Wireless Body Area Networks: A Survey

Samaneh Movassaghi, *Student Member, IEEE,* Mehran Abolhasan, *Senior Member, IEEE,* Justin Lipman, *Member, IEEE,* David Smith, *Member, IEEE,* and Abbas Jamalipour, *Fellow, IEEE*

***Abstract*—Recent developments and technological advancements in wireless communication, MicroElectroMechanical Systems (MEMS) technology and integrated circuits has enabled low-power, intelligent, miniaturized, invasive/non-invasive micro and nano-technology sensor nodes strategically placed in or around the human body to be used in various applications, such as personal health monitoring. This exciting new area of research is called Wireless Body Area Networks (WBANs) and leverages the emerging IEEE 802.15.6 and IEEE 802.15.4j standards, specifically standardized for medical WBANs. The aim of WBANs is to simplify and improve speed, accuracy, and reliability of communication of sensors/actuators within, on, and in the immediate proximity of a human body. The vast scope of challenges associated with WBANs has led to numerous publications. In this paper, we survey the current state-of-art of WBANs based on the latest standards and publications. Open issues and challenges within each area are also explored as a source of inspiration towards future developments in WBANs.**

***Index Terms*—IEEE 802.15.6, Medium access control, Physical Layer, Routing, Wireless Body Area Networks, Wireless Sensor Networks**

I. Introduction

WORLD population growth is facing three major challenges [1, 2]: demographic peak of baby boomers, increase of life expectancy leading to aging population and rise in health care costs. In Australia, life expectancy has increased significantly from 70.8 years in 1960 to 81.7 years in 2010 and in the United States from 69.8 years in 1960 to 78.2 years in 2010, an average increase of 13.5%[1]. Given the U.S. age pyramid[2] shown in Fig. 1, the number of adults ranging from 60 to 80 years old in 2050 is expected to be double that of the year 2000 (from 33 million to 81 million people) due to retirement of baby boomers[3]. It is expected that this increase will overload health care systems, significantly affecting the quality of life. Further, current trends in total health care expenditure are expected to reach 20% of the Gross Domestic Product (GDP) in 2022, which is a big threat to the US economy. Moreover, the overall health care expenditures in the U.S. has significantly increased from 250 billion in 1980 to 1.85 trillion in 2004, even though 45 million Americans were uninsured[4]. These statistics necessitate a dramatic shift in current health care systems towards more affordable and scalable solutions.

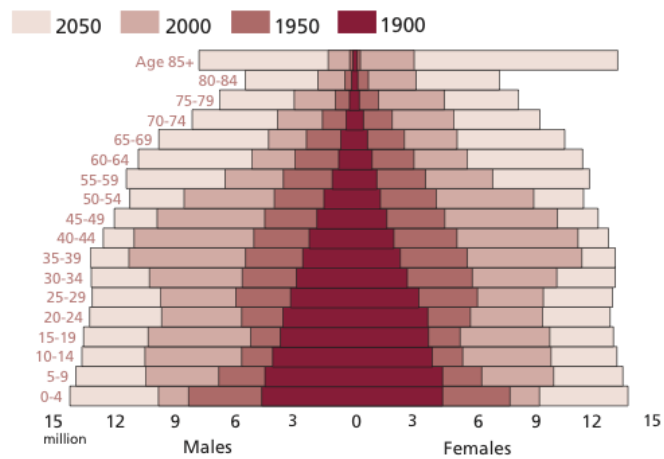

Fig. 1. U.S. Age Pyramid

On the other hand, millions of people die from cancer, cardiovascular disease, Parkinson's, asthma, obesity, diabetes and many more chronic or fatal diseases every year. The common problem with all current fatal diseases is that many people experience the symptoms and have disease diagnosed when it is too late. Research has shown that most diseases can be prevented if they are detected in their early stages. Therefore, future health care systems should provide proactive wellness management and concentrate on early detection and prevention of diseases. One key solution to more affordable and proactive health care systems is through wearable monitoring systems capable of early detection of abnormal conditions resulting in major improvements in the quality of life. In this case, even monitoring vital signals such as the heart rate allows patients to engage in their normal activities instead of staying at home or close to a specialized medical service. This can only be achieved through a network consisting of intelligent, low-power, micro and nano-technology sensors and actuators, which can be placed on the body, or implanted in the human

Manuscript received March 7, 2013; revised August 28, 2013. NICTA is funded by the Australian Government as represented by the Department of Broadband, Communications and the Digital Economy and the Australian Research Council through the ICT Centre of Excellence program.

S. Movassaghi and M. Abolhasan are with the Centre of Real Time Information Networks (CRIN), School of Communication and Computing, Faculty of Engineering and Information Technology, University of Technology, Sydney, NSW 2007, Australia, (e-mail: Seyedehsamaneh.Movassaghigilani@student.uts.edu.au and Mehran.Abolhasan@uts.edu.au).

J. Lipman is with Intel IT Labs, Shanghai, China, (e-mail: Justin.Lipman@intel.com).

D. B. Smith is with National ICT Australia (NICTA), Canberra, ACT 2601, Australia, and also with Australian National University (ANU), Canberra, ACT 0200, Australia , (e-mail: David.Smith@nicta.com.au.)

A. Jamalipour is with School of Electrical and Information Engineering, University of Sydney, NSW, 2006, Australia, (e-mail: Abbas.Jamalipour@sydney.edu.au.)

Digital Object Identifier 10.1109/SURV.2013.121313.00064

[1]http://www.worldlifeexpectancy.com/history-of-life-expectancy

[2]http://thesocietypages.org/socimages/2010/03/08/the-graying-of-america

[3]http://thesocietypages.org/socimages/2010/03/08/the-graying-of-america

[4]http://healthcare-economist.com/2006/01/30/trends-in-health-care-spending

1553-877X/14/$31.00 © 2014 IEEE

body (or even in the blood stream), providing timely data. Such networks are commonly referred to as Wireless Body Area Networks. In addition to saving lives, prevalent use of WBANs will reduce health care costs by removing the need for costly in-hospital monitoring of patients.

The latest standardization of WBANs, IEEE 802.15.6 [3], aims to provide an international standard for low power, short range (within the human body) and extremely reliable wireless communication within the surrounding area of the human body, supporting a vast range of data rates from 75.9 Kbps (narrowband) up to 15.6 Mbps ultra wide band; for different sets of applications [4]. This standard will be introduced in more detail in Section III.

WBANs may interact with the Internet and other existing wireless technologies like ZigBee, WSNs, Bluetooth, Wireless Local Area Networks (WLAN), Wireless Personal Area Network (WPAN), video surveillance systems and cellular networks. Hence, marketing opportunities for services and advanced consumer electronics will thoroughly expand, allowing for a new generation of more intelligent and autonomous applications necessary for improving one's quality of life [5]. WBANs are expected to cause a dramatic shift in how people manage and think about their health, similar to the way the Internet has changed the way people look for information and communicate with each other [2]. WBANs are capable of transforming how people interact with and benefit from information technology. WBAN sensors are capable of sampling, monitoring, processing and communicating various vital signs as well as providing real time feedback to the user and medical personnel without causing any discomfort [2, 6, 7]. The use of a WBAN allows continuous monitoring of one's physiological parameters thereby providing greater mobility and flexibility to patients. Importantly, as WBANs provide large time intervals of data from a patient's natural environment, doctors will have a clearer view of the patient's status [8]. However, formidable technical and social challenges must be dealt with to allow for their practical adoption. These challenges offer various system design and implementation opportunities with the major objectives of minimum delay, maximum throughput, maximum network lifetime and and reducing unnecessary communication related energy consumption (e.g. control frame overhead, idle listening and frame collisions). The user-oriented requirements of WBANs are equally challenging and have been defined as: ease of use, security, privacy, compatibility, value and safety [2, 9].

Our intent in this paper is to investigate recent studies in WBANs, present the challenges in each underlying subfield, and survey the important results in the field. Existing WBAN surveys have explored recent academic literature, but do not cover the actual standardization efforts. Most of these papers have mentioned some aspects of WBANs in terms of applications but do not comprehensively provide detailed study on all the important criteria in WBANs. Therefore, the need for such a survey in an area with such a fast growth is crucial to researchers to provide the latest updates on WBANs, their characteristics, challenges and open issues.

One of the benefits of this paper is that it draws from the existing WBAN surveys and provides the following main contributions:

- An overview of research conducted thus far in different sectors of Wireless Body Area Networks.
- An investigation of the many strict WBAN constraints from different perspectives.
- A classification of the various applications of WBANs in different sectors of medical and non-medical.
- A detailed review and classification of routing protocols and address allocation schemes for these networks.
- An in-depth insight into security challenges in WBANs and proposed protocols.
- Open issues in each area of research for WBANs and explanation of why further research is required.
- The most detailed recent compilation of WBAN projects and publications.

The remaining sections of this paper are reminiscent of a layered architecture. Section II describes WBAN applications. The latest standard on WBANs is presented in Section III. The requirements of WBANs based on the IEEE 802.15.6 standard are provided in Section IV. Characteristics inherent to WBANs are explored in Section V with emphasis on system architecture, topology and types of WBAN nodes. The individual layers that comprise a WBAN are presented in Section VI. The respective channel models, data rates and power requirements are described in Section VII. Important issues associated with WBAN security are described in Section VIII. WBAN routing protocols are described and classified in Section IX. WBAN address allocation schemes and their challenges are discussed in Section X. WBAN specific radio technologies are presented in Section XI. A comparison of WBANs with respect to other wireless networks is provided in Section XII. In Section XIII, the important WBAN challenges and open issues are described. Lastly, Section XIV concludes the paper.

II. Applications of WBANs

WBAN applications span a wide area such as military, ubiquitous health care, sport, entertainment and many other areas. IEEE 802.15.6 categorizes WBAN applications into medical and non-medical (Consumer Electronics) as can be seen in Table I. The main characteristic in all WBAN applications is improving the user's quality of life [8]. However, the technological requirements of WBANs are application-specific. Some in-body and on-body applications are shown in Table II.

A. *Medical Applications*

WBANs have a huge potential to revolutionize the future of health care monitoring by diagnosing many life threatening diseases and providing real time patient monitoring [10]. Demographers have predicted that the worldwide population over 65 will have doubled in 2025 to 761 million from the 1990 population of 357 million. This implies that by 2050 medical aged care will become a major issue. By 2009, the health care expenditure in the United States was about 2.9 trillion and is estimated to reach 4 trillion by 2015, almost 20% of the gross domestic product. Also, one of the leading causes of death is related to cardiovascular disease, which is estimated to be as much as 30 percent of deaths worldwide [11, 12]. Based

TABLE I
APPLICATIONS OF WBANS

WBAN Applications	Medical	Wearable WBAN	Assessing Soldier Fatigue and Battle Readiness
			Aiding Professional and Amature Sport Training
			Sleep Staging
			Asthma
			Wearable Health Monitoring
		Implant WBAN	Cardiovascular Diseases
			Cancer Detection
		Remote Control of Medical Devices	Ambient Assisted Living (AAL)
			Patient Monitoring
			Tele-medicine Systems
	Non-Medical		Real Time Streaming
			Entertainment Applications
			Emergency (non-medical)

on advances in technology (in micro-electronic miniaturization and integration, sensors, the Internet and wireless networking) the deployment and servicing of health care services will be fundamentally changed and modernized. The use of WBANs is expected to augment health care systems to enable more effective management and detection of illnesses, and reaction to crisis rather than just wellness [2, 12].

Using WBANs in medical applications allows for continuous monitoring of one's physiological attributes such as blood pressure, heart beat and body temperature. In cases where abnormal conditions are detected, data being collected by the sensors can be sent to a gateway such as a cell phone. The gateway then delivers its data via a cellular network or the Internet to a remote location such as an emergency center or a doctor's room based on which an action can be taken [13, 14]. Additionally, WBANs will be a key solution in early diagnosis, monitoring and treatment of patients with possibly fatal diseases of many types, including diabetes, hypertension and cardiovascular related diseases. Medical applications of WBANs can be further classified into three subcategories as follows:

1) Wearable WBAN: Wearable medical applications of WBANs can further be classified into the following two subcategories: a) Disability Assistance, b) Human Performance Management. Some of these applications are mentioned bellow:

Assessing Soldier Fatigue and Battle Readiness – The activity of soldiers in the battlefield can be monitored more closely by WBANs. This can be achieved through a WBAN consisting of cameras, biometric sensors, GPS (Global Positioning System) and wireless networking combined with an aggregation device for communication with other soldiers and centralized monitoring. However, in order to prevent ambushes, a secure communication channel should exist among the soldiers [16]. WBANs can also be used by policemen and fire-fighters [8]. The use of WBANs in harsh environments can be instrumental in reducing the probability of injury while providing improved monitoring and care in case of injury.

Aiding Professional and Amature Sport Training – The training schedules of athletes can easily be tuned via WBANs as they provide monitoring parameters, motion capture and rehabilitation. Moreover, the realtime feedback provided to the user in these networks allows for performance improvement and prevents injuries related to incorrect training [17].

Sleep Staging – Sleep is an important behavior and regular physiological function which consumes one-third of our everyday life. A large population is suffering from sleep disorders - an average of 27% of the world population[5]. The consequences of such disorders can be quite severe and lead to cardiovascular diseases, sleepiness at work place and drowsy driving. The effect of sleep disorder on work performance is estimated to cost 18 billion in lost productivity. Therefore, sleep monitoring has gained great interest in the recent years. Sleep disorders can be realized through a polysomnography test which requires analysis of a number of biopotentials recorded over night in a sleep laboratory. However, these measurements require a lot of cables that run from the head to a box connected to the patient's belt and interrupt the patient from falling sleep. It also disturbs the patient's motion and initiates artifacts and noise that reduce the signal quality. WBANs are capable of delocalization of the intelligence and instruments in their sensor nodes and removal of all cables [18].

Asthma – A WBAN and accompanying sensors are capable of monitoring allergic agents in the air and providing real time feedback to a physician, which can help millions of patients suffering from asthma.

Wearable Health Monitoring – WBANs in conjunction with sensors and other devices on the human body can provide real time health monitoring. For instance, a Gluecocellphone which is a cell phone with a glucose module can be used for patients with diabetes. The cellphone receives glucose diagnoses from the glucose module which may then be stored or sent to a doctor for analysis [17].

2) Implant WBAN: This class of applications is relative to nodes implanted in the human body either underneath the skin or in the blood stream.

Diabetes control – 6.4% of the world's adult population, which represent 285 million people, suffered from diabetes in 2010. This number is estimated to reach 438 million by 2030, 7.8% of the adult population[6]. Research has shown Diabetes to result in long-term medical issues if not carefully monitored and treated[7]. Frequent monitoring provided by WBANs is capable of reducing the risk of fainting, enables proper dosing, and eliminates risks of loss of circulation, later life blindness and more complications.

Cardiovascular Diseases – Cardiovascular diseases are known as the major cause of death for 17 million people

[5]http://www.chinadaily.com.cn/china/2013-03/21/content_16320337.htm
[6]http://www.worlddiabetesfoundation.org/composite-35.htm
[7]http://my.clevelandclinic.org/disorders/diabetes_mellitus/hic_longterm _problems _for _people _with _diabetes.aspx

TABLE II
CHARACTERISTICS OF IN/ON-BODY APPLICATIONS [15]

Application Type	Sensor Node	Data Rate	Duty Cycle (per device) % per time	Power Consumption	QoS (Sensitive to Latency)	Privacy
In-Body Application	Glucose sensor	Few Kbps	$< 1\%$	Extremely low	Yes	High
	Pacemaker	Few Kbps	$< 1\%$	low	Yes	High
	Endoscope Capsule	> 2 Mbps	$< 50\%$	low	Yes	Medium
On-Body Medical Application	ECG	3 Kbps	$< 10\%$	Low	Yes	High
	SpO2	32 Kbps	$< 1\%$	low	Yes	High
	Blood Pressure	< 10 bps	$< 1\%$	High	Yes	Medium
On-Body Non-Medical Application	Music for Headsets	1.4 Mbps	High	Relatively High	Yes	Low
	Forgotten Things Monitor	256 Kbps	Medium	Low	No	Low
	Social Networking	< 200 Kbps	$< 1\%$	Low	No	High

annually[8], which can be significantly reduced or prevented with appropriate health care strategies. Myocardial Infarction (MI) can be greatly reduced by monitoring episodic events and other abnormal conditions through WBAN technology.

Cancer Detection – Cancer death rates are estimated to increase by 50%, reaching up to 15 million by 2020[9]. WBAN based sensors capable of monitoring cancer cells in the human body will enable physicians to continually diagnose tumors without biopsy providing more timely analysis and treatment.

3) Remote Control of Medical Devices: The ubiquitous Internet connectivity of WBANs allows for networking of the devices and services in home care known as Ambient Assisted Living (AAL), where each WBAN wirelessly communicates with a back-end medical network [19]. AAL aims to prolong the self-conducted care of patients that are assisted in their home, minimizing the dependency on intensive personal care, increasing quality of life and decreasing society costs. In fact, ambient assisted living will foster a new generation of IT systems with characteristics such as anticipatory behaviour, context awareness, user friendliness and flexibility [20].

Patient Monitoring – One key application of WBANs is its use in monitoring vital signals, as well as providing real time feedback and information on the recovery process in health monitoring applications. More specifically, they sense and wirelessly transmit vital signal measurements such as heart rate, body temperature, respiration rate, blood pressure, body implant parameters and chest sounds. WBANs are also capable of adminstration of drugs in hospitals, remote monitoring of human physiological data, aid rehabilitation and provide an interface for diagnostics. Continuous patient monitoring, and providing necessary medication when required, are considered as important development areas for WBANs. As WBANs can provide interconnection amongst various devices in or around the body such as hearing aids, digital spectacles and so on, their application could go beyond patient monitoring and also include post-treatment follow-up, pharmaceutical research, trauma care, remote assistance in accidents and research in chronic diseases.

Telemedicine Systems – Available telemedicine systems either use a power demanding protocol like Bluetooth, which is open to interference from other devices working in a similar frequency, or dedicated wireless channels for transferring information to remote stations. Therefore, they restrict prolonged monitoring. Whereas integrating WBANs in a telemedicine system allows for long periods of unobtrusive ambulatory health monitoring.

B. Non-Medical Applications:

Non-Medical applications of WBANs can be further classified into five subcategories as follows:

1) Real Time Streaming: This class of applications involve video streaming such as capturing a video clip by the camera in a cellular phone, trading shows for sport goods along with the latest fashion designs and 3D video. Audio streaming is also possible through voice communication for headsets for instance listening to explanation of art at the museum or listening to the bus schedule information on the bus stop, multicasting for conference calls, browsing music samples in a music CD store. This category also includes stream transfer which is used for remote control of entertainment devices, body gesture recognition/motion capture, vital sign and body information-based entertainment service, identification, emotion detection and to monitor forgotten things by sending an alert to the owner.

2) Entertainment Applications: This category consists of gaming applications and social networking. Appliances such as microphones, MP3-players, cameras, head-mounted displays and advanced computer appliances can be used as devices integrated in WBANs. They can be used in virtual reality and gaming purposes (game control with hand gesture, mobile body motion game and virtual world game), personal item tracking, exchanging digital profile/business card and consumer electronics.

3) Emergency (non-medical): Off-body sensors (eg. built into the house) are capable of detecting a non-medical emergency such as fire in the home or flammable/poisionous gas in the house and must urgently communicate this information to body-worn devices to warn the wearer of the emergency condition [17].

4) Emotion Detection: Recent research has shown the effective realization of human emotions via speech and visual data analysis. More specifically, wearable sensing technologies have enabled emotion detection through the induction of physical manifestations throughout the body that leads to the production of signals to be measured via simple bio-sensors. For instance, fear increases respiration rate and heart-beat, which results in palm sweating and more. Therefore, one's emotional status can be monitored anywhere and anytime through monitoring emotion-related physiological signals like ElectroCardioGraph (ECG), ElectroMyoGraph (EMG), ElectroEncephaloGraph (EEG), Electrodermal Activity (EDA), etc.

[8]http://www.who.int/cardiovascular_diseases/resources/atlas.en
[9]http://www.who.int/mediacentre/news/releases/2003/pr27/en

This can be achieved through wearable bio-sensors that can be integrated in blood pressure sensors, earrings or watches, respiration sensors in T-shirts, conductivity sensors deployed in shoes and more.

5) Secure Authentication: This application refers to utilizing both physiological and behavioral biometrics such as iris recognition, fingerprints and facial patterns. This is one of the key applications of WBANs due to duplicability and forgery, which has motivated the use of new behaviorial/physical characteristics of the human body, in essence multi-modal biometric, gait and electroencephalography [5].

