Enabling Technologies for Wireless Body Area Networks: A Survey and Outlook

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ABSTRACT

A wireless body area network is a radio-frequency-based wireless networking technology that interconnects tiny nodes with sensor or actuator capabilities in, on, or around a human body. In a civilian networking environment, WBANs provide ubiquitous networking functionalities for applications varying from healthcare to safeguarding of uniformed personnel. This article surveys pioneer WBAN research projects and enabling technologies. It explores application scenarios, sensor/actuator devices, radio systems, and interconnection of WBANs to provide perspective on the trade-offs between data rate, power consumption, and network coverage. Finally, a number of open research issues are discussed.

INTRODUCTION

With the growing needs in ubiquitous communications and recent advances in very-low-power wireless technologies, there has been considerable interest in the development and application of wireless networks around humans. A wireless body area network (WBAN) is a radio frequency (RF)-based wireless networking technology that interconnects tiny nodes with sensor or actuator capabilities in, on, or around a human body. Typically, the transmissions of these nodes cover a short range of about 2 m. Complementing wireless personal area networks (WPANs),[1] in which radio coverage is usually about 10 m, WBANs target diverse applications including healthcare, athletic training, workplace safety, consumer electronics, secure authentication, and safeguarding of uniformed personnel. A WBAN can also be connected to local and wide area networks by various wired and wireless communication technologies, as illustrated in Fig. 1.

WBANs will play an important role in enabling ubiquitous communications, creating a huge potential market. In the area of healthcare, according to the World Health Organization's statistics, millions of people suffer from obesity or chronic diseases every day, while the aging population is becoming a significant problem. Both the current situation and future trend call for new technologies such as WBANs to facilitate first-hand health monitoring and medical care (point of care). From the consumer electronics perspective, short-range wireless technologies for human-computer interaction (HCI) and entertainment are booming. Take Bluetooth Low Energy technology as an example; a recent report predicts the initial market volume of those ultra-low-power products to be in the billions.

Unlike conventional wireless sensor networks (WSNs), WBANs have their own characteristics, as discussed below, which distinguish them from WSNs and also create new technical challenges.

Architecture: A WBAN consists of two categories of nodes: sensors/actuators in or on a human body, and router nodes around WBAN wearers or second-tier radio devices equipped on the wearers, functioning as an infrastructure for relaying data. In WSNs, however, every node functions as a sensor node as well as a router node.

Density: The number of sensors/actuators deployed on the wearer depends on use cases. Typically, they are not deployed with high redundancy to tolerate node failures as in conventional WSNs, and thus do not require high node density.

Data rate: Most WSNs are applied for event-based monitoring, where events can happen irregularly. In contrast, WBANs are employed for monitoring human physiological activities, which vary in a more periodic manner. As a result, the application data streams exhibit relatively stable rates. Typical WBAN sensors are summarized later.

Latency: For both healthcare and consumer applications, latency resulting from the underlying network such as a WBAN should be minimized. While power saving is definitely beneficial, replacement of batteries in WBAN nodes is much easier than in WSNs, in which nodes may be physically unreachable after deployment. Therefore, it may be necessary to maximize battery life in a WSN at the expense of higher latency.

Mobility: Wearers of WBANs may move around. WBAN nodes affiliated with the same wearer move together and in the same direction. In contrast, WSN nodes are usually considered to be stationary, and any node mobility does not occur in groups.

[1] *There is no strict difference between WBAN and WPAN in their definitions. In this article WBAN refers to a network of wireless devices in or on a human body, while WPAN refers to a network of wireless peripherals in proximity to a person.*

