Body area networks (BAN)

Sergio González-Valenzuela[1], Xuedong Liang[1], Huasong Cao[1], Min Chen[2], Victor C. M. Leung[1]

Abstract Body Area Network (BAN) technology 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 communications resources 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 to their adoption and gradual deployment. We also discuss issues pertaining to sensor node communications, tradeoffs, 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 Wireless · Sensors · Networks · Healthcare

---

[1] Sergio González-Valenzuela, Xuedong Liang, Huasong Cao, Victor C. M. Leung (✉)
Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, Canada
email: vleung@ece.ubc.ca

[2] Min Chen
School of Computer Science and Technology, Huazhong University of Science and Technology, Wuhan, China

Contents

Abbreviations

BAN	Body Area Network
ECG	Electrocardiogram
EEG	Electroencephalography
EEM	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 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, an MCU, and a radio transceiver that eliminates the need for wires to communicate with the node in order to transfer the collected data. In fact, some companies recently introduced wireless MCUs to the open market. These newer devices are merely 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, BANs are merely at the beginning of what can be easily expected to develop into multimillion dollar industries over the next few years.

In their most basic form, sensor devices operate by preloading MCUs with binary programs 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 it to meaningful information that can be interpreted after it has been transmitted by the radio chip to an external device or system for further analysis. As their name implies, 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 their immediate vicinity can establish wireless links in order to coordinate their joint operation, 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 must tackle in order to make BANs efficient, reliable and economical.

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, control applications are intended to serve as human-computer interfaces (HCI) that capture inertial motion readings, which are subsequently fed and interpreter 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 as well as state-of-the-art advances and practical 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/patients that suffer from a medical condition [1]. A side result of this is that clinics and/or hospitals are less overwhelmed by the sheer number of patients paying visits to have their regular check-ups. Moreover, BANs enable the deployment of automated 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 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 work.

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 wireless LAN 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 developed 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 database servers store all pertinent information for on-demand dissemination.

The Disaster Aid Network (AID-N) is another system developed at Johns Hopkins University [4] that targets medical condition monitoring for emergency responders during mass casualty events. Similarly to WHMS, AID-N employs Wi-Fi 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 communications scheme 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 developed at MIT employs sensors that read physiological signals (e.g., electrocardiography, skin temperature, galvanic skin response), to deploy 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 also spearhead 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]. Nonetheless, 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, from 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 BANs applications. The former is an application layer standard that defines interfaces and interactions between high-level components for WSN deployment, whereas the latter is a Physical- and MAC-layer standard. Both of these standards were created with a low power consumption target in mind. The ZigBee standard mainly targets applications in the realm of smart energy use in various types of applicances, as well as home, building and industrial automation. However, ZigBee Health Care framework vision has recently been put forward to meet Continua Health Alliance requirements in the realm of health and fitness monitoring. Because the Zigbee standard was initially targeted to machine-to-machine communications and control, it is easy to see that 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 band, which is considered to be already congested with WLAN traffic. Moreover, studies have shown that radio transmission 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 piconet, which operates in the 2.4 GHz band

and accesses 79 channels through a frequency hopping mechanism. Driven by commercial interest, the Bluetooth Low Energy technology emerged low-power advancement 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 that employs fewer channels for pairing devices, 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 will probably resort to a simpler protocol stack for short-range, star-topology networks that forgo the need for resource-consuming routing algorithms.

2.3 Other technologies

Even though Zigbee and Bluetooth Low Energy are currently the leading contenders for BAN-based applications, other proprietary technologies geared towards health and fitness monitoring are too available. For instance, ANT is a light-weight protocol stack created for sensor networks that require ultra-low power consumption. The ANT specification works over devices operating the 2.4 GHz band and employs the TDMA medium access mechanism to communicate at a data rate of 1Mbps. 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] too 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 [14] advances a proprietary device in the form of an Implantable Medical Device (IMD), which includes an ultra low-power RF transmitter implementing a radio scheme that favours reliable, low-power wireless communications. The Zarlink transceiver too supports a deep-sleep mode of operation at the core of its low-power consumption feature. Zarlink's device has 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 2 frames-per-second, thus enabling non-invasive inspection of the gastrointestinal tract.