III. History of the IEEE 802.15.6 Standard

Early developments in Wireless Personal Area Networks (WPANs) were first made in the 90s by different groups working at MIT (Massachusetts Institute of Technology). Their initial aim was to interconnect information devices attached to the human body. They also intended to use electric field sensing to determine body positioning, through which the capability of modulating the electric field for data transmission throughout the body was realized.

Recent developments in wireless technologies has a major focus on increasing network throughput which shifts the focus of WPANs to short range, low power and low cost technologies [21]. Network lifetime has a greater importance in WBANs as devices are expected to perform over longer periods of time. Also, WPANs do not satisfy the medical communication requirements because of close proximity to the human body tissue. Thus, a standard model was required for the successful implementation of Body Area Networks addressing both its consumer electronics and medical applications.

The IEEE 802 working group had a number of success stories in the realization of the international standardization for WBANs [10]. A standing committee, Wireless Next Generation (WNG), was established in January 2006, within WG15 (Working Group) aiming for the examination of new topics and directions [22]. In May 2006, an interest group of WBAN, namely, (IG-WBAN) was initially established. The executive committee of IEEE 802 WG15, formally approved IG-WBAN as a Study Group namely SG-WBAN [22]. In January 2008, SG-WBAN was further certified as a Task Group (TG6) under 802.15 [3]. The call for WBAN applications by TG6 was later closed in May 2008 and compiled all submitted application into a single document [23]. The IEEE 802.15.6 working group established the first draft of the communication standard of WBANs in April 2010, optimized for low-power on-body/in-body nodes for various medical and non-medical applications [10]. The approved version of the IEEE 802.15.6 standard was ratified in February 2012 [3] and describes its aim as follows: "To develop a communication standard for low power devices and operation on, in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics, personal entertainment and other."

IV. Requirements of WBANs in IEEE 802.15.6

The main requirements of IEEE 802.15.6 standard are listed below [16, 17, 24–26]:

- WBAN links should support bit rates in the range of 10 Kb/s to 10 Mb/s.
- Packet Error Rate (PER) should be less than 10% for a 256 octet payload for a majority (95%) of the best-performing links based on PER.
- Nodes should be capable of being removed and added to the network in less than 3 seconds.
- Each WBAN has to be capable of supporting 256 nodes (Section IV provides additional clarification on number of nodes).
- Nodes should be capable of reliable communication even when the person is on the move. Although it is acceptable for network capacity to be reduced, data should not be lost due to unstable channel conditions. The considered applications include postural body movements relative to sitting, walking, twisting, turning, running, waving arms and dancing among others which result in the shadowing effect and channel fading. Nodes in a WBAN may move individually with respect to each other, however the WBAN itself may move location resulting in interference.
- Jitter, latency and reliability should be supported for WBAN applications that require them. Latency should be less than 125 ms in medical applications and less than 250 ms in non-medical applications whilst jitter should be less than 50 ms.
- On-body and in-body WBANs should be capable of coexisting within range.
- Up to 10 randomly distributed, co-located WBANs should be supported by the physical layer in a $6m^3$ cube.
- All devices should be capable of transmitting at 0.1 mW (-10 dBm) and the maximum radiated transmission power should be less than 1 mW (0 dBm). This complies with the Specific Absorption Rate (SAR) of the Federal Communications Commission's 1.6 W/Kg in 1g of body tissue [10].
- WBANs should be capable of operating in a heterogenous environment where networks of different standards cooperate amongst each other to receive information.
- A WBAN can incorporate UWB technology with a narrow-band transmission to cover different environments and support high data rates. For instance, some medical application such as ECG monitoring might require a UWB-based WBAN to support higher data rates.
- WBANs must incorporate QoS management features to be self-healing and secure as well as allowing priority services.
- Power saving mechanisms should be incorporated to allow WBANs to operate in a power constrained environment.

V. Characteristics of WBANs

A. Types of Nodes in a WBAN

A *node* in a WBAN is defined as an independent device with communication capability. Nodes can be classified into three different groups based on their *functionality*, *implementation* and *role* in the network. The classification of nodes in WBANs based on *functionality* is as follows:

[10] http://www.fcc.gov/oet/rfsafety/sar.html

Personal Device (PD) – This device is in charge of collecting all the information received from sensors and actuators and handles interaction with other users. The PD then informs the user through an external gateway, a display/LEDs on the device or an actuator. This device may also be called body-gateway, sink, Body Control Unit (BCU) or PDA in some applications [8].

Sensor – Sensors in WBANs measure certain parameters in one's body either internally or externally. These nodes gather and respond to data on a physical stimuli, process necessary data and provide wireless response to information. These sensors are either physiological sensors, ambient sensors or biokinetics [8, 9]. Some existing types of these sensors could be used in one's wrist watch, mobile, or earphone and consequently, allow wireless monitoring of a person anywhere, anytime and with anybody. A list of different types of commercially available sensors used in WBANs are as follows: EMG, EEG, ECG, Temperature, Humidity, Blood pressure, Blood glucose, Pulse Oximetry (SpO_2), CO_2 Gas sensor, Thermistor, Spirometer, Plethysmogram, DNA Sensor, Magnetic Biosensor, Transmission Plasmon Biosensor, Motion (Gyroscope/Accelerometer/Tri-Axial Accelerometer), etc.

Actuator – The actuator interacts with the user upon receiving data from the sensors [8]. Its role is to provide feedback in the network by acting on sensor data, for example pumping the correct dose of medicine into the body in ubiquitous health care applications [27].

IEEE 802.15.6 has proposed another classification for nodes in a WBAN based on the way they are *implemented* within the body, which is provided as follows [13, 28]:

Implant Node – This type of node is planted in the human body, either immediately underneath the skin or inside the body tissue.

Body Surface Node – This type of node is either placed on the surface of the human body or 2 centimeters away from it.

External Node – This type of node is not in contact with the human body and rather a few centimeters to 5 meters away from the human body.

The classification of nodes in WBANs based on their *role* in the network is as follows:

Coordinator – The coordinator node is like a gateway to the outside world, another WBAN, a trust center or an access coordinator. The coordinator of a WBAN is the PDA, through which all other nodes communicate.

End Nodes – The end nodes in WBANs are limited to performing their embedded application. However, they are not capable of relaying messages from other nodes.

Relay – The intermediate nodes are called relays. They have a parent node, possess a child node and relay messages. In essence if a node is at an extremity (e.g. a foot), any data sent is required to be relayed by other nodes before reaching the PDA. The relay nodes may also be capable of sensing data.

B. Number of Nodes in a WBAN

In [29–32], which are drafts of IEEE standards related to technical requirements of WBANs, the number of nodes in a WBAN is stated to range from a few actuators or sensors communicating with a portable handset reaching up to tens to hundreds of actuators or sensors communicating with a gateway to the Internet. A typical medical network based on WBANs is stated to have 6 nodes with a scalable configuration that supports up to 256 nodes [32]. The requirements stated in [30] also mention an operating range of $3m$ for WBANs, reaching up to 10 piconets per person with the support of 256 nodes in each network within a $6m^3$ cube [26, 33, 34]. Only one hub is allowed to exist in a WBAN with its number of nodes ranging from 0 to $nMaxBANSize$; which is defined to be 64 in the IEEE 802.15.6 standard due to limitations in transmission strategy [35]. But, since 2-4 WBANs are stated to coexist on the same person (per m^2) [31], a maximum of 256 nodes can exist per network. In respect to address allocation, a one-octet WBAN identifier (WBAN ID) is utilized for allocating an abbreviated address to a node, hub or WBAN in its frame exchanges [36]. The value of this octet ranges between $x00$ and xFF (0-255).

Although the number of nodes in a WBAN is not generally limited, due to limitations in the nature of the network in terms of communication protocols, network architecture and transmission techniques the numbers can be limited in real application scenarios [8]. For instance, in [2] the maximum number of nodes in a WBAN is stated to be 20 nodes as each superframe of length 1 second is divided into non-overlapping 50 ms time slots; thus, enabling 20 nodes to transmit orthogonally. In [36], the maximum number of nodes is considered to be 50, which has been determined as a total of 50 orthogonal channels designed to be allocated to the nodes in each time frame. In fact, the type and number of devices that form a WBAN is stated to change over time based on their interaction with other WBANs and the environment.

C. Topology used in WBANs

The IEEE 802.15.6 working group has considered WBANs to operate in either a one-hop or two-hop star topology with the node in the center of the star being placed on a location like the waist [21, 37]. Two feasible types [38] of data transmission exist in the one-hop star topology: *transmission from the device to the coordinator* and *transmission from the coordinator to the device*.

The communication methods that exist in the star topology are *beacon mode* and *non-beacon mode*. In the *beacon mode*, the network coordinator, which is the node in the center of the star topology controls the communication. It transmits periodic beacons to define the beginning and the end of a superframe to enable network association control and device synchronization. The duty cycle of the system, which is the length of the beacon period, can be specified by the user and based on WBAN's standard [38, 39]. In the *non-beacon mode*, a node in the network is capable of sending data to the coordinator and can use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) when required. The nodes need to power up and poll the coordinator to receive data. However, the coordinator cannot communicate with the nodes at all times as the nodes must wait till they are invited to participate in a communication [38].

Since both one-hop and two-hop star topologies exist in WBANs, careful considerations need to be taken into account

TABLE III
COMPARISON OF ONE-HOP STAR NETWORK AND MULTI-HOP NETWORK [40]

Comparison criteria	Star Networks	Multi-Hop Networks
Energy Consumption	For nodes in close proximity to the PDA, the power used to transmit to the PDA will be low. The nodes further away, however, will consistently require more power to be able to transmit information.	The nodes that are closest to the PDA consume more energy as they will have to forward not only their own information but also information from other nodes.
Transmission Delay	The star network presents the least possible delay present in transmission from any sensor to the PDA, as there is only a single hop.	Dependent on how the network is configured. In terms of delay, the nodes closest to the PDA can get their information through quickly, without any intermediate relay.
Interference	Sensors that are farther away from the PDA require transmission with higher power, increasing the amount of interference.	Since each node is only transmitting to its neighbor nodes, the energy of transmission is kept low and hence mitigates the effects of interference.
Node Failure and Mobility	Only the failed node will be affected and the rest of the network can perform as needed.	The part of the network that involves the failed node has to be reconfigured. Overheads are involved.

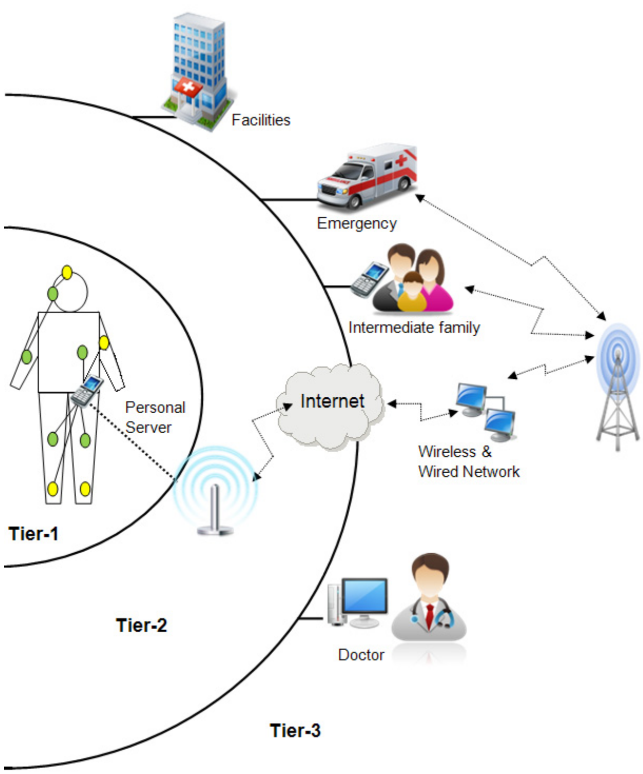

Fig. 2. Communication Tiers in a Wireless Body Area Network

upon the choice of the one-hop or the two-hop topology. When all nodes in the network are directly connected to the sink, the network is considered to have a one-hop star topology. In a WBAN, the coordinator is known as the sink node to which all nodes talk. However, in a multi-hop architecture nodes are connected to access points via other nodes. Table III provides a comparison between a multi-hop network and a one-hop star topology [40]. This table shows that multi-hop transmission has a higher delay and lower transmission power compared to the one-hop star topology. The multi-hop configuration involves overheads along with its network operation; as increasing the number of hops could lead to a high complexity. More specifically, using relays in WBANs assists in reducing the concentration of the transmission power from the source to its destination. Thus, the further apart the source and destination are in distance, the higher transmission power is required. Through the use of relays, the transmission heat will be distributed and a convenient heat will be obtained for the surrounding area of the transmitting sensor. As per the latest version of the IEEE standard proposed for WBANs in February 2012 [3], only two hops are supported in IEEE WBAN standards compliant communication. Proprietary systems could use more than two hops, but then inter-operability would be a problem, as they would not be standard-compliant.

D. *Communication Architecture of WBANs*

The communication architecture of WBANs can be separated into three different tiers as follows:

- Tier-1: Intra-WBAN communication
- Tier-2: Inter-WBAN communication
- Tier-3: Beyond-WBAN communication

Fig. 2 illustrates these communication tiers in an efficient, component-based system for WBANs. In Fig. 2, the devices are scattered all over the body in a centralized network architecture where the exact location of a device is application-specific [41]. However, as the body may be in motion (e.g. running, walking) the ideal body location of sensor nodes is not always the same; hence, WBANs are not regarded as being static [8].

Tier-1: Intra-WBAN communication – Tier-1 depicts the network interaction of nodes and their respective transmission ranges ($\sim$ 2 meters) in and around the human body. Fig. 2 illustrates WBAN communication within a WBAN and between the WBAN and its multiple tiers. In Tier-1, variable sensors are used to forward body signals to a Personal Server (PS), located in Tier-1. The processed physiological data is then transmitted to an access point in Tier-2.

Tier-2: Inter-WBAN communication – This communication tier is between the PS and one or more access points (APs). The APs can be considered as part of the infrastructure, or even be placed strategically in a dynamic environment to handle emergency situations. Tier-2 communication aims to interconnect WBANs with various networks, which can easily be accessed in daily life as well as cellular networks and the Internet [5]. The more technologies supported by a WBAN, the easier for them to be integrated within applications.
The paradigms of inter-WBAN communication are divided into two subcategories as follows:

Infrastructure based architecture – The architecture shown in Fig. 3 is used in most WBAN applications as it facilitates dynamic deployment in a limited space such as a hospital

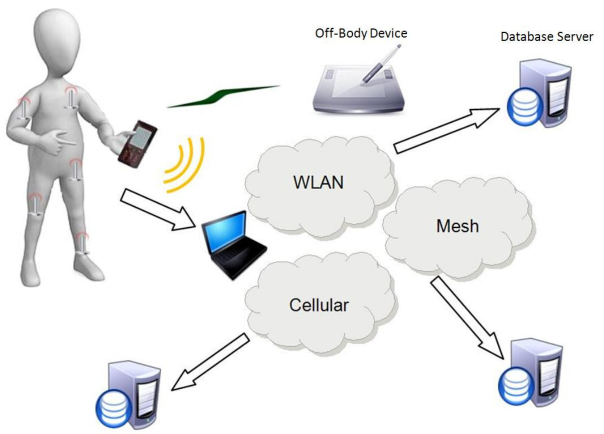

Fig. 3. Inter-WBAN Communication: Infrastructure-based mode

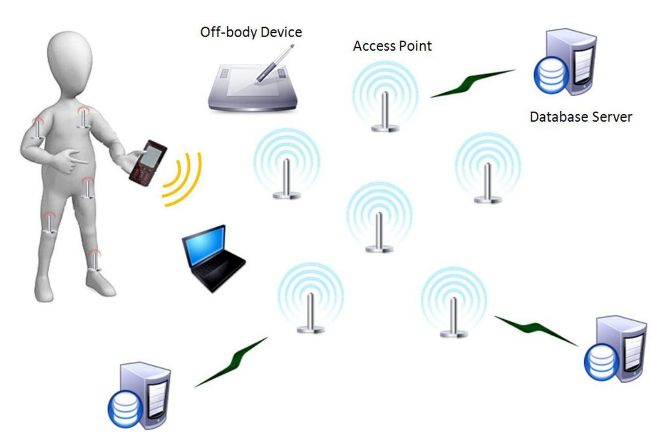

Fig. 4. Inter-WBAN Communication: Ad-Hoc based mode

as well as providing centralized management and security control. The AP can act as a database server related to its application [5].

Ad-hoc based architecture – In this architecture, multiple APs transmit information inside medical centers as shown in Fig. 4. The APs in this architecture form a mesh construction that enables flexible and fast deployment, allowing for the network to easily expand, provide larger radio coverage due to multi-hop dissemination and support patient mobility. The coverage range of this configuration is much larger compared to the infrastructure based architecture, and therefore facilitates movement around larger areas. In fact, this interconnection extends the coverage area of WBANs from 2 meters to 100 meters, which is suitable for both short and long term setups [5].

Tier-3: Beyond-WBAN Communication – The design of this communication tier is for use in metropolitan areas. A gateway such as a PDA can be used to bridge the connection between Tier-2 and this tier; in essence from the Internet to the Medical Server (MS) in a specific application [8]. However, the design of Tier-3 for communication is application-specific. In essence, in a medical environment a database is one of the most important components of Tier-3 as it includes the medical history and profile of the user. Thus, doctors or patients can be notified of an emergency status through either the Internet or a Short Message Service (SMS). Additionally, Tier-3 allows restoring all necessary information of a patient which can be used for their treatment [5]. However, depending on the application, the PS in Tier-1 can use GPRS/3G/4G instead of talking to an AP.

VI. Layers of WBANs

Generally, all approved standards of 802.15.x propose PHY and MAC layers. They do not supply any network, transport or application layer and therefore call for other parties to develop them. The IEEE 802.15.6 (WBAN) working group has defined new Physical (PHY) and Medium Access Control (MAC) layers for WBANs that provide low complexity, low cost, high reliability, ultra-low power and short range wireless communication in or around the human body. The standard has also mentioned that "There may be a logical node management entity (NME) or hub management entity (HME) that exchanges network management information with the PHY and MAC as well as with other layers".

A. Physical Layer

The PHY layer of IEEE 802.15.6 is responsible for the following tasks: activation and deactivation of the radio transceiver, Clear channel assessment (CCA) within the current channel and data transmission and reception. The choice of the physical layer depends on the target application: medical/non-medical, in, on and off-body. The PHY layer provides a procedure for transforming a physical layer service data unit (PSDU) into a physical layer protocol data unit (PPDU). IEEE 802.15.6 has specified three different physical layers: Human Body Communication (HBC), Narrow Band (NB) and Ultra-Wide Band (UWB).

NB PHY is responsible for data transmission/reception, activation or deactivation of the radio transceiver and Clear Channel Assessment (CCA) in the current channel. Based on the NB specifications, in order to construct PPDU, the PSDU has to be pre-appended with a Physical Layer Preamble (PLCP) and a physical layer header (PSDU) shown in Fig. 6. The PCLP preamble aids the receiver in carrier-offset recovery, packet detection and timing synchronization. The PCLP header is sent after the PCLP preamble via the data rates given in its operating frequency band. It transfers the necessary information required for successfully decoding a packet to its receiver. The PSDU, which is the last component of PPDU contains a MAC header, a MAC frame body and a Frame Check Sequence (FCS) [10]. NB PHY uses Differential 8-Phase-shift Keying (D8PSK), Differential Binary Phase-shift Keying (DBPSK) and Differential Quadrature Phase-shift Keying (DQPSK) modulation techniques except at 420-450 MHz where it uses the Gaussian Minimum Shift Keying (GMSK) modulation technique.