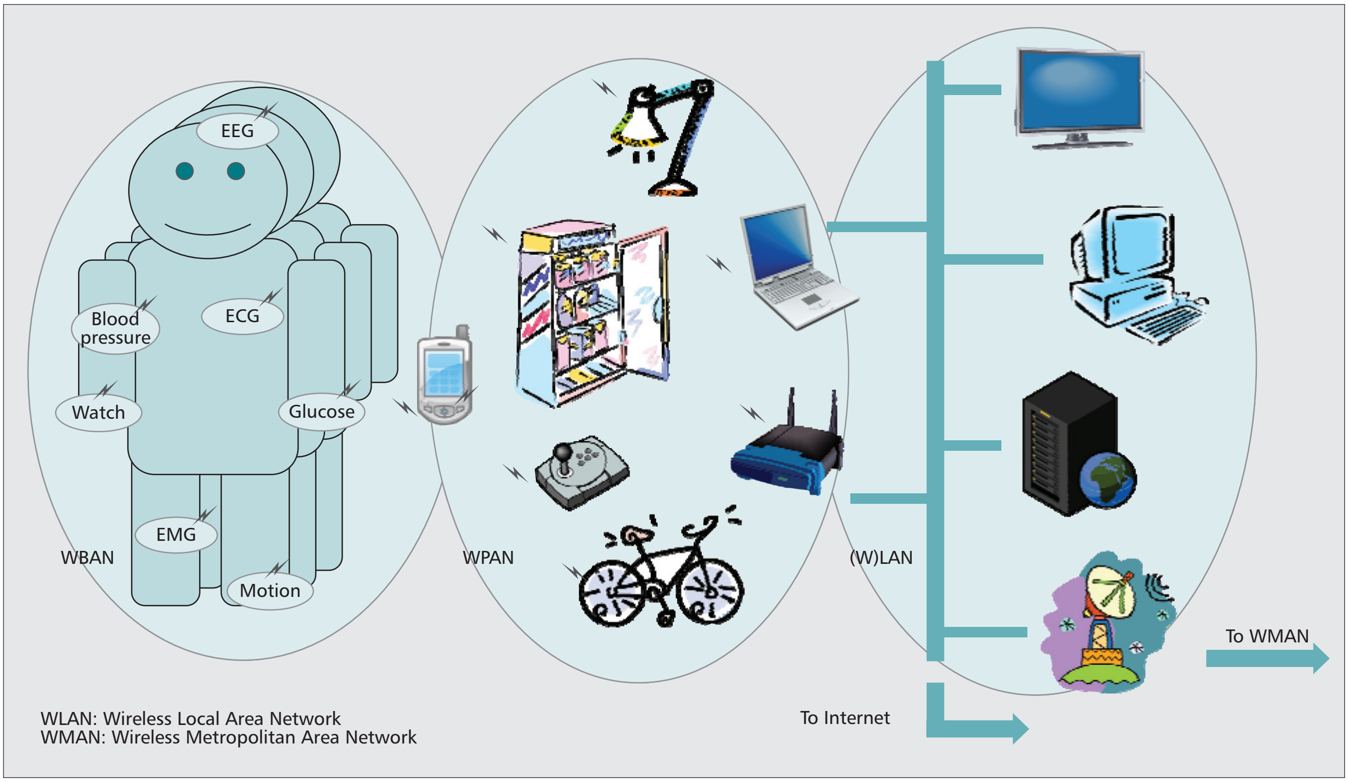

Figure 1. *Interconnection of WBAN, WPAN, (W)LAN, and wide area networks.*

APPLICATIONS OF WBANS

WBAN applications can be categorized based on the type of sensors/actuators, radio systems, network topologies, and use cases. We enumerate here several pioneer healthcare WBAN research projects, as well as platforms for HCI applications.

WBANS FOR HEALTHCARE

WBANs extend conventional bedside monitoring to ambulatory monitoring, providing a point of care to patients, the elderly, and infants in both hospital-based and home-based scenarios. Monitoring, autonomous diagnostic, alarm, and emergency services, as well as management of electronic patient record databases can all be integrated into one system to better serve people.

The CodeBlue project at Harvard University [1] considers a hospital environment where multiple router nodes can be deployed on the wall. All nodes use the same ZigBee radio. Patients/caregivers can publish/subscribe to the mesh network by multicasting; there is no centralized or distributed server or database for control and storage. Localization functionality is provided by MoteTrack with an accuracy of 1 m, based on the same radio. As a result of mobility and multihop transmissions, the system experiences considerable packet loss and is limited to 40 kb/s aggregate bandwidth per receiver.

Based on the CodeBlue architecture, the Advanced Health and Disaster Aid Network (AID-N) is being developed at Johns Hopkins University [2] for mass casualty incidents where electronic triage tags can be deployed on victims. Additional wireless capabilities (e.g., Wi-Fi and cellular networks) are introduced to facilitate communications between personal servers and the central server where data are stored. Furthermore, a web portal is provided to multiple types of users, including emergency department personnel, incident commanders, and medical specialists. A Global Positioning System (GPS) module is employed for outdoor localization, while a MoteTrack system is designed for tracking indoors. However, patients have mobility constraints due to the lack of routers in the network, and a very limited number of sensor nodes can be put on each patient because of the limited bandwidth.

The Wearable Health Monitoring Systems (WHMS) is being developed at the University of Alabama [3] and targets a larger-scale telemedicine system for ambulatory health status monitoring. Unlike CodeBlue and AID-N, WHMS has a star-topology network for each patient, which is connected via Wi-Fi or a cellular network to a healthcare provider. The personal server, implemented on a personal digital assistant (PDA), cell phone, or personal computer (PC), coordinates the data collection from sensor nodes using a time-division multiple access (TDMA) mechanism, provides an interface to users, and transfers data to a remote central server. Physicians can access data via the Internet, and alerts can be created by an agent running on the server. However, the power consumption and cost associated with long-term data uploading can hamper system realization.

WBANS FOR HCI

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of automatically recognizing human motions, gestures, and activities. Disabled people can benefit from novel WBAN platforms based on a series of miniature sensors. The intra-body communications (IBC) applications proposed in [4] can be used to assist handicapped people. For example, an IBC enabled sensor embedded inside the shoes of a blind person can be used to send voice information such as the current location to him/her by an IBC enabled facility, such as a doorway or crosswalk. IBC enabled eyeglasses that can display texts, working with IBC enabled speakers, can help deaf people comprehend audio broadcast announcements.

Early research efforts at MIT Media Lab have produced MITHril [5], a wearable computing platform that includes electrocardiography (ECG), skin temperature, and galvanic skin response sensors for wearable sensing and context-aware interaction. MITHril is not a real WBAN in that multiple sensors are wired to a single processor. A later version of this platform, MITHril 2003, extends MITHril to a multi-user wireless distributed wearable computing platform by utilizing Wi-Fi function available on PDAs (i.e., a PDA acts as a personal server and relays data of each person to a central station).

