ANT+ interoperable system brings wireless connectivity to hundreds of available sport, fitness and health products. ANT+ interoperability enables a new standard consumer devices. To this end, manufacturers may choose a solution that ensures high functionality, low power and seamless user experience in sports and health monitoring (http://www.thisisant.com). ANT devices have already been embedded in some products, such as watches, heart rate monitors, weight scales, foot pods, bike speed and cadence sensors, bike power meters, and bike computers. ANT+ ensures efficient, seamless and practical functionality while requiring very little battery power.

RuBee (IEEE 1902.1) (http://standards.ieee.org/announcements/pr_1902.1stdapproved.html, http://www.rubee.com/) is a two way, active wireless protocol that uses Long Wave magnetic signals to send and receive short (128 byte) data packets in a local network. This protocol is similar to existing IEEE 802 protocols in that it enables networking devices by using on-demand, peer-to-peer, active radiating transceivers, but it uses a 131 kHz low frequency (LF) carrier. One disadvantage is that RuBee is very slow (1,200 baud) when compared to other packet-based network data standards, though its operating frequency provides it with the advantages of ultra low power consumption (in terms of battery life measured in years), and a stable operation near steel structures and/or water. These features make it easy to deploy sensors, controls, or even actuators and indicators. RuBee is complimentary with Radio Frequency Identification (RFID) in terms of frequency bands, battery life, and application scenarios. It is also similar with active RFID. A passive RFID tag obtains energy through RF signals from the reader, while an active RFID tag is powered by an embedded battery, which enables embedding a larger memory block and more functionalities. The main difference between RuBee and active RFID is that RuBee works in the LF band primarily using a magnetic field, whereas active RFID typically works in the very high frequency (VHF), ultra high frequency (UHF) or super high frequency (SHF) bands and with the electric field. They are both used for asset management and tracking, and have all been implemented on silicon chips already being sold.

Sensium (http://www.toumaz.com) provides a proprietary ultra-low-power platform for low data rate on-body applications. The network adopts a star topology, where sensor nodes periodically send multiple vital signs in real-time to a personal server (e.g., PCs, PDAs or cell phones, etc.) that forwards information to health professionals. To reduce energy consumption, all the sensor nodes are in standby or sleep mode until it is time to transmit data in their assigned time slots. Using single-hop communication and centrally controlled sleep/wakeup times leads to significant energy savings. Featured as an ultra-low-power (3mA@1.2V) solution, Sensium allows healthcare providers to monitor patients continuously, wirelessly, intelligently and at a low-cost.

Zarlink (http://www.zarlink.com) uses a Reed-Solomon coding scheme together with CRC error detection to achieve an extremely reliable link, as supported by a proprietary ultra low-power RF transmitter chip as an Implantable Medical Device (IMD). The Zarlink transceiver is usually in a sleep mode that consumes very low current. The IMD transceiver can be woken up by a specially coded 2.45 GHz wakeup message using an ultra low power sniffing method, or by an IMD processor to send an emergency message. Zarlink's RF chip has been used in the world's first swallowable camera capsule, which transmits two movie-quality images per second from the capsule, allowing a more thorough and non-invasive examination of the gastrointestinal tract.

Insteon (http://www.insteon.net/) and Z-Wave (http://www.z-wave.com/) are both proprietary mesh networking technologies for home automation. Z-Wave works in the 2.4 GHz ISM band, while Insteon makes use of both power lines and the 900 MHz ISM band. Z-Wave is a next-generation wireless system that enables networking consumer electronics either internally, or with the user via remote control. It uses simple, reliable, low-power radio waves that easily travel through walls, floors and cabinets. Embedded to electronic devices, these technologies build up an "intelligent" living environment.

## 7 A taxonomy of body sensor projects

In this section, we present the most important aspects pertaining to BAN deployment from a system perspective in terms of body sensor nodes, intra-BAN communication, inter-BAN communication, and beyond-BAN communication. In Fig. 6, we summarize the core architectural components that constitute body sensor system designs in terms of above aspects, and categorize some existing BAN projects, such as Code-Blue [47], AID-N [19], SMART [12], CareNet [28], ASNET [46], MITHril [37], WHMS [34], WiMoCa [16] and MIMOSA [27]. With regards to BAN applications,

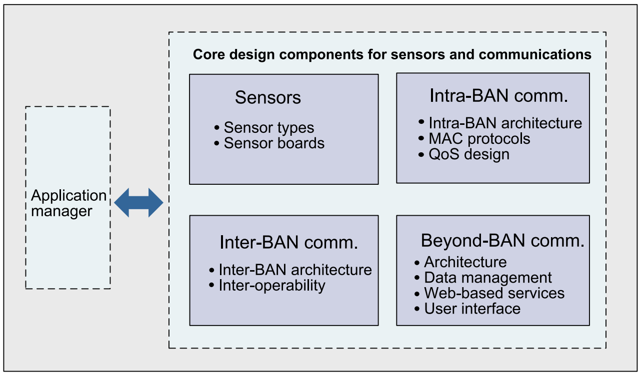


**Fig. 6** Core functional components for body sensor system design

some components are uniquely designed. For example, to enable flexible and fast deployment of inter-BAN communication, a mesh structure is adopted by AID-N [19]. This is because their targeted application is handling incidents where mass casualties occur. Compared to other projects, MIMOSA and WHMS have more focuses on the design for beyond-BAN communications. The reason for this is that WHMS targets telemedicine applications, while the goal of MIMOSA is to support a larger range of applications with an elaborate user interface. In addition, the BAN application also has a direct influence on the type of sensors used by the BAN system. The following presents some previous projects for BAN system design, grouped according to their different application fields such as remote health/fitness monitoring and military, and sport training.

