



VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

A comprehensive review of wireless body area network

This is the Accepted version of the following publication

Hasan, K, Biswas, K, Ahmed, Khandakar, Nafi, NS and Islam, MS (2019) A comprehensive review of wireless body area network. *Journal of Network and Computer Applications*, 143. pp. 178-198. ISSN 1084-8045 (In Press)

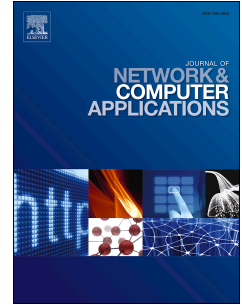
The publisher's official version can be found at
<https://www.sciencedirect.com/science/article/pii/S1084804519302218?via%3Dihub>
Note that access to this version may require subscription.

Downloaded from VU Research Repository <https://vuir.vu.edu.au/38975/>

Accepted Manuscript

A comprehensive review of wireless body area network

Khalid Hasan, Kamanashis Biswas, Khandakar Ahmed, Nazmus S. Nafi, Md Saiful Islam



PII: S1084-8045(19)30221-8

DOI: <https://doi.org/10.1016/j.jnca.2019.06.016>

Reference: YJNCA 2396

To appear in: *Journal of Network and Computer Applications*

Received Date: 6 December 2018

Revised Date: 16 April 2019

Accepted Date: 27 June 2019

Please cite this article as: Hasan, K., Biswas, K., Ahmed, K., Nafi, N.S., Islam, M.S., A comprehensive review of wireless body area network, *Journal of Network and Computer Applications* (2019), doi: <https://doi.org/10.1016/j.jnca.2019.06.016>.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Khalid Hasan[‡], Kamanashis Biswas^{†‡}, Khandakar Ahmed[¶], Nazmus S. Nafi[§], Md. Saiful Islam[‡]

[‡]Griffith University, Gold Coast, Australia

[†]Australian Catholic University, NSW, Australia

[¶]Victoria University, Melbourne, Australia

[§]Melbourne Institute of Technology, Melbourne, Australia

Abstract

Recent development and advancement of information and communication technologies facilitate people in different dimensions of life. Most importantly, in the healthcare industry, this has become more and more involved with the information and communication technology-based services. One of the most important services is monitoring of remote patients, that enables the healthcare providers to observe, diagnose and prescribe the patients without being physically present. The advantage of miniaturization of sensor technologies gives the flexibility of installing in, on or off the body of patients, which is capable of forwarding physiological data wirelessly to remote servers. Such technology is named as Wireless Body Area Network (WBAN). In this paper, WBAN architecture, communication technologies for WBAN, challenges and different aspects of WBAN are illustrated. This paper also describes the architectural limitations of existing WBAN communication frameworks. Furthermore, implementation requirements are presented based on IEEE 802.15.6 standard. Finally, as a source of motivation towards future development of research incorporating Software Defined Networking (SDN), Energy Harvesting (EH) and Blockchain technology into WBAN are also provided.

Keywords: WBAN, IEEE 802.15.6, M2M, SDN, Blockchain

2010 MSC: 00-01, 99-00

1. Introduction

Advancement in wireless communication technologies has impacted our day-to-day life in all aspects. In the era of Internet of Things (IoT) and Big Data, it is inevitable to experience the effect of this advancement in the health sector. Electronic health monitoring [1], fitness monitoring [2], calorie measurement [3], online consultation with specialists, diagnosis and remote healthcare [4] are also possible these days through exploiting various communication technologies. Among the most promising communication technologies that enable applications to monitor human health data and post processing, WBAN is considered as the prime candidate. With the fundamental characteristics of exchanging

Email address: khalid.hasan@griffithuni.edu.au, kamanashis.biswas@acu.edu.au, k.biswas@griffith.edu.au, khandakar.ahmed@vu.edu.au, nnaifi@mit.edu.au, saiful.islam@griffith.edu.au (Khalid Hasan[‡], Kamanashis Biswas^{†‡}, Khandakar Ahmed[¶], Nazmus S. Nafi[§], Md. Saiful Islam[‡])

huge sensory data between participating nodes, this communication can also be classified as one of the candidates of machine-to-machine (M2M) communication in the health sector [5].

M2M communication system includes different fields of applications such as automotive, health, energy, security and surveillance, smart metering, and transportation etc. Application of M2M in the health sector is expected to be a major market driver in the future [6]. Due to the development in health sector, patients with many chronic diseases, such as heart diseases and stroke, find greater physical mobility and are no longer compelled to stay in a hospital to be monitored continuously. The necessity of hospitalization has been reduced greatly due to such improvement in health sector [7]. Healthcare system is now being supported by electronic processes and communication, which is termed as eHealth. Furthermore, healthcare services are becoming mobile and therefore, is termed as mobile health (mHealth) [8]. In the paradigm of telemedicine and mHealth, a relatively new and emerging technology is WBAN. In WBAN, health-related sensors are installed near the patient's body or on the body or in some cases, sensors are implanted [9]. Sensors are interconnected via short-range wireless technologies, such as ZigBee, WiFi, and Bluetooth. Thus forming WBAN. Devices such as, a mobile phone, a Personal Digital Assistant (PDA) or any other device can work as a gateway, which collects data from the sensors and forwards this information to a remote online server, where data processing and analysis takes place with the assistance of some medical software applications. Telecommunication networks such as, WLAN, WiMax, LTE, LTE-A or Satellite etc. could be used as mean of communication link between gateways.

1.1. Related Works

Over the last five years, there have been literature surveys that have attempted to highlight the key findings regarding to the design, challenges and implementation issues of WBAN. Among these, some well cited survey papers [10, 11, 12, 13, 14, 15, 16, 17, 18] on WBAN cover a wide range of topics i.e., WBAN communication architecture, candidate technologies, applications in the medical and non-medical fields, security issues of WBAN, propagation modelling, and implementation requirements etc. Movassaghi et al. [17] identified the application of WBAN in medical and non-medical sectors and detail view of PHY and MAC layers. In addition, the paper provided significant highlights on different routing protocols and security along with various technical challenges pertaining to implementations. Alam et al. [15] proposed one unique application of WBAN wearable devices which is related to safety and critical applications in severe environments, such as oil and gas industries, refineries and many petro chemical industries. This concept presents an inter-WBAN interactions, where WBAN coordinator works as a resourceful device that wirelessly interconnect the body sensors to external network infrastructure utilizing WiFi or Broadband cellular networks such as GSM, GPRS, 3G, and LTE. A comparative analysis of various WBAN technologies and design challenges have been provided in [16]. In addition, the paper concentrates on the radio channel modelling, minimization of energy consumption and coexistence issues in WBAN while providing a few case studies based on the real implementation and experimentation in the field and in simulations. In [18], similar types of discussions based on a previous literature survey is presented, focusing on only a few medical applications and related technologies for WBAN. Analysis of coexistence

issues and interference mitigation solutions in WBAN technologies is explained in [11]. Furthermore, mathematical representation of coexistence issues among IEEE 802.15.6, IEEE 802.15.4 and low-power WiFi technologies and simulation results are compared. The paper also highlights interference mitigation solutions with a system model and definition. A link between WBAN and cognitive radio technologies is demonstrated in [19]. Context awareness at the MAC layer, application layer and challenges are analyzed in [12]. Specific challenges in security and privacy in WBAN for healthcare applications are discussed in [14]. A survey based on the residential environment of WBAN based electronic healthcare (e-healthcare) system is outlined in [10], where an architecture of e-healthcare system in a residential environment and indicates the use of smartphone based healthcare application. The latest review paper [13] on WBAN introduces programming frameworks for WBAN and focuses significantly on energy efficient routing protocols. The paper also indicates the use of virtual reality (VR) as a futuristic vision of WBAN and the merging of WBAN with cognitive radio technology for energy efficiency. However, all these existing surveys limit themselves in the discussion of communication architecture, applications and a few challenges. None of the surveys discuss the pitfalls of current architectures in dealing with management complexities, security, reliability and so on. Moreover, we do not see any significant future direction for research in improving communication architecture, that deals with management complexity, reliability, security and privacy. Our survey paper therefore aims to fill this research gap.

1.2. Contribution

This review paper highlights the overall communication framework of WBAN along with M2M architecture, classifications and applications of WBAN, including medical and non-medical applications. A range of candidate technologies for WBAN is also presented to ensure that the survey covers all the attempts to improve the performance of WBAN system. This study also provides a wide range of challenges in WBAN and some ongoing work is required to cope with the challenges. In more concrete points, the contributions of this study are the following:

- The limitations of current WBAN architecture have been identified, which includes the issues of management complexities, vendor dependencies, static WBAN, network reconfiguration, resource utilization, and security. Moreover, a taxonomy is presented on the basis of various medical and non-medical applications of WBAN projects.
- A comprehensive overview, in particular, important characteristics of the candidate technologies for WBAN and a special focus on the latest WBAN standard IEEE 802.15.6 has been presented to provide a deep technical overview of the state-of-the-art technologies in WBANs. In addition, an in-depth analysis on different implementation challenges and related works to address existing challenges has been critically examined.
- A future research direction involving SDN based WBAN to deal with management complexities and security issues has been presented in this paper. In addition, the impacts of integrating blockchain and EH technologies into WBAN to enhance energy efficiency and security have been

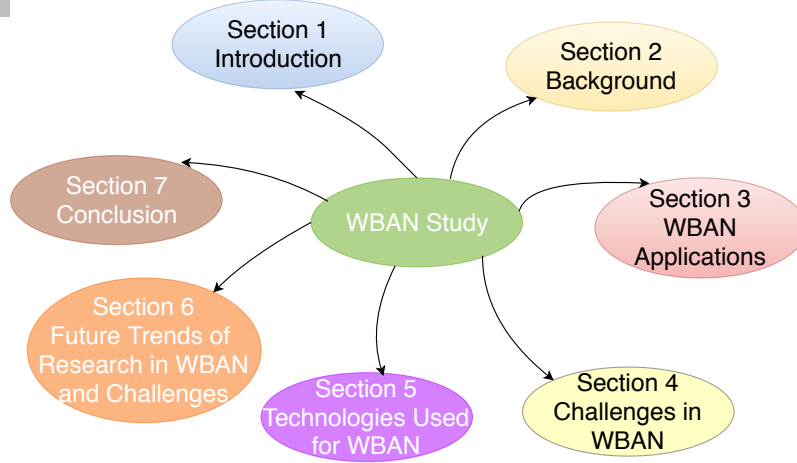


Figure 1: Structure of WBAN Study

investigated and critical challenges in implementing these emerging technologies to WBAN have also been identified.

1.3. Structure of the Paper

This paper is organized as follows. Section 2 presents a brief background on WBAN architecture, M2M architecture, limitations of current WBAN architectures and key differences between Wireless Sensor Network (WSN) and WBAN. Section 3 outlines the major WBAN applications and section 4 provides an overview of the challenges in WBAN. A list of candidate technologies for implementing WBAN, characteristics of different technologies and guidelines for implementations are explained in section 5. In section 6, we indicate future directions of research integrating SDN, Blockchain and EH in WBAN. The concluding remarks are provided in section 7. Figure 1 provides a pictorial representation of the structure of this paper.

2. Background

The number of patients effected with chronic diseases are increasing day by day. These patients are continually readmitted in hospital and healthcare centers, which require significant medical attention. To treat patients efficiently, smart healthcare systems are continuously improving. One such area of improvement is WBAN where different health related applications are used. The primary requirement for developing smart health related application using WBAN, would demand autonomous and self-organizing capabilities of interconnecting devices. A detailed overview of WBAN is presented in the next sub-section.

2.1. Wireless Body Area Network (WBAN)

WBAN is a collection of multiple sensors attached to or in the body, which are used to receive different physical parameters, such as body temperature, blood sugar level, heart rate, pulse rate, respiratory measurement and even the amount of calories, burnt after exercise etc. WBAN is not only used in

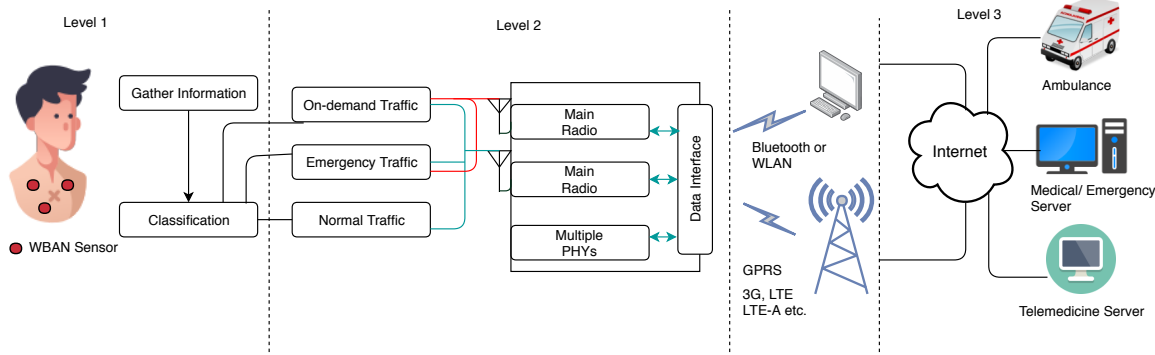


Figure 2: WBAN Architecture for medical and non-medical Applications

medical applications, but is also in multimedia and gaming applications. Sensor nodes can be placed in different topologies such as a star, mesh or tree. However, it does depend on the types of application and most of the cases it follows star topology where the nodes are connected to a central coordinator. A detailed architecture of WBAN based on [20] is presented in Figure 2, which consists of three levels. In level 1, different body sensors are attached to the human body which eventually send data to an aggregator, where the classification of traffic takes place. After the classification in level 2, a network coordinator communicates with the base-station. Level 3 contains a few base-stations that keep patients' physiological data and the healthcare service providers supply necessary diagnostic recommendations based on that data.

WBAN uses different technologies for data transmissions such as Wireless Medical Telemetry Services (WMTS), unlicensed Industrial, Scientific and Medical (ISM) (2.4-2.4835 GHz), Ultra-wideband (UWB) and Medical Implant Communication Services (MICS). Depending on the type of services, these technologies are employed, due to the fact that some of the applications might require high data rates while some are satisfied with low data rates. For example, restricted WMTS (14 MHz) cannot support video nor voice transmission. Instead, 2.4 GHz ISM band could be used. However, it causes adjacent channel interference since Bluetooth, ZigBee, Wi-Fi also uses this band. For implant sensor application an allocated band is MICS (402-405MHz) [20]. Some of the wireless technologies used in medical monitoring are listed in Table 1.

WBAN traffic can be categorized into three types such as on-demand traffic, emergency traffic, and normal traffic (as shown in Figure 2). On-demand traffic is requested by the physicians for diagnostic measurement. Emergency traffic is sent when a patient's condition surpasses to a predefined threshold value. For instance, in the case of blood pressure threshold (set by physician), the monitoring device observes that when the blood pressure is below the threshold, the corresponding node would trigger an emergency alarm informing the practitioner to take necessary action. However, this kind of traffic is not generally the case, but is rather unpredictable. Normal traffic refers regular monitoring the condition of the patient after a certain interval. Example of normal traffic could be the diagnosis of the gastrointestinal tract, neurological disorder, cancer detection, handicap rehabilitation and most serious heart diseases. The coordinator is in charge of processing and sending the data to telemedicine and

Table 1: Wireless Technologies in Medical Monitoring

	MICS	WMTS	IEEE 802.15.6 (UWB)	IEEE 802.15.4 (ZigBee)	IEEE 802.1 (Bluetooth)	WLANs (802.11b/g)
Frequency band	402-405 MHz	608-614, 1395-1400, 1429-1432 MHz	3-10 GHz	2.4 GHz (868/915 MHz Eur./US)	2.4 GHz	2.4 GHz
Bandwidth	3 MHz	6 MHz	>500 MHz	5 MHz	1 MHz	20 MHz
Data Rate	19 or 76 Kbps	76 Kbps	850 Kbps-20 Mbps	250 Kbps (2.4 GHz)	721 Kbps	>11 Mbps
Multiple Access	CSMA/CA, Polling	CSMA/CA, Polling	Not defined	CSMA/CA	FHSS /GFSK	OFDMA, CSMA/CA
Transmission Power	-16 dBm (25W)	10 dBm and <1.8 dBm	-41 dBm	0 dBm	4.20 dBm	24 dBm
Range	0-10 m	>100 m	1.2 m	0-10 m	10-100 m	0-100 m

medical servers for further treatment or recommendations. If necessary, the coordinator might use a wake-up radio circuit to respond to the emergency.