HBC PHY provides the Electrostatic Field Communication (EFC) requirements that covers modulation, preamble/Start Frame Delimiter (SFD) and packet structure. The structure of the Physical Protocol Data Unit (PPDU) is composed of the PLCP preamble, Start Frame Delimiter (SFD), PLCP Header, and PHY Payload (PSDU) as shown in Fig. 5. The SFD and preamble are specified data patterns. They are pre-generated and sent before the payload and packet header. The

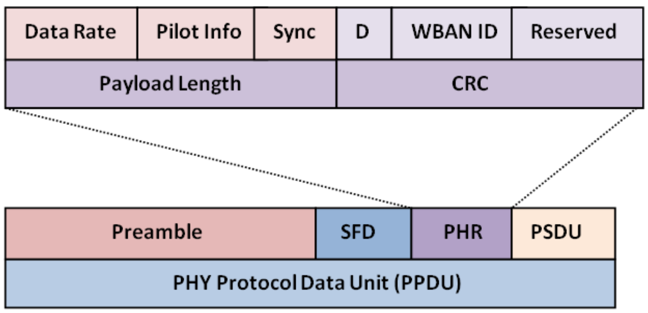

Fig. 5. HBC PPDU Structure of IEEE 802.15.6

SFD sequence is only transmitted once, whereas the preamble sequence is sent four times to assure packet synchronization. The initial PLCP preamble is created as a 64-bit gold code sequence which is repeated four times and is spread using a Frequency Shift Code (FSC). The SFD sequence is also created by using a 64-bit gold code generator that is spread using an FSC. Once the receiver has received the packet, it uses the preamble sequence to detect the beginning of the packet. It then detects the start of the frame using the SFD [10]. The PHY header consists of the following fields: data rate, pilot information, synchronization, WBAN ID, payload length and a CRC calculated over the PHY header.

The UWB physical layer is used for communication between on-body devices and for communication between on-body and off-body devices. Transceivers in a UWB PHY generate similar signal power levels to that used in the MICS band and also allow low implementation complexity. Based on the specifications for UWB PHY, the PPDU bits are converted into RF signals for transmission in the wireless medium. UWB PPDU consists of a Synchronization Header (SHR), a PHY Header (PHR) and PSDU. The SHR is made up of repetitions of Kasami intervals of length 63. It consists of two subfields: the first subfield is a preamble that is intended for packet detection, timing synchronization, and frequency offset recovery; and the second subfield is the SFD shown in Fig. 8. The physical header carries information about the scrambler seed, length of the payload and the data rate of the PSDU. The receiver uses the information in the PHR to decode the PSDU.

A key issue in the development of the IEEE 802.15.6 standard was the selection of physical layer frequency bands to be utilized given varying worldwide regulations. Fig. 7 shows the different frequency bands used by WBANs in IEEE 802.15.6. Ultrawideband frequencies offer higher data rates and higher throughput whilst lower frequencies have less shadowing and attenuation from the body [42]. Table. IV specifies the frequency bands and channel bandwidths for these propagation methods.

The HBC PHY has a bandwidth of 4 MHz and operates in two frequency bands centered at 16 MHz and 27 MHz. The United States, Japan and Korea support both of these frequency bands whereas Europe only supports the 27 MHz operating band.

The NB PHY uses seven different frequency bands shown in Table. IV. It offers various bit rates, channels and modulation schemes. The first licensed band in NB PHY is the Medical Implant Communication Service (MICS) utilized for implant communication with a range of 402-405 MHz in most countries. The next licensed band in NB PHY is the Wireless Medical Telemetry Services (WMTS) utilized in medical telemetry systems. Neither MICS nor WMTS support high data rate applications. The Industrial, Scientific and Medical (ISM) band is available worldwide and supports high data rate applications. But, since various wireless devices such as IEEE 802.15.4 and IEEE 802.15.1 use the ISM band, there is a high probability for interference [10]. The sixth band (2360-2400 MHz) of NB PHY is assigned for medical device use. The seventh band (2400-2483.5 MHz) is a license-free ISM band that has been used most commonly [21]. Importantly the 2360-2400 band is not an ISM band; hence, interference is significantly reduced compared to the 2400+ ISM band.

Two frequency bands exist in the UWB PHY: high band and low band; each of which are divided into channels with a bandwidth of 499.2 MHz. The low band only has 3 channels: (1-3). Channel 2 is considered as a mandatory channel with the central frequency of 3993.6 MHz. The high band has eight channels: (4-11). Channel seven is considered as a mandatory channel with the central frequency of 7987.2 MHz. All other channels are considered to be optional. At least one of the mandatory channels has to be supported by a UWB device. Data rates are typically in the range of 0.5 Mbps to 10 Mbps with 0.4882 Mbps for the mandatory channel [10].

B. MAC Layer

The IEEE 802.15.6 working group defines a MAC layer on top of the PHY layer in order to control channel access. The hub (or coordinator) divides the entire channel (or time axis) into a chain of superframes for time referenced resource allocations. The hub also chooses beacon periods of equal length to bound the superframes. The offsets of the beacon periods can also be shifted by the hub. The beacons are normally sent in each beacon period unless prohibited by regulations in the MICS band or inactive superframes [10].

The coordinator is responsible for channel access coordination through one of the following three access modes:

1) Beacon Mode with Beacon Period Superframe Boundaries: In this channel access mode, the hub sends beacons in each beacon period unless prohibited by restrictions in the MICS band or inactive superframes. The hubs manage the communication of the superframe structure using Timed frames (T-poll) or beacon frames. The superframe structure of IEEE 802.15.6 is shown in Fig. 9. It consists of an Exclusive Access Phase 1 (EAP1), a Random Access Phase 1 (RAP1), a Type I/II phase, an Exclusive Access Phase 2 (EAP 2), a Random Access Phase 2 (RAP 2), a Type I/II phase, and a Contention Access Phase (CAP). In CAPs, RAPs and EAPs, nodes strive for resource allocation via either the slotted Aloha access procedure or CSMA/CA. EAP1 and EAP2 are utilized for high priority traffic such as reporting emergency events; while CAP, RAP1 and RAP2 are only used for regular traffic. Type I/II phases are utilized for bi-link allocation intervals, downlink allocation intervals, uplink allocation intervals, and delay bi-link allocation intervals. Polling is used in type

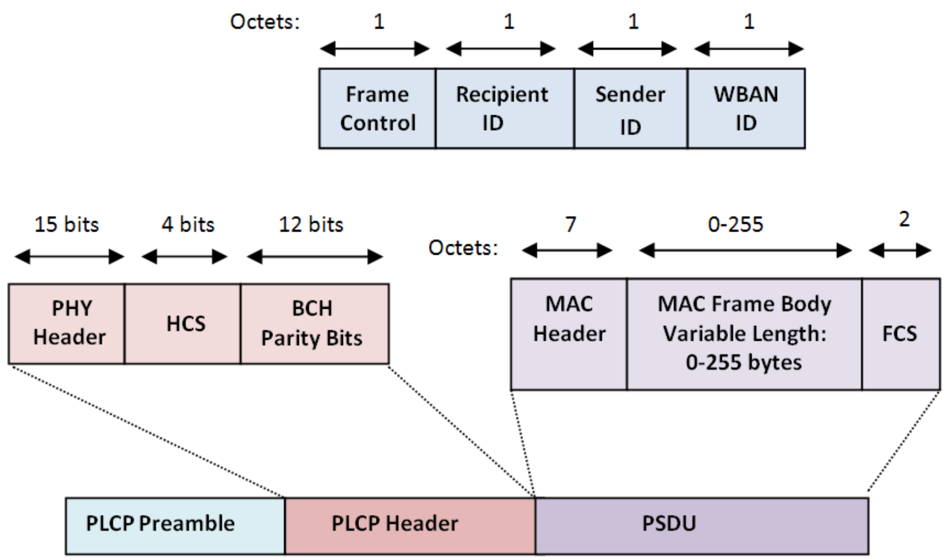

Fig. 6. NB PPDU Structure of IEEE 802.15.6

I/II phases for resource allocation. Based on the application requirements, any of these periods can be disabled by setting the duration length to zero. This channel access mode is most considered by researchers and developers.

2) Non-beacon mode with superframe boundaries: This access mode is not capable of transmitting beacons and is forced to use the Timed frames (T-poll) of the superframe structure. The whole superframe is either covered by one Type I or one Type II access phase, but not both.

3) Non-beacon mode without superframe boundaries: In this access mode, only unscheduled Type II polled allocation is provided by the coordinator, meaning each node has to establish its own time schedule independently.

Three categories of access mechanisms exist in each period of the superframe, which are as follows:

(a) *Scheduled access and variants (connection-oriented contention-free access)* – This access mechanism schedules slot allocation in one or multiple upcoming superframes also named after 1-periodic or m-periodic allocations.

(b) *Unscheduled and improvised access (connectionless contention-free access)* – This access mechanism utilizes posting or polling for resource allocation.

(c) *Random access mechanism* – In this access mechanism either the slotted Aloha procedure or CSMA/CA are used for resource allocation.

VII. Channel Model

Nodes in WBANs are scattered in and over the whole body [8], which creates multiple transmission channels between the nodes based on their location in/on the body. The channel models proposed by IEEE 802.15.6 SGBAN are shown in Table V. In scenarios S_1,S_2 and S_3 in cases where a hundred sensors are attached to a person's body, the system becomes quite bulky to be carried around. Thus, the USA Federal Communications Commission (FCC) and communication authorities of other countries have allocated the MICS band at 402-405 MHz with 300KHz channels to enable wireless communication with implanted medical devices. This leads to better penetration through the human tissue compared to higher frequencies, high level of mobility, comfort and better patient care in implant to implant (S1), implant to body surface (S2) and implant to external (S3) scenarios. Additionally, the 402-405 MHz frequencies have conducive propagation characteristics for the transmission of radio signals in the human body and do not cause severe interference for other radio operations in the same band. In fact, the MICs band is an unlicensed, ultra-low power, mobile radio service for transmitting data to support therapeutic or diagnostic operation related to implant medical devices and is internationally available. It is specifically chosen to provide low-power, small size, fast data transfer as well as a long communication range. The frequency range of the MICS band allows high-level integration with the radio frequency IC (RFIC) technology, which leads to miniaturization and low power consumption. In summary, high level integration is difficult at lower frequencies, and higher frequencies cause severe penetration loss. In fact there is a severe amount of penetration loss at high frequencies (10 dB for 10mm tissue penetration) [43].

Table VI provides a list of different frequency bands based on which the WBAN channel model can be built [28]. These scenarios are established based on the distance of the communication nodes, which are body surface, implant and external; and grouped in classes represented by the Channel Model (CM). External devices are considered to reach a maximum distance of up to 5 meters.

Another important approach is to differentiate electromagnetic wave propagation from devices in or around the body. However, due to the complex structure of the body shape and human tissue, a simple path loss model cannot be easily modeled for WBANs. Moreover, as the node's antenna is either placed in or on the body, the influence of the body on radio propagation also needs to be considered [28].

The authors of [44] have used three types of antennas to characterize two on-body channels at 2.45 GHz, 5.8 GHz and

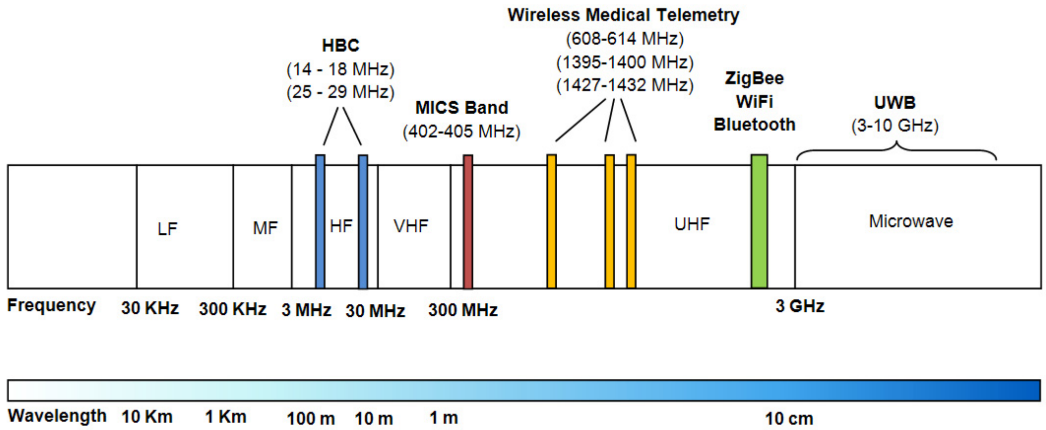

Fig. 7. WBAN Frequency bands

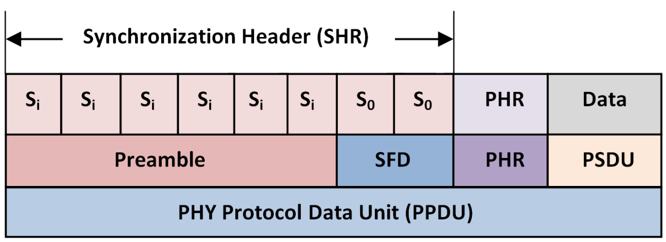

Fig. 8. UWB PPDU Structure of IEEE 802.15.6

TABLE IV
FREQUENCY BAND AND BANDWIDTH OF DIFFERENT PHY LAYERS OF IEEE 802.15.6

Human-Body Communication	
Frequency	Bandwidth
16 MHz	4 MHz
27 MHz	4 MHz
Narrowband Communication	
Frequency	Bandwidth
402-405 MHz	300 kHz
420-450 MHz	300 kHz
863-870 MHz	400 kHz
902-928 MHz	500 kHz
956-956 MHz	400kHz
2360-2400 MHz	1 MHz
2400-2438.5 MHz	1 MHz
UWB Communication	
Frequency	Bandwidth
3.2-4.7 GHz	499 MHz
6.2- 10.3 GHz	499 MHz

10 GHz. Additionally, they have shown long term fading to best fit to a log-normal distribution and short-term fading of the combined signals and envelopes of the branch to be Rician for the fading environment of on-body channels. In [45], two path loss models have been studied that operate at 2.4 GHz and 5.8 GHz and consider propagation channel characterization among two wearable devices that had been placed on a human body. On-body propagation channels for narrowband propagation have shown to present high variability due to relative movement of the body parts. As for UWB channel characterization for WBANs, in cases where surface waves were dominant amongst all waves traveling along the human body via the use of Self-complementary printed horn (HSCA)

TABLE V
SCENARIOS AND DESCRIPTION OF CHANNEL MODELS IN IEEE 802.15.6 [28]

Scenario	Description	Frequency Band	Channel Model
S1	Implant to Implant	402 - 405 MHz	CM1
S2	Implant to Body Surface	402 - 405 MHz	CM2
S3	Implant to External	402 - 405 MHz	CM2
S4	Body Surface to Body Surface (LOS)	13.5, 50, 400, 600, 900 MHz, 2.4, 3.1 - 10.6 GHz	CM3
S5	Body Surface to Body Surface (NLOS)	13.5, 50, 400, 600, 900 MHz, 2.4, 3.1 - 10.6 GHz	CM3
S6	Body Surface to External (LOS)	13.5, 50, 400, 600, 900 MHz, 2.4, 3.1 - 10.6 GHz	CM4
S7	Body Surface to External (NLOS)	13.5, 50, 400, 600, 900 MHz, 2.4, 3.1 - 10.6 GHz	CM4

antenna, decrement in mean Root Mean Square (RMS) delay spread has been noticed [46]. In [47], the physical layer of WBANs is characterized and an estimation on path loss and delay spread in between two nodes using two half-wave length dipoles around the human body has been considered. The path loss exponent is calculated to be 3.1 for line of sight communication using a realistic human body phantom in free space and a multipath environment. The legs and arms have been considered to have similar path loss and the torso has been investigated as having the highest amount of path loss. The RMS delay spread and mean excess delay are shown to increase when antennas are separated. These parameters are used in the path loss model determination and have shown excellent verification to the measured results. Also, a log-normal distribution is described for the extracted models and the distribution function of the derivation of excess delay and RMS delay spread.

In [24], a lognormal distribution is stated to be the best model for small-scale fading in UWB communications. Whilst, either a lognormal distribution or a gamma distribution is stated to be the best fit for small-scale fading in narrowband communications. Importantly, the generalized gamma distribution consists of both of these distributions. Combined models that consider all on-body transceiver locations, which include a typical path loss and small scale fading model with respect to particular locations, are suitable to describe general WBAN applications. In [24], the statistical models used in literature,

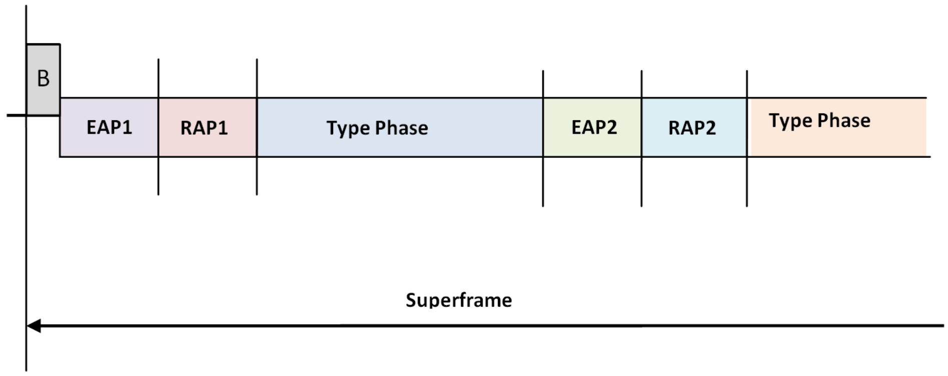

Fig. 9. Superframe Structure of IEEE 802.15.6 [10]

TABLE VI
LIST OF FREQUENCY BANDS FOR IEEE 802.15.6 [28]

Description	Frequency Band
Implant	402 - 405 MHz
On-body	13.5 MHz
On-body	5-50MHz (HBC)
On-body	400 MHz
On-body	600 MHz
On-body	900 MHz
On-body	2.4 GHz
On-body	3.1-10.6 GHz

applied to the simulated or measured channel gain data to describe fading in WBANs, have been compared [48–52]. The most commonly attempted distribution fit is lognormal, followed by Nakagami-m then Ricean. Whilst the best-fit for a particular distribution at any given attempt is most often Weibull, lognormal and gamma[11]. Even though Nakagami-m is most often used as a fit, it has a smaller success rate; and Ricean has considerably smaller success rate compared to Nakagami-m. The Rayleigh distribution, however, is a poor fit for most scenarios and environments where it is used. The details of this comparison can be further studied in [24].

A. Interference

Since a WBAN is most likely to encounter other WBANs, inter-WBAN interference is of the utmost importance. The IEEE 802.15.6 task group requires the system to function properly within a transmission range of up to 3 meters when up to 10 WBANs are co-located [3]. The different types of radio interference that can be encountered in WBANs are shown in Fig. 10. One type of interference occurs when numerous people wearing WBAN devices step into each others range, which makes coordination infeasible (off-body interference). Collision from external sensors may also lead to this type of interference [53]. Additionally, the unpredictable nature of postural body movements leads to networks easily moving into and out of each others range [42]. This issue becomes even more crucial in the case of wireless technologies with higher coverage areas.

Generally interference occurs when no-coordination exists amongst multiple WBANs that coexist in each other's vicinity

[11]considering those distributions tested 10 or more times [24]

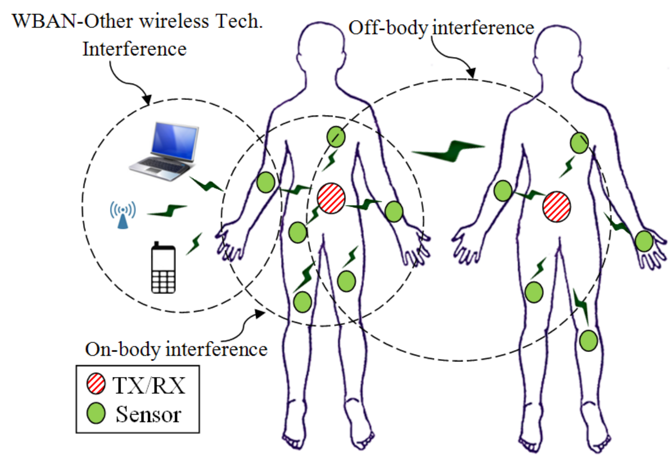

Fig. 10. Interference in WBANs

(Inter-WBAN Interference) [54, 55]. However, due to the nature of a WBAN and its high mobility it is infeasible to allocate a global coordinator to control coexistence amongst multiple WBANs [56]. In cases where co-located WBANs use the same channel (similar frequencies), transmissions can conflict; as the active periods can overlap. Moreover, with the increase in the number of WBANs that can coexist in short proximity of each other, the communication link can suffer performance degradation. Even in cases where small number of WBANs are deployed in each other's vicinity, the received signal strength of the interfering signal can be quite high, which affects the performance of a particular WBAN [54].