## 7.1 Remote health/fitness monitoring

According to the U.S. Census Bureau, worldwide population of elderly people aged 65 and over are expected to more than double by 2020, and more than triple by 2050. Moreover, more than 1 billion people in the world nowadays are overweight, and at least 300 million of those are clinically obese, whereas over 600 million people worldwide have chronic diseases as reported by a World Health Organization study. Statistics have also confirmed the trend of women giving first-time births later in their adult lives.

In addition to the above, we note that in recent years, the electronic health (e-health) concept has evolved from telehealth into a mobile health (m-health) paradigm, enabling long-term ambulatory monitoring, and point-of-care. Moreover, research projects have produced implantable or wearable devices for patients, the disabled, aging people, pregnant women, and neonates. The following is a compilation of the most relevant projects proposed in recent years in the field of m-health, as illustrated in Fig. 7.

*CodeBlue* [47] In this project, several types of body sensors (e.g., pulse oximeter, ECG sensor) are individually connected to Zigbee-enabled radio transmitters, which communicate with APs directly. Thus, there is no intra-BAN communication in CodeBlue, as shown in Fig. 2b. This approach stipulates that multiple APs be attached to a wall. Without centralized control, its inter-BAN communication forms a mesh structure where patients' sensor devices publish all relevant information, while physicians subscribe to the network by multicasting. Using this subscribing message, physicians can specify the information they need, such as the identification of the patient(s) of interest, and the types of body signal that need to be collected. Due to the ad-hoc architecture and the self-organizing capability of the system, it is straightforward to connect various wireless devices. It also has a flexible security model, in addition to the ability to prioritize the critical messages.

*AID-N* [19] This scheme targets applications aimed at dealing with mass casualty incidents. Though AID-N utilizes a similar mesh structure for its inter-BAN communication as done in CodeBlue, its application scenario is different. Instead of deploying APs on the wall, wireless repeaters are located along a predefined emergency route. When APs flash green lights, patients and medical staff can recognize the correct emergency route. Due to its application as a medical emergency response system, a GPS module is included in a PS to provide an outdoors location service, while indoors localization is provided by the MoteTrack system, as in CodeBlue. Similar to CodeBlue, both intra-BAN and inter-BAN communications are supported. The body sensor(s) are first connected to a PS through cable(s), whose signals can be delivered to a remote database by the PS through a WiFi or cellular network.

*SMART* [12] This project was developed to monitor physiological signals from patients in the waiting areas of emergency departments. There have been various cases in which the medical team has found that the patient's health deteriorates rapidly while waiting in an emergency room. Since time is of an essence in this situation, patients' lives cannot be risked because of the lack of attention provided in emergency rooms. To help in solving this problem, the SMART System can be used to collect data from various patients waiting in an Emergency room, and wirelessly send it to a central computer that collects and analyzes the data. Calculations are performed at the central server to

**Fig. 7** A comparison of existing BAN projects

| Projects | Sensors | Intra-BSN communication | Inter-BSN communication | Beyond-BSN communication | Targeted Application |
|---|---|---|---|---|---|
| CodeBlue | Pulse oximeter EKG, motion | Wired | Mesh & Zigbee | N/A | Medical care |
| AID-N | Pulse, Blood, Temperature,ECG | Wired | Mesh & Zigbee | Internet/WiFi/ Cellular Networks | Mass casualty incident |
| SMART | ECG, SpO2 sensor | Wired | 802.11b | N/A | Health monitoring In waiting room |
| CareNet | Tri-axial accelerometer/ gyroscope | N/A | Zigbee | Multi-hop 802.11/ Internet | Remote healthcare |
| ASNET | Blood pressure, temperature | Star topology | GPRS/GSM | N/A | Remote health monitoring |
| MITHril | ECG, EKG | Wired | WiFi | N/A | Healthcare |
| WHMS | ECG, EMG, EEG, SpO2 & motion sensor | Star topology | WLAN/Bluetooth/ GPRS | Internet | Telemedicine |
| WiMoCA | Tri-axial accelerometer | Star topology & Time table-based MAC protocol | Bluetooth | Internet/ Bluetooth/WiFi/ Cellular Networks | Gesture detection/sport |
| MIMOSA | Any sensors/ RFID sensor | Wibree/Bluetooth/ RFID | Cellular Networks | Internet | Ambient intelligence |

issue an alert signal if the health of a particular patient deteriorates. This way, patients can receive treatment before the condition worsens.