2.2. M2M Architecture

As an emerging technology, M2M communication includes autonomous and self-organizing capabilities of interconnecting devices. One of the best features of this technology is monitoring, while controlling the devices remotely [21]. The capability of remote monitoring has aided expansion of the horizon of M2M in diverse fields, including industrial automation, security and surveillance, smart metering, energy management, transportation, and healthcare. Among these, the healthcare is expected to be a major M2M market driver. Figure 3 [22] illustrates a simple architecture of the M2M system for healthcare applications.

The European Telecommunications Standards Institute (ETSI) proposed three important domains for M2M architecture; i) the M2M device domain where the M2M devices communicate with a gateway through short-range area networks; ii) the network domain that connects the gateway to the applications through long-range access and core communication networks; iii) the application domain where various application services are defined based on different use cases.

M2M devices or WBAN sensors/actuators are installed in the vicinity of a patient's body or on the body (wearable) or implanted internally. The resource constrained sensors are capable of transmitting data autonomously or when data is requested. Each device is embedded with wireless communication functions, which enables them to connect to a short-range communication network. The M2M area network interconnects WBAN sensors to the M2M gateway. This M2M network employs different technologies such as ZigBee, IEEE 802.15.6, Bluetooth and Bluetooth Low energy. The M2M gateway works as proxy between the M2M devices and the network domain. In reality, a gateway should be a portable device which has the interfaces of radio communication technology. Mobile phone, PDA or smart watches can be used as a gateway. The M2M communication part connects the M2M gateway to

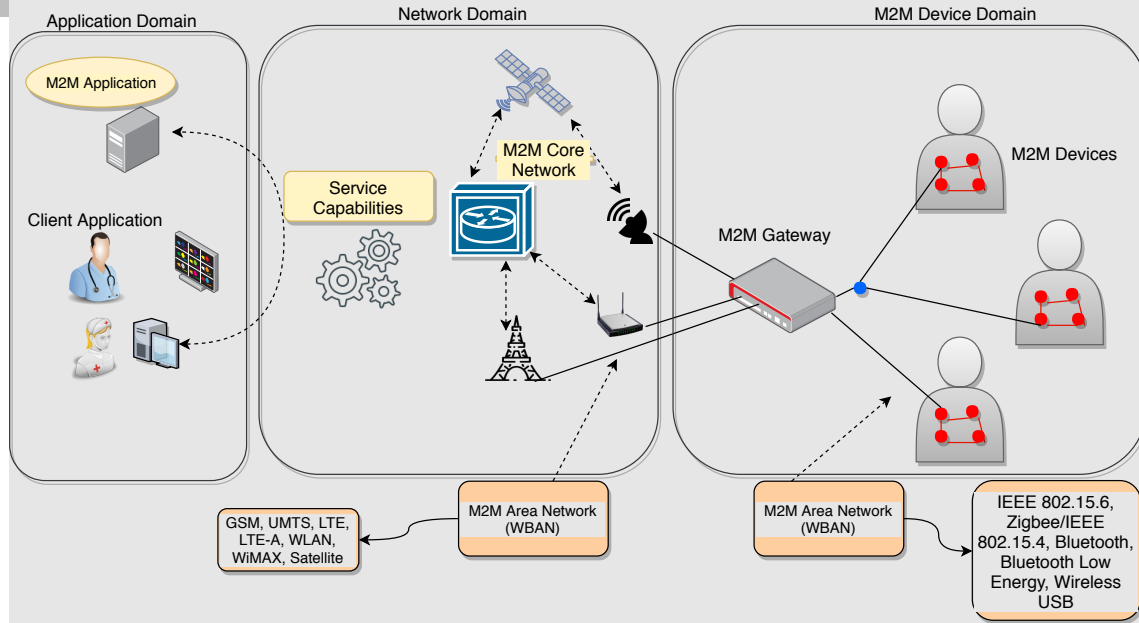


Figure 3: M2M architecture for wireless connectivity in mHealth scenarios

the Internet, which then connects to the application server. This communication part utilizes traditional wireless communication technologies, for instance, Long-term Evolution (LTE), WiMAX and IEEE 802.11 WLAN. The application domain receives the data and processes accordingly with the help of specific software [23].

2.3. Limitations of existing WBAN Architectures

The architecture of WBAN and M2M architecture for mHealth scenarios look intuitive, however, there are still some pitfalls. Many researches have been conducted aiming to solve the common challenges based on WSN. However, there still remains a research gap which is due to the limitations of existing WBAN architecture. One of the important pitfalls of the current architecture is the dependency on the vendors. Body sensors from vendors support only the vendor specific platforms. Therefore, a WBAN comprising of sensors from multi-vendors is difficult of manage and operate since they do not interoperate with each other [24]. It creates the management and operational complexities and also leads to the issue of network reconfigurability. In the case of installing sensors node of different vendors other than the existing one, it would cause a hindrance to the seamlessness of the network, which is undesirable for a robust network. One real life examples is stated in [25]. In Nagoya City University Hospital, an individual network was constructed and any changes in the network settings, caused the whole network to stop and required fixing. This resulted in a management complexity and required a lot of effort.

Static nature of WBAN architecture requires a lengthy process to get updated since the application and infrastructure are closely coupled [26]. Moreover, mobility is an important issue to be dealt with in WBAN, where patients should be able to roam around at all times. Due to this mobility, packet loss and error rate increases [27] which is still a challenging issue to be solved efficiently in the architecture of WBAN.

Integration of current architecture of WBAN with cloud is difficult and complex both economically and technically. In addition, due to the detection capability of normal and abnormal events, data transmission rate of the sensors changes abruptly. Changes in the data volume over time lead to load imbalance in storing data and processing at back-end servers [28].

Existing architecture of WBAN fails to utilize the resources efficiently. Due to the fact of embedded control logic in hardware, resource utilization cannot be controlled dynamically [26]. Consequently, sensors end up transmitting unnecessary readings even when the data is not needed. As a result, this causes an unnecessary waste of bandwidth and most significantly makes the system less energy efficient.

Security and privacy is an important factor in WBAN since it involves a patient's personal health data. Dealing with huge data tends to be complex at times and thus, the system becomes vulnerable to cybercrime [29, 30]. A strict and scalable system is still a big concern for WBANs in terms of data confidentiality, authenticity, integrity and effective management of the network [31].

2.4. *Difference Between WSN and WBAN*

Although the task of both general wireless and body sensor are to sense and send data, but the technical differences are in the implementation scenarios and use cases. It is important to realize the key differences between WSN and WBAN. Both WSN and WBAN applications have different requirements and challenges. Typically, WSN does not tackle the specific challenges related to the monitoring of health, where the prime focus of the WBAN is to reliably monitor the patient's health activities. Therefore, the number of sensor nodes deployed for WBAN depends on different factors, such as physiological parameters dependent and it should be scalable when they are needed for application. On the contrary, in WSN, nodes are typically deployed in a place where human access is limited or is challenging. Sometimes redundant nodes are deployed as a backup in case of some nodes dysfunction. Protocols supported by wireless sensor nodes and body sensor nodes are different in terms of distances to be covered, mobility, and electromagnetic transmission etc. Specially, in WBAN low power transmission is used, since it is concerned with the human health issues [32]. WBAN may occur in a more periodic manner and stable data rate unless emergency event occurs. On the other hand, WSN is employed for event-based monitoring that takes place at an irregular interval [33]. Strict security and privacy is maintained in terms of body sensor implementation while security and privacy in terms of wireless sensors could be a bit relaxed in some applications. One of the important issues in both wireless and body sensor is the energy efficiency. WBAN devices need to be very energy efficient as they have very small form factor which is frequently less than 1 cm^3 [34]. Moreover, for implanted devices, changing the battery is a tough job, which requires high-cost surgery. Therefore, it is expected that the battery should have a long lifetime, that is up to several years or even decades.

3. WBAN APPLICATIONS

There are several applications of WBAN, which includes medical and non-medical applications. A summary of WBAN applications along with the required parameters are presented in Table 2 [35].

Table 2: Wireless technologies in medical monitoring

Application Type	Sensor Node	Data rate	Duty Cycle (per device)	Power Consumption	QoS (Sensitivity to Latency)	Privacy
In-body Applications	Glucose Sensor	Few Kbps	<1%	Extremely Low	Yes	High
	Pacemaker	Few Kbps	<1%	Low	Yes	High
	Endoscope					
	Capsule	>2Mbps	<50%	Low	Yes	Medium
On-body medical Applications	ECG	3 Kbps	<10%	Low	Yes	High
	SpO ₂	32 bps	<1%	Low	Yes	High
	Blood pressure	<10bps	<1%	High	Yes	High
On-body non-Medical Applications	Music for Headset	1.4 Mbps	High	Relatively High	Yes	Low
	Forgotten Things Monitor	256 Kbps	Medium	Low	No	Low
	Social Networking	<200Kbps	<1%	Low	Low	High
Off-body Applications	Motion Sensor	35 Kbps	-	-	-	Low

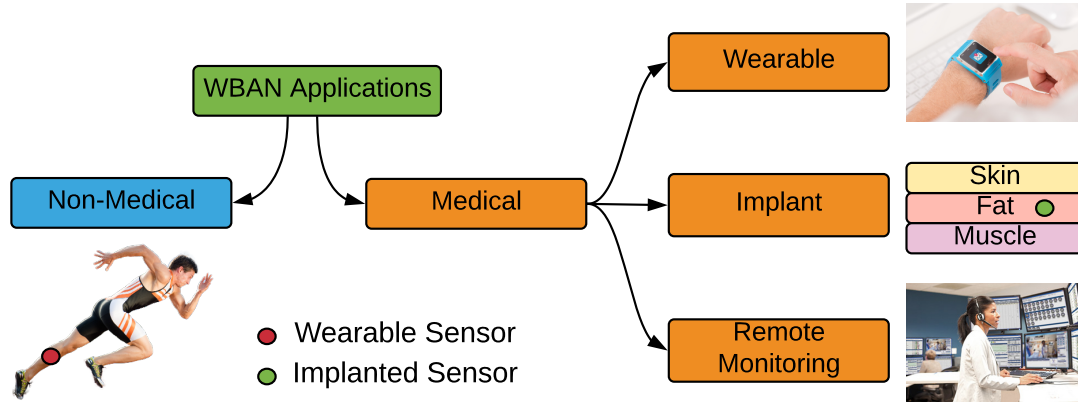


Figure 4: Classification of WBAN

WBAN can further be classified into three categories as depicted in Figure 4.

3.1. Medical Applications

From the perspective of medical applications, based on the usage of devices in applications, there are wearable, implant and remote monitoring devices category. We briefly explain all these categories of Medical Applications in this sub-section.

- **Wearable WBAN-** These WBAN devices are normally attached on the body surfaces using straps. Some of the examples of wearable WBAN applications are discussed below:

The activity of the soldiers can be monitored using WBAN applications in the battlefield. Using GPS enabled devices or camera, it is possible to monitor from a central station and maintain a secure communication. In the cases of preventing ambushes, a secure communication should exist [20].

Individual sports and the level of performance can be observed using WBAN. A personal trainer can follow up the performance level of the athletes, which can be received from the wearable devices attached to an athlete's body. In addition, real-time feedback through this application would lead to the performance improvement and assist to avoid injuries at times [36].

Sleep is an important activity in our daily life. Sleeping disorder eventually affects the productivity at workplace. It is not only in workplace, but also it causes many diseases, such as cardiovascular diseases, dizziness while driving and even loss of appetite. Therefore, monitoring the sleeping pattern of a patient has gained huge attention in the recent days. Polysomnography test is used to analyze the sleeping disorder through the analysis of a number of bio-potentials recorded overnight in a sleep laboratory. In such kind of test, it requires the use of a lot of cables that makes the patient uncomfortable and even causes more disturbances during sleep. WBANs are capable of delocalizing and removing the necessity of cables [37].

Millions of people are suffering from asthma. WBAN can be used to monitor allergic agents in the air and provide real-time feedback to the physicians. A GPS-based device is proposed in [38] that monitors the environmental factors and triggers an alarm in the case of detecting an environment, where the patient is allergic to.

Real-time health monitoring service is available as a part of WBAN application. For example, patient rehabilitation (framework as shown in Figure 5 [20]) center can be monitored using WBAN framework. As Figure 5 depicts, patients can be monitored for long time and physiological data can be forwarded to the cloud in real time basis. On the other hand, a panel of doctors or physicians can monitor patients' activity through video conferencing or through real time database updates.

- **Implant WBAN-** These WBAN devices are normally implanted in the body. Some of the examples of implant WBAN applications are discussed below:

According to the global report on diabetes [39], the number of diabetes patients increased to 422 million since 1980. In Australia, around 1.7 million people have diabetes and more than 100,000 Australians have been diagnosed with diabetes [40]. Different sorts of complications may arise due to this disease, such as heart attack, stroke, blindness, kidney failure and lower limb amputation. A regular monitoring by WBAN would lower the severity of diabetes and therefore keep it under control. Glucocellphone technology, which is used with diabetes patients to provide glucose measurement and forward the readings to the doctors for further analysis [36].

Cardiovascular diseases are one of the major causes of death. It can be monitored through WBAN technology. Myocardial Infraction (MI) can be monitored periodically and therefore brings it to considerably at lower risk. WBAN technology can be applied to monitor various abnormalities of physical health [17].

It is predicted that global cancer rate could increase by 50% to 15 million by 2020 [41]. By monitoring cancer cells through WBAN based sensors, doctors can extract important data related to cancer detection and continue to diagnose tumors without biopsy, which would lead to the

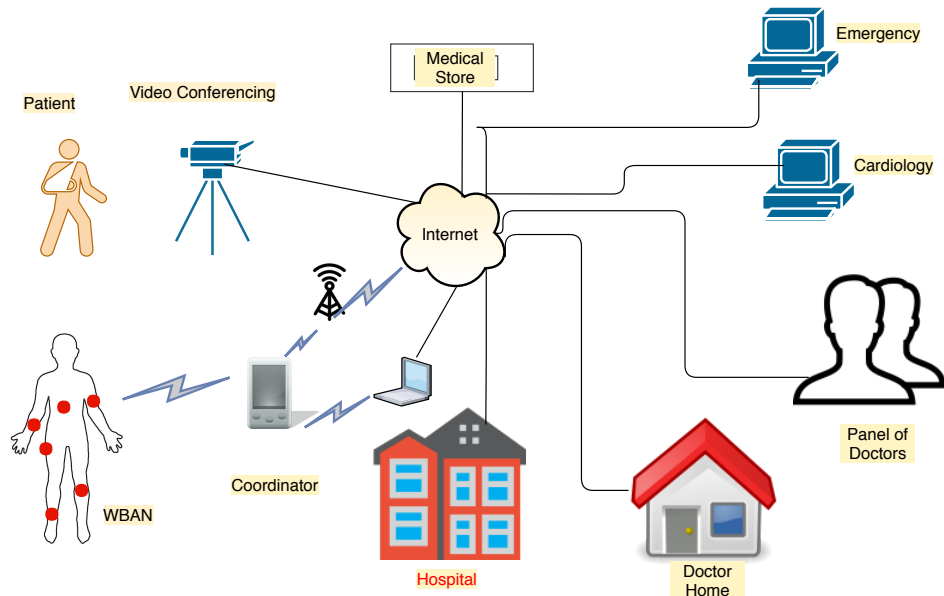


Figure 5: Real-time telemedicine monitoring system for patient rehabilitation

optimum analysis and treatment [17]. More about implant communication technologies of WBAN could be found in [42].