The Microsystems Platform for Mobile Services and Applications (MIMOSA) [6] is a research project involving 15 partners from eight different European countries to create ambient intelligence. MIMOSA's approach is similar to WHMS while it exclusively employs a mobile phone as the user-carried interface device. Wibree, later renamed Bluetooth Low Energy technology, and radio frequency identification (RFID) tags are used for connecting local sensor nodes. NanoIP and Simple Sensor Interface (SSI) protocols are integrated into MIMOSA to provide an application programming interface (API) for local connectivity and facilitate sensor readings.

The Wireless Sensor Node for a Motion Capture System with Accelerometers (WiMoCA) [7] project at several Italian universities is concerned with the design and implementation of a distributed gesture recognition system. The system has a star topology with all sensing nodes sending data to a non-sensing coordinator node using a TDMA-like approach, and the coordinator in turn relays the data to an external processing unit using Bluetooth. The sensing modules, each made up of a tri-axial accelerometer, can be put on multiple parts of the body for motion detection. The radio modules of all nodes work in the 868 MHz European license-exempt band, with up to 100 kb/s data rate. A Java-based graphical user interface (GUI) at the processing unit side interprets the data stream for posture recognition.

Sensor Devices

Sensors are the key components of a WBAN, as they bridge the physical world and electronic systems. Generally, they can be classified into chemical, thermal, mechanical, and acoustic sensors. Previous studies have shown that the frequency and amplitude range of human physiological signals are comparatively low; thus, a low sampling frequency and low data transmission rate would be sufficient. However, what kind of and how many sensors a WBAN system employs depend largely on the application scenario and the system infrastructure. To better monitor a human's vital signals, behavior, and surrounding environment, a wide range of commercially available sensors can be deployed, such as accelerometer and gyroscope, ECG, electromyography (EMG), and electroencephalography (EEG) electrodes, pulse oximetry, respiration, carbon dioxide (CO_2), blood pressure, blood sugar, humidity, and temperature sensors (Table 1). Commonly used sensor devices for WBANs are surveyed below.

Accelerometers are widely used for motion capture. They measure the acceleration relative to freefall in three axes. With an accelerometer mounted on a certain part of a human body, the system can effectively register the subject's movement. As an addition or alternative to an accelerometer, a gyroscope can be used for applications such as ambulatory gait monitoring and analysis. For distinguishing motions, an accelerometer/gyroscope array with tens of sensors can be deployed. This raises questions for positioning and noise reduction techniques. Proper positioning reduces the number of accelerometers/gyroscopes needed and the resulting data rate. Decreasing the number of sensors reduces the motion detection signal-to-noise ratio due to lower redundancy, thus requiring the sensors to be deployed at the planned locations with higher accuracy.

ECG/EMG/EEG sensors measure potential differences across electrodes attached to corresponding parts of the body. The electric current appearing on the skin is a result of heart, muscle, or brain activities and conductivity of the human body. Therefore, temporal graphs obtained from these electrodes provide indirect ways of analyzing and diagnosing certain human physiological conditions. For bedside monitoring, disposable electrodes are usually used. However, long-term usage of these types of sensors may cause artifacts as well as skin problems. An alternate solution is textile-structured electrodes, which are ECG sensors embedded inside garments, such as fiber, yarn, and fabric structures [8]. These textile-structure electrodes, possibly woven into clothes, are more comfortable and suitable for long-term monitoring. They are much more flexible than the disposable electrodes since the shape can change with human movement, and they are also free of skin problems. Again, noise reduction is the crucial problem for these monitoring devices. Ideally, these circuits are implanted to have direct contact with whatever they are monitoring, but that could be too obtrusive. While a particular type of sensor is monitoring a specific physiological signal (e.g., ECG), other physiological signals such as EMG are contributing to the overall noise and need to be suppressed.

With advances in micro-electromechanical systems (MEMS), sensor devices are getting even tinier in size and changing the traditional way of measuring human physiological parameters. Accelerometers and gyroscopes are good examples. It has been reported that MEMS elec-

Sensor	How it works	Data rate
Accelerometer	Measures the acceleration relative to freefall in three axes	High
Gyroscope	Measures the orientation, based on the principles of angular momentum	High
ECG/EEG/EMG	Measures potential difference across electrodes put on corresponding parts of the body	High
Pulse oximetry	Measures ratio of changing absorbance of the red and infrared light passing from one side to the other of a thin part of the body's anatomy	Low
Respiration	Uses two electrodes, cathode and anode covered by a thin membrane to measure the oxygen dissolved in a liquid	Low
Carbon dioxide	Uses the infrared light and measures the absorption of the gas presented	Low
Blood pressure	Measures the systolic pressure (peak pressure) and diastolic pressure (minimum pressure)	Low
Blood sugar	Traditionally analyzes drops of blood from a finger tip, recently, uses non-invasive method including a near infrared spectroscopy, ultrasound, optical measurement at the eye, and the use of breath analysis	Low
Humidity	Measures the conductivity changes of the level of humidity	Very low
Temperature	Uses a silicon integrated circuit to detect the temperature changes by measuring the resistance	Very low

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

trodes for ECG/EEG acquisition have been developed by fabricating little spikes on silicon or polymers.