*CareNet* [28] This project develops an integrated wireless environment used for remote health care systems. It offers features such as: high reliability and performance, scalability, security and integration with web-based portal systems. High reliability is achieved using a 2-tier architecture. The portal allows caregivers to efficiently access the sensor network data through a unified medical record system.

*ALARM-NET* [57] This system provides pervasive and adaptive healthcare for continuous monitoring using environmental and wearable sensors. ALARM-NET implements a WSN for smart healthcare by creating a medical history log, while preserving the patient's privacy. Authorized care providers may monitor resident health and activity patterns, such as circadian rhythm changes, which may signify changes in healthcare needs. For the providers, an automatic monitoring system is valuable for many reasons as it frees healthcare practitioners from committing to 24/7 physical monitoring, thus reducing labor costs and increasing efficiency. Wearable sensor devices can sense even small changes in vital signals that humans might overlook, such as heart rate and blood oxygen levels, boosting accuracy.

*Adaptive body posture analysis and cognitive injured body region detection for elderly-falling with multisensors* [30] When a person accidentally falls, the body part that experiences the initial impact is generally the most affected one, especially when the head or the spinal cord are involved. Information is provided by sensors distributed over the body that transmit positions through radio devices to a computer, which issues a warning when an accident happens. However, since everyone has different living habits, the manifestations of poses will differ as well. Thus, it is a good challenge to adaptively analyze body posture and determine the level of injury to provide relevant data to medical personnel for rescue and treatment.

## 7.2 Military and sport traning

According to Bluetooth Alliance's study on market potential for its low energy technology, the volume of commercial goods for sports and exercise will be 47 million in 2010, and over 100 million in 2012. In addition, the financial results briefing for Nintendo's 2009 fiscal year shows that the most successful Wii game, Wii Sports, had sold 50.54 million copies worldwide as of March 2009. Consequently, the global trend of integrating unobtrusive devices for sports and fitness has caught the attention of the manufacturers of this type of equipment. Smart phones and wrist watches are being connected to wireless networks to enhance the exercise or training experience. A good example is the Nike+Ipod Sports Kit, which connects Nike shoes and Apple's portable devices together, and even integrates with web services.

#### *7.2.1 Sport traning*

Recent research has promoted the use of accelerometers placed on different body areas in order to identify specific postures. With this technology, players in many sports, such as golf, football, and cricket, can easily improve their performance and avoid injuries due to incorrect postures. In [2], a BAN is used to determine the orientation of the golf club and the limbs of the golfer to provide real-time feedback to the golfer in terms of hip movement and stroke details on the golf course. The speed and the swing of the golf club can also be determined. In addition, the body sensory data of a player's movement is collected to analyze how to conserve energy and make the player perform at the highest level over a long period of time. By collecting real-time body movement information, a coach can provide accurate and timely instructions to help players obtain better performance more quickly. In [48], a novel software tool for coaching is suggested to provide biometric and technical feedback to both elite and amateur athletes.

#### *7.2.2 Military operations*

A BANs employed for military operations has the following roles: (a) ensuring that adequate water is delivered and consumed, (b) reducing the likelihood of body harm attributed to harsh environmental conditions, such as heat stroke, and (c) improving the quality of medical care in the event of an injury. To realize these goals, GPS and physiological-sensor information is transmitted through a minimalist, soldier-worn, mesh-networked, software-defined-radio BAN system whose design should include physiological-sensors, predictive models and algorithms, and user interfaces. Planting sensors inside the bodies of soldiers will also help in strategizing the battle. Time is an extremely precious resource in battlefields, and small mistakes may result in death. By using these sensors, a military official can control the positions of soldiers if there is any danger near their surrounding area [25].

### 7.3 BAN based intelligent system

#### *7.3.1 Intelligent biosensor system for vehicle-area-networks*

In addition to standard vehicle information, driver behavior information such as facial expression (e.g. blink-rate, yawning, eyebrow raise, chin-drop, head movements) can be collected [49]. Even physiological signals such as heart-rate variability and EEG signal behavior can be collected to determine the alertness level of the driver [10, 21]. Researchers have reported that there is a high correlation between the level of alertness and the power signal in the alpha and theta band of the EEG signal [65]. Other physiological signals such as ECG (obtained by using wireless wrist-mounted [43] or seat-installed sensors, an electrooculogram (EOG), EMG, blood pressure, and palm sweat (e.g. when driver touches the steering wheel) could be used for fatigue detection and sleep episode prediction. In such platform, sensors and audio/video (i.e. microphone/camera) can be used for collecting signals for this purpose. This platform itself is an in-vehicle network that engages a potentially large number of sensors in the car to collect vehicle/driver information. It also transmits these data to a central monitoring station for processing and receives a normal/abnormal signal/warning for the driver.