- **Remote Monitoring-** Seamless Internet connectivity of WBAN allows to keep track of the vital signals of a patient's body and provides real-time feedback on the healing process. To be specific, WBAN sensors are capable of sensing heart rate, body temperature, pulse rate, respiration rate, blood pressure, and other important physiological parameters. These sensors are continuously or periodically monitoring the patients' health condition and sending data to the doctors. Therefore, doctors find it easy to follow up and provide remote assistance either by video conferencing or phone call.

3.2. Non-Medical Applications of WBAN

WBAN is not only used in medical applications, but also used in various non-medical applications. Few examples of non-medical application of WBAN are described below:

- **Fitness, Performances and Wellness Monitoring:** In the recent days, many devices are being used for physical fitness and wellness. These devices are keeping a record of physical activities and performances. For example, Tomtom smart watch is capable of keeping track of how much calorie is burnt after a certain distance of jogging. Likewise, in a gym, trainer can keep the records about a trainee's fitness condition and follow up with the next level of activities. It is possible to use WBAN sensors, which can be attached to the individuals and then analyze the sensory data. WBAN sensors can be deployed in corporate offices as well to monitor the performances of employees and keep them satisfied, active and productive. For instance, Hitachi's Business

microscope monitors face-to-face communications of the office workers by WBAN wore around the neck in the format of a nametag. This device is capable of sending data regarding workers body movements, voice level, ambient lighting and air temperature. This information is used by the manager to improve work environment, which leads to the better satisfaction and productivity [12].

- **Entertainment Applications:** In social networking and gaming applications, WBAN can be used. It can be used in virtual reality and in gaming. Hand gestures or body movement, personal item tracking, and exchanging business card are some of the examples [17].
- **Emergency:** In the case of fire spread in household, smoke detectors can trigger fire alarm. However, for the deaf elderly people, it is impossible to sense the fire. Using WBAN sensor it is possible to sense the seriousness of the situation and therefore stay safe. Not also in household, but also in industries, which are vulnerable to the fire or poisonous gas, WBAN sensors (off body) can play an important role to save the workplace and life even.
- **Authentication:** For secure authentication purposes, WBAN application can be used. This utilizes the biometric parameters, such as fingerprint, face detection, palm print, hand geometry, iris recognition, retina, and odor. Biometric signals, such as ECG, EEG and electrodermal activity (EDA) provide unique biometric signatures, which are tough to steal, copy, forge or lose. This scheme is commonly known as ‘Cognitive Biometrics’. Future Attribute Screening Technology (FAST) is an example of such technology, which is used by United States of America Department of Homeland Security. The FAST system uses bio-signals collected through off-body sensors, such as heart and respiration rate, facial skin temperature, voice pitch, pupil dilation and body movement [12].

A taxonomy of medical and non-medical applications is given in Table 3 and Table 4.

4. CHALLENGES IN WBAN

WBAN is an emerging technology and facing so many challenges when it comes to the phase of implementation. The challenges include technical, ethical and non-technical challenge. Some of the important challenges are discussed below.

4.1. Heterogeneous Devices and Traffic

WBAN is heterogeneous in nature. Different kinds of sensors and actuators are in the network. Therefore, measurements and data types are also different. Some of the applications require real-time data while some are satisfied with periodic measurements. Furthermore, there are priority and non-priority data as well. Therefore, data types ranging from real-time audio to video content and continuous signals, such as ECG and EMG, should be supported by WBAN.

MAC protocols for WBAN should play an important role in this context. Different activities, such as movement, posture of body, and changes of environment etc., lead to a sudden change in the data

context. Thus, dynamic resource allocation technique should be supported by MAC protocol. WBAN MAC protocol with fixed slot allocation fails to fulfill the demand of heterogeneous and dynamic traffic of WBAN. Some attempts have been taken to deal with context-aware WBAN. For emergency response, an alarm is supported in [90], but it works only when no other node is scheduled to perform data transfer. Use of wake-up signal or wake up radio is used in [91] to switch the node from sleep to active state. However, addition of wake-up circuit makes the hardware implementation complex and costly. In [92], another attempt to support context-aware WBAN is taken, which again lacks the computational ability to analyze the context. A more recent work on the simulation based WBAN MAC can be found in [93] where it is suggested to use hybrid MAC protocols in cases of emergency data. However, this is challenging in case of implementing in heterogeneous applications.

4.2. Energy Efficiency

One of the most important challenges in implementing WBAN is energy efficiency issue. Since the WBAN sensors are supported by small battery, lifetime of the battery is an essential thing to bear in mind. WBAN devices, which are wearable sensors, are easy to replace. However, in the case of implanted sensors, changing the battery might even require a major surgery and thus costly. Implementing energy efficient WBAN could be possible by improving PHY and MAC layers design, efficient hop system (single hop or multihop) or by having an adaptive duty cycle.

In [94], TDMA based MAC protocol for a multi-tier architecture for WBAN has been proposed. This proposal includes sensor nodes in the first tier and a set of master nodes in the second tier and finally, an observation station in the third tier. Master nodes collect the data from the sensor nodes and forward to the monitoring station. The limitation of this proposal is that, it is based on stationary network. Challenge remains when there is movement of the patient and thereby distances between sensor nodes and master nodes vary. Consequently, nodes adjust the transmission power, which makes the system less energy efficient. Authors in [95] discussed energy efficiency in terms of derived path loss model on the human body. It is shown that single hop communication in WBAN is inefficient since nodes are located far away from the sink. Again, the issue of line of sight and non-line of sight exists as well. In the case of transmitter residing at the back, while the receiver is at the front, incurs more path loss. In such cases, multihop WBAN is more advantageous than single hop.

Since different standards are used in WBAN, energy efficiency is different accordingly. IEEE 802.15.6 consumes more energy than IEEE 802.15.4. In the case of IEEE802.15.6 carrier senses the channel and back-off counter decreases its count based on sense. However, in IEEE 802.15.4 back-off counter value goes to zero after only two sensing phases. Despite of this disadvantage in IEEE 802.15.6, successful packet transmission is higher than IEEE 802.15.4. Ultimately, this leaves us with two choices, whether we want reliability or energy efficiency.

Sources of energy inefficiency are discussed in literature [96], which includes collisions, over hearing, idle listening, and resource allocation techniques etc. Energy efficiency by proper resource allocation has been discussed in [97]. The proposed methodology employs the Global Energy Minimization (GEM) scheme in order for optimization. By allocating proper time and power, energy efficiency problem is

formulated. Network lifetime maximization and GEM schemes have been compared with uniform time allocation (UTA). However, in this proposal, energy consumption while nodes are asleep has been ignored due to low consumption of energy.

A TDMA based MAC protocol named BODYMAC is proposed in [98], where main purpose is to reduce packet collision by switching radio state. It used flexible bandwidth management with the help of its superframe structure, where a synchronization beacon in the downlink part is allocated for transmission from coordinator and the uplink part is used for packet transmission from nodes to the coordinator. Uplink part is partitioned in two parts, such as Contention Access Part (CAP) and Contention Free Part (CFP). In CAP, nodes inform the coordinator for the required bandwidth and in CFP part, coordinator grants time slot for the nodes to transmit. In order to support BODYMAC, an efficient sleep mode scheme is also proposed. The sleep mode is initiated by turning the radio transmitter off, where the coordinator responds to the sleep request during CAP period.

4.3. Environmental Challenges

WBANs experience path losses due to many reasons, such as postural body movement, node mobility, environmental obstacles, and absorption through body tissue. In fact, many of these problems can be answered by creating multi-hop links with installing sensors at the significant points. However, this will lead to a change in the operational condition of the network, which will cause interferences and the consequences will be error-prone and incomplete sensor data reception [17]. In addition, due to the strict health science regulations, designing WBAN is a crucial issue. Because, in implant or wearable sensors, antenna shape, size and material used should be in accordance with the constraints followed by healthcare facilities. More about design restrictions in size and shape according to organ and location can be found in [99, 100, 101]. To illustrate, the length of urethra valve is restricted to a diameter of 4mm-6mm and it has to be replaced at a regular interval without surgery. This means that a path antenna, monopole or dipole antenna are difficult to use. In this situation, the alternative solution would be using a helical antenna integrated into the shape of a valve implant [102].

4.4. Security, Authentication, and Privacy

It is indispensable to make WBAN communication very secure to maintain data confidentiality, meaning transmitted information from the WBAN should be accessed only by authorized entities and confirm the authenticity of incoming data. Eavesdropping or false alarm or injection of incorrect data may lead to serious consequences, such as a patient's death. Therefore, security in WBAN should be dealt at different layers e.g., physical, MAC, and network layers [20]. However, implementation of security measures incurs extra overheads and also makes the system less energy efficient. Therefore, in [103], a lightweight security scheme based security is proposed for WBAN, where a lightweight biometric technique is used to authenticate messages in WBAN. In a lightweight biometric technique, a key agreement scheme permits key sharing between WBAN nodes with low overheads. This analysis is proved to be energy efficient. Different authentication methods, for instance, human faces, hand features, and EEG signals are being used in WBAN and continuous improvement is going on both in academia and

industry. An ideal way to provide authentication is to use distinguishable human body characteristics. This is complex and challenging when patients connected to one WBAN reach to the proximity of another WBAN. Therefore, it is important to identify which network a patient belongs to. In [104], authors addressed the issue as node identification from the biometrics point of view. According to [105], security in WBAN could be improved by establishing trust between nodes in the network. An attack resistant and lightweight trust management protocol is proposed in [106]. According to this proposal, the experimental outcomes of this paper proved that network performance improves and protects the network from malicious behaviors.

4.5. Bio-Compatibility

In the context of WSN applications, bio-compatibility is not a big issue. However, for WBAN applications, especially in the case of implant sensors, bio-compatibility is an important issue to deal with. Due to the implanted sensors underneath the skin or any other part of the body, body tissues show a reaction. This reaction is known as bio-fouling, which refers to accumulation of proteins, cells and other unwanted bio-materials on the body surface. Bio-fouling could be the reason for degradation of sensor current and thus may lead to sensor failure [107]. To alleviate the effect of bio-fouling using nine sensors has been discussed in [108]. Another analysis related to bio-compatibility, has been discussed in [102], which identifies two factors for the body's reaction e.g., mechanical and chemical disruption. Mechanical disruption might cause tissue distortion and occlusion of blood vessels. A blunt and rounded shape of sensors could be used to lessen tissue distortion.

4.6. Quality of Service (QoS)

Quality of Service (QoS) is an important issue in WBAN and it is different from WSN applications. QoS in WSN cannot be directly implied to WBAN since QoS depends on the sensitivity of the applications and the nature of transported data. Hence, depending on the applications, QoS is different in WBAN. For critical patients monitoring systems require instant delivery of data, otherwise; delay causes catastrophic situations [109]. According to the authors of [110], it is difficult to set the QoS for a distributed healthcare system due to the unpredictable nature of the WBAN environment. Traditionally, QoS includes latency, transmission power, reliability, and bandwidth reservation. According to [110], to support QoS in WBAN, the following factors need to be considered.

- **Resource Limitations:** Resources such as battery power, available bandwidth, transmission power, buffer size, and processing capacity are important constraints for any sensor node application. Traditional QoS of routing and MAC protocols are not appropriate for WBAN.
- **Unpredictable and Heterogeneous Traffic:** In WSN applications, generally there is periodic traffic and it is easy to define QoS for such applications. However, WBAN experiences different levels of traffic such as no traffic, data burst and sometimes different loads of traffic due to different types of applications in WBAN. This heterogeneous traffic makes QoS support and requirement more complex and challenging.

- **Network Instability and Dynamics:** WBAN may comprise of both stationary and mobile nodes. In addition, some nodes could be in active state whereas some others may stay as inactive for a certain period of time. Apart from these, link failures and power failures are very common in WBAN and therefore, a stable network may become unstable frequently. Routing and medium access become challenging in such unstable conditions.
- **Energy Balance:** Management of energy sources is very important and energy load should be distributed evenly among all sensor nodes and devices.
- **Data Redundancy and Criticality:** It is important to avoid redundant data and hence, save energy. Techniques to avoid redundant data could be data aggregation, but it complicates the network design. Again, not all data are of same importance. Therefore, there should be a QoS mechanism to prioritize emergency data.

According to [111], three components could be used to satisfy QoS in WBAN. These are: i) an asymmetric architecture, in which most of the processing is done on the central node, ii) a virtual MAC that allows it to schedule wireless resources regardless of the MAC protocol used, iii) an adaptive resource scheduler that schedules the remaining bandwidth to fulfill QoS requirements in the case of channel failure due to RF interference because of patient movement.

4.7. Interference and Coexistence

Interference and Coexistence is an unavoidable issue that requires a sincere attention. According to the WBAN standard IEEE 802.15.6 [112], up to 256 nodes should be supported per body in WBAN and the coexistence of up to 10 WBANs in 6x6x6 meters, which is very challenging due to the proximity of nodes. Most importantly, there will be interference, while WBAN is surrounded by the other technologies that operate at the same frequency as WBAN. For example, 2.4 GHz band ZigBee based WBAN experiences interference from Bluetooth, IEEE 802.15.6, and WiFi networks. Some simulations based studies to analyze interference and coexistence scenarios, have been performed in [113, 114] with some wearable sensors. Interference between nodes belonging to the same WBAN were viewed in [113] and interference between nodes of different WBANs was investigated in [114]. Simulation results concluded that interference occurs due to the absence of synchronization between nodes, which creates collisions with nearby nodes. Coexistence experience with IEEE 802.11 b/g was investigated in [115, 116]. In [115], two nodes were used to form a WBAN and attached to right arm and right shin of a person. While conducting the experiment, the person was on the move. It was found that 16 channels of ZigBee were affected with high transmission power of nearby WiFi access points. There was high Packet Loss Ratio (PLR) despite having ZigBee center frequency far from active WiFi stations. However, there are very few works on the implementation of the latest standard pertaining to the comparison of coexistence and interference issues with the existing technologies. In [117] a simulated environment, including five WBAN nodes on a human body, two WiFi nodes, and five ZigBee nodes was set in a room. The channel model used in the simulation included the effect of body propagation and movement. It was

found that with the Minimum Shift Keying (MSK) modulation technique, the MAC of IEEE 802.15.6 performs better than the MAC of ZigBee network. The modified MSK and Gaussian MSK had similar performance in terms of PLR despite the interference. In fact, it was found that IEEE 802.15.6 MAC shows better performance than MAC of IEEE 802.15.4, but consumes more energy due to the longer sensing period.

