Body Area Networks

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Abstract Body area network (BAN) technology has emerged in recent years as a subcategory of wireless sensor network technology targeted at monitoring physiological and ambient conditions surrounding human beings and animals. However, BAN technology also introduces a number of challenges seldom seen before due to the scarcity of hardware and radio communication resources and the special properties of the radio environment under which they operate. In this chapter, we review the foundations of BANs along with the most relevant aspects relating to their design and deployment. We introduce current, state-of-the-art applications of BAN, as well as the most challenging aspects concerning their adoption and gradual deployment. We also discuss issues pertaining to sensor node communications, trade-offs, and interfacing with external infrastructure, in addition to important aspects relating to wearable sensor technology, enabling software and hardware, as well as future trends and open research issues in BANs.

Keywords Health care, Networks, Sensors, Wireless

Contents

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Abbreviations

BAN	Body area network
ECG	Electrocardiogram
EEG	Electroencephalography
EMG	Electromyography
MCU	Microcontroller unit
MEMS	Microelectromechanical systems
WSN	Wireless sensor network

1 Introduction

This section provides a preliminary description of the most important aspects relating to body area network (BAN) technology, including a brief overview of key BAN concepts and operation principles, a review of current state-of-the-art applications and research work on the subject, and a discussion on the most important limitations and technical hurdles of this technology.

1.1 Overview

BANs are commonly regarded as an enabling technology for a variety of applications, including health and fitness monitoring, emergency response and device control. Recent breakthroughs in solid-state electronics afford for the creation of low-power, low-profile devices that can be modularly interconnected in order to create so-called sensor nodes comprised of one or more sensor devices, a microcontroller unit (MCU), and a radio transceiver that eliminates the need for wires to communicate with the coordinator node in order to transfer the collected data. The coordinator node functions either as a gateway to transfer data to an

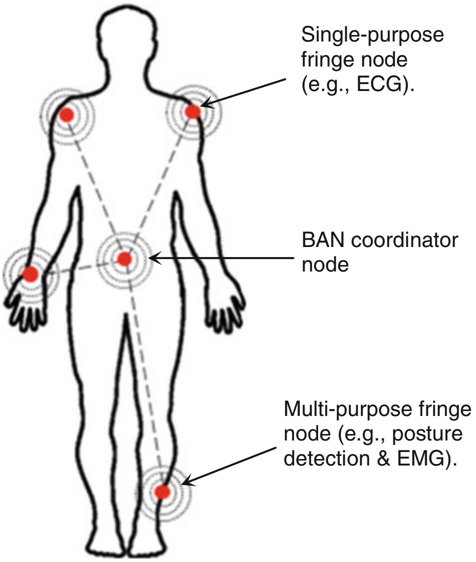

Fig. 1 Placement of BAN nodes

external electronic healthcare (eHealth) monitoring system or as a self-contained hub for local monitoring and control. In fact, some companies have recently introduced wireless MCUs to the open market. These newer devices are single-chip hardware solutions that provide a microcontroller and a radio transceiver in a single package requiring only a few external components, as explained later in this chapter. Given their huge potential to support distinct applications, BAN technology is at the beginning of what can be expected to develop into multi-million dollar industries over the next few years.

In their most basic form, sensor devices operate by preloading MCUs with program codes that access low-level hardware interfaces, which in turn obtain data from the actual sensor devices. Programs contain the necessary instructions for sensor devices to collect one or more readings in a particular time period. Raw sensor data can be subsequently processed in order to convert them to meaningful information that can be interpreted after transmission by the radio chip to an external device or system for further analysis. These sensor nodes are meant to be either worn around or implanted in the human body (or animals for that matter). Moreover, two or more sensor devices in the vicinity of each other can establish wireless links in order to coordinate their joint operations, thus creating a networked system. Therefore, the existing literature often refers to BANs as wireless BAN (WBAN) or wireless body area sensor network (WBASN). The rest of this section introduces some of the most relevant advances in BAN technology, followed by a description of important technical challenges that researchers are tackling in order to make BANs efficient, reliable and economical. Figure 1 illustrates the placement of BAN nodes on a person.

1.2 Practical Applications and State-of-the-Art

BANs enable untethered monitoring and control for a wide range of applications. BAN-based monitoring normally involves raw sensing and pre-processing of physiological signals that help estimate the health condition of a user or patient. On the other hand, BAN-based control applications are intended to serve as human–computer interfaces (HCI) based on inertial motion readings, which are subsequently fed and forwarded to another subsystem for interpretation. In turn, the user's motion is mapped to one or more outputs that control a device or a process. Both application categories and state-of-the-art advances and implementations are discussed next.

BANs facilitate ambulatory health monitoring by functioning as proxies to medical practitioners in order to conveniently obtain the latest physiological readings from users that are suffering from certain medical conditions [1]. A side result of this is that clinics and/or hospitals may become less overwhelmed by the sheer number of patients that otherwise have to have their regular check-ups on-site. Moreover, BANs enable the deployment of automated eHealth systems for diagnostic, alarm and emergency response, while streamlining the provision of emergency services. Added to this is the automated management of electronic patient record databases integrated into a single eHealth system. Nonetheless, a number of legal, ethical, and technical issues remain to be investigated, the latter of which is the matter of intense, state-of-the-art research.