B. Data Rates and Power Requirements

One of the main constraints in WBANs is their limited power supply. Fig. 11 shows a comparison between power requirements and data rates in WBANs compared to other wireless technologies. Accordingly, WBAN protocols require higher power efficiency when compared to the other existing protocols. The sensors in WBANs are capable of transmitting data in a wide range of data rates from 1 Kbit/s to 10 Mbit/s [57]. In essence, the data rate of in-body nodes vary from few Kbps in a pacemaker to quite a few Mbps in a capsular endoscope. Fig. 11 shows that the current technologies meet the speed requirement of IEEE 802.15.6 in terms of data rates but not the power requirements of less than 10mW in WBANs. Currently, most devices used in WBANs store their recorded data or transmit them to a monitoring station that uses IEEE 802.15.4 (Bluetooth) or 802.15.1 (Zig-Bee), which do not meet the power requirements for WBANs.

C. Antenna Design

One major challenge for antenna design in WBANs is related to alterations in the antenna topology based on the shape of the human body, which specifies the need for flexible and textile antennas. However, these types of antennas are not easily adjustable to body dynamics as they are mainly built on top of substrates with little deformation capability [58]. One other major challenge is due to the electromagnetic interaction between the human body and the antenna. The human body is considered as a large inhomogeneous object with high loss and permittivity, which effects the properties of an antenna being placed in its close proximity. Therefore, the most important factors towards the practical deployment of body-antennas can be evaluated through numerical analysis and measurement setup of the radiation signature outside the body, and the resonance characteristics of implanted antennas. Additionally, the surrounding environment of an antenna must be given in-depth consideration [59]. Various other parameters of a user such as weight loss/gain, posture and skin change with age also need to be considered for antenna design in WBANs. Also the limitations of shape, size, material and the intrinsic environment need to be taken into account. In addition, the location of an antenna in the body has major control on the size and shape of the antenna being used, therefore restricting the designer. Moreover skin tissue, muscle and fat change characteristics in respect to heating effects of the electric field should also be considered in WBAN antenna design. Existing antennas in WBANs may be classified into two groups [28]:

1) Magnetic antennas: Magnetic antennas, such as loop antennas, generate an E-field that is mostly tangential to the body tissue and, therefore are not capable of coupling as strongly as the electric antennas. Consequently, body fat does not heat up. Some partially similar antennas to the magnetic antennas are the helical-coil antennas, which have the same heating characteristics as the electrical antennas. Tissue heating is mainly a result of the strong Electrical Field (E-field) existing between the coils [28]. Additionally, the Specific Absorption Rate (SAR) of the far field transmitting antenna is mainly related to the E-field, whereas the SAR of the near field transmitting antenna is related to the Magnetic Field (H-field) [28].

2) Electric antennas: Electric antennas such as dipole antennas form a large amount of E-field perpendicular to the body that is absorbed and increases the temperature of the human tissue. This is because the boundary requirement of the E-field is discontinuous by the ratio of its permittivities at the E-field. Since muscle has higher permittivity than fat, the E-field of the fat tissue is generally higher [28].

The human body is not considered as an ideal medium for electromagnetic wave transmission at radio frequencies.

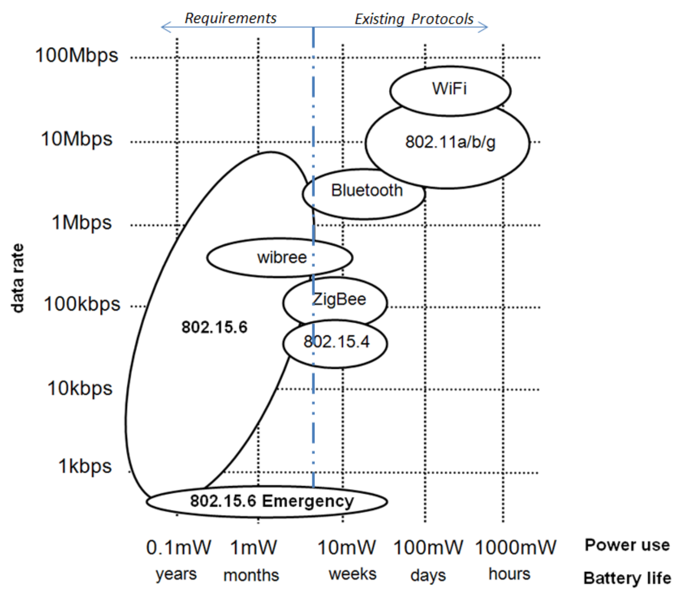

Fig. 11. Power Requirements and Data Rates in WBANs [60]

In Table VII, the electrical properties of the body at three different frequencies are shown. As also seen from Table VII, muscle and fat have different characteristic impedances Z(Ω), conductivities ρ and dielectric constants ϵ_r. Consequently, based on the utilized frequency, high path loss occurs in the human body due to central frequency shift, power absorption and alterations in the radiation pattern. Additionally, absorption effects differ in magnitude based on the characteristics of the tissue and the frequency of the applied field [28]. In general, propagation throughout the body is affected in numerous ways due to the electrical properties of the body, which are as follows:

(1) Body tissue is semi-conductive and therefore capable of absorbing some of the signal.

(2) Body tissue can react as a parasitic radiator.

(3) The electrical length of the electric field antennas like dipoles increase as dielectric constant increases.

The antennas designed for WBANs are classified into two groups based on their location to be either placed on the body or in the body. A brief explanation of these classifications is provided as follows:

In-body Antenna Design – As for the antennas being implanted in the body, only specific types of materials such as titanium or platinum can be used due to their bio-compatible and non-corrosive chemistry, whilst a copper antenna has better performance [5]. The MICS band which is from 402-405 MHz is allocated for in-body communication. The wavelength of this frequency is 744mm and the half wave dipole is 372mm. However, an antenna with such dimensions is not applicable to in-body operation and therefore these constraints lead to a much smaller size than the optimum.

On-body Antenna Design – Two key requirements for on-body communication of antennas are the antenna radiation pattern and the sensitivity of antennas to the human body. In [61], a comparison of antenna combinations for on-body communication is provided. Various antennas have been designed

TABLE VII
ELECTRICAL PROPERTIES OF THE HUMAN BODY [15]

Frequency (MHz)	Muscle			Fat		
	ϵ_r	$\rho(S.m^{-1})$	$Z_0(\Omega)$	ϵ_r	$\rho(S.m^{-1})$	$Z_0(\Omega)$
100	66.2	0.73	31.6	12.7	0.07	92.4
400	58	0.82	43.7	11.6	0.08	108
900	56	0.97	48.2	11.3	0.11	111

and constructed in the 2.5 GHz and ISM band, such as loop antennas, patch antennas, patch array antennas and monopole antennas. Amongst which, the monopole and monopole combinations provide the least link loss and the highest path gain (path gain interprets as the product of all transfer functions along a path) [61]. Whereas, patch antennas that do not require additional space are capable of reducing the spread of the path gain and therefore eliminate multi-path fading [62]. Some other existing antennas such as the spiral, the bow tie, the trailing wire, the Planar Inverted-F Antenna (PIFA) and the loaded PIFA are also applicable in different scenarios.

VIII. SECURITY IN WBANS

Even though security issues are made a high priority in most networks, little study has been done in this area for WBANs. Additionally, due to stringent resource constraints in terms of power, memory, communication rate and computational capability as well as inherent security vulnerabilities, the security specifications proposed for other networks are not applicable to WBANs. The practical deployment of WBANs and the integration of convenient security mechanisms requires knowledge of the security requirements of WBANs which are provided as follows [63]:

1. *Secure Management* – The decryption and encryption operation requires secure management at the coordinator in order to provide key distribution to wireless body area networks. The WBAN coordinator adds and removes WBAN nodes in a secure manner during association and disassociation.

2. *Availability* – The availability of the patient's information to the physician needs to be ensured at all times. An attack towards availability in WBANs could be capturing and disabling an ECG node leading to loss of life. Therefore, the operation, maintenance and capability to switch to another WBAN in case of availability loss is essential.

3. *Data Authentication* – Medical and non-medical applications require data authentication. Both WBAN nodes and the coordinator node require verification that data is being sent from the trust center and not a false adversary. Network nodes in a WBAN and the coordinator node compute a Message Authentication Code (MAC) for all data by sharing a secret key. When the correct MAC is calculated, the network coordinator will realize that the received message is being sent by a trusted node.

4. *Data integrity* – When data is transmitted to an insecure WBAN, its information can be altered. An adversary will then be capable of modifying a patient's information prior to reaching the network coordinator, thus endangering the patient's health and maybe even their life. Therefore, the received data needs to be assured of not being altered by an adversary through proper data integrity by using data authentication protocols.

5. *Data confidentiality* – Protection of data from disclosure is achievable through data confidentiality. WBAN nodes in medical applications transmit sensitive information regarding the status of a patient's health. Critical information can be overheard and eavesdropping is possible in communication, which may cause a considerable amount of damage towards a patient as the data can be issued for illegal purposes. Data confidentiality can be achieved through encryption of a patient's data via a shared key on a communication channel secured among the WBAN nodes and their coordinator.

6. *Data Freshness* – Data integrity and confidentiality can only be supported if data freshness techniques are used. An adversary is capable of capturing data in transmissions and later replaying to create confusion for the WBAN coordinator. Data freshness assures that data is not reused and its frames are in order. Two types of data freshness exist which are as follows: *strong freshness* that guarantees delay as well as frame ordering, and *weak freshness* which provides no guarantee in terms of delay. Strong freshness is necessary in synchronization while a beacon is being transmitted to the WBAN coordinator, whereas weak freshness is necessary for WBAN nodes with low-duty cycle.

The IEEE 802.15.6 standard has proposed a security paradigm for WBANs shown in Fig. 12, that defines three levels of security as follows [64]:

a) *Level 0- Unsecured Communication* – This is the lowest level of security in which data is transmitted in unsecured frames and provides no measure for integrity validation, authenticity and replay defense, privacy protection and confidentiality.

b) *Level 1- Authentication but no Encryption* – In this level of security, data is transmitted in authenticated but unencrypted frames. It consists of measures for integrity validation, authenticity and replay defense. However, it provides no privacy protection or confidentiality.

c) *Level 2- Authentication and Encryption* – This is the highest level of security in which messages are transmitted in authenticated and encrypted frames; therefore, providing measures for integrity validation, authenticity, replay defense, privacy protection and confidentiality. It covers the issues related to level 0 and level 1. During the association process, the required security level is selected. In unicast communication, a pre-shared master key (MK) or a new key (generated through unauthenticated association) is activated. In the next step, a Pairwise Temporal Key (PTK) is generated that is used only once per session. In multicast communication a Group Temporal Key (GTK) is generated that is shared with its corresponding group [10].

All nodes and coordinators in a WBAN have to go through certain stages at the MAC layer before data exchange. This way frames are required or permitted to exchange between a

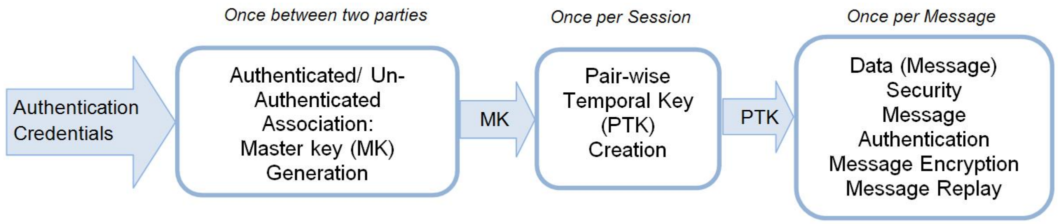

Fig. 12. Security Paradigm of IEEE.802.15.6

hub and a node at each state. The first state is the *Orphan* state at where the node does not have any relationship with the coordinator for secured communication. In fact, this is the initial stage at which the node enters a relation with its coordinator. The coordinator and the node are only allowed to transmit Security Association and control unsecured frames at this stage in order to share a new key or activate a pre-shared one. If the coordinator and the node fail to activate/ establish a shared MK, they are not allowed to proceed to the *Associated* state. At the *Associated* state, the node holds a shared MK with the coordinator for their pairwise temporal key (PTK) creation, which means the node is associated. The node and hub are allowed to exchange PTK frames with each other to confirm the possession of a shared MK, create a PK and transit to the next state, *Secured* state. If the MK is invalid/ missing during the PTK creation, they have to move back to the *Orphan* state.

At the *Secured* state, the node is secured as it holds a PTK with the coordinator for secure frame exchanges. The node and the coordinator can exchange the following frames: security disassociation, connection assignment secure frames, connection request and control unsecured frames. The node can exchange Connection Request and Connection Assignment frames with the hub to form a connection and transit to the final state, *Connected* state. At the *Connected* state the node is connected and holds an assigned $Connected\_NID$, a wakeup arrangement and one or more scheduled allocations with the coordinator, desired wakeup and optionally scheduled and unscheduled access.

One of the key techniques for secure communication in WBANs is known to be via biometrics. This means that the body itself will be used for managing cryptographic keys for sensors attached to the body, which allows for secure distribution of the symmetric key for encryption and decryption. Most biometric security approaches in WBANs have proposed to protect WBANs by generating session keys from the ECG signal and distributing them amongst nodes throughout the network. However, these methods have accuracy of key recoverability less than 100% amongst all nodes throughout the network [65].

In [66], a novel biometrics technique has been proposed that uses the timing information of heartbeat as an intrinsic characteristic of the human body for authentication identity or as a method to secure cipher key distribution for inter-WBAN communication as well as an identity for entity authentication. This approach is set upon a symmetric cryptosystem, which considers the availability of a secured and robust key distribution scheme. The proposed security approach has less memory and computational requirements compared to the traditional cryptosystems and therefore is convenient for use in e-health and telemedicine applications of WBANs.

The BioSec security technique proposed in [67] uses a group of similar random numbers obtained from a combination of biometrics of the human body at different sites to encrypt and decrypt the symmetric key for secured distribution. In addition, a fuzzy commitment scheme was proposed to ensure tolerable recovery of the encryption key due to variations in the biometric trait obtained from different locations of the body. The biometric trait at the transmitting terminal was used to commit the key. At the receiver side, the biosensor received a copy of the trait and would then decommit it to obtain the key.

In [68], the biometric features shared amongst body sensors positioned at various positions of a human body are utilized in the security framework proposed for wireless body area networks. Secure data communication amongst these sensors is obtained from authentication and selective encryption schemes with less resource usage in terms of bandwidth, memory and low computational power when compared with schemes proposed so far. Accurate authentication is obtained via a wavelet-domain Hidden Markov Model (HMM) based on non-Gaussian statistics of ECG signals. Moreover, the biometric information received from the ECG signals are further used for encryption. This protocol achieves accurate performance without requiring strict time synchronization and extra key distribution. In [69], Cyber-physical solutions (CPSS) towards security in WBANs are given providing transparent and plug-n-play explanations to its users. In particular, a specific Plethysmogram based Key Agreement (PKA) is implemented on an FPGA considering accuracy, low latency and minimal resource usage. This design can lead to validation of any CPSS. More specifically, CPSS-integration of cryptographic primitives with signal processing aims to provide usable security solutions in WBANs.

A traditional approach to security in most networks is based on the public key cryptography. However, this method consumes much more resources and cannot be directly deployed for sensors in WBANs due to their considerable limitation of resources and computational capabilities. The authors of [70] propose a novel light-weight security architecture for WBANs, which includes key management, random number generation and a three-step security model. In the first step auto-shared secret (ASS) is generated by a certain kind of the bio-channel via each node under a synchronization indication from the master node. In fact, the ASS is a set of biometric values generated simultaneously by the nodes from physiological data

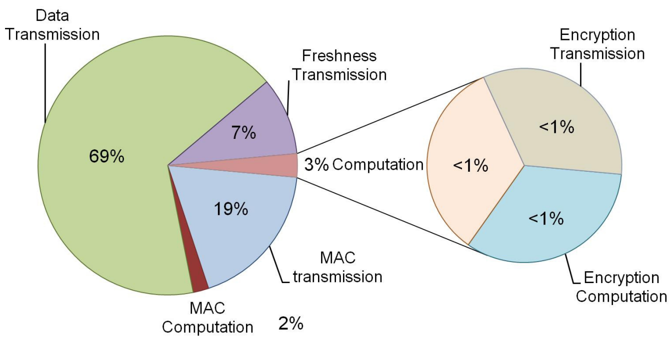

Fig. 13. Energy Consumption of Security Protocols

during a certain time period. In the next step, the initialization key k_{init} is distributed under ASS protection. Next, session keys are then distributed under the protection of k_{init}. This approach is unique in using a combination of bio-channel and wireless channel for secure information transmission, as well as multiple usage of physiological data for numerous security aspects.

The authors in [71] have proposed the use of random channel measurements to create the seed for AES-style scenarios. Therefore, a unique 128 bit AES key can be generated every minute. Therefore, significant improvements to the one-off AES key will be made, even though the Shannon one-time pad level of security is not met. The key sharing rate for WBAN channel model based on RSSI measurements has shown to be very low (4 bit/sec), close to 2 bit/sec. This interprets that key sharing is possible and unconditional security is cannot be achieved for practical communication rates. A lightweight secure sensor association and key management scheme was proposed in [72] for Wireless Body Area Networks where a group of sensor nodes establish initial trust via Group Device Pairing (GDP) without prior secret sharing before the meeting. GDP is an authenticated group key management protocol which allows for visual verification of the legitimacy of each member node by an individual person. After deployment, various types of secret keys can be generated on demand. The GDP protocol does not require extra hardware devices, supports batch deployment of sensor nodes to avoid time wastage and mostly relies on symmetric key cryptography, as well as allowing batch node addition and revocation.

In [73], a secure sensor allocation for WBANs has been proposed, where each sensor node is provided with public key based authentication one-by-one by the controller. Association is verified by the user through a comparison amongst the LED blinking patterns. Unfortunately, the overall association time is quite long as batch deployment is not supported. Additionally, the assumption of sensor nodes being pre-distributed with the public key from a trusted authority is impractical.

Fig. 13 shows the percentage of energy consumption relative to employing security protocols in WBANs. As can be seen in this figure, a small portion of energy consumed in freshness transmission is relative to *computation* (3%), *encryption transmission* (1%) and *encryption computation* (1%). The use of stream cipher is considered to be the most effective solution to energy required for overhead transmission, with the cipher text having the same size as a plain text. Hence, only 16 bytes of the 60 bytes of a data frame are used with no requirement for a Cyclic Redundancy Check (CRC) as data integrity can be self-maintained through the MAC.

IX. WBAN ROUTING

Numerous routing protocols have been designed for Adhoc networks [74] and WSNs [75]. WBANs are similar to MANETs in terms of the moving topology with group-based movement rather than node-based movement [76]. However, WBANs have more strict energy constraints in terms of transmit power compared to traditional sensor and Ad Hoc networks as node replacements particularly for implant nodes can be quite uncomfortable and might require surgery in some scenarios. Therefore, it is crucial for WBANs to have a longer network lifetime to avoid constant recharging and replacement of nodes attached to a person. Additionally, a WBAN has more frequent topology changes and a higher moving speed,whilst a WSN has static or low mobility scenarios [76]. Due to the aforementioned issues and specific WBANs challenges, the routing protocols designed for MANETs and WSNs are not applicable to WBANs [16].

A. Challenges of Routing in WBANs

1. *Postural Body Movements* – Node mobility, energy management and environmental obstacles increase dynamism in WBANs, including frequent changes in topology and network components that amplifies the complexity of Quality of Service (QoS). Additionally, the link quality between nodes in WBANs varies as a function of time due to various body movements [77]. Therefore, the proposed routing algorithm should be adaptive to different topology changes. In this regard, the authors of [78] have considered WBANs to be in the category of Delay Tolerant Networks (DTN) due to disconnection and frequent partitioning relative to postural body movements. Moreover, some body segments and clothing result in signal blockage that intensifies RF attenuation. More specifically, the mobility pattern in WBANs changes with the order of movements within tens of centimeters whereas the scale of mobility in WSNs is in the order of meters and tens of meters.

2. *Temperature Rise and Interference* – In terms of the available energy and computing power, the energy level of nodes needs to be considered in the proposed routing protocol. Also, in order to minimize interference and avoid tissue heating, the transmission power of nodes needs to be extremely low [16].

3. *Local Energy Awareness* – The proposed routing protocol has to disperse its communication data among nodes in the network to balance power usage and minimize failure to battery supply drainage.

4. *Global Network Lifetime* – Network lifetime in WBANs is referred to as the time interval from when the network starts to the time the network is significantly damaged, which leads to network partitioning such that the destination cannot be reached. As battery replacement and charging is not feasible in implant medical devices, network lifetime is of more importance in WBANs compared to WPANs and WSNs [21].