4.8. Hardware Design

One of the important tasks is to design the proper hardware for WBAN. More specifically, the design of the sensor node, which is attached or implanted in the human body. Therefore, the design of the node has to be compliant with the nature of human body tissue. In addition, the design of the antenna is very crucial. Again, the design of an implanted antenna depends on the location and organ, which put a restriction on the designer. The size, material and shape of the antenna needs to be compatible with human tissue and the RF environment. The challenges of antenna design, such as, antenna gain, polarization, sensitivity and ability to connect with the access point for non-line of sight position are very important. At present, UWB technologies have gained significant interest of researchers since they increase SNR levels at the receiver.

4.9. Rules of Engagement

Defining rules of engagement or in other words creating a WBAN, which would meet the requirement of patients, is challenging. According to [118], three points should be taken into account while forming WBAN: i) the environment within which the WBAN nodes can function, ii) which devices are allowed to cooperate or which are not, iii) how device information can be used. Once WBAN is formed, the devices should be able to interchange data, negotiate security parameters, perform data sampling, associate nodes, remove sensors, and change sensor's operational mode and so on. Any changes in the network should be recorded and shared among the other associated devices. In addition, local device registries should be updated once there is some sort of change.

4.10. Wireless Propagation Characteristics

Wireless propagation plays a vital role in communication between nodes. Since nodes are attached to the body, mobility of the patients affects the wave propagation and sometimes devices attached to the back of body experience a shadowing effect. In addition, nodes need to deal with dynamic environments such as twisting, running and multipath propagation. In the case of implanted devices, the position of the device has an effect on the wave propagation. Therefore, it is necessary to have an accurate propagation model that will aid the scientist to predict the impact of realistic channels on network level performance. This will help to design more effective WBAN architecture and routing algorithms. Recently, the use of UWB channel models for body area network has grown interest. Many simulations and experimental approaches are being studied in order to find a proper channel model. There are few literatures regarding the channel model for WBAN. However, there is no general channel model that can be used comprehensively irrespective of gender, age and applications. In [119], author performed an

experiment for in-body communications within the frequency range of 2.36-2.5 GHz. In this experiment, a phantom based radio propagation study was performed, where experimental set up includes Vector Network Analyzer (VNA), styrofoam container, phantom aqueous solution and coaxial cable. Insulated dipole antenna and free space coax-fed helical antenna were used for in-body and off-body measurement, respectively. This is a practical approach to model WBAN channel; however, authentic path loss data were not provided, and results were presented only for human muscle tissue. Also no latter work was done to validate the path loss model. An attempt was made to develop WBAN channel model for capsule endoscopy in [120]. An electromagnetic simulation software named SEMCAD was used to model path loss between implant nodes and coordinator. In this case operating frequency was 403.5 MHz, which is defined in the standard IEEE 802.15.6 for Medical Implant Communication Service (MICS) band. However, the study lacks experimental validation. Frequency and distance dependent path loss model was investigated in [121]. In this case, a human body model was used in ANSYS HFSS (High Frequency Structural Simulator). Investigation was performed for wide frequency range i.e., from 10 Hz to 100 GHz. The path loss model obtained from this experiment does not accurately represent the real WBAN case since the measurement performed beyond the defined frequency standard of WBAN. Some other investigations [122, 123] were performed to find out the path loss model for in body communication in homogeneous human muscle tissue, brain, fat and skin. However, it is significant to validate the previous path loss model through simulation and experiment.

4.11. Overheating

Since the WBAN sensors are sometimes attached directly to the human skin, overheating of the sensors is crucial factor. Usually, overheating origins from the radiation of antenna during data transmission. This may cause damage to heat sensitive human body tissue [124, 125]. In addition, the routing protocols used in WBAN plays prime role in temperature rise of the sensors which ultimately causes discomfort and damages of tissues. Therefore, the issue of overheating should be kept in mind while designing routing protocols [126]. Electric and electromagnetic radiation causes temperature rise in the sensor devices which leads the tissue to absorb a part of the temperature. The effect of temperature rise and specific absorption ratio is discussed in [127]. There have been few researches to avoid overheating problem due to routing protocols. To deal with the overheating issue of implanted nodes, Temperature Aware Routing Algorithm (TARA) was proposed which works based on some threshold temperature to find appropriate routes. However, this protocol suffers from high end-to-end delay and also less energy efficient [128]. Least Temperature Rise (LTR) aims to rectify the problems encountered by TARA. LTR works by selecting the nodes with least temperature [129]. An improved version of LTR, Adaptive Least Temperature Rise (ALTR) utilizes proactive delay technique to reduce the temperature of the nodes and follow that route [130]. Although these routing protocols try to avoid overheating nodes to route the packets, the reliability is compromised in most cases. Therefore, temperature aware routing protocols also need to adhere with the stringent constraints of WBAN.

5. WBAN Communication Technologies

WBAN supports a number of short-range technologies to communicate with the gateway, for instance, Bluetooth, Bluetooth Low Energy, ZigBee, and IEEE 802.15.6. All of these short-range communication technologies possess a variety of characteristics and support different operating frequency and networking topologies. A summary of the characteristics of the wireless technologies used in WBAN are provided in Table 6. Gateway to server communication utilizes long-range communication technologies such as, WiMax, LTE, and LTE-Advance. In this section, we focus on a number of short-range candidate technologies for WBAN only. In addition, we provide an implementation guideline for WBAN based on the latest IEEE 802.15.6 standard.

5.1. Bluetooth

Bluetooth technology is designed for short-range communication with high data rates. It operates in 79 channels of each 1 MHz. As a short-range technology, Bluetooth is a good choice to be implemented in WBAN. However, Bluetooth consumes high energy, and therefore not suitable for WBAN applications. Bluetooth operates in 2.4 GHz frequency band and the typical operating range is 10-100 m. This technology works like a star topology, where a master and seven slaves form the network. The master node provides clock and frequency hopping patterns. Nonetheless, the limitation is, involving seven active slaves only, which puts a threshold on the maximum number of nodes to be used in WBAN network. In the early 2000s, a WBAN project named MOBI Health used Bluetooth technology to transmit sensor data from a front-end device to a mobile phone or PDA [131].

5.2. Bluetooth Low Energy

Bluetooth Low Energy (BLE) is also known as Bluetooth 4.0. It was previously called Bluetooth Low-End Extension (LEE) and later Wibree. It is designed to operate with low power consumption, provide low latency, and operate in short-range and on small coin battery cells. It was first introduced by Nokia in 2004 to connect small devices wirelessly. After some development in LEE under a project named MIMOSA (for the use cases of WBAN and WPAN), LEE was announced publicly with the name Wibree in 2006. BLE supports a data rate of 1 Mbps. To provide better latency for crucial WBAN applications, BLE has the capability to employ few channels for pairing devices, and synchronization can be done in milliseconds. Similar to Bluetooth, the BLE technology forms a star network [132]. A continuous data mode operation of BLE consumes similar energy as classical Bluetooth. The star topology used in BLE offers mobility support for WBAN applications.

5.3. ZigBee/IEEE 802.15.4

ZigBee is another most widely used technology for WBAN applications. ZigBee supports variable data rate ranging from 20 Kbps to 250 Kbps. It operates in 16 channels over 2.4 GHz ISM band (250 Kbps), in 10 channels over 915 MHz bands (40 Kbps), and in one channel over 868 MHz bands (20 Kbps) [133].

ZigBee provides two modes for the multiple access procedure such as beacon mode and non-beacon mode. In beacon-enabled mode, a superframe structure uses two phases of operation namely, active and inactive phases. During the inactive phase, sensor nodes stay in low power mode to reduce energy consumption. The active phase consists of two parts: i) Contention Access Phase (CAP) and ii) Contention Free Phase (CFP) [134]. In CAP, nodes compete to get access to data transmission using a slotted CSMA/CA mechanism and in CFP, Guaranteed Time Slots (GTS) are assigned to specific nodes to transmit data. This gives an opportunity to transmit emergency data during the GTS slots. However, fixed number of GTS is not suitable for emergency data transfer in some WBAN applications. According to researchers, the performance of IEEE 802.15.4 is not satisfactory for WBANs. It has been pointed out that ZigBee can suffer from interference from other WLAN transmissions. Again, the maximum supported data rate is 250 Kbps, which are not sufficient for some real-time WBAN applications or large-scale deployment of WBAN.

5.4. Ultra Wideband (UWB)

UWB technology is an attractive choice for using in WBAN because of the regulated low transmission power. The operating frequency band for UWB is 3.1-10.6 GHz, which is high. Although UWB is supposed to have low transmission power, high operating frequency makes it to consume high power. Therefore, designers experience difficulty in designing such UWB nodes. However, the possibility to avoid high power consumption of an UWB receiver is to employ transmitter only networks for low power networks like WBAN. In this case, only one transmitter is used to send data and monitor physiological parameters of a patient's body. A unique identification number of individual sensors assists in distinguishing individual patients [135]. According to [134], UWB is an attractive choice for several reasons. For example, for WBAN tracking in indoor environments, the UWB technology can provide precise localization. It is also concerned with power absorption by human tissue, therefore regulates low transmission power and a low transmission duty cycle.

5.5. IEEE 802.15.6

The popularity, demand, and effectiveness of a real-time healthcare monitoring system would revolutionize future healthcare technology. IEEE 802 has established a task group named IEEE 802.15.6 for the purpose of standardization of WBAN. The aim of the standard is to support low power communication for in/on body nodes to forward physiological data to the access point. Based on the standard, WBAN is categorized in medical and non-medical applications. IEEE 802.15.6 defines physical layer specifications and MAC layer specifications as well. A description of Physical and MAC layer are given below.

PHY Layer Specification: The IEEE 802.15.6 standard supports three PHYs, i) Narrowband (NB) PHY, ii) Ultra Wideband (UWB) PHY and iii) Human Body Communications (HBC) PHY. A description of each PHY layer is as follows.

- **NB PHY:** The responsibility of NB PHY is to perform the following three tasks: i) activation and deactivation of the radio transceiver, ii) Clear Channel Assessment (CCA) within the current

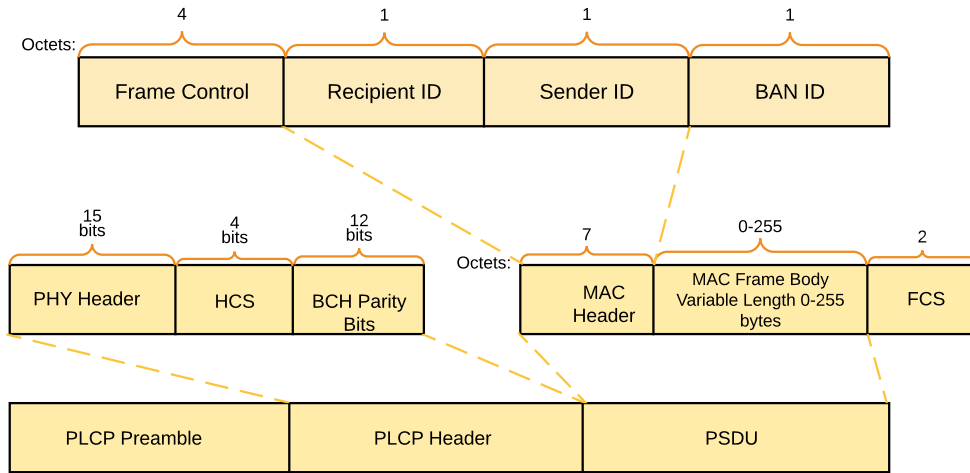


Figure 6: IEEE 802.15.6 standard NB PPDU structure

channel, and iii) data transmission and reception. The Physical Layer Protocol Data Unit (PPDU) consists of three parts: i) Physical Layer Convergence Protocol (PLCP) ii) the PLCP header and iii) Physical Layer Service Data unit (PSDU). Figure 6 illustrates IEEE 802.15.6 NB PPDU structure.

Packet transmission is carried out in an orderly manner. The first component to be transmitted is the PLCP preamble, then PLCP Header and finally PSDU. PSDU is pre-appended by PLCP Preamble and PLCP header. PLCP preamble is used at the receiver to synchronize time and offset recovery. The PLCP header is a transmitter with a given header data rate in the operating frequency. The PSDU unit consists of a MAC header, a variable MAC frame body length (0-256 bytes) and frame check sequence. A WBAN compliant device should be able to support transmission and reception in at least one of the following frequency bands: 402-405 MHz, 420-450 MHz, 863-870 MHz, 902-928 MHz, 2360-2400 MHz, and 2400-2483.5 MHz. Modulation parameters are different for different frequency bands of operation. According to the standard, modulation techniques such as, Differential Binary Phase-shift Keying (DBPSK), Differential Quadrature Phase Shift Keying (DQPSK) and Differential 8-Phase Shift Keying (D8PSK) are used in NB PHY. However, in 420-450 MHz, Gaussian Minimum Shift Keying (GMSK) technique is used [136].

- **UWB PHY:** High band and Low band are the two frequency bands that are used in the UWB PHY. Each of the bands is divided into channels of bandwidth 499.3 MHz. The low band comprises of three channels of which channel 2 is considered as mandatory with the central frequency of 3993.6 MHz. The high band consists of eight channels, where the seventh channel is considered to be mandatory with a central frequency of 7987.2 MHz. A WBAN device should be able to support at least one of the mandatory channels [136].

The UWB PHY is expected to be robust when performing in WBANs and thereby implementation in large scales. In addition, in UWB PHY, signal power levels are in the order of those used in MICS band, which provide a harmless power level for the human body and low interference to

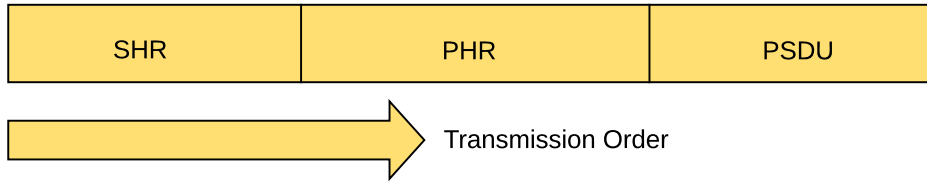


Figure 7: IEEE 802.15.6 UWB PPDU Structure

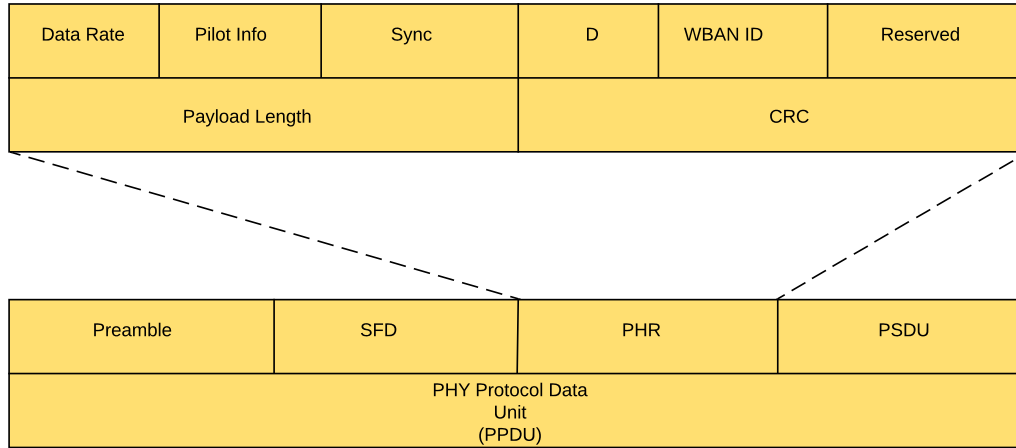


Figure 8: IEEE 802.15.6 HBC PPDU Structure

other devices. Some other functionalities of the UWB PHY include:

- Activation and deactivation of the radio transceivers.
 - The PPDU is constructed by Synchronization Header (SHR), Physical Layer Header (PHR) and Physical Layer Service Data Unit (PSDU), respectively (as shown in Figure 7). The PPDU bits are converted into RF signals for transmission in the wireless medium.
 - The UWB PHY may provide clear channel assessment (CCA) indication to the MAC in order to verify activity in the wireless medium.
- **HBC PHY:** Electric Field Communication (EFC) is used for human body communications for PHY layer. It covers the entire communications for BANs, such as modulation, preamble/ Start Frame Delimiter (SFD), and Packet structure. The structure of the PPDU includes PLCP preamble, Start Frame Delimiter (SFD), PLCP Header and PHY Payload as shown in Figure 8.