A good example of an ambulatory system for health monitoring is the wearable health monitoring systems (WHMS) developed by researchers at the University of Alabama [2]. This investigation advances a larger-scale system for ambulatory, health-status monitoring and telemedicine. WHMS employs traditional WiFi wireless local area network (WLAN) technology and cellular networks to forward data from BANs to an external system, and facilitates data visualization and collection by using diverse types of devices, such as personal computers and smart phones. Medical practitioners can access patient data via the Internet, which also serves to issue alerts when a health-related anomaly is detected.

Hospital environments can also benefit from the deployment of BANs, as exemplified by the CodeBlue project at Harvard University [3]. CodeBlue targets hospital environments that can host several router nodes employing ZigBee radio technology, as explained later in this chapter. Their proposed system allows BAN users to connect to this network, whereby servers store all pertinent information in a database for on-demand dissemination.

The Disaster Aid Network (AID-N) is a system developed at Johns Hopkins University [4], which targets medical condition monitoring for emergency responders during mass casualty events. Similar to WHMS, AID-N employs WiFi and cellular networks to establish communications between personal, smart phone-based servers and the system's database servers. In addition to this, the system employs a web portal to facilitate the interactions between first-responders.

A BAN can be employed as an alternative input method to traditional computer interfaces (e.g., keyboards, joysticks, etc.) to control a device or a process according to the readings input by inertial motion sensors. To this end, BAN sensor devices capture and digitize human motion and gestures for immediate interpretation. Applications ranging from custom communication interfaces for disabled people and entertainment/gaming experience enhancements can be implemented.

Investigators in [5] propose a variety of ways in which BANs can be employed to assist people with distinct handicaps. To this end, so-called intra-body communication applications enable spatiotemporal navigation, text display in eyeglasses and closed-captioned audio broadcasts by embedding a variety of sensor types to different items worn by users. On the other hand, the MITHril project at Massachusetts Institute of Technology employs sensors that read physiological signals (e.g., electrocardiography, skin temperature, galvanic skin response) in a wearable computing scheme that interacts with WiFi and smart phones to enable intelligent context-awareness in the user's living space [6].

European investigators have also developed state-of-the-art platforms based on wearable sensor technology. For instance, the Microsystems Platform for Mobile Services and Applications (MIMOSA) project is a large research initiative that also promotes advances in ambient intelligence using BANs in conjunction with smart phones [7]. Furthermore, European advancements in this area also take place at the embedded device level (e.g., Bluetooth Low Energy technology). In another effort, a group of researchers in Italian universities have produced the Wireless Sensor Node for a Motion Capture System with Accelerometers (WiMoCA) [8], which implements a distributed gesture recognition system.

1.3 Principal Challenges

The widespread adoption of technology employing BANs still faces many technical hurdles, among which battery drain is a critical one. This problem requires attention from both the hardware and software fronts. On the hardware side, recent advances in solid-state electronics enable the production of MCUs and radio chips that consume electric currents in the nano-Ampere range when operated in low-power modes. However, when in active mode of operation, the power consumed by a radio chips depends significantly on the amount of data transmissions, radiated power and duty cycle. In the latter case, radio chips that transmit/receive at low data rates would expect to see an increased duty cycle in order to send/receive relatively large amounts of sensor data. This is where computer scientists and software engineers can help by creating efficient sensor data processing algorithms that reduce the amount of radio transmissions and save battery power. However, excessive data processing routines effectively shifts power consumption and active duty cycles from the radio chip to the MCUs, though the latter regularly consumes less power compared to the former. This circumstance normally warrants trade-off analysis for the particular application being developed. The next sections elaborate on each of these factors from a BAN perspective.

2 Supporting Technologies

This section introduces the latest radio-communications technology advancements that support rapid development and deployment of BAN platforms, specifically, the ZigBee/IEEE 802.15.4 standards, and Bluetooth Low Energy.

2.1 *ZigBee and IEEE 802.15.4*

ZigBee [9] and IEEE 802.15.4 [10] technology are two complementary technologies that provide a solid foundation and operation principles for implementing distinct BAN's applications. The latter is a standard covering the physical (PHY) and medium access control (MAC) layers targeting low-rate short-range radio-communications that is suitable for BAN nodes, while the former enhances the IEEE 802.15.4 standard by adding network and security layers and an application framework to enable the development of complete wireless sensor network (WSN) systems. Both of these standards were created with a low power consumption target in mind. The ZigBee standard incorporates a number of public application profiles that facilitate the deployment of systems with interoperable multi-vendor devices. For example, the ZigBee Smart Energy and Building Automation Profiles mainly target applications in the realm of smart energy use involving various types of appliances in the home environment, and building and industrial automation in the commercial environment, respectively. Recently, the ZigBee Health Care Profile has been put forward to meet Continua Health Alliance requirements in the realm of health and fitness monitoring. Because the ZigBee standard initially targeted machine-to-machine monitoring and control, most research projects stemming from academia solely employ IEEE 802.15.4-based hardware and their corresponding software interfaces, but not the ZigBee protocol stack. An additional disadvantage of the ZigBee/IEEE 802.15.4 duo is that it is set to operate in the 2.4 GHz industry, scientific and medical (ISM) band, which is already heavily congested with WLAN traffic. Moreover, studies have shown that radio transmissions over this band suffer significantly from highly variable path loss around the human body [9]. This, along with data-rate limitations, hinders the widespread adoption of ZigBee for the support of BAN applications.