5. *Efficient Transmission Range* – The low RF transmission range in WBANs leads to frequent partitioning and disconnection amongst sensors in WBANs, which results in similar performance to DTNs [78]. In cases where the transmission range of sensors are less than a threshold value, there are fewer choices for routing to adjacent sensors which leads to a higher number of transmissions leading to overall temperature rise. Also, the fewer the number of neighbors, the lower the probability for packets to arrive at the destination within a certain hop count. Thus, packets will take longer to arrive at the destination which leads to an average increase in overall temperature rise [79].

6. *Limitation of Packet Hop Count* – According to the IEEE 802.15.6 standard draft for WBANs [30], one-hop or two-hop communication is allowed in WBANs. Whilst multihop transmission provides stronger links leading to overall increase in system reliability. The larger the number of hops, the higher the energy consumption [80]. However, the limitation of packet hop count has not been considered in most WBAN routing protocols. Additionally, half-duplex devices in WBANs reduce the bandwidth as successive hops are introduced.

7. *Heterogeneous environment* – Specific applications of WBANs may require heterogeneous data collection from different sensors with different sampling rates. Therefore, QoS support in WBANs may be quite challenging.

8. *Limitation of resources* – Data capacity, energy and device lifetime of WBANs is strictly limited as they require a small form factor. Due to limitation of available resources in WBANs, therefore, WBAN nodes are bound to fail due to unavailable battery power, memory and bandwidth limitations, which are major threats to QoS.

This section provides an overview of research being done in routing protocols for WBANs, which have only been developed in the past few years, to assist in overall knowledge of routing challenges in WBANs and possible solutions. Routing protocols in WBANs can be classified into five groups based on their location, network structure, temperature, layer and QoS metrics.

B. Classification of Routing Protocols in WBANs

1) Cluster-based Algorithms: The first class of routing protocols in WBANs are *Cluster-based routing algorithms* that divide nodes in WBANs into different clusters and assign a cluster-head for each cluster. Data is routed through the cluster-heads from the sensors to the sink. The aim of this class of routing protocols is to decrease the number of direct transmissions from the sensors to the base station. However, the huge overhead and delay relative to cluster selection are the main drawbacks of these protocols.

In [81], a data gathering protocol, namely Anybody is proposed to reduce the number of direct transmissions to a base station. The proposed approach is based on LEACH [82] and spreads energy dissipation by choosing its cluster-head at regular time intervals. The data is then collected and sent to the base station via the cluster-head. LEACH assumes all nodes to be in the sending range of the base station whereas Anybody solves this issue by changing the cluster-head selection and building a backbone network consisting of cluster-heads. However, reliability is not considered and energy-efficiency is not completely investigated. One other improvement to the LEACH protocol is Hybrid Indirect Transmissions (HIT) [83] that forms chains by combining the clusters that improve energy efficiency.

2) Probabilistic Algorithms: Probabilistic routing protocols periodically update their cost function based on the link state information, and establish their path among routes with minimum cost. However, these protocols require a large number of transmissions for updating link-state information.

Movassaghi et. al [84] have proposed an energy efficient, thermal and power aware routing algorithm for WBANs, named Energy Efficient Thermal and Power Aware routing (ETPA). This protocol calculates a cost function for route allocation based on a node's temperature, energy level and received power from adjacent nodes. ETPA has shown to significantly decrease temperature rise and power consumption and provide a more efficient use of available resources. Additionally, it has a considerably high depletion time that guarantees longer lasting communication among nodes in WBANs.

A routing protocol is proposed in [77] for WBANs, the moving nature of the body is considered in the routing protocol through an opportunistic scheme that ensures high communication probability with the sink at all times. Consequently, it defines two scenarios for communication between the sensor node and the sink node. For one thing, in cases where the wrist is at the back of the body, non line of sight (NLOS) communication is considered where the sensor node will send data to the relay node and then to the sink node. Whereas, when the wrist is in the front, line of sight (LOS) communication exists between the sensor node and sink. Liang et. al [85] have proposed the distributed (PSR) routing framework for WBANs where each node n_i maintains the matrix M_i $(s \times p)$. This way it stores link quality measurements between itself and all other nodes in the network during the past p time slots (p is a predefined parameter and the initial matrix is empty). PRPLC [86] sets a Link Likelihood Factor (LLF) namely P_{ij}^t $(0 \leq P_{ij}^t \leq 1)$, which denotes the likelihood for link L_{ij} between node i and j to be connected over a discrete time slot t. LLF is determined to be dynamically updated after the tth time slot. When a node i wants to route data to a node d (sink node) and meets node j, node i forwards the packet to node j if and only if $P_{i,d}^t \leq P_{j,d}^t$ is valid.

DVRPLC [78] proposes that all nodes preserve the cumulative path cost to the common sink node. As in PRPLC, this protocol chooses high likelihood paths to decrease end-to-end packet delivery delay and decrease intermediate storage delay relative to storing packets at nodes with low link likelihood. DVRPLC specifies a Link Cost Factor (LCF) of $C_{ij}^t(0 \leq C_{ij}^t \leq C_{max})$, which stands for the routing cost of link L_{ij} in a discrete time slot t. OBSFR [87] attempts to avoid network partitioning, which may arise, by allowing each node to maintain its *source_id, seq_No* and list of *node-ids* that demonstrate its path from the source node. Hence, once a packet arrives at a node for the first time, the node continues to store the packet until it meets at least one node that is not listed in the *node-ids* of the packet.

3) Cross-Layer Algorithms: The third category is *cross layer routing protocols* that combines the challenges of the network layer with other layers. Even though these protocols have low energy consumption, high throughput and fixed end-to-end delay, they cannot supply high performance in scenarios with high path loss and body motion. The Wireless Autonomous Spanning Tree Protocol (WASP) proposed in [80] sets up a spanning tree and divides the time axis into slots referred as *WASP-cycles* in a distributed manner to provide medium access coordination and traffic routing using the same spanning tree, which leads to higher throughput and lower energy consumption. The Controlling Access with Distributed Slot Assignment protocol (CICADA) [88] is a low energy cross layer routing protocol for WBANs based on multi-hop TDMA scheduling. CICADA enhances reliability by the definition of a lognormal distribution for link probability rather than a circular coverage region. Also, it provides two way communication, which is an improvement to the WASP protocol.

Timezone Coordinated Sleeping Mechanism (TICOSS) [89] adjusts all nodes as Full Functional Devices (FDD) and enhances the IEEE 802.15.4 standard by configuring the shortest path route to the WBAN coordinator, preserving energy and minimizing hidden terminal collisions through V-scheduling (due to V-shape communication flow), which doubles the operational lifetime of IEEE 802.15.4 for high traffic scenarios and extending IEEE 802.15.4 to support mobility. BIOCOMM is another cross-layer routing protocol for WBANs designed based on the interaction of the network and MAC layer to optimize overall network performance [90]. Adaptive Multihop tree-based routing (AMR), proposed in [91] is a distributed spanning-tree based approach which considers battery level, Received Signal Strength Indicator (RSSI) and number of hops. AMR balances energy consumption amongst nodes by which it provides extended network lifetime and an efficient number of transmissions per delivered packet.

4) Temperature-based Algorithms : Radio signals generated via wireless communication generate electric and magnetic fields. The exposure of these electromagnetic fields leads to radiation absorption, which results in average temperature rise in the human body [92]. Thus, blood flow will be reduced and sensitive organs may face severe thermal damage. More specifically, prolonged temperature rise within the body tissue may result in tissue damage, blood flow reduction in certain organs and effect enzymatic reactions [93]. The amount of radiation energy absorbed by the body tissue is defined as the Specific Absorption Rate (SAR) shown in (1) [92].

$$SAR = \frac{\sigma |E|^2}{\rho} \qquad (W/kg) \tag{1}$$

where E is the electric field induced by radiation, σ is the electrical conductivity of the tissue, and ρ is the density of tissue. Exposure to SAR of 8 W/kg for 15 minutes has shown to result in severe tissue damage [92]. In fact, SAR specifies the exact upper bound of the allowable transmit power. Thus, WBAN routing protocols have to actively decrease radiation emission and temperature. Accordingly, even routes with light traffic and short delay might not be efficient in terms of temperature, which makes routing and forwarding infeasible. The main objective of all temperature based routing algorithms studied in the literature is to avoid routing to hot-spots.

Heating affects and radiation absorption on the body are the most important issues when considering wireless communication on or around the body. Tissue heating can be reduced with the use of traffic control algorithms and by limiting the radio's transmission power. To achieve this aim, communication between the sensor nodes must be balanced. One existing solution is the Thermal Aware Routing Algorithm (TARA) [92], which routes data through low temperature zones. More specifically, packets are withdrawn from high temperature zones and rerouted via alternative paths. In cases where the number of hops reaches three, shortest path routing is selected via the proposed routing algorithm. However, TARA does not consider reliability, has a high packet loss ratio, a low network lifetime and does not consider reliability. Improvements to TARA where given by the Least Temperature Routing (LTR) [94] and Adaptive Least Temperature Routing (ALTR) [94], which reduce the irrelevant loops and hops by maintaining a list of recently visited nodes. In cases where a predetermined number of hops are reached, ALTR switches to shortest path routing in order to eliminate energy consumption. One other solution is the Least Total Route Temperature (LTRT) [79] that is a combination of short path routing and LTR where the temperature of the nodes is translated into graph weights leading to minimum temperature routes. Through this routing protocol, lower temperature rise and better energy efficiency is obtained. However, since each node needs to know the temperature of all other nodes, overhead becomes a significant drawback [8].

HPR [93] is a biomedical sensor network routing algorithm for delay-sensitive applications such as medical monitoring. It aims to decrease average packet delay and avoid hotspot formation. HPR chooses the route with minimum hops from the sender node to the destination unless a hotspot exists in that path. The routing algorithm for networks of homogenous and Id-less biomedical sensor nodes (RAIN) [95] is fault tolerant and operates efficiently even with the depletion of a number of nodes due to lack of energy. Thermal-Aware Shortest Hop Routing (TSHR) is another temperature based routing protocol specifically designed for applications that require a high priority for transmitting a packet to the destination. The main drawback of temperature routing approaches is that they overlook network lifetime and reliability. Movassaghi et al. [96], have provided a detailed comparison amongst the routing protocols proposed thus far for WBANs.

5) QoS-based Routing Algorithms: The last category is *QoS routing* protocols, which mainly provide a modular approach by presenting separate modules for different QoS metrics that operate in coordination with each other. The modules used in this method are the *power efficiency module*, the *reliability-sensitive module*, the *delay-sensitive module* and the *neighbor manager*. Hence, these approaches provide higher reliability, lower end-to-end delay and higher packet delivery ratio. However, these protocols mainly suffer from high complexity due to the design of several modules based on different QoS metrics. A novel QoS-based routing protocol (LOCALMOR) has been proposed in [97] for biomedical applications of sensor networks. The proposed protocol functions in a localized, distributed, computation and memory efficient way. It also classifies data traffic into several categories based on the required QoS metrics where different techniques and routing metrics are provided for each category.

Razzaque et. al [98] have proposed a data-centric multi-objective QoS-aware routing protocol, namely DMQoS, for delay and reliability domains in WBANs. The proposed protocol provides customized QoS services for each traffic category based on their generated data types. It employs a modular design architecture that consists of different units that operate in coordination with each other to support multiple QoS services. A reinforcement learning based routing protocol with QoS support (RL-QRP) has been proposed in [99], which uses the basic idea of location information. Sensor nodes can compute the available QoS routes based on the link qualities of the available routes and the QoS requirements of the data packet, and then forward data packets to one of the neighbor nodes. This procedure is continued in forwarding the data packets to the sink node and is repeated at each relaying node until the packets reach the sink node. Liang et. al [100] have proposed a QoS-aware routing protocol for biomedical sensor networks with the aim of providing differential QoS support and prioritized routing service in the network. This procedure is accomplished via the following tasks: establishment and maintenance of QoS-aware routes, prioritized packet routing, feedback on network conditions to user application, adaptive network traffic balance and Application Programming Interfaces (API).

In summary, each classification of routing protocols only aims to satisfy a specific requirement of WBANs. Thus, designs of new routing protocols are required to meet all the conditions for operations of WBANs..

X. Address Allocation in WBANs

Each node has to be assigned with a unique address for effective information exchange. As some nodes in a WBAN are actuators, for the purpose of proper functionality information has to reach the nodes at the appropriate time and in the same order as they were first transmitted. On the other hand, sensor nodes in health monitoring applications have to send their data such that it reaches health monitoring devices in an appropriate time and provides the medical staff with efficient management of the WBAN. Recently, various addressing methods have been proposed for WPANs using different technologies. These addressing schemes normally rely on IP addressing, mathematical graph algorithms, etc. However, given the unique characteristics of WBANs, address allocation in these networks introduce various challenges which are described as follows:

1. *Limitation of address space in WBANs* – Due to the stringent limitation of resources (memory, space, etc.) in WBANs, their address space is limited. This short addressing space is kept for identifying child nodes, routers and the network coordinator [2]. In [101], this issue has been solved by an appropriate choice of the prime numbers used in the original Prophet scheme to minimize the number of collisions for different topologies. In fact, the closer the prime numbers, the higher the number of collisions.

2. *Address interference* – Each node has to be assigned with a unique address once it wants to join the network. Existing addressing schemes [101, 102] provide short addresses for each node but do not guarantee collision-free address allocation. In fact, as shown in [101], there is a trade off between the number of collisions and the effective address space.

3. *Node mobility for address allocation* – Postural body movements generate a dynamic environment in WBANs which affects the density and topology of nodes in the network as will move in or out of range.

4. *Address wastage and duplication*– In order to make efficient use of the limited address space in WBANs and prevent address duplication, address reuse should be allowed once a node wants to join or leave the network.

5. *Issues of static addressing* – Static addressing assigns a static address to each node to avoid address interference. However, the network topology changes once a node leaves or joins the network. Most of the addressing architectures proposed thus far have used flat or static addressing, which requires individual tracking of each node. If not, the network is flooded in each route request which causes a massive overhead that is proportional to the size of the network.

Recently, two address allocation schemes have been specifically proposed for WBANs. Movassaghi et al. [103], have proposed an addressing scheme for WBANs called Hierarchical Collision-free Addressing Protocol (HCAP). The proposed protocol is collision-free, tackles the address wastage problem and eliminates power consumption. The usability and efficiency of the proposed protocol in WBANs is evaluated across two scenarios, random location and fixed location.

Movassaghi et al have enhanced the performance of an address allocation scheme, namely Prophet allocation for use in WBANs. Each node in the Prophet algorithm receives a message, which consists of a state vector and an address. In the next step these addresses and states are updated for each node. The most important issue with the Prophet algorithm is the number of collisions related to a change of topology. In fact, the percentage of collisions in a network with more number of hops is more than a network with less hops [101]. This issue has been addressed in the Optimized Prophet Address Allocation method (OPAA) [101]. It considers the requirement of each node in a WBAN to be assigned a free address before participating in any sort of communication. The allocation scheme is a fully decentralized addressing scheme, which is applicable to WBANs as it provides low latency, low communication overhead and low complexity. Theoretical analysis and simulation experiments have also been conducted to demonstrate the benefits of this allocation scheme when compared to other potential schemes. It also solves the issues related to network partitioning and merging effectively.

In [104], the OPAA and HCAP schemes have been compared. Through simulations it has been shown that the HCAP scheme outperforms the OPAA scheme in terms of address interference but has a higher energy consumption.

XI. Radio Technologies used in WBANs

Given the complexities associated with implementing WBANs, an appropriate wireless technology is required. In essence, data being sent from a patient to a central health care system needs to have continuous awareness of the patient's vital functions to provide suitable solutions in case of alerts. Therefore, communication of WBANs with other wireless networks becomes crucial [41]. Accordingly, the central node of a WBAN is capable of communicating with the outside world using a standard telecommunication structure such as Bluetooth, WLANs or 2G/3G/4G cellular networks in different projects.

One important factor in the choice of a wireless technology is its power usage, which is tied with the design of a power efficient WBAN. Existing wireless technologies have a huge peak current and usually reduce the average current drawn by duty cycling the radio between sleep and active modes. Technically, WBANs in IEEE 802.15.6 have to be scalable and have a peak power consumption up to 30 mW in fully active mode and between 0.001-0.1 mW in stand-by mode [9].

Even though WBAN devices are low-power and there is not enough power available for the whole-body SAR to be a concern, the device may be in close proximity to, or inside a human body or the localized SAR could be quite large if all the available power is concentrated in a small volume. Therefore, the localized SAR into the body must be at its minimum. Based on the IEEE 802.15.6 standard, WBAN devices must follow local or international SAR regulations. In Europe, the European Council Recommendation 519/1999/EC for exposure guidelines has complied with the recommendations made by the International Commission on Non-Ionising Radiation Protection (ICNIRP Guidelines 1998). In the US, the Federal Communications Commission (FCC) has set the safety guidelines of the radio frequency which is required from all phones before being sold in the US. This interprets that SAR has set certain limits for local exposure (Head); which is 2 W/kg in 10 gram in EU and 1.6 W/kg in 1 gram in US. This limits the TX power in EU to $\lesssim$ 20 mW and in US to $\lesssim$ 1.6 mW [26].

On the other hand, a WBAN deployed on a human body may need to support different applications with different requirements in power usage, reliability, data rate and frequency. Therefore, consistent data transfer amongst different wireless technologies being used is required to be scalable, provide uninterrupted connectivity, promote information exchange, ensure efficient migration across networks and interconnect plug and play devices. Thus the chosen wireless technology has to handle the mixture of these requirements. In terms of QoS, periodic parametric data, episodic data, real time wave form data and emergency alarms need to be supported with peer to peer latency of 10 ms-250 ms and a BER of 10^{-10} to 10^{-3} [9].

The existing and emerging radio technologies [105] suitable for WBANs are provided in Table VIII which are listed as follows: UWB, ZigBee and IEEE 802.15.4, Bluetooth, Bluetooth Low Energy and a few more leading competitors in recent WBAN markets such as Z-Wave[12], Zarlink[13], RFID, Rubee[14], ANT[15] and Sensium[16]. An appropriate radio technology for WBANs can be decided upon based on the specific requirements of a WBAN application. For instance, UWB is considered most appropriate for short-range (5-10 m) and high speed applications with high data rate requirements (110 - 480 Mbps). It has no restrictions on the frequency being used as it has the dominant features of potentially high data rates and low power consumption. On the other hand, the Zarlink technology is most appropriate for medical implant applications requiring low frequency and low data rates.

Rubee does not require line of sight communication for its operation, which is quite advantageous compared to other radio technologies provided in this literature. Additionally, Rubee has the advantage of efficient transmission distance, high security level, ultra-low power consumption, stable operation providence and long battery lifetime, which makes convenient for use in patient monitoring, storehouse management, mobile health care, tracking purposes, management asset and deployment in controls, sensors, actuators and indicators [5, 106]. Moreover, due to Rubee's low operation frequency it will not be attenuated by metal or liquid and can be deployed in any environment that RFID cannot handle [106, 107].

One significant disadvantage of Zigbee for WBAN applications is due to interference with WLAN transmission, specially in 2.4 GHz where numerous wireless systems operate. Other deficiencies of Zigbee are related to its low data rate (250 Kbps), which makes it inappropriate for large-scale and real time WBAN applications [108] whilst appropriate for deployment in home automation and control, and industrial areas [109]. Whereas, Bluetooth LEE is more likely for use in the deployment of low power devices around a human body due to its lower cost and lower power consumption (92 nJ/b). On the other hand, Bluetooth is advantageous in supporting applications with different data rates, network coverage and power requirements and most convenient for short-term high data rate applications in which two peer to peer devices are connected in an ad hoc configuration, such as between two personal servers of two WBANs or between a WBAN and a PC [5]. Thus, different operational environments and characteristics of different WBAN applications require an appropriate choice of the wireless radio technology being used [107].