The preamble and SFD are fixed in size. They are pre-generated and sent in advance of packet header and payload. In order to ensure Packet Synchronization, the preamble sequence is transmitted four times while SFD is sent only once. Once the receiver receives the packet, it catches the beginning of the packet by identifying preamble sequence and then it finds the start of the frame by detecting the SFD [136].

MAC Layer Specification: To provide channel access, IEEE 802.15.6 working group defines Media Access Control (MAC) layer on top of PHY layer. The coordinator or hub divides the entire channel in a superframe structure, where time referenced resources are allocated. The hub chooses the beacon period of equal length to bound superframes. The offset of the beacon period can be shifted by the hub. Beacons are transmitted in each beacon period of active superframe unless prohibited by some MICS band regulations [136]. According to the standard IEEE 802.15.6, hub has the responsibility to allow one of the following three access modes:

1. Beacon Mode with Beacon Period Superframe Boundaries.
2. Non-Beacon Mode with Superframe Boundaries.
3. Non-Beacon Mode without Superframe Boundaries.

Beacon Mode with Beacon Period Superframe Boundaries: In this mode, beacons are transmitted by the coordinator or hub in each beacon period except for inactive superframes. Hence, for inactive superframes hub does not provide any access. Figure 9 illustrates the structure of the superframe, which comprises of two Exclusive Access Phases (EAP1 and EAP2), two Random Access Phases (RAP1 and RAP2), Type I/II access and Contention Access Phase (CAP).

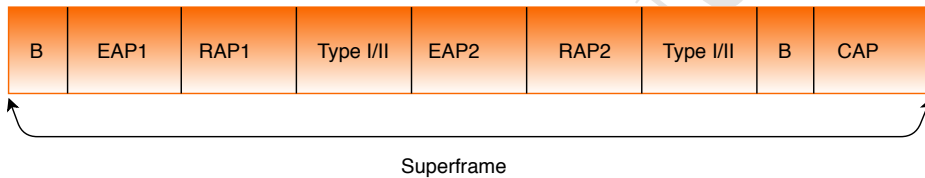


Figure 9: Beacon mode with Beacon Period superframe Boundaries

In the above figure, B stands for beacon. The hub has the control to set any of the access phases to zero length. However, it allows to end RAP1 first when a guaranteed time is allocated for connected nodes. EAP1 and EAP2 phases are used for emergency traffic. RAP and CAP are used for normal traffic. In EAP, RAP and CAP phases, access is provided through CSMA/CA or slotted Aloha. Type I/II access phase is also called Managed Access Phase (MAP). Type I/II access phases are used for both uplink and downlink allocation intervals. In Type I/II access polling mechanism is used for resource allocation.

Non-Beacon Mode with Superframe Boundaries: In this mode, beacon is not transmitted at all. The whole duration of the superframe boundary includes either Type I or Type II access phase as shown in the 10. In type I polling mechanism, allocation length is specified in terms of the duration of time granted for transmission, whereas in type II polling mechanism, allocation length is specified in terms of the number of frames granted for transmission.

Non-Beacon Mode without Superframe Boundaries: This mode allows unscheduled Type II polling or posted allocations as shown in Figure 11. It is a non-reoccurring time interval that a hub grants to itself using posting access for initiating a frame transaction.

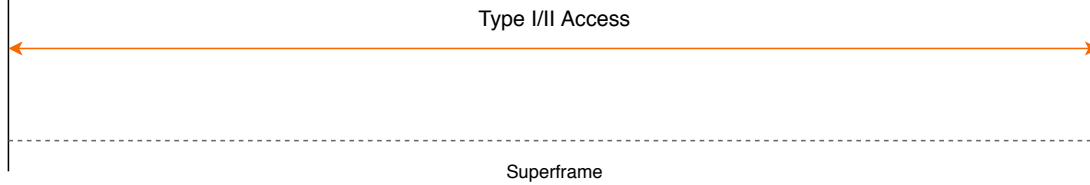


Figure 10: Non-Beacon Mode with Superframe Boundaries

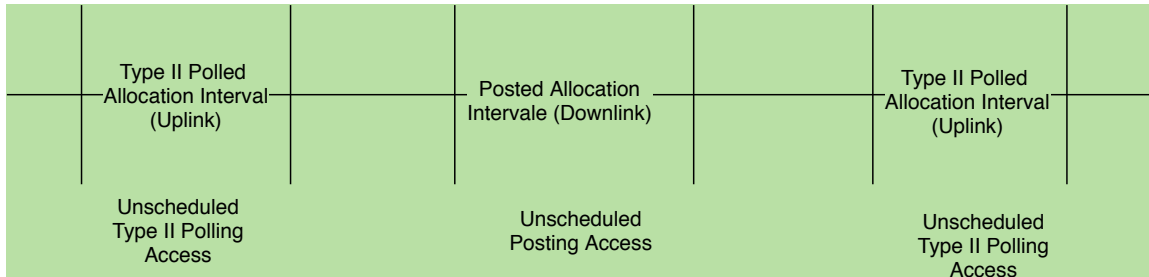


Figure 11: Non-Beacon Mode without Superframe Boundaries

5.6. Guidelines for WBAN Implementations

IEEE 802.15.6 approved some key requirements in order to implement WBAN. The requirements are as follows [20, 36, 137] .

- The number of nodes in body area network should be scalable up to 256 nodes.
- WBAN link should be able to support bit rate between 10 Kbps and 10 Mbps.
- Packet Error Rate (PER) should be less than 10% for a 256 octet payload (256x8 bits of data) for a majority (95%) of the best performing links based on PER (i.e., at a given signal-to-noise ratio 5% of channels that give the worst PER performance should not be used to determine whether this PER guideline is met).
- Nodes should be able to be added or removed to/from the network within 3 seconds time.
- Nodes should be capable of reliably communicating with the network despite all sorts of movement due to sitting, turning, twisting arms, running, waving arms and dancing with others which may result in shadowing and channel fading.
- The maximum radiated transmission should not exceed 0 dBm or 1 mW. All devices should be capable of transmitting at 0.1 mW (-10 dBm). This complies with the specific absorption-rate (SAR) guideline of the Federal Communication Commission (FCC) of 1.6 W/kg in 1 g of body tissue [138].
- Jitter, latency, and reliability should be supported for WBAN applications that require them. Latency in medical application should be less than 125 ms, and 250 ms in non-medical applications. Jitter should be less than 50 ms.

- Power saving mechanisms should be followed when WBAN operates in power-constrained environments.
- In-body and on-body area networks should be capable of coexisting in and around the body.
- Coexistence with heterogeneous environment should be supported where networks of different standards cooperate amongst each other to receive information.
- Some medical diagnoses might require high data rate. For instance, ECG monitoring might require a UWB-based WBAN to support high data rates.
- WBAN must incorporate QoS management features to be self-healing and secure as well as allowing priority services.
- The physical layer should support collocated operation of up to 10 randomly distributed body area networks in a 6mx6mx6m volume.

6. Future Trends of Research in WBAN and Challenges

Researchers have continually tried to find optimal solution to the challenges of WBAN either by modifying the existing solutions or incorporating new technologies. Management related complexities, vendor dependencies, mobility, data privacy and security, energy efficiency, and traffic priority management are some of the most crucial constraints of WBAN. As an approach of dealing with the challenges of WBAN, two recent and attractive technologies are Software Defined Networking (SDN) and Blockchain. SDN and Blockchain, both are making revolutionary changes by offering lucrative prospects in the domain of IoT applications, especially in WBAN. On one hand, a centralized programmatic control system of SDN solves the management related complexities and vendor dependencies, whilst decentralized distributed ledger of blockchain creates an effective and secured data sharing platform. Furthermore, Energy Harvesting (EH) is another promising technology with self-sustainable energy sources for WBAN. In this section, we highlight the benefits and challenges of incorporating SDN, Blockchain and EH in WBAN.

6.1. SDN based WBAN

In the recent years, software defined networking has received significant attention of both industry and academia. SDN is a new networking paradigm, which separates the control plane from the data plane. Decoupling control plane, from the data plane offers the operators to work with a centralized control program instead of numerous, multi-vendor, network devices to implement their favorite policies [139]. The control plane is a software-based controller and network devices become a simple packet forwarding device (the data plane) which can be programmed via an open interface e.g., ForCES [140] and OpenFlow [141]. A contrasting architecture of traditional network and SDN is given in [142] and a three layered of SDN architecture is explained in [143]. In SDN, controller machine creates packet-forwarding rules for any changes in network topology, connection initiated by end hosts, shifts in traffic loads or messages from other controllers. Controller drives these rules towards programmable switches

where necessary functionalities are implemented. This feature of SDN allows easier deployment of new protocols and applications.

The theoretical concept of SDN is expected to reduce the complexity of network management whether it is wired or wireless. When it comes to the implementation in WBAN, it offers flexibility and programmatic control over the network. Open standards such as Openflow, ForCes simplify the network design and operations which diminishes the dependency on vendor specific instructions and protocols as instructions and commands are provided from a controller [144]. Among the other benefits of SDN, reserving bandwidth for delay sensitive application [26], secured patient monitoring technique through tracking the patients locations [145], efficient and secured data delivery [31], use of centralized routing algorithm to facilitate mobility [146], updating the routing table [147] and dynamically activation and deactivation of sensors [26] to support energy efficiency are the most significant. To leverage the potential benefits of SDN in WBAN, a SDN based WBAN architecture is proposed in [148]. However, incorporating SDN in WBAN would experience few challenges. Some of the challenges we present here.

- **WBAN Inherent Challenges:** Many of the WBAN challenges are not yet adequately addressed. Although SDN indicates promising insights of resolving many of the current challenges of WBAN. Specially, SDN paradigm promises a huge reduction in energy consumption by the node. However, the extent of this claim needs to be evaluated and quantified. The amount of processing needed in proportion to the energy usage should be determined. In addition, application-based energy usage must be figured out.

The aggregated sensed data is also paramount and needs closer research attention. In addition, WBAN deals with heterogeneous applications, hence, data aggregation from the heterogeneous application is also critical. This aggregation problem in heterogeneous WBAN needs to be explored.

The transmission of the data is also a major concern. It might not be pragmatic to have all sensors transmitting their raw data to the controller as that will result in an excessive delay and congestion in the network. In the design, having local controllers or some sink nodes could be used. However, this needs to be tested to evaluate its efficiency.

- **Implementation and Evaluation:** The idea of having SDN into WBAN is very recent. However, many researchers are proposing SDN for WBAN for to provide security and authentication services. Still simulation and practical implementation need to be done. Some implementations have been successful in applying OpenFlow standard in sensor nodes and serving it as SDN enabled switch for data plane and controller communication. However, practical implementation is needed to provide a clear indication of the progress made thus far. This would also usher in an opportunity to evaluate issues such as QoS, reliability, packet loss, bandwidth, stability, efficiency, and scalability.
- **Inter and Intra-Plane Communications:** The communication between the control plane and application plane is important for the overall structural security of the network. Hence, any protocol considered needs to adequately address the security concerns. On the other hand, communication between the controller and the infrastructure devices, the southbound API, is also

particularly important because it is the enabler of the transition from the high resourced control plane to the low resourced data plane. This transition presents an open research problem to be explored.

- **Standardization:** There is no standardized protocol available the SDWBAN. Researchers from all around the world are proposing many general frameworks. However, the The lack of standard could derail the development and further exacerbate the issue of the dependent compatibility, which the SDN model seeks to avoid. Therefore, there is an urgent need for SDWBAN standardization. The lack of standardization would result in different incoherent and incompatible architectures that may violate SDN's principal of heterogeneity.
- **Distributed Control System:** In order to provide scalability, reliability and performance in SDWBAN, an efficient distributed control system is needed. Distributed control solutions have been proposed for SDN enterprise networks and SDN based smart grid solutions. But there is none for SDWBAN. This necessitates the need to investigate a novel distributed control system for SDWBAN without compromising any of the quality imperatives.

6.2. Blockchain Technology for WBAN

Blockchain technology has gained sincere attention of the researchers in the past few years. Although, the technology was first used by Satoshi Nakamoto in a whitepaper [149] to explain the challenges of ownership pertaining to digital currencies, many other projects in IoTs, especially healthcare services started to use the concept of Blockchain to maintain security and privacy [150]. WBAN in medical applications can be benefitted by employing the concept of Blockchain. Specially, management system for the various parties such as, general practitioners, medical specialists, hospitals, and therapists, can be supported when they need access to same information [151]. An US based startup, Gem Health Network [152], utilized the Ethereum Blockchain Technology [153], that offers a structural platform to allow businessmen, individuals and experts to have access to latest treatment information and also enables the experts to track the past history of the patients. A real and proven example is the Estonian healthcare infrastructure which uses Guardtime Blockchain [154] to regain information on medical treatments performed in Estonia.

Wearable WBAN sensors generate a large volume of data that are important of diagnostic process and also useful resource for medical research. Storing and sharing personal data is an important task. To facilitate secure data storage, a Swiss based startup invented healthbank Blockchain that offers an individualized data trading platform to share the personal data for research purpose and even shared data can be tracked with a timestamp [155]. One of the latest studies [156], introduced BloCHIE, a blockchain based platform for health information exchange to store huge amount of data remotely that will enhance the collaborations between clinical research enterprises. Although, the prospects of blockchain for WBAN seems to be attractive, it comes with a variety of challenges. Some of the crucial challenges of incorporating blockchain can be found in [157]. We briefly discuss some crucial aspects of integrating blockchain in WBAN.

- **Mutual Trust and Agreement:** It is highly important to have trust between the participating entities such as, patients, health insurer, medical research team, and healthcare providers. Permission to share and view the patient's private is a must when it comes to further research of a specific disease.
- **Traffic Management:** The diverse nature of WBAN traffic demands exclusive priority mechanism to process normal monitoring data and emergency data. Emergency data need to be addressed with first most priority basis so that emergency data experience the minimum amount of delay.
- **QoS:** As WBAN requires the delivery of data within a strict time frame in accordance with the specific applications, when block verification takes place by the miners, it constitutes some additional delays. And as the number of patients increase, computational complexity and load enhances, which ultimately effects the overall QoS of the network.
- **Data Controller:** One of the properties of blockchain is immutability, which means resistance to the modification of data. Device dysfunctions in WBAN might cause erroneous data recorded in Electronic Health Record (EHR). Since modification of data is not possible in blockchain, finding a data controller to deal with erroneous data is very challenging and yet to be resolved.
- **Smart Contracts:** Generating self-executable clauses for smart contract for different WBAN applications, is very challenging. Because the model of the smart contract should be representable and quantifiable.