2.2 *Bluetooth Low Energy*

Bluetooth technology was designed as a short range wireless communication standard that is widely used for connecting a variety of personal devices that enable data and voice communications. Bluetooth devices connect by forming a star-shaped network topology known as a piconet, which operates in the 2.4 GHz ISM band and accesses 79 channels through a frequency hopping mechanism. Driven by commercial interest, the Bluetooth Low Energy technology has emerged as a low-power solution to wirelessly connect small, resource-limited devices to mobile terminals, making it an ideal contender for implementing BAN-based applications [11]. Bluetooth Low Energy technology supports a data rate of up to 1 Mbps using fewer channels for pairing devices, thus greatly speeding up the device connection process. This is highly beneficial for latency-critical BAN applications in the realm of emergency response that also require power saving features. Bluetooth Low Energy technology employs a simplified protocol stack for short-range, star-topology networks that forgo the need for resource-consuming routing algorithms. The master device in the hub of the star-topology piconet most likely will employ a dual protocol stack that supports both Bluetooth Low Energy and conventional Bluetooth, enabling a BAN based on this technology to easily communicate with the outside world through more computationally powerful devices such as laptops, tablets, and smartphones.

2.3 Other Technologies

Even though ZigBee and Bluetooth Low Energy are currently the leading contenders for BAN communications, other proprietary technologies geared towards health and fitness monitoring are also available. For instance, ANT is a lightweight protocol stack created for sensor networks that require ultra-low power consumption. The ANT specification works over the 2.4 GHz ISM band and employs a time division multiple access (TDMA) MAC to communicate at a data rate of 1 Mbps. The ANT+ specification is backed by an alliance of more than 200 members, and supports sport, fitness and health product interoperability [12].

Similar to ANT, Sensium [13] also provides a proprietary platform for on-body health monitoring applications that require ultra-low power consumption. Sensium facilitates the creation of a wireless links to smart phones, thus favouring health monitoring applications at a low cost. Zarlink (now Microsemi) [14] produces proprietary radio transceiver chips suitable for implantable (and ingestible) medical devices (IMDs), which are designed for reliable, low-power wireless communications. The Zarlink transceiver supports a deep-sleep mode of operation at the core of its low-power consumption feature. Zarlink devices have been used successfully in the implementation of a camera capsule that can be swallowed in order to transmit images from inside the human body at two frames per second, thus enabling non-invasive inspection of the gastrointestinal tract.

3 BAN Hardware

Selection of an appropriate hardware platform is one of the most important aspects to consider during the inception of any BAN system. In particular, application-specific requirements unequivocally highlight battery consumption, form-factor (i.e., physical shape and packaging) and processing capabilities at the core of a

BAN's architecture design. In this section, we describe the most important characteristics and limitations of the sensor types commonly seen in BAN devices, as well as their data processing and communication features that fulfill the needs inherent to this type of networked system.

3.1 Sensor Types

Sensors turn BANs into useful systems with well-defined purposes. The objective of using sensors in or around the body is to collect signals corresponding either to physical activities or to physiological conditions of the user. In addition, the data they provide can be referenced to make assessments on the effectiveness of a drug and/or medication therapy. Sensors yield data in the form of analog or digitized signals that are fed to the sensor node's MCU for immediate processing. However, depending on the circumstances, some form of specialized pre-processing or filtering can also take place beforehand, either as part of an algorithm implemented in the MCU, or as part of an intermediate hardware component (though the former case has become prevalent). The following is a non-exhaustive list of common sensor types employed in BAN devices:

- *Inertial motion sensors*. Accelerometers and gyroscopes are by far the most common devices employed to estimate and monitor body posture and miscellaneous human motion patterns. This capability is indispensable for many types of applications, especially in the realm of health care, sports and console gaming. To this end, accelerometers measure gravitational pull and inclination, whereas gyroscopes measure angular displacement. In general, their combined use yields orientation information and diverse user motion patterns [15].
- *Bioelectrical sensors*. These particular types of sensors are employed to measure electrical variations over the user/patient's skin that can be directly or indirectly correlated with the current activity or condition of a body organ. Electrocardiography (ECG) sensors are typical examples of these, which usually take on the form of circular pads that are strategically placed around the human torso and extremities to monitor heart activity [16]. Similarly, electromyography (EMG) sensors are placed over the skin to measure the electrical activity of skeletal muscles in order to help in the diagnosis of nerve and muscle disorders.
- *Electrochemical sensors*. These types of sensors generate an electrical output driven by a small chemical reaction between the sensor's chemical agent and bodily substance. A good example is the blood glucose sensor, which measures the amount of glucose in the blood stream. Another example is the monitoring of carbon dioxide concentration levels in human respiration.
- *Optical sensors*. Devices that emit and receive light in both the visible and the infrared light bands are commonly employed in the non-invasive measurement of oxygen saturation in blood circulating in the human body. To this end, a pulse oximeter measures the degree of light absorption as light passes through the user/patient's blood vessels and arteries.