XII. Comparison With Other Wireless Networks

Fig. 14 shows the realm of WBANs when compared with other wireless networks such as Wireless Personal Area Networks (WPAN), Wireless Local Area Networks (WLAN), Wireless Metropolitan Area Networks (WMAN) and Wireless Wide Area Networks (WWAN). As shown in Fig. 14, wireless networks can be categorized based on their geographical coverage [10]. A WBAN operates close to the human body with a restricted communication range of up to 1-2 meters. It primarily deals with the interconnection of one's wearable devices, whereas a WPAN is a broader network environment that surrounds the person. Even the WPAN communication

[12]http://www.z-wave.com

[13]http://www.zarlink.com/zarlink/hs/medical Wireless Telemetry.htm

[14]www.rubee.com

[15]www.thisisant.com

[16]http://www.toumaz.com/page.php/page.sensium intro

TABLE VIII
CHARACTERISTICS OF WIRELESS TECHNOLOGIES USED IN WBANS

Technology	Frequency	Data Rate	Coverage	Modulation	Network Topology
Bluetooth V.1 802.15.1	2.4 GHZ ISM	780 Kbps	10-150 m (on-body only)	GFSK	star
Bluetooth V.2 + Enhanced Data Rate (EDR)	2.4 GHZ ISM	3 Mbps	10-100 m (on-body only)	GFSK,PSK,8-DPQSK,π/4DQPSK	star
Bluetooth V3.0 + High Speed (HS)	2.4 GHZ ISM and 5 GHz	3-24 Mbps	10 m (on-body only)	GFSK	star
Bluetooth V4.0 + Low End Extension (LEE)	2.4 GHZ ISM	1 Mbps	10 m (on-body only)	GFSK	star
ZigBee (IEEE 802.15.4)	868 MHz, 915 MHz, 2.4 GHz ISM	20,40,250Kbps	10-100 m (on-body only)	O-QPSK,BPSK(+ ASK)	star, mesh, cluster-tree
Ultra Wideband (UWB)	3.1-10.6 GHz	110-480Mbps	5-10 m (on-body only)	OFDM,DS-UWB,BPSK,QPSK	star
RFID (ISO/IEC 18000-6)	860 to 960 MHz	10 to 100Kbps	1 to 100 m	FSK,PSK,ASK	peer-to-peer
Near Field Communication (NFC)	13.56 MHz	106,212,424 Kbps (1 Mbps planned for future)	up to 20 cm	ASK	peer-to-peer
Sensium	868 MHz,915 MHz	50 Kbps	1-5 m (on-body only)	BFSK	star
Zarlink (ZL70101)	402-405MHz,433-434 MHz	200-800 Kbps	2 m (in-body only)	2FSK,4FSK	peer to peer
RuBee (IEEE 1902.1)	131 KHz	9.6 Kbps	30 m	ASK,BPSK,BMC	peer-to-peer
Z-wave	900 MHz ISM	9.6 Kbps	30 m	BFSK,FSK	mesh
ANT	2.4 GHz ISM	1 Mbps	30 m (on-body only)	GFSK	star, mesh, peer to peer, tree

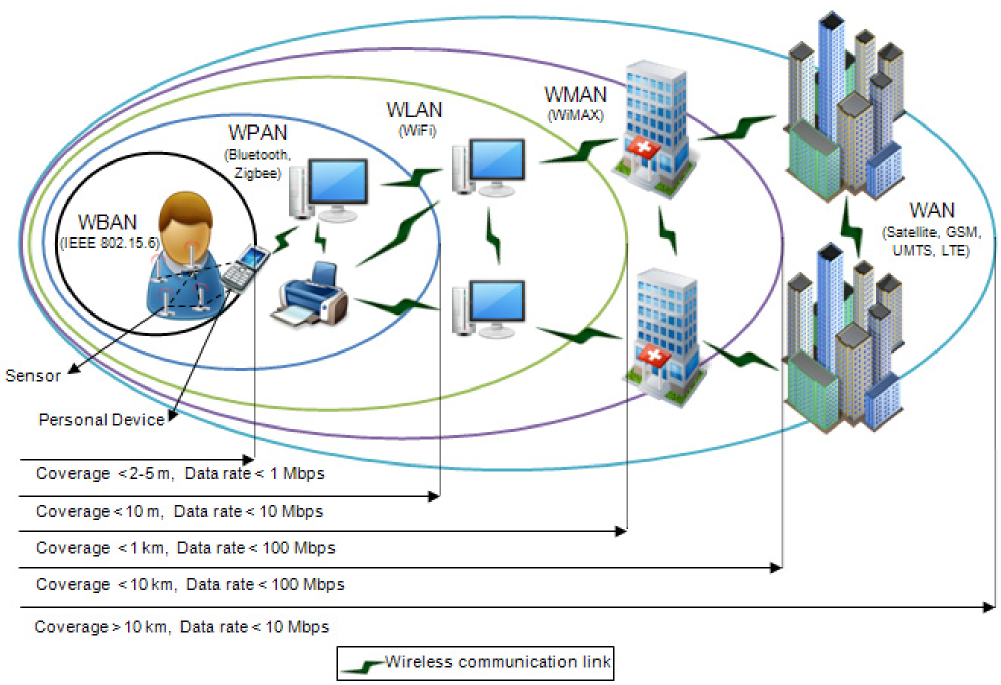

Fig. 14. WBANs vs. Other Wireless Technologies

range reaches over several tens of meters for low data rate applications and up to 10 meters for high data rate applications. However, previous WPANs do not fulfill medical (within close vicinity of the human tissue) and communication regulations for specific applications. Additionally, they do not support the combination of data rate and reliability required for the broad range of WBAN applications [4]. A WLAN has a communication range of up to 100 meters. WWANs cover the largest geographical region such as in mobile telephone systems and satellite communication [110]. In summary, IEEE 802.15.6 overcomes the constraints of the aforementioned wireless technologies as its focus is specifically on networking within and around the body.

WBANs are considered to be a subset of WSNs or Wireless Sensor or Actuator network (WSAN) [8]. However, they tackle their own challenges related to the interaction of the human body with different environments, and general challenges of WSNs in human body monitoring. The entire WBAN network is in motion due to postural body movements, the base-station are mobile and weak, and coordination amongst WBANs is impossible [14]. Since the base stations of WBANs are mobile; they can move in and out of each others range, very quickly, or may stay in each others range for long periods [4]. Table IX provides an overview of challenges in WBAN compared to WSNs, which is explained in more detail as follows [8, 13, 111]:

A. Network Structure

Nodes that comprise the topology of a WBAN are attached to different parts of the body. Some parts of the body (e.g. chest, waist) are stationary with respect to other parts (e.g. arms, legs, head), which move given the body's ambulatory motion. The mixed motion of nodes differs from WSNs. WBAN's therefore need to be more robust and respond more quickly to changes in their topology. In terms of network dimensions, few to several thousands of nodes can be deployed in WSNs over an area from meters to kilometers, dependent on the mentioned environment, whereas WBANs have a dense distribution of nodes limited by the human body size. Different factors are considered by users in the choice of number of actuator/sensor nodes to be deployed. Nodes in a WBAN are usually either hidden under clothing or strategically placed on the human body. Additionally, WBANs do not have any redundant nodes. In fact, all devices have equal importance and can be added when required to avoid different types of failure.

B. Limitation of Resources

Communication capabilities, available memory and computational power is limited for nodes in WBANs, specifically those implanted inside the body. Also recharging or changing batteries in WBANs is not feasible even for devices that require a long lifetime. Each node has an extremely low transmit power due to their very small form factor (normally less than $1cm^3$). These considerations aim to minimize interference as well as coping with health concerns [8]. Additionally, the implantable settings in WBANs causes inaccessibility and replacement difficulties in providing battery and power supply. However, the lifetime of nodes in both WBANs and WSNs is application-specific.

C. Data Requirements

WBANs are deployed to register one's physiological actions and activities in a periodic manner resulting in constant data rates, whereas WSNs are applied in event-based monitoring that can happen in sporadic time intervals [5]. They are usually heterogenous and therefore have different demands or different resources regarding reliability, data rates and power consumption [8]. In addition, latency is considered a key requirement in WBAN applications. However, it can be traded for improved energy consumption and reliability in WSNs. Consequently, maximizing battery life-time at the expense of higher latency may be necessary in WSNs [5].

D. Technological Requirements

The surrounding area of a human body is regarded as a lossy medium for wave propagation. Consequently, signals in WBAN devices are attenuated considerably before they reach the receiver [8]. Also, WBANs have an ultra short communication range and a small scale structure [111]. Therefore, context awareness is quite significant in WBANs due to their sensitive content exchange whereas in WSNs, as their environment is generally static, this is not a significant concern.

E. Security

In terms of security, the strictly confidential and private character of medical data has to be ensured via stringent security mechanisms required in WBANs as their devices operate in hostile environments and collect life-critical information [63], whereas a lower level security is required in WSNs which can be application-specific [8]. Also, the limitation of communication and power efficiency in WBANs leads to many security challenges compared to WSNs since the integration of a high-level security mechanism in resource-constraint and low-power sensor increases communication, computational and management costs [63].

XIII. CHALLENGES AND OPEN ISSUES OF WBANS

The major challenges in the realization of WBANs are summarized as follows:

1. Environmental Challenges – WBANs experience high path loss due to body absorption that must be minimized through heterogenous and multi-hop links with different types of sensors at various locations. Additionally, change in operational conditions may lead to error-prone and incomplete sensor data relative to inherent sensor limitation, human postures and motions, sensor breakdown and interference. As health care facilities and human subjects have specific regulations, the design of implants and wearable devices becomes crucial. Channel models are far more complex due to mobility and multi-path. Even more challenging issues rise in terms of antenna design because of certain constraints of WBANs in shape of antenna, material, size and malicious RF environment. In essence, there are design restrictions in size and shape relative to the organ and its location [35, 112–114]. In fact, the location of the implant dictates its antenna options. For instance, a urethra valve has to be replaced at regular intervals without surgery. The length is restricted and its available diameter is 4mm to 6mm; which means a path antenna cannot be used and maintaining a dipole or monopole antenna would be quite difficult. The best solution would be a helical antenna integrated into the shape of a valve implant [115]. Additionally, as implants can only use bio-compatible and non-corrosive material like titanium and platinum, their antennas are not as strong as a copper antenna.

2. Physical Layer Challenges – PHY layer protocols should be designed to minimize power consumption without compromising reliability. PHY protocols should be convenient for interference-agile places where high-power devices use the unlicensed bands. One important metric in the choice of an appropriate wireless technology for WBANs is related to its power usage, which is undoubtedly tied with the design of a power efficient WBAN. Current wireless technologies have a high peak current and mainly minimize the average current drawn by duty cycling the radio between active and sleep (standby) modes. Hence, further improvements in radio hardware, sensing technologies, integrated circuits and miniaturization is required to dramatically decrease the peak current drawn [9]. Advancements in low power RF technology is expected to significantly lower the peak power consumption, which leads to the production of small, disposable and low cost patches. Technically, WBANs are required to be scalable

TABLE IX
COMPARISON OF WBANs AND WSNs

Comparison criteria	Wireless Sensor Network	Wireless Body Area Networks
Network Dimensions	Few to several thousand nodes over an area from meters to kilometers	Dense distribution limited by body size
Topology	Random, Fixed/Static	One-hop or two-hop star topology
Node Size	Small size preferred (no major limitation in most cases)	Miniaturization required
Node Accuracy	Accuracy outweighs large number of nodes and allows for result validation	Each of the nodes have to be accurate and robust
Node Replacement	Easily performed (some nodes are disposable)	Difficultly in replacement of implanted nodes
Bio-compatibility	Not a concern in most applications	Essential for implants and some external sensors
Power Supply and Battery	Accessible, Capable of changing more frequently and easily	Difficultly in replacement and accessibility of implanted settings
Node Lifetime	Several years / months / weeks (application-dependant)	Several years / months (application-dependant)
Power Demand	Power is more easily supplied, hence apparently greater	Energy is supplied more difficultly hence apparently lower
Energy Scavenging	Wind and Solar power are most apparent candidates	Thermal (body heat) and Motion are most apparent candidates
Data Rate	More frequently homogenous	More frequently heterogenous
Data Loss Impact	Data loss over wireless transfer is compensated by the large number of nodes	Data loss is considered more significant (may need additional measures to ensure real time data interrogation capabilities and QoS)
Security Level	Lower (application-dependant)	Higher security level to protect patient information
Traffic	Application specific, Modest data rate, Cyclic/sporadic	Application specific, Modest data rate, Cyclic/sporadic
Wireless Technology	WLAN, GPRS, Zigbee , Bluetooth and RF	802.15.6, ZigBee, Bluetooth, UWB.
Context Awareness	Insignificant with static sensors in a well defined environment	Very significant due to sensitive context exchange of body physiology
Overall Design Goals	Self-operability, Cost optimization, Energy Efficiency	Energy Efficiency, Eliminate electromagnetic exposure

and have peak power consumption between 0.001-0.1mW in stand-by mode and up to 30mW in fully active mode [9].

Interference is also known as one of the crucial drawbacks of WBAN systems. On one hand, interference occurs in cases where several people that are wearing WBAN devices and step into each others range, which makes coordination impossible (off-body interference). Also, importantly, by 2014 there will be 420 million WBAN devices sold, and this figure will continue to rise. The coexistence issues becomes more prominent with higher WBAN density. Furthermore, the value of employing transmit power control, in terms of minimizing interference and saving power consumption as well as increasing WBAN node battery lifetime should be given more thought. Additionally, since postural body movements are unpredictable, networks can easily move in and move out of each others range [42]. This issue becomes more dominant in the use of wireless technologies with higher coverage area. On-body devices deployed in one WBAN may also have interference with one another (on-body interference). Off-body interference may also occur due to collision from external sensors [53].

3. MAC Layer Challenges – The mechanisms given in IEEE 802.15.6 do not build up a complete MAC protocol. In fact, only the basic requirements for ensuring interoperability amongst IEEE 802.15.6 devices have been outlined in terms of message exchange protocols and packet formats whilst further research questions have not been stated. For one thing, density and topology changes relative to body movements resulting in nodes moving into or out of coverage should be considered in the MAC protocol design. The MAC protocol should be robust enough to support multiple WBANs in parallel applications. Thus, reliability is of major importance in such networks. In this regard, the IEEE 802.15.6 standard has allowed the deployment of dynamic channel hopping, which assists the network to minimize interference from other narrowband transmitters. Additionally, the proposed standard aims to eliminate interference by shifting beacon transmission via a known offset at each beacon period. Also, in cases where the required levels of reliability cannot be achieved through a one-hop star topology, the use of relays is allowed [42]. In addition, MAC protocols must support the energy efficiency requirement of WBAN applications, prolong sensor lifetime, allow flexible duty cycling and save energy by periodically switching the radio on/off. Channel polling must be used to check if the nodes are awake to transmit/receive instead of idle listening. Nodes with low duty cycle should not receive frequent control packets and synchronization if they do not intend to send or receive data. However, the MAC protocols proposed thus far for WBANs do not provide efficient network throughput and delay performance at varying traffic and the synchronization of duty cycles of their sensors with variant traffic characteristics and power requirements remains a challenge [5].

WBANs also have specific QoS requirements which need to be met by the MAC proposal. For this purpose, the high sampling rate from sensors in WBANs needs to be handled by allowing data to be sent out as soon as possible or to transmit data packets with the earliest deadline [5]. For instance, in emergency applications the MAC protocol must allow quick access of its nodes to the channel to transmit life-critical data to the coordinator. MAC proposals for WBANs are either contention-based such as Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) or scheduled-based such as TDMA. The contention-based protocols do not have the constraint of strict time synchronization. However, they incur heavy collision for high traffic nodes. On the other hand, the TDMA MAC proposals are energy efficient, reduce the duty cycle and do not incur overhearing, contention or idle listening. However, their periodic time synchronization requires extra energy [16]. Movassaghi et al. [116] have proposed a practical energy efficient network coding approach for WBANs using decode and forward, namely decode and forward network coding (DF-NC) relays. This approach combines messages from various sources at the relays to create one message which is then transmitted to the destination. Thus, only one transmission slot is required for transmission and near optimal outage probability is achieved while minimizing the number of transmissions per node, maximizing the energy efficiency of WBANs, and minimizing the delay. In [117], the use of a novel cooperative transmission scheme via network

TABLE X
EXISTING PROJECTS ON WIRELESS BODY AREA NETWORKS

Project	Target Application	Intra-BAN Comm.	Inter-BAN Comm.	Beyond BAN Comm.	Sensors
Mobi-Health[118]	Ambulatory Patient Monitoring	Manually	ZigBee/Bluetooth	GPRS/UMTS	ECG, Heart rate, Blood Pressure
AID-N[119]	Mass Casualty Incident	Wired	Mesh/ZigBee	WiFi/Internet/ Cellular Networks	Blood, Pulse, ECG, Temperature
MAHS[120]	Health Care	Bluetooth	Wireless Network	Internet	Spirometer, Pulse, Temperature, Pressure
CodeBlue[121]	Medical Care	Wired	ZigBee/Mesh	N/A	Motion, EKG, Pulse Oximeter
LifeMinder[122]	Real time daily self-care	Bluetooth	Bluetooth	Internet	Galvanic Skin Reflex (GSR) Electrodes, Pulse Meter, Thermometer, Accelerometer
SMART[123]	Health Monitoring in Waiting Room	Wired	802.11.b	N/A	SpO_2 sensor, ECG
Tele-medicare[17]	Home-based Care and Medical Treatment	Bluetooth	Internet	Internet	Temperature,ECG, Oximeter, Blood pressure
CareNet[124]	Remote Health Care	N/A	ZigBee	Internet/Multi-hop 802.11	Gyroscope, Tri-axial accelerometer
ASNET[125]	Remote Health Monitoring	Wired or Wireless Interface (WiFi)	WiFi/Ethernet	Internet/GSM	Temperature, Blood Pressure
IBBT IM3[18]	Telecare and Telemedicine Services	N/A	N/A	Internet	Respiration, ECG, Heart rate
MITHril[19]	Health Care	Wired	WiFi	N/A	EKG, ECG
BASUMA [126]	Health Monitoring	UWB	N/A	N/A	ECG, Reactive Oxygen Sensor (ROS), SpO_2 Sensor, Spirometer
WHMS [1]	Health Care	Wired	WiFi	N/A	EKG, ECG
HUMAN++ [127]	Sport, Entertainment, Medical, Assisted Living, Lifestyle	UWB	N/A	N/A	ECG, EMG, EEG
WiMoCA [128]	Sport/Gesture Detection	Star Topology and Time table-based MAC protocol	Bluetooth	WiFi/Internet/ Cellular Networks/Bluetooth	Tri-axial Accelerometer
AYUSHMAN [129]	Health Monitoring	ZigBee	802.11	Internet	EKG, Blood pressure , Oximeter, Gyroscopic sensors, Accelerometer, Gait monitoring sensors
MIMOSA [130]	Ambient Intelligence	RFID/Bluetooth/ Wibree	UMTS/GPRS	Internet	RFID sensors, Any sensors
UbiMon[20]	Health Care	ZigBee	WiFi/GPRS	WiFi/GPRS	3Leads ECG, 2Leads ECG strip, SpO_2
LifeGUARD[21]	Ambulatory physiologic monitoring for space and terrestrial applications	Wired	Bluetooth/Internet	Bluetooth/Internet	ECG, Respiration Electrodes, Pulse Oximeter, Blood Temperature, Built-in Accelerometer
HealthService24[22]	Mobile Health Care	Wired	UMTS/GPRS	UMTS/GPRS/ Internet	ECG, EMG, SpO_2, Pulse rate, Respiration, Skin temperature, Activity, Plethysmogram

coding, namely Random XOR Network Coding (RXNC), has been proposed for Wireless Body Area Networks (WBANs) to enhance reliability and throughput. In this approach, each relay demodulates the received signal from each sensor node and then selects a number different coded symbols amongst them and XORs them to generate a network coded symbol. The optimum number of coded symbols is calculated through an analytical approach by minimizing the probability that an XOR network coded symbol is incorrectly generated. The proposed RXNC scheme has shown to outperform the no-cooperation and conventional bitwise network coding schemes in all channel signal to noise ratios (SNRs) from 0 dB to 18 dB.

4. Security Challenges – Due to limitation of resources in terms of energy, memory, processing power and lack of user interface existing security mechanisms proposed for other communication networks are not applicable to WBANs and more resource-efficient and lightweight security protocols need to be developed. As an example, an adversary could be capable of inducing heart failure by the detection and execution of vulnerabilities in an Implantable Cardioverter Defibrillator (ICD). Moreover, numerous non-technical factors are trivial to mass marketing in WBANs such as acceptance, comfort, user friendliness, regulatory, affordability, regulatory, ethical and legal issues [5]. Further detail about the security challenges of WBANs can be found in Section VIII.