6.3. Energy Harvesting in WBAN

Energy harvesting is another promising aspect to support energy efficiency of WBAN sensors. Although there have been numerous effort of enhancing energy efficiency of tiny WBAN sensors, EH is now being considered as a prime mechanism of boosting energy efficiency. EH refers to the collection of power from a limitless ambient sources and converting the power to operational electric energy [158]. The electric energy can be used to function the WBAN sensors when required. There can be multiple sources of EH all around us including human body. We provide a brief introduction for various EH techniques for WBAN that are being researched and investigated.

- **Photovoltaic Energy Harvesting (PVEH):** The mechanism of PVEH works based on the received sunlight or lights from any other sources, which are absorbed in the cells made of semiconductor materials. The absorbed light generates electrons through p-n junction effect. Thus, from generated electrons a voltage difference is created [159]. The output direct-current (DC) of photovoltaic cell can be stored and used for WBAN sensors.
- **Piezoelectric Energy Harvesting (PEH):** Biomechanical energy sources such as kinetic energy received from various internal and external motion of human body work as the inputs of PEH. Biomechanical sources such as heartbeat, blood pressure, locomotion, breathing, footfalls, arm motion etc. can be scavenged using various piezoelectric and mechanical generators [158].

- **Thermoelectric Energy Harvesting (TEH):** This method extracts energy utilizing thermoelectric generator from the temperature differences created by human body. Nowadays, this method is gaining popularity for WBAN applications as human body is capable of creating a temperature difference between a hot and cold surfaces of thermoelectric generator. This consistent temperature difference can be converted into electric energy [160].
- **RF Energy Harvesting (RFEH):** Due to increased uses of Radio Frequency (RF) technologies, there are abundance of RF sources which can be used as an input for RFEH and thereby powering up WBAN sensors [161]. A power conversion circuit is employed to convert the available RF radiations into electric energy. The effectiveness of this process depends on the availability of the RF sources and the location.

Although various EH technologies offer lucrative insights towards improvement of energy efficiency of WBAN sensors, the implementation of EH technology needs to deal with few challenges. We highlight future issues and challenges of incorporating EH technology in WBAN.

- **Power Allocation:** As EH technology supports a mean of supplying scavenged electric energy to WBAN sensors, it is crucial to measure the outage probability in the implementation scenario. Therefore, extensive research require to be conducted in simulation environment for various WBAN applications with fading channels. Furthermore, efficient power management among various modules such as utilization of extra energy, optimal data collection, routing decisions and avoidance of overcharging are significant [158]. Consequently, a lot of research work should address the issues of power allocation to ensure QoS requirements as per protocol and application.
- **Availability of sources::** To enable the effect of EH, it is very significant to assess the feasibility of the available sources for particular EH mechanism. For instance, ambient sources such as sunlight or RF radiations might not be available always or it could be limited. To illustrate, photovoltaic cells require direct contact of sunlight or in cases the RF radiation, the vicinity of the radiation emitting source plays a vital role in producing electric energy. Hence, before implementation of EH, the degree of the availability of sources must be assessed.
- **Design Complexities:** The physical design of the WBAN sensors become more challenging while implementing EH technology for energy efficiency. Additional functionalities will make the sensor design critical as complex circuits need to be integrated in the hardware. The integration results in size and costs of implementation. Thus, integration level of EH technology is a critical parameter to consider for various WBAN applications.

7. Conclusion

WBAN is an emerging field of research within the domain of healthcare. In this survey, a review of current research in WBANs, recent literatures on different research challenges are provided. Some of the key differences between WSN and WBAN are also pointed here. Several limitations of traditional WBAN

architecture are elaborated. In this context, it is essential to understand the existing architectures and limitations to address the challenges efficiently. This survey highlights the applications of WBAN in both medical and non-medical fields. Furthermore, a taxonomy of medical and non-medical applications is provided with appropriate references. A comprehensive study on different candidate technologies for WBAN is also carried out, where characteristics of candidate technologies are highlighted. This study emphasizes on the implementation guidelines of WBAN based on the latest standard IEEE 802.15.6, which will aid the future investigators, professionals and researchers. We believe that successful implementation of WBAN will certainly improve quality of life whether it is medical or non-medical aspect. It will bring down the costs of hospitalization of patients and assist early detection of any abnormalities. Finally, as new technologies like SDN, EH and blockchain are emerging, incorporating these technologies with WBAN will bring revolutionary changes in healthcare sector. It is expected that SDN and blockchain will be able to solve most of the crucial challenges of WBAN.

References

- [1] A. Bouazizi, G. Zaibi, M. Samet, A. Kachouri, Wireless body area network for e-health applications: Overview, in: 2017 International Conference on Smart, Monitored and Controlled Cities (SM2C), IEEE, 2017, pp. 64–68.
- [2] D. S. Gangwar, Biomedical sensor network for cardiovascular fitness and activity monitoring, in: 2013 IEEE Point-of-Care Healthcare Technologies (PHT), IEEE, 2013, pp. 279–282.
- [3] S. V. B. Peddi, A. Yassine, S. Shirmohammadi, Cloud based virtualization for a calorie measurement e-health mobile application, in: 2015 IEEE International Conference on Multimedia & Expo Workshops (ICMEW), IEEE, 2015, pp. 1–6.
- [4] H.-y. Zhou, K.-m. Hou, Pervasive cardiac monitoring system for remote continuous heart care, in: 2010 4th International Conference on Bioinformatics and Biomedical Engineering, IEEE, 2010, pp. 1–4.
- [5] S. H. Shin, R. Kamal, R. Haw, S. I. Moon, C. S. Hong, M. J. Choi, Intelligent m2m network using healthcare sensors, in: 2012 14th Asia-Pacific Network Operations and Management Symposium (APNOMS), IEEE, 2012, pp. 1–4.
- [6] B. Wire, Research and Markets: Machine-to-Machine (M2M) Communication in Healthcare 2010-20: Reviews the Major Drivers and Barriers for Growth of M2M, [Available Online]: <https://www.businesswire.com/news/home/20110526005774/en/research-markets-machine-to-machine-m2m-communication-healthcare-2010-20>, [Accessed on: 2019-03-20].
- [7] V. Patil, S. S. Thakur, V. Kshirsagar, Health monitoring system using internet of things, in: 2018 Second International Conference on Intelligent Computing and Control Systems (ICICCS), IEEE, 2018, pp. 1523–1525.

- [8] P. Van Daele, I. Moerman, P. Demeester, Wireless body area networks: status and opportunities, in: 2014 XXXIth URSI General Assembly and Scientific Symposium (URSI GASS), 2014, pp. 1–4.
- [9] A. Darwish, A. E. Hassanien, Wearable and implantable wireless sensor network solutions for healthcare monitoring, *Sensors* 11 (6) (2011) 5561–5595.
- [10] M. Ghamari, B. Janko, R. S. Sherratt, W. Harwin, R. Piechockic, C. Soltanpur, A survey on wireless body area networks for ehealthcare systems in residential environments, *Sensors* 16 (6) (2016) 831.
- [11] T. Hayajneh, G. Almashaqbeh, S. Ullah, A. V. Vasilakos, A survey of wireless technologies coexistence in wban: analysis and open research issues, *Wireless Networks* 20 (8) (2014) 2165–2199.
- [12] D. P. Tobón, T. H. Falk, M. Maier, Context awareness in wbans: a survey on medical and non-medical applications, *IEEE Wireless Communications* 20 (4) (2013) 30–37.
- [13] R. A. Khan, A.-S. K. Pathan, The state-of-the-art wireless body area sensor networks: A survey, *International Journal of Distributed Sensor Networks* 14 (4) (2018) 1–23.
- [14] S. Al-Janabi, I. Al-Shourbaji, M. Shojafar, S. Shamshirband, Survey of main challenges (security and privacy) in wireless body area networks for healthcare applications, *Egyptian Informatics Journal* 18 (2) (2017) 113–122.
- [15] M. M. Alam, E. B. Hamida, Surveying wearable human assistive technology for life and safety critical applications: Standards, challenges and opportunities, *Sensors* 14 (5) (2014) 9153–9209.
- [16] R. Cavallari, F. Martelli, R. Rosini, C. Buratti, R. Verdona, A survey on wireless body area networks: Technologies and design challenges, *IEEE Communications Surveys & Tutorials* 16 (3) (2014) 1635–1657.
- [17] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, A. Jamalipour, Wireless body area networks: A survey, *IEEE Communications Surveys & Tutorials* 16 (3) (2014) 1658–1686.
- [18] R. Negra, I. Jemili, A. Belghith, Wireless body area networks: Applications and technologies, *Procedia Computer Science* 83 (2016) 1274–1281.
- [19] B. Antonescu, S. Basagni, Wireless body area networks: challenges, trends and emerging technologies, in: Proceedings of the 8th international conference on body area networks, ICST (Institute for Computer Sciences, Social-Informatics and . . . , 2013, pp. 1–7.
- [20] S. Ullah, H. Higgins, B. Braem, B. Latre, C. Blondia, I. Moerman, S. Saleem, Z. Rahman, K. S. Kwak, A comprehensive survey of wireless body area networks, *Journal of medical systems* 36 (3) (2012) 1065–1094.
- [21] D. Chandramouli, B. Covell, V. Held, H. Hietalahti, J. Hofmann, R. Ratasuk, Massive machine type communication and the internet of things, *5G for the Connected World* (2019) 377–439.

- [22] E. Kartsakli, A. S. Lalos, A. Antonopoulos, S. Tennina, M. D. Renzo, L. Alonso, C. Verikoukis, A survey on m2m systems for mhealth: a wireless communications perspective, *Sensors* 14 (10) (2014) 18009–18052.
- [23] T. ETSI, 102 690, machine-to-machine communications (m2m), functional architecture, European Telecommunications Standards Institute (ETSI) 20 (2011) 332.
- [24] A. Drescher, A survey of software-defined wireless networks, Dept. Comput. Sci. Eng., Washington Univ. St. Louis, St. Louis, MO, USA, Tech. Rep (2014) 1–15.
- [25] NEC, Software-Defined Networking (SDN) Solution Nagoya City University Hospital, [Available Online]: http://au.nec.com/en_au/media/docs/case-studies/nec-sdn-case-study-nagoyai-city-university-hospital.pdf, [Accessed on: 2019-01-09].
- [26] L. Hu, M. Qiu, J. Song, M. S. Hossain, A. Ghoneim, Software defined healthcare networks, *IEEE Wireless Communications* 22 (6) (2015) 67–75.
- [27] G. Cova, H. Xiong, Q. Gao, E. Guerrero, R. Ricardo, J. Estevez, A perspective of state-of-the-art wireless technologies for e-health applications, in: 2009 IEEE International Symposium on IT in Medicine & Education, Vol. 1, IEEE, 2009, pp. 76–81.
- [28] T. Bhardwaj, S. C. Sharma, Cloud-wban: An experimental framework for cloud-enabled wireless body area network with efficient virtual resource utilization, *Sustainable Computing: Informatics and Systems* 20 (2018) 14–33.
- [29] G. B. Satrya, N. D. Cahyani, R. F. Andreta, The detection of 8 type malware botnet using hybrid malware analysis in executable file windows operating systems, in: Proceedings of the 17th International Conference on Electronic Commerce 2015, ACM, 2015, p. 5.
- [30] G. B. Satrya, S. Y. Shin, Optimizing rule on open source firewall using content and pcre combination, *Journal of Advances in Computer Networks* 3 (3) (2015) 308–314.
- [31] M. Al Shayokh, A. Abeshu, G. Satrya, M. Nugroho, Efficient and secure data delivery in software defined wban for virtual hospital, in: 2016 International Conference on Control, Electronics, Renewable Energy and Communications (ICCEREC), IEEE, 2016, pp. 12–16.
- [32] IEEE Standards Coordinating Committee, IEEE standard for safety levels with respect to human exposure to radio frequency electromagnetic fields, 3khz to 300ghz, IEEE C95. 1-1991.
- [33] S. N. Ramli, R. Ahmad, Surveying the wireless body area network in the realm of wireless communication, in: 2011 7th International Conference on Information Assurance and Security (IAS), IEEE, 2011, pp. 58–61.
- [34] B. Gyselinckx, R. Borzi, P. Mattelaer, Human++: Emerging technology for body area networks, in: *Wireless Technologies*, CRC Press, 2007, pp. 227–246.

- [35] S. Ullah, P. Khan, N. Ullah, S. Saleem, H. Higgins, K. S. Kwak, A review of wireless body area networks for medical applications, *International Journal of Communications, Network and System Sciences* 2 (8) (2010) 797–803.
- [36] D. Lewis, 802.15. 6 call for applications in body area networks response summary, 15-08-0407-05-0006.
- [37] N. de Vicq, F. Robert, J. Penders, B. Gyselinckx, T. Torfs, Wireless body area network for sleep staging, in: 2007 IEEE Biomedical Circuits and Systems Conference, IEEE, 2007, pp. 163–166.
- [38] H.-T. Chu, C.-C. Huang, Z.-H. Lian, J. J. Tsai, A ubiquitous warning system for asthma-inducement, in: IEEE International Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing (SUTC'06), Vol. 2, IEEE, 2006, pp. 186–191.
- [39] World Health Organization, Global report on diabetes, [Available Online]: <http://www.who.int/news-room/fact-sheets/detail/diabetes>, [Accessed on: 2019-03-29].
- [40] Diabetes Australia, Diabetes in Australia, [Available Online]: <https://www.diabetesaustralia.com.au/diabetes-in-australia>, [Accessed on: 2019-04-02].
- [41] World Health Organization, Global cancer rates could increase by 50% to 15 million by 2020, [Available Online]: <http://www.who.int/mediacentre/news/releases/2003/pr27/en/>, [Accessed on: 2019-02-02].
- [42] A. K. Teshome, B. Kibret, D. T. Lai, A review of implant communication technology in wban: Progress and challenges, *IEEE reviews in biomedical engineering* 12 (2019) 88–99.
- [43] J. Habetha, The myheart project-fighting cardiovascular diseases by prevention and early diagnosis, in: Engineering in Medicine and Biology Society, 2006. EMBS'06. 28th Annual International Conference of the IEEE, IEEE, 2006, pp. 6746–6749.
- [44] J. Luprano, J. Sola, S. Dasen, J. M. Koller, O. Chetelat, Combination of body sensor networks and on-body signal processing algorithms: the practical case of myheart project, in: International Workshop on Wearable and Implantable Body Sensor Networks (BSN'06), 2006, pp. 79–82.
- [45] T. Tanaka, T. Fujita, K. Sonoda, M. Nii, K. Kanda, K. Maenaka, A. C. C. Kit, S. Okochi, K. Higuchi, Wearable health monitoring system by using fuzzy logic heart-rate extraction, in: World Automation Congress 2012, IEEE, 2012, pp. 1–4.
- [46] S. Khan, A.-S. K. Pathan, N. A. Alrajeh, *Wireless sensor networks: Current status and future trends*, CRC press, Boca Raton, FL, 2012.