3 BAN Hardware

Hardware selection of is one of the most important aspects to consider during the inception of any BAN-based system. In particular, application-specific requirements unequivocally highlight battery consumption, form-factor (i.e., physical shape) 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 communications 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's node 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*. In this category, 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 healthcare, 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 to the current activity or condition of a body organ. Electrocardiographic 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 (ECG) [16]. Similar types of sensors placed over the skin are employed to measure the electrical activity of skeletal muscles (EMG) 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 of example is the blood glucose sensor, which measures the amount of glucose circulating in the blood. Another example is the monitoring of carbon dioxide (CO_2) 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 in various places around the human body, and is routinely employed during physiological assessment of patients.

3.2 Wearable and implantable devices: limitations and constraints

Sensors employed in BAN devices need to be in direct contact with the user or patient, but some of them can even be implanted in the human body. In such case, their size and bio-compatibility to human tissue becomes of crucial importance. Nonetheless, the latter choice poses risks to the patient for obvious reasons, and is avoided when possible. In either case, a compact device design is of foremost importance. For this reason, recent advances in circuit design and MEMS technology play a crucial role towards reducing the need to implant body sensor devices. Moreover, small, wearable devices for physiological and bio-kinetic user monitoring can significantly reduce medical services and healthcare cost by enabling users or patients to reduce their dependence on dedicated monitoring at medical facilities.

The latest MEMS-based sensors and actuator devices targeted at bio-monitoring applications (Bio-MEMS) implement components in the 1-100 micrometer 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. 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 [17]. 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. This alternative eliminates skin problems 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 too be employed for EEG and EMG monitoring systems.

3.3 Data processing and communications devices

MCU selection for healthcare monitoring applications is an important aspect of wearable sensor nodes 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 $2 to $5 US range), thus becoming attractive choices for data and signal processing of physiological signals that wearable sensors capture [18]. 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 latter is commonly publicized as spanning a 5-10 year life, 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 afford between 500 and 1000 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 in the $2 to $5 US range for large quantities) routinely support data rates in the 250Kbps to 2Mbps 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 battery 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 accommodate 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 physical layer, often termed as PHY, is the lowest layer in a BAN's communication stack. The Physical layer defines the mechanisms of transmitting raw information bits over a wireless medium and provides a peer-to-peer communication link for two communicating nodes. A number of frequency bands have been investigated for communications between nodes deployed in or around the human body. Whereas the 402-405 Hz range seems favourable for implanted sensors, the 13.5MHz, 5-50 MHz, 400 MHz, 600MHz, 900 MHz, 2.4 GHz and 3.1-10.6 GHz 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. In addition, path loss increases when the transmitting and receiving antennas are placed at different sides of the body than when they are on the same side of the body [19]. Moreover, a dynamic environment, body movements and multipath fading further complicate the empirical validation of channel models [20]. For instance, in-body channel exhibits a path loss between 35 dB and 40 dB with a standard deviation between 8 dB and 9 dB, while the in-to-on-body surface channels exhibit a path loss between 47 dB and 49 dB with a standard deviation between 7 dB and 8 dB. For the on-body channel, a channel in the 13.5 MHz 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 [21].

One radio technology that promises to significantly support BAN applications is Ultra-Wide Band (UWB). UWB operates in the license-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

The data link layer resides at the top of the physical layer, and can be subcategorized in the logical link control (LLC) and medium access control (MAC) sublayers. The data link layer protocol provides a reliable communication link between two transceivers and is in charge of:

- Framing bit sequences into packets.
- Error control to ensure packets' delivery to their destination without error.
- Flow control of packets' transmission between two nodes.
- Channel access control to a commonly-shared medium.

Most MAC layer 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 by transmission code spreading (e.g., [22]). For instance, in the IEEE 802.15.4 standard with beacon-enabled mode, 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 carrier sense multiple access with collision avoidance (CSMA/CA) mechanism is the most prevailing MAC protocol, and is supported in most of the commercially-available nodes. 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 [23], [24].