- *Temperature sensors*. This popular sensor type is placed over the skin at various places around the human body to measure the body temperature and is routinely employed during physiological assessment of patients.

3.2 Wearable Sensor Devices

Compact sensors employed in BAN devices need to be in direct contact with the user or patient in order to obtain the desired readings. However, realizing small devices that are amenable to everyday monitoring had proven an elusive goal through the years. It was until recently that noteworthy advancements in field of solid-state electronics fabrication enabled the design and fabrication of devices with such characteristic. In particular, microelectromechanical systems (MEMS) technology plays a crucial role towards implementing effective and efficient wearable sensor devices aimed at physiological and bio-kinetic user monitoring that may not necessarily be bounded to life-critical requirements. This has the added potential to reducing medical services and health-care cost by enabling users or patients to reduce their dependence on direct monitoring at medical facilities.

The latest MEMS-based sensors and actuator devices targeted at bio-monitoring applications (Bio-MEMS) [17] implement components in the 1–100 μm range, and their effectiveness have had significant impact in the adoption of wearable accelerometers and gyroscopes for diverse types of motion sensing applications, as described in the previous sub-section. Moreover, the reliability of Bio-MEMS spurred their application diversification into the realm of automated drug delivery systems [18]. Such delicate manoeuvre is possible by endowing Bio-MEMS with tiny spikes on silicon or polymers, whereby liquid drug is administered in a controlled fashion through the user/patient's epidermis as specified by a primary device (e.g., an MCU).

Wearable sensors also come in different types and shapes. Those employed for ECG monitoring are a good example [19]. They employ electrodes traditionally made of silver chloride (AgCl) adhered to the various parts of the torso. However, their prolonged usage leads to defective skin contact and other problems. One solution promotes using electrodes embedded into textile fabrics that can be worn as regular clothing garments [20]. This alternative eliminates problems with skin contacts to a good extent and is a more comfortable and convenient one for the users. Also, compared to AgCl-based electrodes, they are more flexible and thus better suited to human motion. Consequently, a similar kind of electrodes can also be employed for electroencephalography (EEG) and EMG monitoring systems [21].

3.3 Implantable Sensor Devices

Some types of sensor devices can be implanted in the human body, though this practice is often considered less desirable because of the associated risks to patients, including: (1) the natural rejection of the body towards extraneous objects and (2) the risk of sensor malfunctioning due to either a body-induced chemical reaction or external factors. Because of this, their size and bio-compatibility to human tissue become properties of foremost importance. Additionally, implantable sensors have to reliably and effectively deal with aspects pertaining to antenna design for efficient signal propagation, ultra-low-power consumption for long-lasting operation, and recovery from unexpected errors due to faulty software (firmware) if applicable [22].

Typical examples of applications driven by sensor/actuator implants include cardiac pacemakers and defibrillators, as well as neuromuscular stimulators. These devices are expected to provide absolute reliability and responsiveness when compared to their wearable counterpart in order to immediately respond to the life-critical triggering event for which they were designed. Once again, miniaturization technologies allow for the design of these devices with a higher degree of flexibility that enables their adaptation to the prevailing circumstances. Consequently, these devices have evolved so as to allow not only remote monitoring but also remote programming through wireless communications. This means that a pacemaker can be programmed by a cardiologist not only to select an appropriate set of heart pacing parameters, but also to regularly upload monitoring data to a server for remote diagnosis [23]. In this case, a typical implantable device should generate or consume a negligible amount of data communications traffic when wirelessly connected in order to prolong the lifetime of the power source. While the power source is often assumed to be a battery, this is not always the case. For instance, low-frequency electromagnetic induction has been employed for powering implantable electronics for many years [24], though recent advances in low-power electronics have sparked a renewed interest in this long-standing technology.

Another important aspect in the deployment of implantable BAN devices is antenna design and radio frequency considerations, where transmission power loss due to tissue absorption becomes the main concern. Among the different ISM frequency bands, studies reported in [22] indicate the 900 MHz band to be the most favourable for radio signal propagation within the human body, though other studies provide a strong incentive to exploring competitive alternatives. For instance, researchers in [25] have suggested that employing micro-strip patch antennas is an effective solution for devices operating in the 402–405 MHz band. A caveat here is the fact that cardiac pacing devices possessing wireless interfaces for external communications with other devices are highly prone to electromagnetic interference from multiple sources. For instance, studies in [26] report that the now pervasive devices employed for a myriad of radio frequency identification (RFID)-based applications may interfere with commercially available pacemakers. This and similar findings clearly warrant development and extensive evaluations of interference mitigation techniques that are amenable to low-power, resource-limited embedded MCUs. Additional provisions to be considered for the case of wearable sensors also appear in Sect. 4.1.