- [47] D. H. Lee, A. Rabbi, J. Choi, R. Fazel-Rezai, Development of a mobile phone based e-health monitoring application, *International Journal of Advanced Computer Science and Applications (IJACSA)* 3 (3) (2012) 38–43.
- [48] S. Kannan, Wheats: a wearable personal healthcare and emergency alert and tracking system, *Eur. J. Sci. Res* 1 (2012) 382–393.
- [49] İ. Kirbaş, C. Bayilmiş, Healthface: A web-based remote monitoring interface for medical healthcare systems based on a wireless body area sensor network, *Turkish Journal of Electrical Engineering & Computer Sciences* 20 (4) (2012) 629–638.
- [50] M. Zhang, A. Sawchuk, A customizable framework of body area sensor network for rehabilitation, in: *International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL)*, 2009, pp. 1–6.
- [51] A. Hadjidj, M. Souil, A. Bouabdallah, Y. Challal, H. Owen, Wireless sensor networks for rehabilitation applications: Challenges and opportunities, *Journal of Network and Computer Applications* 36 (1) (2013) 1–15.
- [52] S. Bouwstra, W. Chen, L. Feijs, S. B. Oetomo, Smart jacket design for neonatal monitoring with wearable sensors, in: *2009 Sixth International Workshop on Wearable and Implantable Body Sensor Networks*, IEEE, 2009, pp. 162–167.
- [53] A. Basak, S. Narasimhan, S. Bhunia, Kims: Kids' health monitoring system at day-care centers using wearable sensors and vocabulary-based acoustic signal processing, in: *2011 IEEE 13th International Conference on e-Health Networking, Applications and Services*, IEEE, 2011, pp. 1–8.
- [54] A. Guraliuc, A. Serra, P. Nepa, G. Manara, F. Potorti, Detection and classification of human arm movements for physical rehabilitation, in: *2010 IEEE Antennas and Propagation Society International Symposium*, IEEE, 2010, pp. 1–4.
- [55] A. Chhikara, A. Rice, A. H. McGregor, F. Bello, Wearable device for monitoring disability associated with low back pain, *World* 10 (2008) 13.
- [56] P. Iso-Ketola, T. Karinsalo, J. Vanhala, Hipguard: A wearable measurement system for patients recovering from a hip operation, in: *2008 Second International Conference on Pervasive Computing Technologies for Healthcare*, IEEE, 2008, pp. 196–199.
- [57] T. Watanabe, H. Saito, Tests of wireless wearable sensor system in joint angle measurement of lower limbs, in: *2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, IEEE, 2011, pp. 5469–5472.
- [58] G. Anania, A. Tognetti, N. Carbonaro, M. Tesconi, F. Cutolo, G. Zupone, D. De Rossi, Development of a novel algorithm for human fall detection using wearable sensors, in: *SENSORS*, 2008 IEEE, IEEE, 2008, pp. 1336–1339.

- [59] W.-S. Baek, D.-M. Kim, F. Bashir, J.-Y. Pyun, Real life applicable fall detection system based on wireless body area network, in: 2013 IEEE Consumer Communications and Networking Conference (CCNC), IEEE, 2013, pp. 62–67.
- [60] F. Felisberto, F. Fdez-Riverola, A. Pereira, A ubiquitous and low-cost solution for movement monitoring and accident detection based on sensor fusion, *Sensors* 14 (5) (2014) 8961–8983.
- [61] S. Yazaki, T. Matsunaga, A proposal of abnormal condition detection system for elderly people using wireless wearable biosensor, in: 2008 SICE Annual Conference, IEEE, 2008, pp. 2234–2238.
- [62] S. Patel, K. Lorincz, R. Hughes, N. Huggins, J. H. Growdon, M. Welsh, P. Bonato, Analysis of feature space for monitoring persons with parkinson’s disease with application to a wireless wearable sensor system, in: 2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, IEEE, 2007, pp. 6290–6293.
- [63] T. Falck, J. Espina, J. . Ebert, D. Dietterle, Basuma - the sixth sense for chronically ill patients, in: International Workshop on Wearable and Implantable Body Sensor Networks (BSN’06), 2006, pp. 60–63.
- [64] K. Wac, R. Bults, B. van Beijnum, I. Widya, V. Jones, D. Konstantas, M. Vollenbroek-Hutten, H. Hermens, Mobile patient monitoring: The mobihealth system, in: 2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2009, pp. 1238–1241.
- [65] T. Gao, T. Massey, L. Selavo, D. Crawford, B.-r. Chen, K. Lorincz, V. Shnayder, L. Hauenstein, F. Dabiri, J. Jeng, et al., The advanced health and disaster aid network: A light-weight wireless medical system for triage, *IEEE Transactions on biomedical circuits and systems* 1 (3) (2007) 203–216.
- [66] E. Kang, Y. Im, U. Kim, Remote control multi-agent system for u-healthcare service, in: KES International Symposium on Agent and Multi-Agent Systems: Technologies and Applications, Springer, 2007, pp. 636–644.
- [67] V. Shnayder, B.-r. Chen, K. Lorincz, T. R. F. F. Jones, M. Welsh, Sensor networks for medical care, in: Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems, SenSys ’05, 2005, pp. 314–314.
- [68] K. Ouchi, T. Suzuki, M. Doi, Lifeminder: a wearable healthcare support system using user’s context, in: Proceedings 22nd International Conference on Distributed Computing Systems Workshops, 2002, pp. 791–792.
- [69] T. Sheltami, A. Mahmoud, M. Abu-Amara, Warning and monitoring medical system using sensor networks, in: The Saudi 18th national computer conference (NCC18), 2006, pp. 63–68.

- [70] K. Venkatasubramanian, G. Deng, T. Mukherjee, J. Quintero, V. Annamalai, S. K. Gupta, Ayushman: A wireless sensor network based health monitoring infrastructure and testbed, in: Proceedings of the First IEEE international conference on Distributed Computing in Sensor Systems, Springer-Verlag, 2005, pp. 406–407.
- [71] D. Curtis, E. Shih, J. Waterman, J. Guttag, J. Bailey, T. Stair, R. A. Greenes, L. Ohno-Machado, Physiological signal monitoring in the waiting areas of an emergency room, in: Proceedings of the ICST 3rd international conference on Body area networks, ICST, 2008, p. 5.
- [72] E. L. van den Broek, J. H. D. M. Westerink, Biofeedback systems for stress reduction - towards a bright future for a revitalized field, in: HEALTHINF, 2012.
- [73] A. D. Wood, J. A. Stankovic, G. Virone, L. Selavo, Z. He, Q. Cao, T. Doan, Y. Wu, L. Fang, R. Stoleru, Context-aware wireless sensor networks for assisted living and residential monitoring, IEEE Network 22 (4) (2008) 26–33.
- [74] H. Ghasemzadeh, V. Loseu, E. Guenterberg, R. Jafari, Sport training using body sensor networks: A statistical approach to measure wrist rotation for golf swing, in: Proceedings of the Fourth International Conference on Body Area Networks, ICST, 2009, p. 2.
- [75] V. Sivaraman, S. Grover, A. Kurusingal, A. Dhamdhare, A. Burdett, Experimental study of mobility in the soccer field with application to real-time athlete monitoring, in: 2010 IEEE 6th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), IEEE, 2010, pp. 337–345.
- [76] S. Akram, N. Javaid, A. Tauqir, A. Rao, S. N. Mohammad, The-fame: Threshold based energy-efficient fatigue measurement for wireless body area sensor networks using multiple sinks, in: 2013 8th International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA), IEEE, 2013, pp. 214–220.
- [77] M. Garcia, A. Catalá, J. Lloret, J. J. Rodrigues, A wireless sensor network for soccer team monitoring, in: 2011 International Conference on Distributed Computing in Sensor Systems and Workshops (DCOSS), IEEE, 2011, pp. 1–6.
- [78] M. Lauzier, P. Ferrand, H. Parvery, A. Fraboulet, J.-M. Gorce, Wbans for live sport monitoring: an experimental approach, early results and perspectives, in: EURO-COST IC1004-European Cooperation in the Field Of Scientific and Technical Research, 2012.
- [79] K. Revett, S. T. de Magalhães, Cognitive biometrics: Challenges for the future, in: International Conference on Global Security, Safety, and Sustainability, Springer, 2010, pp. 79–86.
- [80] S. Coyle, D. Morris, K. Lau, D. Diamond, N. Taccini, D. Costanzo, P. Salvo, F. Di Francesco, M. G. Trivella, J. Porchet, J. Luprano, Textile sensors to measure sweat ph and sweat-rate during exercise, in: 2009 3rd International Conference on Pervasive Computing Technologies for Healthcare, 2009, pp. 1–6.

- [81] D. Morris, B. Schazmann, Y. Wu, S. Coyle, S. Brady, J. Hayes, C. Slater, C. Fay, K. T. Lau, G. Wallace, D. Diamond, Wearable sensors for monitoring sports performance and training, in: 2008 5th International Summer School and Symposium on Medical Devices and Biosensors, 2008, pp. 121–124.
- [82] L. De Nardis, D. Domenicali, M. G. Di Benedetto, Mobility model for body area networks of soccer players, in: The 3rd European Wireless Technology Conference, 2010, pp. 65–68.
- [83] M. Lapinski, E. Berkson, T. Gill, M. Reinold, J. A. Paradiso, A distributed wearable, wireless sensor system for evaluating professional baseball pitchers and batters, in: 2009 International Symposium on Wearable Computers, 2009, pp. 131–138.
- [84] M. Walsh, J. Barton, B. O’Flynn, C. O’Mathuna, M. Tyndyk, Capturing the overarm throw in darts employing wireless inertial measurement, in: SENSORS, 2011 IEEE, 2011, pp. 1441–1444.
- [85] R. Marin-Perianu, M. Marin-Perianu, D. Rouffet, S. Taylor, P. Havinga, R. Begg, M. Palaniswami, Body area wireless sensor networks for the analysis of cycling performance, in: Proceedings of the Fifth International Conference on Body Area Networks, ACM, 2010, pp. 1–7.
- [86] G. Magenes, D. Curone, L. Caldani, E. L. Secco, Fire fighters and rescuers monitoring through wearable sensors: The proetex project, in: 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, 2010, pp. 3594–3597.
- [87] H. B. Lim, D. Ma, B. Wang, Z. Kalbarczyk, R. K. Iyer, K. L. Watkin, A soldier health monitoring system for military applications, in: 2010 International Conference on Body Sensor Networks (BSN), IEEE, 2010, pp. 246–249.
- [88] D. Chen, J. Hart, R. Vertegaal, Towards a physiological model of user interruptability, in: IFIP Conference on Human-Computer Interaction, Springer, 2007, pp. 439–451.
- [89] T. M. Connolly, E. A. Boyle, E. MacArthur, T. Hainey, J. M. Boyle, A systematic literature review of empirical evidence on computer games and serious games, *Computers & Education* 59 (2) (2012) 661–686.
- [90] O. Omeni, A. C. W. Wong, A. J. Burdett, C. Toumazou, Energy efficient medium access protocol for wireless medical body area sensor networks, *IEEE Transactions on biomedical circuits and systems* 2 (4) (2008) 251–259.
- [91] M. Al Ameen, J. Liu, S. Ullah, K. S. Kwak, A power efficient mac protocol for implant device communication in wireless body area networks, in: 2011 IEEE Consumer Communications and Networking Conference (CCNC), IEEE, 2011, pp. 1155–1160.
- [92] T. O’Donovan, J. O’Donoghue, C. Sreenan, D. Sammon, P. O’Reilly, K. A. O’Connor, A context aware wireless body area network (ban), in: 2009 3rd International Conference on Pervasive Computing Technologies for Healthcare, 2009, pp. 1–8.

- [93] G. Pradhan, R. Gupta, S. Biswas, Study and simulation of wban mac protocols for emergency data traffic in healthcare, in: 2018 Fifth International Conference on Emerging Applications of Information Technology (EAIT), IEEE, 2018, pp. 1–4.
- [94] S. Marinkovic, C. Spagnol, E. Popovici, Energy-efficient tdma-based mac protocol for wireless body area networks, in: 2009 Third International Conference on Sensor Technologies and Applications, IEEE, 2009, pp. 604–609.
- [95] B. Braem, B. Latreč, I. Moerman, C. Blondia, E. Reusens, W. Joseph, L. Martens, P. Demeester, The need for cooperation and relaying in short-range high path loss sensor networks, in: 2007 International Conference on Sensor Technologies and Applications (SENSORCOMM 2007), 2007, pp. 566–571.
- [96] S. Ullah, B. Shen, S. Riazul Islam, P. Khan, S. Saleem, K. Sup Kwak, A study of mac protocols for wbans, *Sensors* 10 (1) (2009) 128–145.
- [97] X. Zhou, T. Zhang, L. Song, Q. Zhang, Energy efficiency optimization by resource allocation in wireless body area networks, in: 2014 IEEE 79th Vehicular Technology Conference (VTC Spring), IEEE, 2014, pp. 1–6.
- [98] G. Fang, E. Dutkiewicz, Bodymac: Energy efficient tdma-based mac protocol for wireless body area networks, in: 2009 9th International Symposium on Communications and Information Technology, 2009, pp. 1455–1459.
- [99] W. Scanlon, G. Conway, 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, Vol. 11803, 2007.
- [100] M. Patel, J. Wang, Applications, challenges, and prospective in emerging body area networking technologies, *IEEE Wireless Communications* 17 (1) (2010) 80–88.
- [101] A. Kiourti, K. S. Nikita, A review of implantable patch antennas for biomedical telemetry: Challenges and solutions [wireless corner], *IEEE Antennas and Propagation Magazine* 54 (3) (2012) 210–228.
- [102] G.-Z. Yang, G. Yang, *Body Sensor Networks*, Springer-Verlag, London, 2006.
- [103] G. Selimis, L. Huang, F. Massé, I. Tsekoura, M. Ashouei, F. Catthoor, J. Huisken, J. Stuyt, G. Dolmans, J. Penders, et al., A lightweight security scheme for wireless body area networks: design, energy evaluation and proposed microprocessor design, *Journal of medical systems* 35 (5) (2011) 1289–1298.
- [104] C. C. Poon, Y.-T. Zhang, S.-D. Bao, A novel biometrics method to secure wireless body area sensor networks for telemedicine and m-health, *IEEE Communications Magazine* 44 (4) (2006) 73–81.

- [105] D. He, C. Chen, S. Chan, J. Bu, A. V. Vasilakos, A distributed trust evaluation model and its application scenarios for medical sensor networks, *IEEE Transactions on Information Technology in Biomedicine* 16 (6) (2012) 1164–1175.
- [106] D. He, C. Chen, S. Chan, J. Bu, A. V. Vasilakos, Retruster: Attack-resistant and lightweight trust management for medical sensor networks, *IEEE transactions on information technology in biomedicine* 16 (4) (2012) 623–632.
- [107] C. A. Chin, G. V. Crosby, T. Ghosh, R. Murimi, Advances and challenges of wireless body area networks for healthcare applications, in: *2012 International Conference on Computing, Networking and Communications (ICNC)*, IEEE, 2012, pp. 99–103.
- [108] N. Wisniewski, M. Reichert, Methods for reducing biosensor membrane biofouling, *Colloids and Surfaces B: Biointerfaces* 18 (3-4) (2000) 197–219.
- [109] S. Ullah, K. S. Kwak, Throughput and delay limits of IEEE 802.15.6, in: *Wireless Communications and Networking Conference (WCNC)*, IEEE, 2011, pp. 174–178.
- [110] N. Xiong, A. V. Vasilakos, L. T. Yang, L. Song, Y. Pan, R. Kannan, Y. Li, Comparative analysis of quality of service and memory usage for adaptive failure detectors in healthcare systems, *IEEE Journal on Selected Areas in Communications* 27 (4) (2009) 495–509.
- [111] G. Zhou, J. Lu, C. . Wan, M. D. Yarvis, J. A. Stankovic, Bodyqos: Adaptive and radio-agnostic qos for body sensor networks, in: *IEEE INFOCOM 2008 - The 27th Conference on Computer Communications*, 2008, pp. 565–573.
- [112] I. S. Association, et al., IEEE standard for local and metropolitan area networks—part 15.6: Wireless body area networks, *IEEE Standard for Information Technology*, IEEE 802 (6) (2012) 1–271.
- [113] D. Domenicali, M. Di Benedetto, Performance analysis for a body area network composed of IEEE 802.15.4a devices, in: *2007 4th Workshop on Positioning, Navigation and Communication*, 2007, pp. 273–276.
- [114] D. Domenicali, L. De Nardis, M. Di Benedetto, UWB body area network coexistence by interference mitigation, in: *2009 IEEE International Conference on Ultra-Wideband*, 2009, pp. 713–717.
- [115] J.-H. Hauer, V. Handziski, A. Wolisz, Experimental study of the impact of WLAN interference on IEEE 802.15.4 body area networks, in: *European Conference on Wireless Sensor Networks*, Springer, 2009, pp. 17–32.
- [116] J. Hou, B. Chang, D.-K. Cho, M. Gerla, Minimizing IEEE 802.11 interference on ZigBee medical sensors, in: *Proceedings of the Fourth International Conference on Body Area Networks, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering)*, 2009, p. 5.
- [117] F. Martelli, R. Verdone, Coexistence issues for wireless body area networks at 2.45 GHz, in: *European Wireless 2012; 18th European Wireless Conference 2012*, 2012, pp. 1–6.