To reduce energy consumption and prolong the overall network's lifetime, a number of energy-efficient MAC protocols have been proposed for WSN nodes when operating in the idle listening mode. In these protocols (e.g., S-MAC [25] and T-MAC [26]), nodes only switch on their radios when they have packets to exchange, and switch off the radios in the idle periods. B-MAC [27] and wise-MAC [28] 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 TRAMA [29], nodes synchronize their transmission schedules to avoid packet collision, and to have nodes switch to low power mode when there are no data packets destined to those nodes. In LEACH [30], 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 time division multiple access (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 this, several MAC protocols have also been proposed specifically for BANs:

- CICADA [31] 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 often instead of buffering it locally).
- 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. 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] is a novel TDMA-based MAC protocol designed for BANs, and it 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.

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), in which routes are only discovered and established 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:

- SPIN [34]: 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 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.

- TEEN [35]: 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 its radio on and transmits only when: (1) the current sensed value (SV) 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 in WSNs that runs on nodes. The OS manages hardware resources and provides common services for efficient execution of various user application programmes. The main functions of an OS are as follows.

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

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 subsection.

TinyOS [36] 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 by employing the nesC [36] language, which is a C language variant that adds additional features.

Contiki [37] is an open source, multi-tasking operating system 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 Conkiti 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 [38] 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 [39] 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 by using C language and provides a set of application programme interfaces (APIs) for developers.

T-kernel [40] 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 fault application code, performs pre-emption, and supports virtual memory management. With the advantages, the T-kernel raises the system abstraction level that is visible to application programmers.

LiteOS [41] 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 often implemented on a WSN's base station interacts with nodes only when the nodes are present. Therefore, LiteShell and LiteFS are connected with a dashed line in this system. The LiteOS kernel 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 perform 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 serve for physiological signal monitoring. 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. Pending issues and on-going research directions can be summarized as follows:

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, electrical and magnetic propagation of the radio employed should have very limited effects on human tissue and organs (e.g., heating). In addition, device form factor flexibility 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 exceptional user experiences.

Application-specific protocols. From a technical perspective, BAN protocol design is always subject to a variety of trade-offs. At the physical 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 industrial, scientific and medical band. For life-critical applications, however, researchers are considering employing radio bands restricted to medical systems while looking for alternative solutions, such as UWB radio. At 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-layer requirements and restrictions (e.g. type of data, deployment setting and security) into middle-layer and physical-layer trade-offs, and to engineer a 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 6 is an example of a standardization body working to solve this issue.

Novel applications. Last but not least, novel applications are the driven power for the advancements of the above two. 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 on-going research efforts, we foresee a bright future of BANs for being widely deployed around us.

Acknowledgments

This work was supported in part by the National Sciences and Engineering Research Council of the Canadian Government under grant STPGP 365208-08, and by the Ministry of Knowledge Economy, Korea, under the Information Technology Research Center support program supervised by the NIPA National IT Industry Promotion Agency, NIPA-2010-(C1090-1011-0004).