Since MCU miniaturization affords greater flexibility in the operation of implantable sensor devices, it becomes evident that software security and reliability too becomes of paramount importance. Thus, firmware development for life-critical applications must undergo a battery of tests like no other given the implications that any malfunction may have. In this case, exhaustive analysis of performance and failure recovery scenarios must be performed to ensure proper operation of the host sensor device. In addition, extra-efforts should not be spared in order to facilitate code maintainability and avoid superfluous complexity. This can be achieved by employing platforms that enable higher-level software/firmware programming, contrary to implementations based purely on assembly code [27]. Similarly, effective tamper protection features must be available at all times in order to prevent access from unauthorized individuals. For example, firmware may be skilfully modified to conceal anomalous device operation, which may manifest not necessarily in the form of a blatant system malfunction, but perhaps in the form of a power-hungry device whose original algorithms were replaced to explicitly drain the battery faster. A life-threatening malfunction of this type may thus only be solved by resorting to an emergency surgical procedure as per the nature of implanted devices.

It is worth mentioning that in vivo, sensor-based monitoring may not necessarily take place in the form of implantable devices. For instance, based on recent advances in image sensing and multimedia technology, researchers have made it possible to encapsulate a video cameras into pills that can be swallowed in order to examine areas along the digestive track that were difficult to reach by means of traditional medical devices [22]. To this end, high definition video can now be recorded or transmitted to an on-body receiver for live monitoring from a pill. Therefore, this type of device need not be semi-permanently implanted in the body, instead residing in vivo only temporarily. Device localization mechanisms thus need to be investigated to pinpoint abnormalities in the human body with as much accuracy as possible. Other applications that also rely on sensor implants, such as brain–computer interfaces are too being aggressively investigated.

3.4 Data Processing and Communications Devices

MCU selection for health-care monitoring applications is an important aspect of wearable sensor node’s design. Most contemporary MCUs are actually evolved versions of microprocessors that were highly popular during the 1980s. Nonetheless, these MCUs are by far more compact, energy efficient, and affordable in large quantities (e.g., well within the range of US$2–5 per unit), thus becoming attractive choices for data and signal processing of physiological signals that wearable sensors capture [28]. Texas Instrument’s MSP430 and Atmel’s AVR MCU families are good examples of popular MCUs for mixed signal processing at the time of this writing. They provide 8-, 16-, and 32-bit architectures to meet the needs of most BAN applications and are specifically designed to reduce power consumption in order to prolong battery life. However, although the battery life is commonly publicized as lasting up to 5–10 years, in reality the actual battery lifetime of

BAN sensor nodes depends on many factors including: sensor data sampling rate, algorithm complexity (for data processing), duty cycle, number of erasure cycles, etc. However, a careful design should consider the low-power consumption features of these MCUs in order to prolong the BAN's continuous operation without battery replacement. This is particularly important in order to build low-profile devices using button-cell batteries that typically have an energy capacity between 500 and 1,000 mAh.

Sensor-class chips for low data rate wireless communications have also come a long way from earlier designs, and their selection is just as important in a good BAN device design. Transceiver chips (also available for US$2–5 per unit for large quantities) routinely support data rates in the 250 Kbps to 2 Mbps range while supporting deep-sleep modes that draw a few nano-Amperes, such as those available in the CC24xx family by Texas Instruments, the nRF24xx family by Nordic Semiconductor, and the AT86RFxx family by Atmel. Similar to their MCU companions, radio transceivers' duty cycle needs careful management in order to make the most of their energy-saving features. Moreover, efficient antenna design becomes of foremost importance in order to maximize effective radiated power from the transceiver, which in turn reduces unnecessary energy expenditure, as well as the number of retransmissions due to lost data packets in the wireless medium.

In addition to the above, we note that recent advances in solid-state devices have enabled the emergence of single-chip wireless MCUs—devices that incorporate both the MCU and the radio transceiver in a single package (e.g., Atmel's ATmega128RFA1). BAN designers and engineers can benefit from this for various reasons. A single-chip solution yields a smaller board footprint, thus improving form factor. Also, sensor node production is simpler and cheaper because of the reduced space. At the firmware level, programs also become simpler because direct register read/write routines replace inter-chip communications interfaces that are necessary to handle call-backs driven by interrupt signals, which leads to smaller memory requirements and faster processing. Finally, duty-cycling and power management routines need to target only a single chip, instead of two.