Figure 2 shows a typical sensor node with sensor, radio, and memory modules. The sensor module consists of a sensor, a filter, and an analog-to-digital converter (ADC). The sensor converts some form of energy to analog electric signals, which are bandpass filtered and then digitalized by the ADC for transmissions or further processing. We discuss radio systems for WBANs and WPANs used for transmissions of sensed data in the next section.

Radio Technologies

Radio Propagation

In the past few years, researchers have made considerable progress in characterizing the body area propagation environment through both measurement-based and simulation-based studies in order to support prediction of link level performance in alternative sensor deployment configurations, and development of more effective antennas with, say, lower specific absorption and better coupling to the dominant propagation modes. These works have been conducted in both the industrial, scientific, and medical (ISM) bands between 400 MHz and 2.45 GHz, and the ultra-wideband (UWB) frequency allocation between 3.1 and 10.6 GHz [9]. In each of the frequency bands, intra-body, on-body, and off-body channels have been studied. Figure 3 shows an example of the path loss measurements for several body locations and frequency bands based on [10]. The intra-body propagation channel can be described using an appropriate model. For example, the Ricean distribution can be used for modeling the intra-body propagation channel based on the K-factor, which is the ratio between the average powers of the direct and reflected paths [4], and indicates the channel quality. Significant progress has also been made toward:

- Identification of the propagation mechanisms that affect signal transmissions between nodes
- Assessment of the effects of multipath reflections from the external environment to signal transmissions between nodes
- Characterization of the fading statistics on body links that occur with body motion and change of body position in both sparse and rich scattering environments
- Development of standard UWB channel impulse response models and evaluation of typical modulation schemes utilizing them [11]

Following is a comparative study of emerging and existing standards for WBANs and WPANs, including Bluetooth Low Energy, UWB, Bluetooth 3.0, and ZigBee. They are listed in Table 2 for comparison. Also summarized in the table are proprietary and open technologies like Insteon, Z-Wave, ANT, RuBee, and RFID. Insteon and Z-Wave are both proprietary mesh networking technologies for home automation. Z-Wave works in the 2.4 GHz ISM band, while Insteon makes use of both power lines and the 900 MHz ISM band. ANT is another proprietary sensor networking technology, featuring a simpler protocol stack and lower power consumption. ANT has been embedded in some Nike shoes to collect workout data and is able to talk to iPod products. RuBee and RFID are both used for asset management and tracking. They are complimentary to each other in terms of frequency bands, battery life, and application scenarios. These technologies have all been implemented on silicon chips and are being sold in comparable volumes each year. With advances in very large-scale integration (VLSI), dual and

Bluetooth LEE was designed to wirelessly connect small devices to mobile terminals. Those devices are often too tiny to bear the power consumption as well as cost associated with a standard Bluetooth radio, but are ideal choices for health-monitoring applications.