References

[1] S. González-Valenzuela, M. Chen and V.C.M. Leung, “Mobility Support for Health Monitoring at Home Using Wearable Sensors”, *IEEE Trans. Information Technology in BioMedicine*, vol. 15, no. 4, pp. 539-549, July 2011.
[2] A. Milenkovic, C. Otto, E. Jovanov, “Wireless sensor networks for personal health monitoring: Issues and an implementation,” Computer Communications, vol. 29, no. 13-14, pp. 2521-2533, Elsevier Science Publishers, August 2006.
[3] D. Malan, T. Fulford-Jones, M. Welsh and S. Moulton, “CodeBlue: An Ad Hoc Sensor Network Infrastructure for Emergency Medical Care,” in *Proceedings of the Workshop on Applications of Mobile Embedded Systems (WAMES)*, Boston, USA, 6 June, 2004.
[4] T. Gao, T. Massey, L. Selavo, D. Crawford, B. Chen, K. Lorincz, V. Shnayder, L. Hauenstein, F. Dabiri, J. Jeng, A. Chanmugam, D. White, M. Sarrafzadeh and M. Welsh, “The Advanced Health and Disaster Aid Network: A Light-Weight Wireless Medical System for Triage,” *IEEE Transactions on Biomedical Circuits and Systems*, vol. 1, no. 3, pp. 203-216, September 2007.
[5] J. A. Ruiz and S. Shimamoto, “Novel Communication Services Based on Human Body and Environment Interaction: Applications inside Trains and Applications for Handicapped People,” in *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 2240-2245, Las Vegas, USA, 3-6 April, 2006.
[6] S. Pentland, “Healthwear: Medical Technology Becomes Wearable,” IEEE *Computer*, vol. 37, no. 5, pp. 42-49, May 2004.
[7] I. Jantunen et al., “Smart Sensor Architecture for Mobile-Terminal-Centric Ambient Intelligence,” *Sensors and Actuators A: Physical*, vol. 142, no.1, pp. 352–60, March 2004.
[8] E. Farella, A. Pieracci, L. Benini, L. Rochi and A. Acquaviva, “Interfacing Human and Computer with Wireless Body Area Sensor Networks: The WiMoCA Solution,” *Multimedia Tools and Applications*, vol. 38, no. 3, pp. 337-363, July 2008.
[9] ZigBee Specification, ZigBee Alliance, 2005, http://www.zigbee.org.
[10] IEEE Standard 802.15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)", IEEE, 2003.
[11] Bluetooth Low Energy Specification, Bluetooth Special Interest Group, http://www.bluetooth.com.
[12] ANT+ Communications Protocol for Wireless Sensor Networks. http://www.thisisant.com.
[13] Sensium Low Power Hardware Platform for Health Monitoring. http:// http://www.toumaz.com.
[14] Zarlink Semiconductor. http://www.zarlink.com.

[15] G. Lo, A. Suresh, S. Gonzalez-Valenzuela, L. Stocco and V.C.M. Leung, “A Wireless Sensor System for Motion Analysis of Parkinson's Disease Patients”, in Proc. IEEE PerCom, Seattle, WA, Mar. 2011.

[16] H. Cao, H. Li, L. Stocco, and V.C.M. Leung, “Wireless Three-pad ECG System: Challenges, Design and Evaluations”, Journal of Communications and Networks, vol. 13, no. 2, pp, 113-124, Apr. 2011.

[17] H. Cao, H. Li, L. Stocco and V.C.M. Leung, “Design and Evaluation of A Novel Wireless Three-pad ECG System for Generating Conventional 12-lead Signals”, in Proc. BodyNets, Corfu, Greece, Sep. 2010.

[18] S. González-Valenzuela, M. Chen and V.C.M. Leung, "Evaluation of Wireless Body Area Sensor Placement for Mobility Support in Healthcare Monitoring Systems”, in Proc. AdhocNets, Victoria, BC, Aug. 2010.

[19] A. Taparugssanagorn, A. Rabbachin, M. Hamalainen, J. Saloranta, and J. Iinatti, “A Review of Channel Modelling for Wireless Body Area Network in Wireless Medical Communications”, in Proceedings of the 11th International Symposium on Wireless Personal Multimedia Communications, Saariselka, Finland, 2008.

[20] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao and V. Leung, "Body Area Networks: A Survey", ACM/Springer Mobile Networks and Applications (MONET), vol. 16, no. 2, pp. 171-193, April 2010.

[21] H. Cao, V.C.M. Leung, C. Chow and H.C.B. Chan, “Enabling Technologies for Wireless Body Area Networks: A Survey and Outlook”, IEEE Communications Magazine, vol. 47, no. 12, pp. 84-93, Dec. 2009.

[22] P. Abouzar, K. Shafiee, D. Michelson and V.C.M. Leung, “Action-based scheduling technique for 802.15.4/ZigBee wireless body area networks”, to appear at IEEE PIMRC, Toronto, ON, Sep. 2011.

[23] N. Torabi, W. Wong and V.C.M. Leung, “A Robust Coexistence Scheme for IEEE 802.15.4 Wireless Personal Area Networks”, in Proc. IEEE CCNC, Las Vegas, NV, Jan. 2011.

[24] N. Torabi and V.C.M. Leung, “Robust License-free Body Area Network Access for Reliable Public m-Health Services”, in Proc. IEEE HealthCom, Columbia, MO, June 2011.