5. Transport (QoS) Challenges – The QoS requirements of applications in WBANs must be met without degrading performance and improving complexity. In addition, real time life-critical WBAN applications are both loss-sensitive and delay-sensitive. Therefore, the limited memory in WBANs requires efficient acknowledgement, retransmission, secure correction and error detection strategies. Also, a WBAN deployed on one human body may be used to provide different applications with different requirements in data rates, frequency, reliability and power usage. Hence, WBANs have to ensure consistent data transfer amongst the different wireless technologies being used to be scalable, promote information exchange, interact plug and play devices, provide uninterrupted connectivity and ensure efficient migration across networks. Additionally, devices in a WBAN may have different frequency, data rate and power requirements. Hence, the chosen wireless technology must be capable of handling a mixture of these requirements. In terms of QoS, episodic data, real time wave form data, periodic parametric data and emergency alarms need to be supported with a BER of 10^{-10} to 10^{-3} and peer to peer

[17]http://www.ist-world.org/ ProjectDetails.aspx/ProjectId=07a46fe732b64e07a622e8e5 ecde2874
[18]http://projects.ibbt.be/im3
[19]http://www.media.mit.edu/wearables/mithril
[20]http://www.ubimon.net
[21]http://actuators.stanford.edu/Archive/CPOD.htm
[22]http://www.healthservice24.com

latency from 10ms-250ms [9]. Hence, QoS features such as bandwidth, reliability, delay, etc., require comprehensive study. The desired QoS could also affect energy consumption, which is one of the prominent requirements in WBANs. For instance, to achieve a lower packet loss, the transmit power should be increased, which also increases the relative power consumption.

In this section we have summarized the main pitfalls that can be experienced in WBANs. For one thing, Rayleigh distribution is a very poor fit for small-scale fading compared to the other standard distributions. Generally, Rayleigh fading provides a good fit when multipath in the radio channel is additive in the linear domain. Therefore, other radio networks avoid the combination of multipaths that occur in WBANs; which is normally additive in the log domain or multiplicative and are mainly dominated by the shadowing. Thus, in fact the best fit for a small-scale fading is gamma distribution. Additionally, a distance-based path loss model provides poor measurements in terms of the received signal strength for a link. In fact, the environment and location are more dominant factors than distance. More specifically, the position of a transmitter with respect to a receiver is important in terms of path loss but the position in relevance to body posture, body movements, shadowing as well as the surrounding environment are more important. One other pitfall that most WBAN researchers need to be aware of is that the characterization of an on-body link as LOS or NLOS is not practical or meaningful as the signal states vary as much from NLOS to LOS because of dynamics, changes in posture and body movements. Whilst the rate of movement needs to be captured to statistically characterize the path loss of the link [24].

Another major pitfall is the danger of relying on a one-hop star topology as such a network cannot be sufficiently reliable for WBAN communications specifically in health care applications that require the use of relays and cooperative communication for reliable communication. The one-hop star topology was only desired in the initial stages of IEEE 802.15.6, however since it did not meet the reasonable reliability requirement of WBANs, multi-hop and cooperative communication were later added as an option to IEEE 802.15.6. Based on the standard, only one relay can be added to a single WBAN. Relays can be more complex and powerful devices compared to a typical WBAN as relays have greater energy consumption. The necessity of using relays can be further realized in a scenario where a patient is sleeping as the WBAN channel will be quasi-stationary [131].

Table X provides a brief comparison of current and ongoing WBAN projects. Important aspects considered in these projects are listed in Table X in terms of their actual application, intra-WBAN communication, inter-WBAN communication, beyond-WBAN communication and the sensors being used.

In summary, even though WBANs will provide major enhancements in human life style through the use of ubiquitous networking, various challenges remain in this area that need to be taken into account before being widely deployed such as interoperability of WBANs and other wireless technologies, energy efficient and high bandwidth communication protocols, privacy and security, biosensor design, QoS, power scavenging issues, mobility and scalability, standardization of interfaces and design of successful applications [1, 5, 11, 110].

XIV. Conclusion

In this survey, a review of the on-going research in WBANs in terms of system architecture, address allocation, routing, channel modeling, PHY layer, MAC layer, security and applications is provided. A comparison of WBANs with respect to WSNs and other wireless technologies is given. Additionally, a list of existing and applicable sensors, radio technologies and current research projects, open issues, and future work in WBANs is also presented. WBANs will allow for continuous monitoring of patients in medical applications, capable of early detection of abnormal conditions resulting in major improvements in the quality of life. Importantly, even basic vital signs monitoring (e.g. heart rate) can enable patients to engage in normal activities as opposed to being home bound or nearby specialized medical services. In summary, the procedural research on this valuable technology has significant importance in better usage of available resources that will no doubt truly affect our future well being. We truly believe this research to be a source of inspiration towards future developments in WBANs.

Acknowledgment

The authors would like to thank Mahyar Shirvanimoghaddam from The University of Sydney for his assistance.

References

[1] A. Milenkovic, C. Otto, and E. Jovanov, "Wireless sensor networks for personal health monitoring: Issues and an implementation," *Computer Communications (Special issue: Wireless Sensor Networks: Performance, Reliability, Security, and Beyond*, vol. 29, pp. 2521–2533, 2006.

[2] C. Otto, A. Milenkovic', C. Sanders, and E. Jovanov, "System architecture of a wireless body area sensor network for ubiquitous health monitoring," *J. Mob. Multimed.*, vol. 1, pp. 307–326, Jan. 2005.

[3] "IEEE standard for local and metropolitan area networks: Part 15.6: Wireless body area networks," *IEEE submission*, Feb. 2012.

[4] D. Smith and L. Hanlen, "Wireless body area networks : Towards a wearable intranet," *ISCIT Tutorial*, Sept. 2012.

[5] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, and V. Leung, "Body area networks: A survey," *Mobile Networks and Applications*, vol. 16, pp. 171–193, 2011.

[6] S. Ullah, B. Shen, S. M. R. Islam, P. Khan, S. Saleem, and K. S. Kwak, "A study of medium access control protocols for wireless body area networks," *arXiv preprint arXiv:1004.3890*, 2010.

[7] H. Kwon and S. Lee, "Energy-efficient multi-hop transmission in body area networks," in *20th IEEE Int. Symp. on Personal, Indoor and Mobile Radio Commun. (PIMRC)*, pp. 2142 –2146, Sept. 2009.

[8] B. Latré, B. Braem, I. Moerman, C. Blondia, and P. Demeester, "A survey on wireless body area networks," *Wirless Network*, vol. 17, pp. 1–18, Jan. 2011.

[9] M. Hanson, H. Powell, A. Barth, K. Ringgenberg, B. Calhoun, J. Aylor, and J. Lach, "Body area sensor networks: Challenges and opportunities," *Computer*, vol. 42, pp. 58 –65, Jan. 2009.

[10] K. Kwak, S. Ullah, and N. Ullah, "An overview of IEEE 802.15.6 standard," in *3rd Int. Symp. on Applied Sciences in Biomedical and Communication Technologies (ISABEL)*, pp. 1 –6, Nov. 2010.

[11] S. Ullah, H. Higgin, M. A. Siddiqui, and K. S. Kwak, "A study of implanted and wearable body sensor networks," in *Proc. 2nd KES Int. Conf. on Agent and multi-agent systems: technologies and applications*, (Berlin, Heidelberg), pp. 464–473, Springer-Verlag, 2008.

[12] E. Dishman, "Inventing wellness systems for aging in place," *Computer*, vol. 37, pp. 34 – 41, May. 2004.

[13] J. Xing and Y. Zhu, "A survey on body area network," in *5th Int. Conf.on Wireless Communications, Networking and Mobile Computing (WiCom '09)*, pp. 1 –4, Sept. 2009.

[14] B. Wang and Y. Pei, "Body area networks," *Encyclopedia of Wireless and Mobile Communications,Edited by Borko Furht, Taylor and Francis*, vol. 98, 2007.

[15] S. Ullah, P. Khan, N. Ullah, S. Saleem, H. Higgins, and K. Kwak, "A review of wireless body area networks for medical applications," *arXiv preprint arXiv:1001.0831*, vol. abs/1001.0831, 2010.

[16] S. Ullah, H. Higgins, B. Braem, B. Latre, C. Blondia, I. Moerman, S. Saleem, Z. Rahman, and K. Kwak, "A comprehensive survey of wireless body area networks," *J. of Medical Systems*, pp. 1–30, 2010.

[17] D. Lewis, "802.15.6 call for applications in body area networks-response summary," in *15-08-0407-05-0006*, Nov. 2008.

[18] N. de Vicq, F. Robert, J. Penders, B. Gyselinckx, and T. Torfs, "Wireless body area network for sleep staging," in *IEEE Biomedical Circuits and Systems Conf. (BIOCAS 2007)*, pp. 163–166, 2007.

[19] M. Lipprandt, M. Eichelberg, W. Thronicke, J. Kruger, I. Druke, D. Willemsen, C. Busch, C. Fiehe, E. Zeeb, and A. Hein, "Osami-d: An open service platform for healthcare monitoring applications," in *2nd Conf. on Human System Interactions (HSI'09)*, pp. 139–145, IEEE, 2009.

[20] J. Nehmer, M. Becker, A. Karshmer, and R. Lamm, "Living assistance systems: an ambient intelligence approach," in *Proc. 28th Int. Conf. on Software engineering*, pp. 43–50, ACM, 2006.

[21] C. Tachtatzis, F. Franco, D. Tracey, N. Timmons, and J. Morrison, "An energy analysis of IEEE 802.15.6 scheduled access modes," in *IEEE GLOBECOM Workshops (GC Wkshps)*, pp. 1270 –1275, Dec. 2010.

[22] A. W. Astrin, H.-B. Li, and R. Kohno, "Standardization for body area networks," *IEICE Trans. Commun.*, vol. no. 2, pp. 366–72, 2009.

[23] D. Lewis, "802.15.6 call for applications-response summary," in *15-08-0407-00-0006-tg6-applications-summary.doc*.

[24] D. Smith, D. Miniutti, T. A. Lamahewa, and L. Hanlen, "Propagation models for body area networks: A survey and new outlook," *to appear in IEEE Antennas and Propagation Mag.*, Dec. 2013.

[25] J. Y. Khan, M. R. Yuce, G. Bulger, and B. Harding, "Wireless body area network (wban) design techniques and performance evaluation," *J. of medical systems*, vol. 36, no. 3, pp. 1441–1457, 2012.

[26] B. Zhen, M. Patel, S. Lee, E. Won, and A. Astrin, "Tg6 technical requirements document (TRD) IEEE p802.15-08-0644-09-0006.," Sept. 2008.

[27] S. Wang and J.-T. Park, "Modeling and analysis of multi-type failures in wireless body area networks with semi-markov model," *Comm. Letters.*, vol. 14, pp. 6–8, Jan. 2010.

[28] K. Y. Yazdandoost and K. Sayrafian-Pour, "Channel model for body area network (BAN)," *Networks*, p. 91, 2009.

[29] "IEEE p802.15-07–0867-04-0ban," in *15-10-0245-06-0006*, Oct. 2007.

[30] "IEEE p802.15.6/d0 draft standard for body area network," *IEEE Draft*, 2010.

[31] D. Lewis, "IEEE p802.15.6/d0 draft standard for body area network," in *15-10-0245-06-0006*, May. 2010.

[32] "IEEE p802. 15-10 wireless personal area networks,," July, 2011.

[33] A. Zhang, D. Smith, D. Miniutti, L. Hanlen, D. Rodda, and B. Gilbert, "Performance of piconet co-existence schemes in wireless body area networks," in *IEEE Wireless Commun. and Netw. Conf. (WCNC)*, pp. 1 –6, April. 2010.

[34] L. Hanlen, D. Miniutti, D. B. Smith, D. Rodda, and B. Gilbert, "Co-channel interference in body area networks with indoor measurements at 2.4 GHz: Distance-to-interferer is a poor estimate of received interference power.," *IJWIN*, vol. 17, no. 3-4, pp. 113–125, 2010.

[35] M. Patel and J. Wang, "Applications, challenges, and prospective in emerging body area networking technologies," *Wireless Commun.*, vol. 17, pp. 80–88, Feb. 2010.

[36] T. Zasowski, F. Althaus, M. Stager, A. Wittneben, and G. Troster, "Uwb for noninvasive wireless body area networks: channel measurements and results," in *IEEE Conf. on Ultra Wideband Systems and Technologies*, pp. 285 – 289, Nov. 2003.

[37] R. Shah and M. Yarvis, "Characteristics of on-body 802.15.4 networks," in *2nd IEEE Workshop on Wireless Mesh Networks (WiMesh)*, pp. 138 –139, Sept. 2006.

[38] M. Sukor, S. Ariffin, N. Fisal, S. S. Yusof, and A. Abdallah, "Performance study of wireless body area network in medical environment," *Asia Int. Conf. on Modelling & Simulation*, pp. 202–206, 2008.

[39] "IEEE standard for information technology- telecommunications and information exchange between systems- local and metropolitan area networks- specific requirements part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs)," *IEEE Std 802.15.4-2006 (Revision of IEEE Std 802.15.4-2003)*, pp. 0_1 –305, 2006.

[40] A. Natarajan, M. Motani, B. Silva, K. Yap, and K. Chua, "Investigating network architectures for body sensor networks," in *Proc. 1st ACM SIGMOBILE Int. Workshop on Systems and networking support for healthcare and assisted living environments*, (New York, NY, USA), pp. 19–24, ACM, 2007.

[41] D. Domenicali and M.-G. Di Benedetto, "Performance analysis for a body area network composed of IEEE 802.15.4a devices," in *4th Workshop on Positioning, Navigation and Communication (WPNC '07)*, pp. 273 –276, Mar. 2007.

[42] A. Boulis, D. Smith, D. Miniutti, L. Libman, and Y. Tselishchev, "Challenges in body area networks for healthcare: The mac," *IEEE Commun. Mag.*, May. 2012.

[43] M. R. Yuce, S. W. Ng, N. L. Myo, C. K. Lee, J. Y. Khan, and W. Liu, "A mics band wireless body sensor network," in *Wireless Commun. and Netw. Conf. (WCNC)*, pp. 2473–2478, IEEE, 2007.

[44] I. Khan, Y. Nechayev, and P. Hall, "On-body diversity channel characterization," *IEEE Trans. Antennas Propag.*, vol. 58, pp. 573 –580, Feb. 2010.

[45] A. Guraliuc, A. Serra, P. Nepa, and G. Manara, "Channel model for on body communication along and around the human torso at 2.4GHz and 5.8GHz," in *Int. Workshop on Antenna Technology (iWAT)*, pp. 1–4, Mar. 2010.

[46] Y. Hao, "Antennas and propagation for body centric wireless communications," in *2011 IEEE Int. Conf. on Microwave Technology Computational Electromagnetics (ICMTCE)*, May 2011.

[47] E. Reusens, W. Joseph, B. Latre, B. Braem, G. Vermeeren, E. Tanghe, L. Martens, I. Moerman, and C. Blondia, "Characterization of on-body communication channel and energy efficient topology design for wireless body area networks," *IEEE Trans. Inf. Technol. Biomed.*, vol. 13, pp. 933 –945, Nov. 2009.

[48] S. L. Cotton, W. G. Scanlon, and G. Jim, "The κ-μ distribution applied to the analysis of fading in body to body communication channels for fire and rescue personnel,"

[49] D. B. Smith, L. W. Hanlen, J. A. Zhang, D. Miniutti, D. Rodda, and B. Gilbert, "Characterization of the dynamic narrowband on-body to off-body area channel," *in IEEE Int. Conf. Commun. ICC*, pp. 1–6, 2009.

[50] W. G. Scanlon and S. L. Cotton, "Understanding on-body fading channel at 2.45 GHz using measurements based on user state and environment," *in Loughborough Antennas and Propagation Conference, Loughborough, UK*, pp. 10–13, 2008.

[51] P. W. A. Fort, C. Desset and L. Biesen, "Indoor body-area channel model for narrowband communications,," *IET Microwaves, Antennas and Propagation*, pp. 1197–1203, December 2007.

[52] D. B. Smith, L. W. Hanlen, D. Miniutti, J. A. Zhang, D. Rodda, and B. Gilbert, "Statistical characterization of the dynamic narrowband body area channel,," *in Int. Symp. on Applied Sciences in Bio-Medical and Communication Technologies,*, pp. 1–5, Oct. 2008.

[53] M. Yuce and J. Khan, *Wireless Body Area Networks: Technology, Implementation, and Applications*. Pan Stanford Publishing, 2011.

[54] W.-B. Yang and K. Sayrafian-Pour, "Interference mitigation for body area networks," in *22nd Int. Symp. on Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 2193–2197, IEEE, 2011.

[55] B. de Silva, A. Natarajan, and M. Motani, "Inter-user interference in body sensor networks: Preliminary investigation and an infrastructure-based solution," in *6th Int. Workshop on Wearable and Implantable Body Sensor Networks (BSN)*, pp. 35–40, IEEE, 2009.

[56] J. Dong and D. Smith, "Cooperative body-area-communications: Enhancing coexistence without coordination between networks," in *IEEE 23rd Int. Symp. Personal Indoor and Mobile Radio Commun. (PIMRC)*, pp. 2269–2274, IEEE, 2012.

[57] S. Marinkovic, E. Popovici, C. Spagnol, S. Faul, and W. Marnane, "Energy-efficient low duty cycle MAC protocol for wireless body area networks," *IEEE Trans. Inf. Technol. Biomed.*, vol. 13, pp. 915 –925, Nov. 2009.

[58] A. Arriola, J. Sancho, S. Brebels, M. Gonzalez, and W. De Raedt, "Stretchable dipole antenna for body area networks at 2.45 ghz," *Microwaves, Antennas Propagation, IET*, vol. 5, 13 2011.

[59] J. Kim and Y. Rahmat-Samii, "Implanted antennas inside a human body: simulations, designs, and characterizations," *IEEE Trans. Microw. Theory Tech.*, vol. 52, pp. 1934 – 1943, Aug. 2004.

[60] L. Hanlen, D. Smith, A. Boulis, B. Gilbert, V. Chaganti, L. Craven, D. Fang, T. Lamahewa, D. Lewis, D. Miniutti, O. Nagy, D. Rodda, K. Sithamparanathan, Y. Tselishchev, and A. Zhang, "Wireless body-area-networks : toward a wearable intranet," in *National ICT Australia*, 2011.

[61] M. Kamarudin, Y. Nechayev, and P. Hall, "Performance of antennas in the on-body environment," in *IEEE Antennas and Propagation Society Int. Symp.*, vol. 3A, pp. 475 – 478, July. 2005.

[62] Z. Hu, M. Gallo, Q. Bai, Y. Nechayev, P. Hall, and M. Bozzettit,

"Measurements and simulations for on-body antenna design and propagation studies," in *2nd European Conf. on Antennas and Propagation (EuCAP)*, pp. 1–7, Nov. 2007.

[63] S. Saleem, S. Ullah, and H. S. Yoo, "On the security issues in wireless body area networks," *JDCTA*, vol. 3, no. 3, pp. 178–184, 2009.

[64] "IEEE p802.15 working group for wireless personal area networks (WPANs):medwin MAC and security proposal documentation," *IEEE802.15.6 technical contribution*, 2009.

[65] M. Mana, M. Feham, and B. A. Bensaber, "Trust key management scheme for wireless body area networks.," *Int. J. Netw. Security*, 2011.

[66] C. Poon, Y.-T. Zhang, and S.-D. Bao, "A novel biometrics method to secure wireless body area sensor networks for telemedicine and m-health," *IEEE Commun. Mag.*, vol. 44, pp. 73 – 81, April. 2006.

[67] S. Cherukuri, K. Venkatasubramanian, and S. Gupta, "Biosec: a biometric based approach for securing communication in wireless networks of biosensors implanted in the human body," in *Proc. Int. Conf. on Parallel Processing Workshops*, pp. 432 – 439, Oct. 2003.

[68] H. Wang, H. Fang, L. Xing, and M. Chen, "An integrated biometric-based security framework using wavelet-domain hmm in wireless body area networks (wban)," in *IEEE Int. Conf. on Commun. (ICC)*, pp. 1 –5, June. 2011.

[69] A. Banerjee, K. Venkatasubramanian, and S. Gupta, "Challenges of implementing cyber-physical security solutions in body area networks," in *Proc. of 4th Int. Conf. on Body Area Networks*, 2009.

[70] S.-D. Bao and Y.-T. Zhang, "A design proposal of security architecture for medical body sensor networks," in *Int. Workshop on Wearable and Implantable Body Sensor Networks (BSN)*, April. 2006.

[71] L. W. Hanlen, D. Smith, J. A. Zhang, and D. Lewis, "Key-sharing via channel randomness in narrowband body area networks: Is everyday movement sufficient?," in *Proc. 4th Int. Conf. on Body Area Networks*, BodyNets '09, pp. 17:1–17:6, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2009.