#### *7.3.2 Pervasive healthcare and affective computing*

Early research efforts in affective computing aim at understanding human emotions by analyzing visual and speech data. More recently, the availability of wearable sensing technologies has opened further possibilities for emotion detection. Emotions typically induce physical manifestations in the human body, thus producing signals that can be measured through ordinary biosensors. For example, fear increases heart-beat and respiration rates, causes palm sweating, and so forth. Monitoring emotion-related physiological signals, allows to recognize users' emotional states. Different, wearable bio-sensors have been recently made available on the market that can play an important role in emotion detection, such as, EEG, EMG, ECG, Electrodermal Activity (EDA), and so forth. It is worth stressing, that the availability of wearable and low-cost bio-sensors opens the possibility to monitor individuals' emotional reactions anywhere and anytime [7]. Wearable bio-sensing solutions are unobtrusive and can be integrated into commonly available objects in everyday life. For example, skin conductivity sensors may be integrated in shoes, blood pressure sensors can be deployed in earrings or watches, respiration sensors may be deployed in T-Shirts, and so forth [14]. These sensors enable monitoring of users under various every-day conditions ranging from driving to home-based healthcare [23, 38].

PEACH [51] is the abbreviation of Pervasive Environment for AffeCtive Healthcare. It is designed to detect changes in patients' physiological and emotional states, and for sharing this information to interested caregivers, such as professional medical staff, relatives, and friends. The PEACH framework is a context-aware, middleware-level solution capable of integrating together sensors that are capable of detecting changes in the patients' psychophysical conditions, aggregating sensing information, detecting potentially dangerous situations for the patients, and, in this case, promoting and supporting the formation of groups of individuals willing to provide prompt assistance to the patient.

Digital-Being [15] enables dancers to express their feelings and moods by dynamically and automatically adjusting music and lighting in a dance environment to reflect the dancers' arousal states while presenting their gestures and body movements. To this effect, a central system combines data obtained from pressure sensors embedded in the stage's floormat, and from wireless sensors worn by dancers in order to dynamically manipulate light and music effects in real-time. A three-layer scheme is used here. First, Layer 1 defines a sensor system that analyzes and synthesizes physiological and pressure sensor signals. Layer 2 employs an intelligent system that controls light direction, color and projected imagery, as well as music effects in order to portray a dancer's arousal state. The intelligent on-stage lighting system dynamically adjusts on-stage lighting direction and color. The intelligent virtual lighting system dynamically adapts virtual lighting in the projected imagery. Finally, Layer 3 translates the high-level adjustments made by the intelligent systems in Layer 2 to appropriate lighting control board, image rendering, and audio box commands.

## 8 Open research issues

While BANs will undoubtedly play an important role in enabling ubiquitous communications, some challenging issues remain to be addressed before BAN technologies are widely applied, as summarized below:

### 8.1 Communications and services

#### *8.1.1 Integrating emerging wireless technologies in Inter-BAN communication*

Recently, with the rapid development of ubiquitous communications, some emerging wireless technologies enable very low power-based data disseminations. A typical example is the Bluetooth Low Energy. Various functions are integrated into a single chip, which is called BlueCore7. It is a breakthrough solution for adding wireless-related connectivity features into mobile handsets. Combining Bluetooth, Bluetooth low energy, enhanced GPS and FM radio reception and transmission, the single-chip is the world's most highly integrated wireless solution for embedded applications [5]. Compared to its counterpart Zigbee technology, Bluetooth Low Energy technology has less communication overhead because it is devised for inter-BAN communication exclusively by supporting a single hop topology, short range coverage, and compatibility with widely used Bluetooth devices. Thus, it is anticipated that the Bluetooth Low Energy technology will achieve a dominating position in the ultra low-power applications of the future consumer electronics market.

Since utilizing these new technologies for improving the performance of BAN systems is still in its infancy, a strong need exists for further research and development.

#### *8.1.2 Enabling advanced E-healthcare services by using BANs*

If BAN technology can be incorporated with other technologies, such as RFID, WSNs, and video surveillance, the technology can support far more intelligent E-healthcare applications with better service provisioning in the future, and extend the capability of the existing E-healthcare systems. For example, the patient's identification stored in the RFID tag attached to a patient can be read by healthcare providers. Once the identification is verified, the healthcare provider can retrieve not only the medical history of the patient, but also the measured physiological signal in real-time as read by the BAN's sensors worn by the patient. Such information can be utilized by the medical staff to make a more accurate, timely diagnosis.

## 8.2 Sensor devices

### *8.2.1 Advanced sensor devices*

The main features of a sensor system should be: (1) comfortable to wear; not intrusive and not obtrusive; (2) do not require skillful preparation to apply to patients, and (3) do not require accurate positioning. Research should address sensor materials, signal extraction, conditioning and processing, etc.

The new generation sensor devices should possess the following features. First, they should be more comfortable for the patients. To achieve this, improved schemes regarding circuit design, signal processing, and communications are needed in order to minimize the overall power consumption and the size of body sensor, but also to reduce the detrimental effect introduced by human skin on low-power radio signals. Second, wires should be completely removed. For example, in the early ECG equipment, the electrodes are wired to a remote receiver. Later, instead of connecting to a remote receiver, all leads were wired to a common radio device, now known as "wireless ECG", although it is actually a mixed wired and wireless scheme. Currently, it still remains a challenge to design electrodes with individual radios to connect wirelessly with the ECG sensor board by the architecture shown in Fig. 2e. Thirdly, advanced sensor devices should support sensing pads that can be developed with embedded radios and small batteries. However, this will lead to more research challenges, such as optimization of signal collection/digitization/packetization/transmission, management of radio channel for sharing with minimal contention between sensors, power management to maximize battery life, etc.