[25] W. Ye, J. Heidemann, and D. Estrin, “Medium access control with coordinated, adaptive sleeping for wireless sensor networks”, IEEE/ACM Transactions on Networking, No. 12, Vol. 3, pp. 493-506, June 2004.

[26] T. Dam and K. Langendoen. “An adaptive energy-efficient mac protocol for wireless sensor networks”, in Proceedings of the 1st ACM SenSys Conference, pp. 171-180, Los Angeles, California, USA, November 2003.

[27] J. Polastre, J. Hill, and D. Culler, “Versatile low power media access for wireless sensor networks”, in Proceedings of the 2nd ACM SenSys Conference, pp. 95-107, Baltimore, MD, USA, November 2004.

[28] A. Hoiydi, J. Decotignie, C. Enz, and E. Roux, “WiseMAC: An ultra low power MAC protocol for the wisenet wireless sensor networks”, in Proceedings of the 1stACM SenSys Conference, Los Angeles, CA, July 2003.

[29] V. Rajendran, K. Obraczka, and J. Garcia-Luna-Aceves, “Energy-efficient, collision-free medium access control for wireless sensor networks”, in Proceedings of the 1st ACMSenSys Conference, pp. 181-193, Los Angeles, California, USA, November 2003.

[30] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-efficient Communication Protocols for Wireless Microsensor Networks”, in Proceedings of the Hawaii International Conference on Systems Science, pp. 1-10, Maui, Hawaii, USA, January 2000.

[31] B. Latr, B. Braem, I. Moerman, C. Blondia, E. Reusens, W. Joseph and P. Demeester, " A Low-delay Protocol for Multihop Wireless Body Area Networks", in Proceedings of Mobiquitous, Philadelphia, PA, August 2007.

[32] H. Li, J. Tan, "An Ultra-low-powerMedium Access Control Protocol for Body Sensor Network," in Proceedings of IEEE-EMBS, Reading, UK, 2005.

[33] H. Li, J. Tan, "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, 2007.

[34] W.R. Heinzelman, J. Kulik, and H. Balakrishnan, "Adaptive Protocols for Information Dissemination in Wireless Sensor Networks", in Proceedings of Fifth ACM/IEEE MOBICOM Conference (MobiCom '99), pp. 174-185, New York, NY, USA, August 1999.

[35] A. Manjeshwar and D. P. Agarwal, "TEEN: a Routing Protocol for Enhanced Efficiency in Wireless Sensor Networks," in Proceedings of 15th International Parallel and Distributed Processing Symposium, pp. 2009-2015, San Francisco, California, USA, April 2001.

[36] The TinyOS Website, available at http://tinyos.net/, 2011.

[37] A. Dunkels, B. Grönvall, and T. Voigt. "Contiki - a lightweight and flexible operating system for tiny networked sensors", In Proceedings of the 1st IEEE Workshop on Embedded Networked Sensors (Emnets-I), Tampa, Florida, USA, November 2004.

[38] The ScatterWeb Website, available at http://cst.mi.fu-berlin.de/projects/ScatterWeb/, 2011.

[39] S. Bhatti, J. Carlson, H. Dai, J. Deng, J. Rose, A. Sheth, B. Shucker, C. Gruenwald, A. Torgerson, and R. Han, "MANTIS OS: An Embedded Multithreaded Operating System for Wireless Micro Sensor Platforms", Journal of Mobile Networks and Applications, vol. 10, no. 4, pp. 563-579, August 2005.

[40] L. Gu and J.A. Stankovic "t-kernel: Providing reliable OS support to wireless sensor networks", In Proceedings of the 4th ACM Conf. on Embedded Networked Sensor Systems (SenSys'06), pp. 1-14, Boulder, Colorado, USA, Nov. 2006.

[41] Q. Cao, T. Abdelzaher, J. Stankovic and T. He, "The LiteOS Operating System: Towards Unix-like Abstractions for Wireless Sensor Networks", In Proceedings of the 7th international conference on Information processing in sensor networks (IPSN '08), pp. 233-244, St. Louis, Missouri, USA, April 2008.