4 System Architecture of BANs

4.1 Physical Layer

The lowest layer in a BAN's communication stack is PHY, which defines the mechanisms of transmitting raw information bits by a transmitter over a wireless medium and the reception of these information bits at a receiver. A number of frequency bands have been investigated for communications between nodes deployed in or around the human body. Whereas the 402–405 MHz Medical Implant Communications Service (MICS) band seems favourable for implanted sensors, the 13.5 MHz, 400 MHz, 900 MHz, 2.4 GHz (the ISM bands) and 3.1–10.6 GHz [the licence-free ultra-wide band (UWB)] seem best suited for on-body sensors. In general, radio signal propagation is more likely to diffract around the human body rather than to pass through it. Consequently, path loss is much higher when the transmitting and receiving nodes are placed on different sides of the body than when they are on the same side of the body [29]. Moreover, a dynamic propagation environment caused by body movements and multipath fading further complicates the empirical validation of channel models [30]. For the 2.4 GHz ISM band, the Ricean distribution and the exponential decay pattern can be used to describe the small-scale fading and path loss models around the perimeter of the body, respectively. For the on-body channel, a radio signal in the 13.5 MHz ISM band (about 21 kHz wide) exhibits a path loss that is nearly similar to free space. The high variability of these results underlines the need for careful consideration of body sensor placement when architecting a BAN application with a specific purpose [31].

One radio technology that promises to significantly support BAN applications is UWB. Some recent research on using UWB for in-body communications can be found in [32, 33]. UWB operates in the licence-free, 3.1–10.6 GHz band possessing relatively low power spectral density emission, making it suitable for short-range communications at data rates of up to 480 Mbps. Hospital environments would greatly benefit from this feature, given that radio interference to medical equipment is highly undesirable. The newly created IEEE 802.15.6 standard specifically crafted for BANs will be a prime target for using UWB technology. Nonetheless, commercial products and radio transceiver chips that implement UWB are currently unavailable.

4.2 Medium Access Control Layer

In a BAN, the nodes usually share a common wireless channel for data transmissions. Access to the shared channel is controlled by a common MAC employed by all the nodes in the BAN.

In general MAC protocols can be classified into two main categories, namely: schedule-based and contention-based. In schedule-based MAC protocols, a coordinator ensures multiple nodes' fairly access to a commonly shared wireless medium. To avoid packet collision, the coordinator regulates the nodes' channel access by assigning different time slots, frequency bands, or spreading code (e.g., [34]). For instance, with beacon-enabled mode in the IEEE 802.15.4 standard, a personal area network (PAN) coordinator allocates time slots to multiple nodes in the contention free period (CFP), so that the nodes can access the channel in a scheduled manner to avoid collisions. In contention-based MAC protocols, multiple nodes determine which, when, and how to access the channel in a distributed manner by employing predefined channel-sharing mechanisms. For instance, the IEEE 802.15.4 standard employs the carrier sense multiple access with collision avoidance (CSMA/CA) mechanism in the contention access period. In fact CSMA/CA is the most prevailing MAC protocol as it is the basic access method employed by IEEE 802.11 WLANs. Compared with schedule-based MAC protocols, contention-based MAC protocols are often more feasible in most of WSN applications due to their distributed nature and scalability. However, a BAN operating in the beacon-enabled mode allows its devices to enter the sleep state whenever possible, instead of keeping their respective receivers continuously active, thus enabling an energy conservation feature [35, 36].

Due to the very limited battery capacity of typical body sensors, energy-efficient MAC protocols will play an important role in reducing energy consumption and prolonging the overall network's lifetime. To this end, a number of energy-efficient MAC protocols for WSN nodes have been proposed in order to reduce battery consumption when operating in the idle listening mode. In these protocols (e.g., S-MAC [37] and T-MAC [38]), nodes switch on their radios only when they have packets to exchange and otherwise switch off the radios during idle periods. B-MAC [39] and wiseMAC [40] use long preambles to ensure that the receiver stays awake to catch the actual packets, and employ low-power listening (LPL) approaches to reduce the power consumption in the preamble sampling period. In TRaffic-Adaptive Medium Access (TRAMA) [41], nodes synchronize their transmission schedules to avoid packet collision, and switch to low power mode when there are no data packets destined to those nodes. In Low-Energy Adaptive Clustering Hierarchy (LEACH) [42], nodes are grouped into a number of clusters and controlled by the elected cluster-heads (CHs). In each cluster, the CH coordinates the communications among its members by employing a TDMA scheme. Members wait for their allocated time slots to send data to the CH if they have packets to send. The rest of the time they power down their radio to conserve energy. To achieve balanced energy consumption, nodes randomly swap their member or CH roles. In addition to the above, several MAC protocols have also been proposed specifically for BANs:

- Controlling Access with Distributed slot Assignment (CICADA) [43] is a low-energy protocol designed for wireless, multi-hop, mobile BANs. CICADA has been developed to support high-traffic BANs with short delays (i.e., all sensors send data frequently instead of buffering them locally).
- BAN–MAC [44] 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. 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.
- Hybrid MAC (H-MAC) [45] is a TDMA-based MAC protocol designed for BANs, which aims to improve energy efficiency by exploiting heartbeat rhythm information to perform time synchronization. Biosensors in a BAN can extract the heartbeat rhythm from their own sensory data through ECG wave-peak detection. Following the naturally synchronized rhythm, biosensors can achieve time synchronization without the need to receive periodic timing information from a central coordinator and thus reduce energy costs ascribed to time synchronization tasks.