### *8.2.2 Physical characteristics of sensor/actuator materials and electronic circuits*

Since sensors/actuators will be worn or implanted in people, their size, form factor, and physical compatibility with human tissues become crucial aspects. This motivates the search and synthesis of novel materials. At the same time, concerns with electromagnetic energy absorbed by human tissue from RF circuits placed in close proximity means that BAN devices need to employ low transmission power and low transmission duty cycles. In this regard, UWB outperforms conventional transmission methods and becomes highly attractive for BAN use.

## 8.3 Physical layer

### *8.3.1 Development and evaluation of improved propagation and channel models*

Body area propagation environments have been characterized extensively at the link level. There is still a need for accurate models that help researchers predict the impact of realistic channels on network level performance. Taking into account, reliability, latency, mutual interference, energy consumption and mobility factors in such a model will yield a more effective network architecture, so that better routing algorithms for BANs can be devised. Recent years have a seen growing interests in using UWB channel models for BANs. For example, in [64], an experiment was done on a human body over the 3.1 to 10.6 GHz band in an anechoic chamber to study changes on the path loss exponent under various conditions. Another related issue is performance evaluation. For example, when a BAN signal is transmitted between two sensors, the signal propagation through the body is affected by the diffraction around the body and the reflections from the body or other objects. Path loss and delay spread will affect the performance of the system, especially when the sensors are placed on different sides of a body.

## 8.4 MAC layer

### *8.4.1 BAN MAC and QoS support*

Despite the recent efforts in the design of efficient BAN MAC protocols, several critical issues at the MAC level still require further investigation:

- Network capacity: The typical packet size generated by the sensors is quite small (less than 100 bytes), leading to a low performance capacity due to inefficient MAC operations. MAC protocols with reduced overhead would be desirable.
- Tradeoff between duty cycle and performance: The ultra-low power consumption requirement demands MAC operations. However, this leads to increased frame delays and may violate the QoS objective of some sensor nodes. In addition, the sensor power level and expected battery lifetime affect the optimal configuration of MAC duty cycles.
- Sensor node heterogeneity: Sensor nodes have different storage capacity, power consumption limits, and QoS requirements. As per the requirement

to support a broad range of sensor devices, this heterogeneity factor makes the design of a comprehensive and QoS supportive MAC protocol quite challenging.

On the QoS support aspect, it is desirable that the following issues be addressed, either based on an existing standard (e.g., IEEE 802.15.4) or on emerging standards (e.g., IEEE 802.15.6):

- Tradeoff between throughput/delay and energy efficiency: Low duty cycle leads to lower throughput and higher packet delay. Adaptive adjustment of duty cycles is thus desirable for better performance.
- Prioritized channel access coordination and scheduling: Based on the application's requirements, sensors may have different battery lifetime, memory limits, data sampling rates, and data priorities. How to design a service differentiation and scheduling strategy that meets the real-time demands of certain sensors, while taking advantage of such broad sensor heterogeneity is also a significant challenge.

#### *8.4.2 Synchronization and calibration*

Synchronization and calibration of biomedical sensors for distributed data collection are critical problems that need to be addressed. Although several schemes have been studied for WSNs, limited work has been done for BANs. Since distributed sensor devices do not share a common power source, accurate calibration between wireless sensor nodes is required. Tight synchronization is needed when measuring a delay between two sensor nodes which involve two clocks. The synchronization between different clocks has a tremendous impact on the accuracy of the delay measurement. In addition, tight synchronization enables sensor nodes to quickly turn-around from transmit to receive and fast wake up from power-saving sleep mode, while delivering real-time sensory data in a timely fashion to contribute significant power savings.

#### *8.4.3 Multi-radio and multi-channel design*

Both synchronous and asynchronous MAC mechanisms can be used for scheduling and collision avoidance for BANs that utilize two radios. This architecture can effectively extend the system coverage to a larger area, at the expense of increased power consumption and other associated costs. The dual-radio approach is especially useful in environments where power and cost are not a concern, (e.g., on a disaster site), and where using an additional radio is desirable to increase overall system performance. Furthermore, there can be a hybrid approach where both router nodes and a second radio are used.

### 8.5 Other issues

#### *8.5.1 Power supply issues*

As all BAN devices require an energy source for data collection, processing and transmission, the development of suitable power supplies becomes paramount. Most BAN devices are powered by batteries, which may not even be replaceable in cases where the devices are implanted in the human body; thus techniques like remote battery recharging are important. In addition to energy harvesting methods, i.e., based on body movements, that many researchers are studying, researchers at MIT have recently reported wireless energy transmission to power electronic devices over a short range (i.e., several meters) using evanescent waves [29].