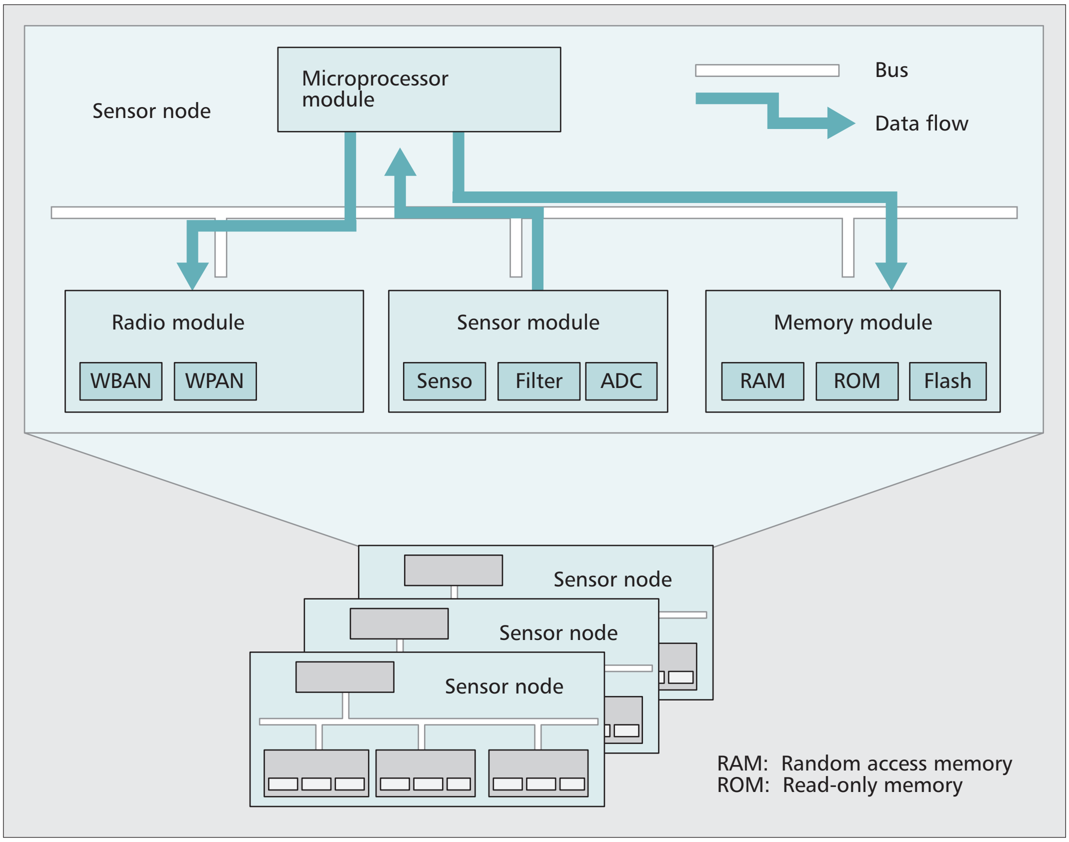

Figure 2. *Typical modules on a sensor node.*

multiple-standard radios can be integrated into a single chip, greatly reducing the cost and power consumption, while fostering combining as well as merging of technologies.

Bluetooth Low Energy Technology

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

Bluetooth Low Energy technology is expected to provide a data rate of up to 1 Mb/s. Using fewer channels for pairing devices, synchronization can be done in a few milliseconds compared to Bluetooth's seconds. This benefits latency-critical WBAN applications (e.g., alarm generation and emergency response) and enhances power saving. Bluetooth Low Energy products can be categorized into two groups: dual-mode chips and standalone chips. As the names indicate, standalone chips are intended to be equipped with sensors/actuators and talk to each other only, while dual-mode chips are to be equipped with a personal server (e.g., smart phone) and also be able to connect to traditional Bluetooth devices.

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

UWB

According to the Federal Communications Commission (FCC), UWB refers to any radio technology having a transmission bandwidth exceeding the lesser of 500 MHz or 20 percent of the arithmetic center frequency. FCC also regulates license-free use of UWB in the 3.1–10.6 GHz band to have a relatively low power spectral density emission. This leads to the suitability of UWB applications in short-range and indoor environments, and environments sensitive to RF emissions (e.g., in a hospital). Commercial products based on UWB provide extremely high data rates; for example,

Technology	Frequency band	Data rate (b/s)	Multiple access method	Coverage area (meter)	Network topology
Bluetooth Low Energy	2.4 GHz ISM	1 M	FH + TDMA	10	Star
UWB (ECMA-368)	3.1~10.6 GHz	480 M	CSMA/TDMA	<10	Star
Bluetooth 3.0 + High Speed	2.4 GHz ISM	3~24 M	FH + TDMA/CSMA (Wi-Fi)	10	star
ZigBee (IEEE 802.15.4)	ISM	250 k	CSMA	30~100	Star/mesh
Insteon	131.65 KHz (powerline) 902~924 MHz	13 k	Unknown	Home area	Mesh
Z-Wave	900 MHz ISM	9.6 k	Unknown	30	Mesh
ANT	2.4 GHz ISM	1 M	TDMA	Local area	Star/mesh
RuBee (IEEE 1902.1)	131 KHz	9.6 k	unknown	30	Peer-to-peer
RFID (ISO/IEC 18000-6)	860~960 MHz	10~100 k	Slotted-Aloha/binary tree	1~100	Peer-to-peer

FH: Frequency hopping
TDMA: Time-division multiple access
CSMA: Carrier sense multiple access

Table 2. *A comparison of WBAN and WPAN technologies. (Only most commonly acknowledged and/or applied parameters are listed here due to space limitation.)*

certified wireless USB devices work at up to 480 Mb/s, enabling short-range wireless multimedia applications, such as wireless monitors, wireless digital audio and video players, and other HCI use cases. These multimedia devices can be either wirelessly connected with WBANs or themselves portable as part of a WBAN. UWB is also an ideal technology for precise localization, which complements GPS in the indoor environment for WBAN tracking.

An emerging WBAN standard, IEEE 802.15.6 — Body Area Networks (BANs), will likely employ UWB, according to recent proposals and meeting minutes. The standard intends to endow future generation electronics in close proximity to or inside the human body. However, when this standard and any electronics that utilize it will become available remains unknown.

Bluetooth 3.0 + High Speed

Bluetooth technology was designed as a replacement of RS232 cables, and later evolved to become a widely accepted wireless alternative for connecting a variety of personal devices. It differs from others in separately supporting audio and data traffic streams. This is probably why Bluetooth headsets are seen everywhere. The newly adopted standard, Bluetooth 3.0 + HS, introduces the 802.11 protocol adaptation layer (PAL) into the protocol stack, and increases data rate support from 3 Mb/s to 24 Mb/s, supporting applications like transferring bulk data files. Together with its Low Energy extension, Bluetooth accommodates applications with different data rate, power consumption, and network coverage requirements.

Limitations of Bluetooth include the small number of active slaves (seven) that each piconet supports and indirect communications between slaves. Although one slave can participate in more than one piconet, it is not an efficient way of connecting nodes. A WBAN project, MobiHealth, developed in the early 2000s employed Bluetooth for transmitting sensor data from a front-end device to a mobile phone or PDA [12]. However, the emergence of Bluetooth Low Energy presents a more suitable alternative. Bluetooth is most suitable for short-term high-data-rate communications, connecting two peer devices in an ad hoc way, such as exchanging data between two personal servers in two WBANs, or between a WBAN and a PC. Bluetooth has already been widely adopted in the mobile phone industry to connect headsets, PCs, and other mobile computing platforms together. Commercial WPAN products employing Bluetooth include carkits, printers, digital cameras, Nintendo's Wii, and Sony's PlayStation 3.