In addition to energy efficiency, it is highly desirable to support quality of service (QoS) needs in BANs in order to set minimum acceptable limits on reliability, latency and bandwidth. This circumstance calls for trade-off analyses between: (1) throughput/delay and energy efficiency in order to leverage power consumption through adaptive adjustment of duty cycles and (2) data type priorities and scheduling performance in order to provide service differentiation and scheduling strategy that meets the real-time demands of sensors that output time-sensitive readings (e.g. ECG). To this end, an effective design that takes in to consideration sensor heterogeneity remains a significant challenge.

4.3 Network Layer Protocols and Topology

The network layer protocol is responsible for effective and efficient packet delivery from a source node to a destination node, often through a number of intermediate nodes. The main tasks of a network layer protocol are route finding, route establishment and route maintenance. Two routing protocols are supported in ZigBee's network layer. One is the Ad hoc On-demand Distance Vector (AODV) protocol, which discovers and establishes routes only when they are needed; and the other protocol is the Hierarchical Routing Algorithm (HERA), which is a tree-based routing scheme based on a hierarchical structure established among nodes during the network formation phase. There are also a number of routing protocols specially designed for energy-constrained WSNs:

- Sensor Protocols for Information via Negotiation (SPIN) [46]: Nodes use meta-data to describe the actual sensor information, and use two control messages: ADV and REQ, both of which contain meta-data for negotiation. A source node broadcasts the ADV message to advertise its data, and the interested node replies with the REQ message to request for the data so that the source node can send the DATA message containing actual sensor data to the interested node. It is thus based on a polling scheme.
- Threshold sensitive Energy Efficient sensor Network (TEEN) [47]: Based on a hierarchical clustering scheme, TEEN is a reactive, event-driven protocol for time-critical applications. In TEEN, a node senses the environment continuously, but the node turns on its radio and transmits only when: (1) the current sensed value is greater than a hard threshold; and (2) the value difference is equal to or greater than a soft threshold. The values of the hard and soft thresholds are determined at the CHs.

4.4 Middleware and Operating Systems

An operating system (OS) is the most important piece of software that runs in WSN nodes. The OS manages hardware resources and provides common services for efficient execution of various user application programs. The main functions of an OS are as follows.

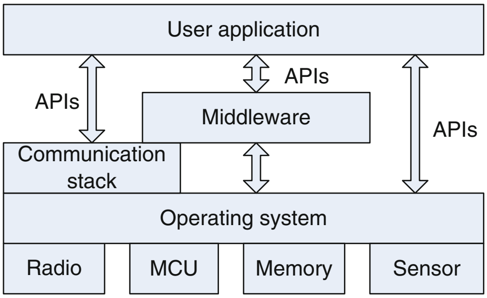

Fig. 2 A generic architecture of a BAN node

- Manages multiple processes and provides concurrency support.
- Manipulates communication devices, sensors, memory, and other peripheral devices.
- Facilitates the efficient development of software applications by providing convenient and safe abstraction of hardware resources.

Figure 2 illustrates a generic architecture of a node in a BAN. The OS manages the node's hardware resources, e.g., radios, sensors, timers, memory, and other peripheral devices, while providing an abstraction of system resources and application programming interfaces (APIs). Some advanced OS can provide a concurrency mechanism that allows multi-tasking and multi-threaded programming. The middleware subsystem resides between the user application and the OS, and is often service-oriented. Middleware modules often span communication, localization, QoS, and data management modules that provide the corresponding services for user applications.

In a BAN, the communication stack is often a simplified version of the ISO Seven-Layer Open Systems Interconnection Model (ISO OSI 7-Layer Model), and typically consists of a PHY layer, a MAC layer and a network layer. Each of the layers plays an important role in the communication link establishment, communication medium sharing and route discovery and management. BAN nodes connect via short-range wireless links by following a set of communication protocols, e.g., a routing protocol allows the nodes to form an interconnected network and to route data packets through multi-hop routes.

Compared with a general-purpose OS, the OS for a WSN is typically lightweight and less complex, as sensor nodes are often severely resource-constrained in terms of computing power, memory and power supply. A sensor node's OS should be flexible enough to facilitate being ported to devices produced by distinct hardware vendors without having to put much effort in rewriting the OS kernel and device drivers. Significant work has been done in developing OS for WSNs, as discussed in this sub-section.

TinyOS [48] is probably the earliest OS targeting WSNs with specific applications and resource constraints in mind. TinyOS is an event-driven, component-based OS. It is comprised by a number of small software components that perform well-defined tasks, and which are connected to each other through interfaces (e.g., commands and events). The components interact with each other by employing asynchronous communications and events. TinyOS programs are created using the nesC [48] language, which is a C language variant that adds additional features.

Contiki [49] is an open source, multi-tasking OS specially targeting memory-constrained WSNs. The kernel of Contiki is event-driven, but the system also supports pre-emptive multi-threading. The Contiki system consists of two parts: the core and the loaded program. The core consists of the Contiki OS kernel, the program loader, the language run-time, and the communication stack with device drivers for communication devices. The kernel consists of a lightweight event scheduler that dispatches events to running processes and periodically calls the processes' polling handlers. Programs are loaded into the system by the program loader. In Contiki, a process may be either a user application program or a system service, which is a process that implements functionality that can be used by other processes. Typical services include communication protocol stacks, sensor device drivers, and high-level functionality, such as sensor data processing algorithms. Application programs in Contiki are written in C language and the programs can be dynamically loaded and unloaded at run time.