#### *8.5.2 Security, authentication and privacy issues*

Security concerns require effective and efficient authentication techniques in BANs. Multimodal authentication schemes based on human faces, hand features, and EEG signals, are being actively developed in both academia and industry. Complex but distinguishable human body characteristics provide an ideal way for authenticating users, but they also create other challenges (e.g., protecting the privacy of the users). Different levels of security should be identified and appropriate mechanisms shall be developed to distinguish life-threatening requests from other applications with various security priorities and appropriate privacy-protection measures.

#### *8.5.3 Standardization*

Efforts have been put into the interoperability of desktop telemedicine systems and bedside devices, e.g., the development of Health Level 7 and ISO/IEEE 11073 standards [55]. However, intelligent monitoring and treatment systems employing BANs require standardized rules for ambulatory environments that provide point-of-care regardless of the user's location, while protecting the patient's privacy. Interoperability protocols at the application or domain level, e.g., sample rate, data precision, association/disassociation, device descriptions, and nomenclature, should all be addressed by vendor-independent attributes, and standardized user interfaces should be made.

## 9 Conclusions

BAN is a promising technology which can revolutionize next generation healthcare and entertainment applications. BAN brings out a new set of challenges in terms of scalability, energy efficiency, antenna design, QoS, coexistence, interference mitigation, and security and privacy to name a few, which are highlighted in this paper. We also discuss state-of-art technologies and standards which are relevant to BANs, as well as their merits and demerits. Developing a unifying BAN standard which addresses the core set of technical requirements is the quintessential step for unleashing the full potential of BANs, and is currently under discussion in the IEEE 802.15.6 Task Group. In the end several non-technical factors would also play crucial roles in the success of the BAN technology in mass marketing, such as affordability, legal, regulatory and ethical issues, and user friendliness, comfort and acceptance. BAN technology needs the widespread acceptance of key stakeholders in the healthcare domain, including the medical-electronics industry, patients, caregivers, policy makers, patient advocacy groups and ordinary consumers for it to become a truly pervasive technology. Engineers, researchers and practitioners from multiple disciplines must come together and strive hard to overcome technical roadblocks in order to bring the vision of ubiquitous healthcare network to reality. We have presented a comprehensive survey of body sensor networks. Sensor hardware, system architecture, communication protocols, applications, and design issues are discussed in detail. We have also summarized core functional components for BAN system design. Despite advances in these areas, there are many challenges that still need to be addressed, especially on high bandwidth and energy efficient communication protocols, interoperability between BANs and other wireless technologies, and the design of successful applications.

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## References

1. Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E (2002) Wireless sensor networks: a survey. Comput Networks 38(4):393–422
2. Arvind DK, Bates A (2008) The speckled golfer. In: Proceedings of BodyNets 2008. Tempe, USA
3. Baker CR, Armijo K, Belka S, Benhabib M, Bhargava V et al (2007) Wireless sensor networks for home health care. In: International conference on advanced information networking and applications workshops, AINAW'07, pp 832–837
4. Barth A, Wilson S, Hanson M, Powell H, Unluer D, Lach J (2008) Body-coupled communication for body sensor networks. The 3rd international conference on body area networks (BodyNets). Tempe, Arizona
5. Bluecore. Available at: http://www.csr.com/bc7/
6. Body Sensor Networks. Available at: http://ubimon.doc.ic.ac.uk/bsn/m621.html
7. Cacioppo JT (2003) Introduction: emotion and health. In: Handbook of affective stress, 1st edn. Oxford University Press
8. Cao H, Chow C, Chan H, Leung V (2009) Enabling technologies for wireless body area networks: a survey and outlook. IEEE Wirel Commun Mag 47(12):84–93
9. Cao H, Gonzalez-Valenzuela S, Leung V (2010) Employing IEEE 802.15.4 for quality of service provisioning in wireless body area sensor networks. In: Proc. IEEE advanced information networking and application, AINA 2010. Perth, Australia
10. Cobb W (1983) Recommendation for the practice of clinical neurophysiology. Elsevier, Amsterdam
11. Corchado J, Bajo J, Tapia D, Abraham A (2010) Using heterogeneous wireless sensor networks in a telemonitoring system for healthcare. IEEE Trans Inf Technol Biomed 14(2):234–240
12. Curtis D, Shih, E, Waterman J, Guttag J, Bailey J et al (2008) Physiological signal monitoring in the waiting areas of an emergency room. In: Proceedings of BodyNets 2008. Tempe, Arizona, USA
13. Dam T, Langendoen K (2003) An adaptive energy-efficient mac protocol for wireless sensor networks. In: Proceedings of the first ACM SenSys conference, pp 171–180. Los Angeles, CA, USA
14. Dara C, Monetta L, Pell MD (2008) Vocal emotion processing in Parkinson's disease: reduced sensitivity to negative emotions. Brain Res 1188:100–111
15. El-Nasr M, Vasilakos A (2008) DigitalBeing—using the environment as an expressive medium for dance. Inf Sci 178: 663–678
16. Farella E, Pieracci A, Benini L, Rocchi L, Acquaviva A (2008) Interfacing human and computer with wireless body area sensor networks: the WiMoCA solution. Multimedia Tools and Applications 38(3):337–363
17. Felemban E, Lee C-G, Ekici E (2006) MMSPEED: multipath MultiiSPEED protocol for QoS guarantee of reliability and. Timeliness in wireless sensor networks. IEEE Trans Mob Comput 5(6)738–754
18. Fleury A, Vacher M, Noury N (2010) SVM-based multimodal classification of activities of daily living in health smart homes: sensors, algorithms and first experimental results. IEEE Trans Inf Technol Biomed 14(2):274–283
19. Gao T, Massey T, Selavo L, Crawford D, Chen B, Lorincz K, Shnayder V, Hauenstein L, Dabiri F, Jeng J, Chanmugam A, White D, Sarrafzadeh M, Welsh M (2007) The advanced health and disaster aid network: a light-weight wireless medical system for triage. IEEE Trans Biomed Circuits Syst 1(3):203–216
20. Ghasemzadeh H, Jafari R, Prabhakaran B (2010) A body sensor network with electromyogram and inertial sensors:

multi-modal interpretation of muscular activities. IEEE Trans Inf Technol Biomed 14(2):198–206
21. Gu H, Ji Q (2004) An automated face reader for fatigue detection. In: FGR, pp 111–116
22. Hall PS, Hao Y (2006) Antennas and propagation for body-centric wireless communications. Artech House Publishers, Boston
23. Healey JA, Picard RW (2005) Detecting stress during real-world driving tasks using physiological sensors. IEEE Trans Intell Transp Syst 6(2):156–166
24. Hoiydi A, Decotignie J, Enz C, Roux E (2003) WiseMAC: an ultra low power MAC protocol for the wisenet wireless sensor networks. In: Proceedings of the first ACM SenSys Conference. Los Angeles, CA
25. Hoyt, R.W (0000) SPARNET—Spartan sensor network to improve medical and situational awareness of foot soldiers during field training. Available at: http://mobisensors.cs.pitt.edu/files/papers/hoyt.pdf
26. IEEE 802.15 Task Group 6 (BSN). Available at: http://ieee802.org/15/pub/TG6.html
27. Jantunen I, Laine H, Huuskonen P, Trossen D, Ermolov V (2004) Smart sensor architecture for mobile-terminal-centric ambient intelligence. Sens Actuators A Phys 142(1): 352–360
28. Jiang S, Cao Y, Lyengar S, Kuryloski P, Jafari R, Xue Y, Bajcsy R, Wicker S (2008) CareNet: an integrated wireless sensor networking environment for remote healthcare. In: Proc. of international conference on body area networks. Tempe, Arizona
29. Kurs A, Karalis A, Moffatt R, Joannopoulos JD, Fisher P, Soljacic M (2007) Wireless power transfer via strongly coupled magnetic resonances. Science 317(5834):83–86
30. Lai C, Huang Y, Park J, Chao H (2010) Adaptive body posture analysis using collaborative multi-sensors for elderly falling detection. IEEE Intell Syst 25(2):20–30
31. Latr B, Braem B, Moerman I, Blondia C, Reusens E, Joseph W, Demeester P (2007) A low-delay protocol for multihop wireless body area networks. In: Proceedings of mobiquitous. Philadelphia, PA
32. Li H, Tan J (2005) An ultra-low-power medium access control protocol for body sensor network. In: Proceedings of IEEE-EMBS. Reading, UK
33. Li H, Tan J (2007) Heartbeat driven medium access control for body sensor networks. In: Proceedings of ACM SIGMOBILE international workshop on systems and networking support for healthcare and assisted living environments. San Juan, Puerto Rico
34. Milenkovic A, Otto C, Jovanov E (2006) Wireless sensor networks for personal health monitoring: issues and an implementation. Comput Commun 29(13–14):2521–2533
35. Omeni O (2008) A perspective of the BSN MAC. Internet draft, January 11, 2008
36. Patel M, Wang J (2010) Applications, challenges, and prospective in emerging body area networking technologies. IEEE Wirel Commun Mag 17(1):80–88
37. Pentland A (2004) Healthwear: medical technology becomes wearable. Computer 37(5):42–49
38. Picard RW (2001) Affective medicine: technology with emotional intelligence. In: Bushko RG (ed) Future of health technology. OIS
39. Polastre J, Hill J, Culler D (2004) Versatile low power media access for wireless sensor networks. In: Proceedings of the 2nd ACM SenSys conference, pp 95–107. Baltimore, MD, USA
40. Rajendran V, Obraczka K, Garcia-Luna-Aceves J (2003) Energyefficient, collision-free medium access control for wireless sensor networks. In: Proceedings of the first ACM SenSys conference, pp 181–193. Los Angeles, CA, USA
41. RFID. Available at: http://www.rfid.org/
42. Ruiz JA, Shimamoto S (2006) Novel communication services based on human body and environment interaction: applications inside trains and applications for handicapped people. In: Proc. of the IEEE wireless communications and networking conference, WCNC 2006. Las Vegas, Nevada
43. Saeed A, Faezipour M, Nourani M, Tamil LS (2009) Plug-and-play sensor node for body area networks. In: Proceedings of the IEEE-NIH life science systems and applications workshop, (LISSA'09), pp 104–107. Bethesda, Maryland, USA
44. Schwiebert L, Gupta SKS, Weinmann J (2001) Research challenges in wireless networks of biomedical sensors. In: Proc. ACM Mobicom'01. Rome, Italy
45. Sensor Node Wiki. Available at: http://en.wikipedia.org/wiki/Sensor_node
46. Sheltami T, Mahmoud A, Abu-Amara M (2006) Warning and monitoring medical system using sensor networks. In: The Saudi 18th national computer conference (NCC18), pp 63–68. Riyadh, Saudi Arabia
47. Shnayder V, Chen B, Lorincz K, Fulford-Jones TRF, Welsh M (2005) Sensor networks for medical care. Harvard University Technical Report TR-08-05
48. Smeaton AF, Diamond D et al (2008) Aggregating multiple body sensor for analysis in sports. In: International workshop on wearable micro and nanosystems for personalised health—pHealth. Valencia, Spain
49. Takeda K, Hansen JH, L, Erdogan H, Abut H (2009) In-vehicle corpus and signal processing for driver behavior. Springer
50. Takizawa K, Aoyagi T, Kohno R (2009) Channel modeling and performance evaluation of uwb-based wireless body area networks. In: Proc. of the IEEE international conference on communications, ICC 2009. Dresden, Germany
51. Taleb T, Bottazzi D, Nasser N (2010) A novel middleware solution to improve ubiquitous healthcare systems aided by affective information. IEEE Trans Inf Technol Biomed 14(2):335–349
52. Taparugssanagorn A, Rabbachin A, Hamalainen M, Saloranta J, Iinatti J (2008) A review of channel modelling for wireless body area network in wireless medical communications. In: The 11th international symposium on wireless personal multimedia communications. Saariselka, Finland
53. TinyOS for wireless embedded sensor networks. Available at: http://www.tinyos.net
54. US Bureau of the Census (2000) Population projections of the United States by age, sex, race and Hispanic origin: 1995–2050, Current Population Reports, P25-1130
55. Warren S, Jovanov E (2006) The need for rules of engagement applied to wireless body area networks. In: Proc. of the IEEE consumer communications and networking conference, CCNC 2006. Las Vegas, Nevada
56. WLAN Interference to IEEE802.15.4. Available at: z-wavealliance.org. Retrieved on 2007-11-22
57. Wood A, Virone G, Doan T, Cao Q, Selavo L, Wu Y, Fang L, He Z, Lin S, Stankovic J (2006) ALARM-NET: wireless sensor networks for assisted-living and residential monitoring. Technical Report CS-2006-11, Department of Computer Science, University of Virginia
58. Xu PJ, Zhang H, Tao XM (2008) Textile-structured electrodes for electrocardiogram. Text Prog 40(4):183–213
59. Yazdandoost K, Sayrafian-Pour K (2009) Channel model for body area network (BSN). Doc. # IEEE P802.15-08-0780-06-0006. Available online at http://mentor.ieee.org/802.15/