ZigBee

ZigBee/IEEE 802.15.4 targets low-data-rate and low-power-consumption applications. Specifically, the ZigBee Alliance has been working on solutions for smart energy, and home, building, and industrial automation. The recently completed ZigBee Health Care public application profile provides a flexible framework to meet Continua Health Alliance requirements for remote health and fitness monitoring. These solutions better suit WBAN deployment scenarios in a limited area (e.g., a hospital or a house), as in the cases of CodeBlue [1] and AID-N [2].

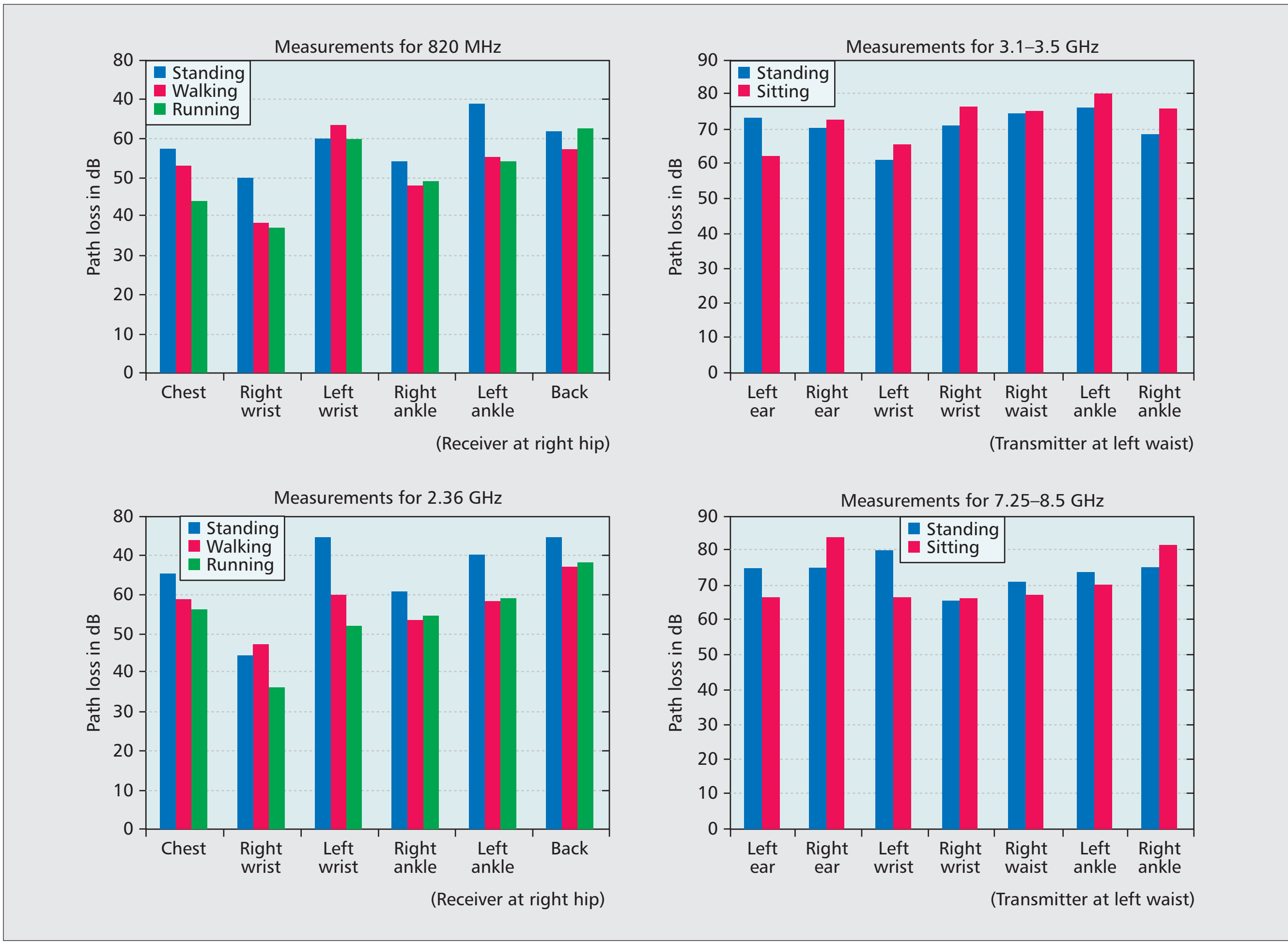

Figure 3. *Path loss values for different body locations and frequency bands (based on [10]).*

Compared to Bluetooth and UWB, ZigBee/IEEE 802.15.4 devices can operate in three ISM bands, with data rates from 20 kb/s to 250 kb/s. ZigBee supports three types of topologies: star, cluster tree, and mesh. In the star topology, a coordinator initiates and controls the network (i.e., similar to a piconet in Bluetooth), but there is no need for synchronization. The major advantage of ZigBee is its capability of providing multihop routing in a cluster tree or mesh topology. As a result, WBAN network coverage can be expanded to a WPAN using the same radio. A ZigBee mesh network may include both full-function devices (FFDs) and reduced-function devices (RFDs), where an RFD is equivalent to a standalone chip in Bluetooth Low Energy and can only act as an end device, while an FFD is equivalent to a dual-mode chip and can also act as a coordinator or router.