[72] M. Li, S. Yu, W. Lou, and K. Ren, "Group device pairing based secure sensor association and key management for body area networks," in *IEEE INFOCOM Proc.*, pp. 1 –9, Mar. 2010.

[73] S. L. Keoh, E. C. Lupu, and M. Sloman, "Securing body sensor networks: Sensor association and key management," in *PerCom*, IEEE Computer Society, 2009.

[74] M. Abolhasan, T. Wysocki, and E. Dutkiewicz, "A review of routing protocols for mobile ad hoc networks," *Ad Hoc Networks*, vol. 2, pp. 1–22, Jan. 2004.

[75] K. Akkaya and M. Younis, "A survey on routing protocols for wireless sensor networks," *Ad Hoc Networks*, vol. 3, pp. 325–349, 2005.

[76] S. Cheng and C. Huang, "Coloring-based inter-wban scheduling for mobile wireless body area network," *IEEE Trans. Parallel Distrib. Syst.*.

[77] A. Maskooki, C. B. Soh, E. Gunawan, and K. S. Low, "Opportunistic routing for body area network," in *IEEE Consumer Commun. and Netw. Conf. (CCNC)*, pp. 237 –241, Jan. 2011.

[78] M. Quwaider and S. Biswas, "DTN routing in body sensor networks with dynamic postural partitioning," *Ad Hoc Networks*, vol. 8, no. 8, pp. 824–841, 2010.

[79] D. Takahashi, Y. Xiao, F. Hu, J. Chen, and Y. Sun, "Temperature-aware routing for telemedicine applications in embedded biomedical sensor networks," *EURASIP J. of Wireless Commun. Netw.*, Jan. 2008.

[80] B. Braem, B. Latré, I. Moerman, C. Blondia, and P. Demeester, "The wireless autonomous spanning tree protocol for multihop wireless body area networks," *In proc. 3rd Annu. Int. Conf. on Mobile and Ubiquitous Systems: Networking Services*, pp. 1 –8, July 2006.

[81] T. Watteyne, I. Auge-Blum, M. Dohler, and D. Barthel, "Anybody: a self-organization protocol for body area networks," in *2nd Int. Conf. on Body Area Networks (BodyNets)*, vol. 5, (Florence, Italy), pp. 8020–8024, June. 2007.

[82] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *Proc. 33rd Annu. Hawaii Int. Conf. on System Sciences*, vol. 5, pp. 8020–8024, Jan. 2000.

[83] M. Moh, B. J. Culpepper, L. Dung, T.-S. Moh, T. Hamada, and C.-F. Su, "On data gathering protocols for in-body biomedical sensor networks," in *Proc. of Global Telecommunications Conf.*.

[84] S. Movassaghi, M. Abolhasan, and J. Lipman, "Energy efficient thermal and power aware (ETPA) routing in body area networks," in *23rd IEEE Int. Symp. on Personal Indoor and Mobile Radio Commun. (PIMRC)*, Sept. 2012.

[85] X. Liang, X. Li, Q. Shen, R. Lu, X. Lin, X. Shen, and W. Zhang, "Exploiting Prediction to Enable Secure and Reliable Routing in Wireless Body Area Networks," in *31st IEEE Int. Conf. on Computer Commun. (INFOCOM)*, (Orlando, United States), 2012.

[86] M. Quwaider and S. Biswas, "Probabilistic routing in on-body sensor networks with postural disconnections," *Proc. 7th ACM Int. Symp. on Mobility management and wireless access (MobiWAC)*, pp. 149–158, 2009.

[87] M. Quwaider and S. Biswas, "On-body packet routing algorithms for body sensor networks," *1st Int. Conf. on Networks and Commun. (NETCOM '09)*, pp. 171 –177, Dec. 2009.

[88] B. Braem, B. Latré, C. Blondia, I. Moerman, and P. Demeester, "Improving reliability in multi-hop body sensor networks," *Proc. 2008 2nd Int. Conf. on Sensor Technologies and Applications*, pp. 342–347, 2008.

[89] A. G. Ruzzelli, R. Jurdak, G. M. O'Hare, and P. Van Der Stok, "Energy-efficient multi-hop medical sensor networking," *Proc. 1st ACM SIGMOBILE Int. Workshop on Systems and networking support for healthcare and assisted living environments (HealthNet)*, pp. 37–42, 2007.

[90] A. Bag and M. A. Bassiouni, "Biocomm - a cross-layer medium access control (mac) and routing protocol co-design for biomedical sensor networks," *Int. J, of Parallel, Emergent and Distributed Systems*, vol. 24, Feb. 2009.

[91] A. Ortiz, N. Ababneh, N. Timmons, and J. Morrison, "Adaptive routing for multihop IEEE 802.15.6 wireless body area networks," in *20th Int. Conf. on Software, Telecommunications and Computer Networks (SoftCOM),*, pp. 1–5, 2012.

[92] Q. Tang, N. Tummala, S. K. S. Gupta, and L. Schwiebert, "Communication scheduling to minimize thermal effects of implanted biosensor networks in homogeneous tissue," in *IEEE Trans. Biomed. Eng.*, vol. 52, pp. 1285–1294, July. 2005.

[93] A. Bag and M. Bassiouni, "Hotspot preventing routing algorithm for delay-sensitive biomedical sensor networks," *IEEE Int. Conf. on Portable Information Devices (PORTABLE07)*, pp. 1 –5, May. 2007.

[94] A. Bag and M. A. Bassiouni, "Energy efficient thermal aware routing algorithms for embedded biomedical sensor networks," in *IEEE Trans. Mobile Adhoc and Sensor Systems (MASS)*, (Vancouver), pp. 604–609, 2006.

[95] A. Bag and M. Bassiouni, "Routing algorithm for network of homogeneous and id-less biomedical sensor nodes (RAIN)," *IEEE Sensors Applications Symp. (SAS)*, pp. 68 –73, Feb. 2008.

[96] S. Movassaghi, M. Abolhasan, and J. Lipman, "A review of routing protocols in wireless body area networks," *J. of Networks*, March 2013.

[97] D. Djenouri and I. Balasingham, "New QoS and geographical routing in wireless biomedical sensor networks," in *6th Int. Conf. on Broadband Communications, Networks, and Systems (BROADNETS)*, pp. 1 –8, Sept. 2009.

[98] M. A. Razzaque, C. S. Hong, and S. Lee, "Data-centric multiobjective QoS-aware routing protocol for body sensor networks," *Sensors*, Jan. 2011.

[99] X. Liang, I. Balasingham, and S.-S. Byun, "A reinforcement learning based routing protocol with QoS support for biomedical sensor networks," in *1st Int. Symp. on Applied Sciences on Biomedical and Communication Technologies (ISABEL '08)*, pp. 1 – 5, Oct. 2008.

[100] X. Liang and I. Balasingham, "A QoS-aware routing service framework for biomedical sensor networks," in *4th Int. Symp. on Wireless Commun. Systems (ISWCS)*, pp. 342 –345, Oct. 2007.

[101] S. Movassaghi, M. Abolhasan, and J. Lipman, "Optimized prophet address allocation (OPAA) for body area networks," in *Proc. 7th Int. Wireless Communications and Mobile Computing Conf. (IWCMC 2011)*, pp. 2098–2102, July. 2011.

[102] C. Lauradoux and M. Minier, "A mathematical analysis of prophet dynamic address allocation," in *Rapport de recherche,INRIA*, no. RR-7085.

[103] S. Movassaghi, M. Abolhasan, and J. Lipman, "Hierarchical collision-free addressing protocol(HCAP) for body area networks," in *Proc. 3rd Int. Workshop on Wireless Sensor, Actuator and Robot Networks (WiSARN)*, pp. 549 –554, April. 2011.

[104] S. Movassaghi, M. Abolhasan, and J. Lipman, "Addressing schemes for body area networks," *IEEE Commun. Lett.*, vol. 15, pp. 1310 –1313, Dec. 2011.

[105] H. Cao, V. Leung, C. Chow, and H. Chan, "Enabling technologies for wireless body area networks: A survey and outlook," *IEEE Commun. Mag.*, vol. 47, pp. 84–93, Dec. 2009.

[106] X.Yu, X.Xia, and X.Chen, "Design and application of rubee-based telemedicine data acquisition system," in *IEEE/ACIS 10th Int. Conf. on Computer and Information Science (ICIS),*, pp. 365 –370, May. 2011.

[107] S. Movassaghi, P. Arab, and M. Abolhasan, "Wireless technologies for body area networks: Characteristics and challenges," in *Int. Symp. on Communications and Information Technologies (ISCIT)*, pp. 42 –47,

Oct. 2012.
[108] H.-B. Li, K. i. Takizawa, B. Zhen, and R. Kohno, "Body area network and its standardization at IEEE 802.15 MBAN," *in 16th 1ST Mobile and Wireless Communications Summit*, pp. 1 –5, July. 2007.
[109] C. Liolios, C. Doukas, G. Fourlas, and I. Maglogiannis, "An overview of body sensor networks in enabling pervasive healthcare and assistive environments," *Proc. 3rd Int. Conf. on Pervasive Technologies Related to Assistive Environments (PETRA '10)*, pp. 43:1–43:10, 2010.
[110] K. Bilstrup, "A preliminary study of wireless body area networks," in *Technical Report,IDE0854, Halmstad University, Sweden*, Aug. 2008.
[111] Z. Chen, C. Hu, J. Liao, and S. Liu, "Protocol architecture for wireless body area network based on nrf24l01," in *IEEE Int. Conf. on Automation and Logistics (ICAL)*, pp. 3050 –3054, Sept. 2008.
[112] W. Scanlon, G. Conway, and S. Cotton, "Antennas and propagation considerations for robust wireless communications in medical body area networks," in *IET Seminar on Antennas and Propagation for Body-Centric Wireless Communications*, p. 37, IET, 2007.
[113] R. Serrano, S. Blanch, and L. Jofre, "Small antenna fundamentals and technologies: Future trends," in *1st European Conf. on Antennas and Propagation (EuCAP)*, pp. 1–7, IEEE, 2006.
[114] A. Kiourti and K. S. Nikita, "A review of implantable patch antennas for biomedical telemetry: Challenges and solutions [wireless corner]," *IEEE Antennas Propagat. Mag.*, vol. 54, no. 3, pp. 210–228, 2012.
[115] H. Higgins, "Wireless communication," in *Body Sensor Networks*, pp. 117–143, Springer, 2006.
[116] S. Movassaghi, M. Shirvanimoghaddam, M. Abolhasan, and D. Smith, "An energy efficient network coding approach for wireless body area networks," in *The 38th IEEE Conf. on Local Computer Networks (LCN)*, 2013.
[117] S. Movassaghi, M. Shirvanimoghaddam, and M. Abolhasan, "A co-operative network coding approach to reliable wireless body area networks with demodulate-and-forward," in *9th Int. Wireless Commun. and Mobile Computing Conf. (IWCMC)*, 2013.
[118] K. Wac, R. Bults, B. van Beijnum, I. Widya, V. Jones, D. Konstantas, M. Vollenbroek-Hutten, and H. Hermens, "Mobile patient monitoring: The mobihealth system," in *Annu. Int. Conf. on Engineering in Medicine and Biology Society (EMBS)*, pp. 1238 –1241, Sept. 2009.
[119] 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 Trans. Biomed. Circuits Syst.*, vol. 1, pp. 203 –216, Sept. 2007.
[120] E. Kang, Y. Im, and U. Kim, "Remote control multi-agent system for u-healthcare service," in *Proc. 1st KES Int. Symp. on Agent and Multi-Agent Systems: Technologies and Applications (KES-AMSTA)*, (Berlin, Heidelberg), pp. 636–644, Springer-Verlag, 2007.
[121] V. Shnayder, B. Chen, K. Lorincz, T. Fulford-Jones, and M. Welsh, "Sensor networks for medical care," in *Harvard University Technical Report TR-08-05*, 2005.
[122] K. Ouchi, T. Suzuki, and M. Doi, "Lifeminder: a wearable healthcare support system using user's context," in *Proc. 22nd Int. Conf. on Distributed Computing Systems Workshops*, pp. 791 – 792, Nov. 2002.
[123] D. Curtis, E. Shih, J. Waterman, J. Guttag, J. Bailey, T. Stair, R. Greenes, and L. Ohno-Machado, "Physiological signal monitoring in the waiting areas of an emergency room," in *Proc. 3rd ICST Int. Conf. on Body Area Networks*.
[124] S. Jiang, Y. Cao, S. Iyengar, P. Kuryloski, R. Jafari, Y. Xue, R. Bajcsy, and S. Wicker, "Carenet: an integrated wireless sensor networking environment for remote healthcare (bodynets)," in *Proc. 3rd ICST Int. Conf. on Body Area Networks*, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008.
[125] T. Sheltami, A. Mahmoud, and M. Abu-amara, "Warning and monitoring medical system using sensor networks," in *the Saudi 18th National Computer Conf. (NCC18)*, (Riyadh, Saudi Arabia), pp. 63–68, 2006.
[126] T. Falck, J. Espina, J.-P. Ebert, and D. Dietterle, "Basuma - the sixth sense for chronically ill patients," in *Int. Workshop on Wearable and Implantable Body Sensor Networks (BSN)*, pp. 4–6, Apr. 2006.
[127] B. Gyselinckx, R. Vullers, C. Hoof, J. Ryckaert, R. Yazicioglu, P. Fiorini, and V. Leonov, "Human++: Emerging technology for body area networks," in *Int. Conf. on Very Large Scale Integration (IFIP)*, pp. 175 –180, Oct. 2006.
[128] E. Farella, A. Pieracci, L. Benini, L. Rocchi, and A. Acquaviva, "Interfacing human and computer with wireless body area sensor networks: the wimoca solution," *Multimedia Tools and Applications*, vol. 38, pp. 337–363, 2008.
[129] K. Venkatasubramanian, G. Deng, T. Mukherjee, J. Quintero, V. Annamalai, and S. S. Gupta, "Ayushman A wireless sensor network based health monitoring infrastructure and testbed.," *Springer Lecture Notes in Computer Science*, vol. 3560, pp. 406–407, 2005.
[130] I. Jantunen, H. Laine, P. Huuskonen, D. Trossen, and V. Ermolov, "Smart sensor architecture for mobile-terminal-centric ambient intelligence," *Sensors and Actuators A Physical*, vol. 142, no. 1, pp. 352–360, 2008.
[131] D. B. Smith, D. Miniutti, and L. W. Hanlen, "Characterization of the body-area propagation channel for monitoring a subject sleeping," *IEEE Trans. Antennas Propag.*, vol. 59, no. 11, pp. 4388–4392, 2011.

Samaneh Movassaghi received a B.Sc. from University of Tehran in 2009 and a Master by Research in Telecommunication Engineering from the University of Technology, Sydney in 2012. She is currently a PhD student at the University of Technology, Sydney and is conducting research in the field of Wireless Body Area Networks. She is currently an IEEE Student member. She has been the reviewer of a number of conference papers and journals. Her research interests are in Wireless Body Area Networks, Energy Efficient Communication, Interference Mitigation, Address Allocation, Routing Schemes, Energy efficient Scheduling and QoS provisioning in wireless sensor networks. She is a recipient of the UTS International Research Scholarship (IRS), UTS President's scholarship (UTSP) and UTS Teaching Fellowship Award.

Mehran Abolhasan completed his B.E in Computer Engineering and PhD in Telecommunications on 1999 and 2003 respectively at the University of Wollongong. From July 2003, he joined the Smart Internet Technology CRC and Office of Information and Communication Technology within the Department of Commerce in NSW, where he proposed a major status report outlining strategies and new projects to improve the communications infrastructure between the NSW Emergency Services Organisations. In July 2004, he joined the Desert knowledge CRC and Telecommunication and IT Research Institute to work on a joint project called the Sparse Ad hoc network for Deserts project (Also known as the SAND project). During 2004 to 2007 A/Prof. Abolhasan led a team of researchers at TITR to develop prototype networking devices for rural and remote communication scenarios. Furthermore, he led the deployment of a number of test-beds and field studies in that period. In 2008, A/Prof. Abolhasan accepted the position of Director of Emerging Networks and Applications Lab (ENAL) at the ICTR institute. During this time as the Director of ENAL, A/Prof. Abolhasan won a number of major research project grants including an ARC DP project and a number of CRC and other government and industry-based grants. He also worked closely with the Director of ICTR in developing future research directions in the area wireless communications. In March 2010, he accepted the position of Senior Lecturer at the School of Computing and Communications within the faculty of Engineering and IT (FEIT) at the University of Technology Sydney, where he is now an Associate Professor. A/Prof. Abolhasan has authored over 90 international publications and has won over one million dollars in research funding. His Current research Interests are in Wireless Mesh, Wireless Body Area Networks, 4th Generation Cooperative Networks and Sensor networks. He is currently a Senior Member of IEEE.

Justin Lipman received a B.E. Computer Engineering and Ph.D. Telecommunications Engineering from the University of Wollongong, Australia in 1999 and 2003 respectively. He joined Intel in 2006 as a Sr. Research Scientist and is currently a member of Intels IT Labs based in Shanghai, China. Justin has led research and architecture efforts for numerous Intel products such as the Intel classmate PC for 1:1 Education where he innovated, architected and filed patents for optimized data transfer in densely populated Wi-Fi networks and wireless device to device proximity detection. His research and architecture contributions to productize Intels long range Wi-Fi based Rural Connectivity Platform led to the technology being selected by the Clinton Global Initiative in 2008. Prior to Intel, he was Program Manager for Research and Innovation at Alcatel where he managed a technically diverse team of talented research engineers charged with determining the next generation of product concepts and internal ventures for Alcatel. These included WiMAX Mesh and Backhaul, Wireless over Copper Distribution, Distributed Antennae Systems, Reliable IPv6 Multicast efficiency and signaling, 2G/3G Enhancements, Single Frequency Reuse, and Mobile Gaming. Prior to Alcatel, Justin was a visiting fellow at the University of New South Wales for the Smart Internet CRC where he prototyped research on the patented Swarm Phone concept and supervised research students in mesh and sensor networks. He has published over 40 international peer reviewed publications, has one US patent and a further 25 patent applications under review with the USPTO. He has a strong interest in distributed and ubiquitous computing with an emphasis on Mesh Networks, Body Area Networks, Internet of Things, Wireless Localization and Location Based Services.

David Smith is a Senior Researcher at National ICT Australia (NICTA) and is an adjunct Fellow with the Australian National University (ANU), and has been with NICTA and the ANU since 2004. He received the B.E. degree in Electrical Engineering from the University of N.S.W. Australia in 1997, and while studying toward this degree he was on a CO-OP scholarship. He obtained an M.E. (research) degree in 2001 and a Ph.D. in 2004 both from the University of Technology, Sydney (UTS), and both in Telecommunications Engineering. His research interests are in technology and systems for wireless body area networks; game theory for distributed networks; mesh networks; disaster tolerant networks; radio propagation and electromagnetic modeling; MIMO wireless systems; coherent and non-coherent space-time coding; and antenna design, including the design of smart antennas. He also has research interest in distributed optimization for smart grid. He has also had a variety of industry experience in electrical engineering; telecommunications planning; radio frequency, optoelectronic and electronic communications design and integration. He has published over 70 technical refereed papers and made various contributions to IEEE standardization activity; and has received four conference best paper awards.

Abbas Jamalipour is the Professor of Ubiquitous Mobile Networking at the University of Sydney, Australia, and holds a PhD in Electrical Engineering from Nagoya University, Japan. He is a Fellow of the Institute of Electrical, Information, and Communication Engineers (IEICE) and the Institution of Engineers Australia, an ACM Professional Member, and an IEEE Distinguished Lecturer. He is the author of six technical books, nine book chapters, over 300 technical papers, and three patents, all in the area of wireless communications. He was the Editor-in-Chief IEEE Wireless Communications and has been an editor for several journals. He is the Vice President-Conferences (2012-13) and a member of Board of Governors of the IEEE Communications Society. Previously he has held positions of the Chair of the Communication Switching and Routing and the Satellite and Space Communications Technical Committees and Vice Director of the Asia Pacific Board, in ComSoc. He was a General Chair or Technical Program Chair for several IEEE ICC, GLOBECOM, WCNC and PIMRC conferences. Dr. Jamalipour is also an elected member of Board of Governors (2014-16), IEEE Vehicular Technology Society. He is the recipient of a number of prestigious awards such as the 2010 IEEE ComSoc Harold Sobol Award, the 2006 IEEE ComSoc Distinguished Contribution to Satellite Communications Award, the 2006 IEEE ComSoc Best Tutorial Paper Award.