ScatterWeb [50] is a simple and lightweight WSN OS. A ScatterWeb program consists of two parts: firmware, and application program. The firmware is responsible for the hardware initialization, management, and the communications with the application program. The application program defines a node's behaviour and is user-specific.

MANTIS (MOS) [51] is multi-threaded OS that supports a pre-emptive model for task management. For instance, a short-lived, time-sensitive task (e.g., processing incoming packets) can pre-empt a long-lived, time-consuming complex task, such as data compression and encryption that can block the execution of other processes. MANTIS is implemented in the C language and provides a set of APIs for developers.

T-kernel [52] is an OS which mainly aims to improve the reliability of WSNs and to facilitate developing complex software. T-kernel supports three advanced OS features: OS protection, virtual memory, and pre-emptive scheduling by employing a load-time modification approach. That is, the kernel modifies the necessary native instructions when it loads the application's instructions and dispatches them for execution. By doing so, the modified program guarantees OS control against possibly faulty application codes, performs pre-emption, and supports virtual memory management. With the features, the T-kernel raises the system abstraction level that is visible to application programmers.

LiteOS [53] maps a WSN into a UNIX-like file system and provides Unix-like abstractions to WSNs. The overall architecture of LiteOS is partitioned into three subsystems: LiteShell, LiteFS, and the LiteOS kernel. The LiteShell subsystem, which is often implemented in a WSNs base station, interacts with nodes only when the nodes are present. The LiteOS kernel not only employs the thread-based approach but it also allows user applications to handle events using call-back functions for system efficiency. Both priority-based scheduling and round-robin scheduling are supported in the kernel. LiteOS also supports dynamic loading and unloading of user applications, as well as a set of system calls for the separation between the kernel and applications.

5 Conclusion

In this chapter, we have reviewed a broad range of topics concerning BANs. BANs are formed by devices that possess unique features and work together to enable well-defined applications. In particular, BAN devices (sensors/actuators) have the distinct feature of operating in close proximity to the human body, and can even be embedded into it in order to provide a physiological monitoring service. Although BANs are expected to play an important role in many aspects of everyday life, as of today, deployment of this type of network is rather limited. This can be explained by pending issues of technology advancement, legal and ethic aspects, and user acceptance. We summarize these issues from the perspective of feasibility.

Technology advancement. The goal of BAN technology is to enable wearable devices with ubiquitous connectivity and seamless usability. Outstanding achievements have been accomplished on sensor functionalities, device form factor, software and communication protocols, and human–computer interface. However, hardware limitations still hinder fundamental advancements at the physical material's level, which limits BAN deployment.

Legal and ethic issues. On the one hand, a lengthy regulatory approval process adversely delays immediate application of advanced BAN technologies. This is particularly true in the case of medical equipment, which can take years to approve and licence, thus hindering a rapid adoption. On the other hand, without adequate legal and ethic protection, BAN users' health, privacy and financial resources may be put at risk.

Human-friendly devices. "Human-friendly" approaches require various technology advancements. First of all, physical materials of BAN devices have to be compatible with human physiology. Then, electromagnetic radiation of the radios employed should not have any adverse effects on human tissue and organs (e.g., heating). In addition, the form factor of a device must strictly adhere to the application's requirements. Furthermore, a user-friendly computer interface and lasting power supply will always play important roles in providing an acceptable user experience.

Application-specific protocols. From a technical perspective, BAN protocol design is always subject to a variety of trade-offs. At the PHY layer, it is challenging to attain suitable network coverage at the highest data rate but with the lowest power consumption. For consumer applications, enhanced robustness is required for BAN to overcome the intrinsic difficulties of operating in the already crowded ISM band. For life-critical applications, however, researchers are considering employing radio bands restricted to medical systems while looking for alternative solutions, such as UWB radios. In the middle layers, design trade-offs occur between reliability, latency and energy consumption. In order to design protocols that best fit a BAN application, researchers need to translate specific application requirements and restrictions (e.g., type of data, deployment setting and security) into middle-layer and physical-layer trade-offs, in order to engineer a suitable solution for that application. From a standardization perspective, interoperability is the top priority. For BANs, communication between BAN devices is not the only task; coexistence and interoperability between BANs and existing systems have to be guaranteed. The IEEE 802.15.6 Task Group is an example of a standardization body working to solve this issue.

Novel applications. But not least, novel applications are the driving force for the advancements of BAN technologies. A novel application can be one that utilizes the outcome of these enabling technologies, or one that helps to bridge the gap between existing and human-friendly schemes. Possible examples of these are: (a) using human skin as the signal propagation channel, (b) embedding camera and radio devices into a capsule for medical examination, and (c) supplying energy to a BAN device remotely through another BAN device.

With these issues being addressed by ongoing research efforts, we foresee a bright future for BANs being widely deployed around us.

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