There have been many academic research projects utilizing ZigBee for transporting health-related data. For example, a wireless ECG Plaster for WBAN developed at the National University of Singapore uses an ECG front-end developed in-house and a TI CC2430 chip to collect ECG streams [13]. Most prototypes mentioned earlier, however, are based on IEEE 802.15.4 chips that do not employ the higher-layer ZigBee protocol stack, because either networking capability is not a must, or researchers are interested in devising more appropriate protocols. In our view, ZigBee may have a better chance to be adopted in the area of home automation and industrial automation and control, while in the area of connecting low-power peripheral devices around the human body (e.g., watches, health-related monitors, and sports sensors), Bluetooth Low Energy technology has greater potential to be widely employed, due to its association with Bluetooth as well as lower cost and lower power consumption.

Connecting WBANs and the World

While the coverage of a WBAN is limited to about 2 m, it may interwork with other wireless networks to largely extend its coverage area, facilitating connectivity between those sensory devices and the outside world (Fig. 4). This enables emergency alarms to be generated both locally and remotely, and monitoring, data storage, and management capabilities to be supported in a more capable computing platform at a distant location. These services can be provided based on push or pull strategies.

A global trend for interconnection of data networks is to use IP. WBAN packets can be

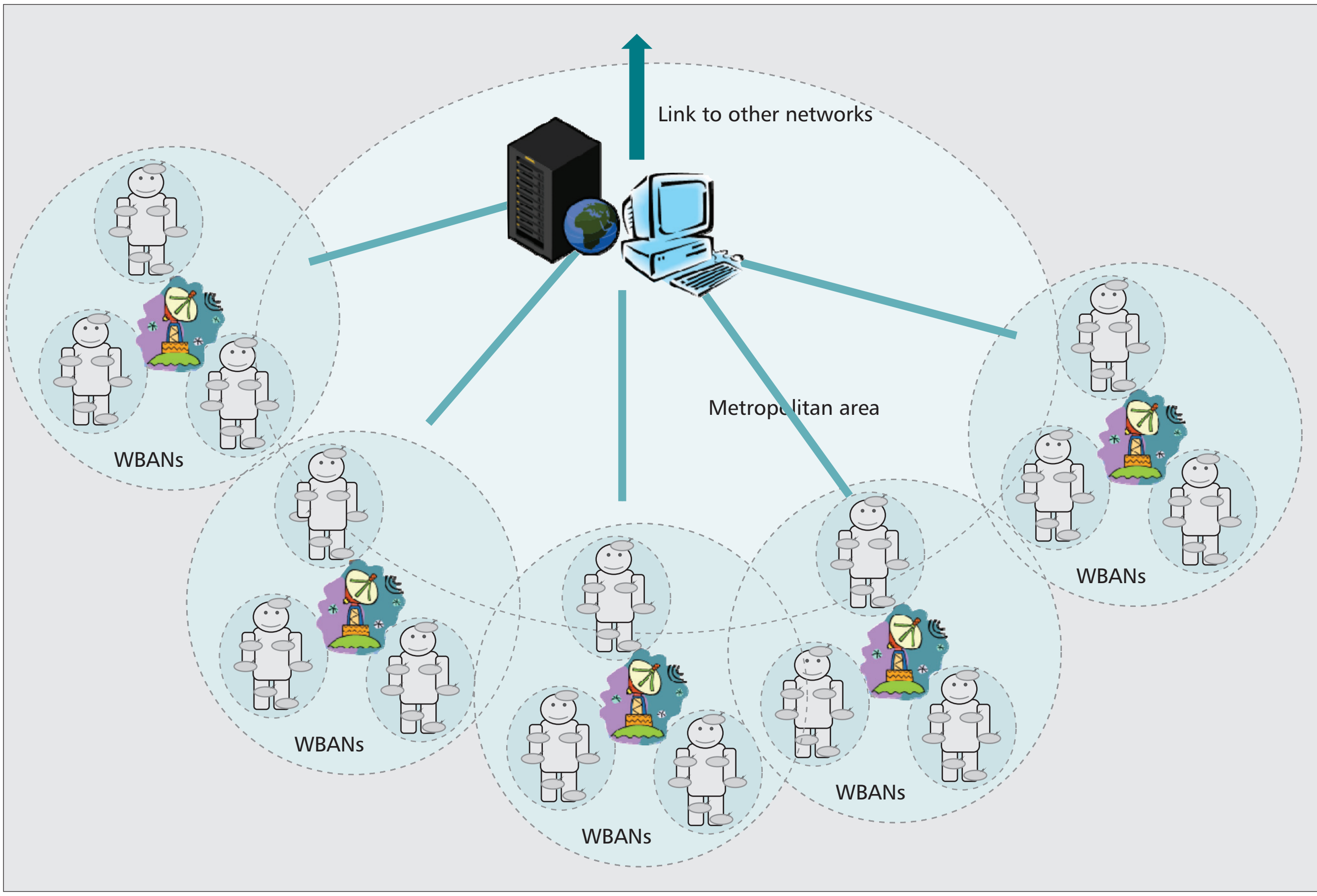

Figure 4. *Connecting WBANs to the world and global data storage, management and sharing.*