60. Ye W, Heidemann J (2005) SCP-MAC: reaching ultra-low duty cycles (poster). In: IEEE SECON'05. Santa Clara, CA, USA
61. Ye W, Heidemann J, Estrin D (2004) Medium access control with coordinated, adaptive sleeping for wireless sensor networks. IEEE/ACM Trans Netw 3(12):493–506
62. Younis M, Akkaya K et al (2004) On handling QoS traffic in wireless sensor networks. In: Proceedings of the 37th annual Hawaii international conference on system sciences. Hawaii
63. Yu J-Y, Liao W-C, Lee C-Y (2006) A MT-CDMA based wireless body area network for ubiquitous healthcare monitoring. In: Proc. IEEE biomedical circuits and systems conference, BioCAS 2006, pp 98–101
64. Zhang YP, Bin L, Qi C (2007) Characterization of on-human-body UWB radio propagation channel. Microw Opt Technol Lett 49(6):1365–1371
65. Zhang Z, Zhang JS (2006) Driver fatigue detection based intelligent vehicle control. In: Proceedings of the 18th IEEE international conference on pattern recognition, ICPR'06, pp 1262–1265. Washington, DC
66. Zhen B, Patel M, Lee S, Won E, Astrin A (2008) TG6 technical requirements document (TRD) IEEE P802.15-08-0644-09-0006. https://mentor.ieee.org/802.15
67. Zhou G, Liu J, Wan C, Yarvis M, Stankovic J (2008) BodyQoS: Adaptive and radio-agnostic QoS for body sensor networks. In: Proceedings of IEEE INFOCOM. Phoenix, USA
68. ZigBee Specification. Available at: http://www.zigbee.org. Retrieved on 2008-03-18
69. Zigbee Standard. Available at: http://www.digi.com/technology/rf-articles/wireless-zigbee.jsp