translated into IP datagrams by a gateway at the edge of a WBAN, as in the AID-N, WHMS, and MIMOSA platforms. In particular, such a gateway can be a smart phone equipped with multiple network interfaces, which enables the owner to interact with his/her WBAN and forward data anywhere in the world. Existing communications technologies such as short message services (SMS), general packet radio services (GPRS), and email services can also be used to speed up or assist the data transfer. Another approach is to natively integrate IP into WBAN packets; as a result, the underlying network infrastructure will be transparent to applications. There are ongoing projects aimed at this goal, such as Bluetooth Personal Area Networking Profile, IPv6 over Low Power Wireless Personal Area Networks (6LoWPAN), and IP for Smart Objects (IPSO). The ZigBee Alliance recently also announced its decision to incorporate standards from the Internet Engineering Task Force (IETF) into its specifications.

The ubiquitous access and connectivity of WBANs into the global network requires not only network infrastructure support, but also low-power and low-footprint software implementations for routing, flow/error control, remote procedure calls, database management, and user interface. Recently, user interfaces are increasingly provided through Web 2.0 portals, considering the easy access to its services and strong interactive characteristics.

Open Research Issues

While WBANs will undoubtedly play an important role in enabling ubiquitous communications, many issues remain to be addressed before WBAN technologies are widely applied, as summarized below.

Physical Characteristics of Sensor/Actuator Materials and Electronic Circuits

As sensors/actuators are going to be put on human bodies or even implanted, their size, form factor, and physical compatibility to human tissues are crucial. This motivates the search for and synthesis of novel materials. At the same time, concerns regarding electronic and magnetic energy absorbed by human tissues from RF circuits placed in close proximity to humans mean that WBAN devices need to employ low transmission power and low transmission duty cycles. In this regard UWB outperforms conventional transmission methods and thus attracts much attention.

Development and Evaluation of Improved Propagation and Channel Models

As discussed earlier, body area propagation environment has been characterized extensively at link level. There is still a need for accurate models that help researchers predict the impact

While WBAN technologies provide a promising platform to enable ubiquitous communications, several open issues still need to be addressed. In particular, for those life-saving applications, thorough studies and tests should be conducted before WBANs can be widely applied to humans.

of realistic channels on network level performance. Taking into account factors such as reliability, latency, mutual interference, energy consumption, and mobility effects in such a model, more effective network architecture and routing algorithms for WBANs can be devised. Recent years have seen growing interest in using UWB channel models for WBANs. For example, in [14] an experiment was done on a human body over 3.1–10.6 GHz in the indoor and anechoic chamber to study the path loss exponent under various conditions. Another related issue is performance evaluation. For example, when the WBAN signal is transmitted between two sensors, the signal propagation through the body is affected by the diffraction around the body and the reflections from the body or other objects. Path loss and delay spread will affect the performance of the system, especially when the sensors are placed on different sides of a body. According to one study, the packet error rate should generally be kept less than 1 percent [15].

Networking and Resource Management Schemes

As the application scenarios of WBANs are different from traditional sensor networks, problems like power management, sensor calibration, and context-aware network configuration need to be revisited as well. Sensor nodes can join/leave the network at any time, and thus impose the requirements of configuring the devices on the fly. Dynamic management of resources, including both sensor functionalities and communication bandwidth, is also necessary.

Security, Authentication, and Privacy Issues

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

Power Supply Issues

As all WBAN devices require an energy source for data collection, processing, and transmission, development of suitable power supplies becomes paramount. Most WBAN devices are powered by batteries, which may not even be replaceable in cases where the devices are implanted in the human body; thus, techniques like remote battery recharging are important. In addition to energy harvesting methods (e.g., based on body movements) many researchers are studying, recently researchers at MIT have reported wireless energy transmission to power electronic devices over a short range (i.e., several meters) using evanescent waves [16].

Rules of Engagement

Efforts have been put into the interoperability of desktop telemedicine systems and bedside devices (e.g., the development of Health Level 7 and ISO/IEEE 11073 [17]). However, intelligent monitoring and treatment systems employing WBANs require standardized rules of engagement in ambulatory environments, providing point of care without limitation of the wearer's location/mobility while protecting the patient's privacy. Interoperability protocols at the application or domain level (e.g., sample rate, data precision, association/disassociation, device descriptions, and nomenclature) should all be addressed, and vendor-independent attributes and user interfaces shall be made available.

Conclusion

As a complement to existing wireless technologies, the WBAN plays a very important role in ubiquitous healthcare applications and enjoys a huge potential market in the area of consumer electronics. Its advancements have been the result of interdisciplinary research and development. In this article we have provided a comprehensive review and outlook of this promising field through a survey of pioneer WBAN research projects and enabling technologies, including application scenarios, sensor/actuator devices, radio systems, and interconnection of WBANs. While WBAN technologies provide a promising platform to enable ubiquitous communications, several open issues still need to be addressed. In particular, for life-saving applications, thorough studies and tests should be conducted before WBANs can be widely applied to humans.

Acknowledgments

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