- [118] S. Warren, E. Jovanov, The need for rules of engagement applied to wireless body area networks, in: Proceedings of the IEEE consumer communications and networking conference, CCNC, 2006.
- [119] R. Chávez-Santiago, C. Garcia-Pardo, A. Fornes-Leal, A. Vallés-Lluch, G. Vermeeren, W. Joseph, I. Balasingham, N. Cardona, Experimental path loss models for in-body communications within 2.36-2.5 ghz., *IEEE J. Biomedical and Health Informatics* 19 (3) (2015) 930–937.
- [120] T. Aoyagi, K. Takizawa, T. Kobayashi, J.-i. Takada, R. Kohno, Development of a wban channel model for capsule endoscopy, in: *IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, 2009, pp. 1–4.
- [121] Y. Liu, R. D. Gitlin, A phenomenological path loss model of the in vivo wireless channel, in: *IEEE 16th Wireless and Microwave Technology Conference*, 2015.
- [122] D. Kurup, W. Joseph, G. Vermeeren, L. Martens, In-body path loss model for homogeneous human tissues, *IEEE Transactions on Electromagnetic Compatibility* 54 (3) (2012) 556–564.
- [123] D. Kurup, G. Vermeeren, E. Tanghe, W. Joseph, L. Martens, In-to-out body antenna-independent path loss model for multilayered tissues and heterogeneous medium, *Sensors* 15 (1) (2014) 408–421.
- [124] D. Takahashi, Y. Xiao, F. Hu, Ltrt: Least total-route temperature routing for embedded biomedical sensor networks, in: *IEEE GLOBECOM 2007-IEEE Global Telecommunications Conference*, IEEE, 2007, pp. 641–645.
- [125] A. Bag, M. A. Bassiouni, Hotspot preventing routing algorithm for delay-sensitive applications of in vivo biomedical sensor networks, *Information Fusion* 9 (3) (2008) 389–398.
- [126] F. T. Zuhra, K. A. Bakar, A. Ahmed, M. A. Tunio, Routing protocols in wireless body sensor networks: A comprehensive survey, *Journal of Network and Computer Applications* 99 (2017) 73–97.
- [127] K. Awan, K. N. Qureshi, M. Mehwish, Wireless body area networks routing protocols: a review, *Indonesian Journal of Electrical Engineering and Computer Science* 4.
- [128] Q. Tang, N. Tummala, S. K. Gupta, L. Schwiebert, Tara: thermal-aware routing algorithm for implanted sensor networks, in: *International Conference on Distributed Computing in Sensor Systems*, Springer, 2005, pp. 206–217.
- [129] A. Bag, M. A. Bassiouni, Energy efficient thermal aware routing algorithms for embedded biomedical sensor networks, in: *2006 IEEE International Conference on Mobile Ad Hoc and Sensor Systems*, IEEE, 2006, pp. 604–609.
- [130] C. Oey, S. Moh, A survey on temperature-aware routing protocols in wireless body sensor networks, *Sensors* 13 (8) (2013) 9860–9877.
- [131] R. Istepanian, S. Laxminarayan, C. S. Pattichis, *M-health*, Springer, Boston, MA, 2006.

- [132] H. Cao, V. Leung, C. Chow, H. Chan, Enabling technologies for wireless body area networks: A survey and outlook, *IEEE Communications Magazine* 47 (12).
- [133] F. Touati, R. Tabish, U-healthcare system: State-of-the-art review and challenges, *Journal of medical systems* 37 (3) (2013) 9949.
- [134] M. Chen, S. Gonzalez, A. Vasilakos, H. Cao, V. C. Leung, Body area networks: A survey, *Mobile networks and applications* 16 (2) (2011) 171–193.
- [135] H. C. Keong, M. R. Yuce, Analysis of a multi-access scheme and asynchronous transmit-only uwb for wireless body area networks, in: *2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2009, pp. 6906–6909.
- [136] K. S. Kwak, S. Ullah, N. Ullah, An overview of IEEE 802.15.6 standard, in: *Applied Sciences in Biomedical and Communication Technologies (ISABEL)*, 2010 3rd International Symposium on, IEEE, 2010, pp. 1–6.
- [137] D. B. Smith, D. Miniutti, T. A. Lamahewa, L. W. Hanlen, Propagation models for body-area networks: A survey and new outlook, *IEEE Antennas and Propagation Magazine* 55 (5) (2013) 97–117.
- [138] Federal Communications Commission, Cell Phones and Specific Absorption Rate, [Available Online]: <https://www.fcc.gov/general/cell-phones-and-specific-absorption-rate>, [Accessed on: 2018-11-09].
- [139] J. H. Cox, J. Chung, S. Donovan, J. Ivey, R. J. Clark, G. Riley, H. L. Owen, Advancing software-defined networks: A survey, *IEEE Access* 5 (2017) 25487–25526.
- [140] A. Doria, J. H. Salim, R. Haas, H. Khosravi, W. Wang, L. Dong, R. Gopal, J. Halpern, Forwarding and Control Element Separation (ForCES) Protocol Specification, RFC 5810, Tech. rep. (2010).
- [141] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, J. Turner, Openflow: enabling innovation in campus networks, *ACM SIGCOMM Computer Communication Review* 38 (2) (2008) 69–74.
- [142] M. Casado, N. Foster, A. Guha, Abstractions for software-defined networks, *Communications of the ACM* 57 (10) (2014) 86–95.
- [143] H. I. Kobo, A. M. Abu-Mahfouz, G. P. Hancke, A survey on software-defined wireless sensor networks: Challenges and design requirements., *IEEE Access* 5 (1) (2017) 1872–1899.
- [144] HITInfrastructure, Benefits of Software-Defined Networking in Healthcare, [Available Online]: <https://hitinfrastructure.com/features/benefits-of-software-defined-networking-in-healthcare>, [Accessed on: 2019-01-09].

- [145] V. Varadharajan, U. Tupakula, K. Karmakar, Secure monitoring of patients with wandering behavior in hospital environments, *IEEE Access* 6 (2018) 11523–11533.
- [146] B. T. De Oliveira, L. B. Gabriel, C. B. Margi, Tinysdn: Enabling multiple controllers for software-defined wireless sensor networks, *IEEE Latin America Transactions* 13 (11) (2015) 3690–3696.
- [147] Y. Choi, Y. Choi, Y.-G. Hong, Study on coupling of software-defined networking and wireless sensor networks, in: *International Conference on Ubiquitous and Future Networks*, 2016, pp. 900–902.
- [148] K. Hasan, X.-W. Wu, K. Biswas, K. Ahmed, A novel framework for software defined wireless body area network, in: *Intelligent Systems, Modelling and Simulations (ISMS)*, 2018 8th International Conference on, IEEE, 2018, pp. 114–119.
- [149] S. Nakamoto, Bitcoin: A peer-to-peer electronic cash system, Tech. rep. (2008).
- [150] D. E. Kouicem, A. Bouabdallah, H. Lakhlef, Internet of things security: A top-down survey, *Computer Networks* 141 (2018) 199 – 221.
- [151] M. Mettler, Blockchain technology in healthcare: The revolution starts here, in: *2016 IEEE 18th International Conference on e-Health Networking, Applications and Services (Healthcom)*, IEEE, 2016, pp. 1–3.
- [152] G. Prisco, The Blockchain for healthcare: Gem launches Gem Health Network with Philips Blockchain Lab, [Available Online]: <https://bitcoinmagazine.com/articles/the-blockchain-for-healthcare-gem-launches-gem-health-network-with-philips-blockchain-lab-1461674938/>, [Accessed on: 2018-11-09].
- [153] S. Huh, S. Cho, S. Kim, Managing iot devices using blockchain platform, in: *2017 19th International Conference on Advanced Communication Technology (ICACT)*, IEEE, 2017, pp. 464–467.
- [154] O. Williams-Grut, Estonia is using the technology behind bitcoin to secure 1 million health records, [Available Online]: <https://www.businessinsider.com.au/guardtime-estonian-health-records-industrial-blockchain-bitcoin-2016-3?r=us&ir=t>, [Accessed on: 2018-11-09].
- [155] P. Nichol, Blockchain applications for healthcare, *Najdeno* 4 (9) (2016) 2017.
- [156] S. Jiang, J. Cao, H. Wu, Y. Yang, M. Ma, J. He, Blochie: a blockchain-based platform for healthcare information exchange, in: *2018 IEEE International Conference on Smart Computing (SMARTCOMP)*, IEEE, 2018, pp. 49–56.
- [157] K. Hasan, K. Biswas, K. Ahmed, M. S. Islam, Challenges of integrating blockchain in wireless body area network, *The 3rd Symposium on Distributed Ledger Technology*, 2018 Griffith University, Australia.

- [158] F. Akhtar, M. H. Rehmani, Energy harvesting for self-sustainable wireless body area networks, *IT Professional* 19 (2) (2017) 32–40.
- [159] C. Gould, R. Edwards, Review on micro-energy harvesting technologies, in: 2016 51st International Universities Power Engineering Conference (UPEC), IEEE, 2016, pp. 1–5.
- [160] M. Saida, G. Zaibi, M. Samet, A. Kachouri, Improvement of energy harvested from the heat of the human body, in: 2016 17th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA), IEEE, 2016, pp. 132–137.
- [161] S. Akbari, Energy harvesting for wireless sensor networks review, in: 2014 Federated Conference on Computer Science and Information Systems, IEEE, 2014, pp. 987–992.

Table 3: Taxonomy of Medical Applications

Medical Applications	Focus	References
Cardiovascular Disease (CVD)(MyHeart)	Self-managed Monitoring System of CVD and Real-time Monitoring	[43], [44]
Heart Rate Monitoring	Electrocardiogram (ECG), Heart Rate (HR), Body Acceleration, Temperature Sensors	[45], [46]
Real-time Monitoring and Analysis of Human Health	Blood Pressure, Body Temperature, ECG, Blood Flow	[47], [48]
Health Face	Web-based Remote Health Monitoring	[49]
RehabSPOT	Stroke and Physical Dysfunction	[50]
Rehabilitation	Improve Rehabilitation and Assisting in Mobility	[51]
Comfortable Health Monitoring for New Born (Smart Jacket)	ECG	[52]
Kids Health Monitoring System (KiMS)	Temperature and Pulse Rate Sensor	[53]
Rehabilitation and Recovery Monitoring	Rehabilitation Exercise Monitoring	[54]
IMPAIRED	Low Back Pain	[55]
HipGuard	Leg and Hip Position Rotation	[56]
Real-time Activity Monitoring	Exercise Monitoring for patients with motor impairment	[57]
Fall Detection	Posture of Humans especially elderly people	[58], [59], [60]
Abnormal Condition Detection System	Monitors sitting, walking, lying and falling	[61]
Neurodegenerative	Parkinson	[62]
BASUMA	Health Monitoring (ECG, Reactive Oxygen Sensor, SpO ₂ sensor, Spirometer)	[63]
MobiHealth	Ambulatory Patient Monitoring (ECG)	[64]
AID-N	Emergency Response of Blood Pulse, ECG	[65]
MAHS	Spirometer, Pressure, Temperature, Pulse	[66]
Code Blue	Motion, Pulse , Oximeter	[67]
LifeMinder	ECG, Thermometer, SpO ₂ , Galvanic Skin Response	[68]
ASNET	Remote Monitoring (Temperature and Blood Pressure)	[69]
Ayushman	EKG, Blood Pressure, Oximeter, Gyroscopic Sensor	[70]
SMART	ECG, SPO ₂	[71]
Biofeedback	Controlling Emotion such as Stress	[72]
Assisted Living	Disable People	[73]

Table 4: Taxonomy of Non-Medical Applications

Non-Medical Applications	Focus	References
Golf Training	Wearable sensors used to monitor quality of movements	[74]
Soccer Player Monitoring	Routing techniques to monitor soccer player's movement	[75]
THE-FAME	Muscle fatigue through sensing accumulation of lactic acid	[76]
Fitness Monitoring	Improvement in user's quality of life	[46]
Physical State Monitoring	Identifying exhausted player	[77]
Performance of Marathon Athlete	Real-time data collection in dense dynamic environment	[78]
Biometrics	User authentication	[79]
Sweat pH Analysis	Textile-based sensor	[80]
Indoor Positioning System	Assists visually impaired person to determine objects	[81]
DynaMo	Mobility pattern of players	[82]
Baseball Game	Calculates force, torque during baseball game	[83]
Precision Analysis of Dart Game	Measurement of speed, acceleration and timing.	[84]
Cyclist performance Analysis	Motion sensors used for monitoring lower limb kinematics	[85]
Project ProeTEX	Sensor based garments for activity monitoring of fire fighters	[86]
Soldiers Activity Monitoring	Estimates the impact of blast and effects on soldier	[87]
Management of Notification	Intelligent notification tool	[88]
Serious Gaming	Detects stress level and improve effectiveness of games	[89]

Table 5: Taxonomy of WBAN challenges and related works

Challenges References	Heterogeneous Devices and Traffic	Energy Efficiency	Environmental Challenges	Security, Authentication, and Privacy	Bio-Compatibility	QoS	Interference and Coexistence	Wireless Propagation Characteristics
[90, 91]	✓	✓						
[92]	✓							
[94, 96, 97]		✓						
[95]		✓						✓
[98]		✓				✓		
[17, 99, 100]			✓					
[99, 101]			✓					✓
[20, 104, 105, 106]				✓				
[103]		✓		✓				
[107, 108]					✓			
[109, 110, 111]						✓		
[112, 113, 114, 115, 116, 117]							✓	
[102]			✓		✓			
[119, 120, 121, 122, 123]								✓

Table 6: Characteristics of Wireless Technologies Used in WBAN

<i>Technology</i>	<i>Operating Frequency</i>	<i>Data Rate</i>	<i>Coverage</i>	<i>Network Topology</i>
<i>Bluetooth V.1 802.15.1</i>	2.4 GHz ISM	780 Kbps	10-150 m (on-body only)	star
<i>Bluetooth V.2 + Enhanced Data Rate (EDR)</i>	2.4 GHz ISM	3 Mbps	10-100 m (on-body only)	star
<i>Bluetooth V.3+ High Speed (HS)</i>	2.4 GHz ISM & 5 GHz	3-24 Mbps	10 m (on-body only)	star
<i>Bluetooth V.3+ Low End Extension (LEE)</i>	2.4 GHz ISM	1 Mbps	10 m (on-body only)	star
<i>RFID (ISO/IEC 18000-6)</i>	860-960 MHz	10-100 Kbps	1-100m	Peer-to-Peer
<i>Ultra Wideband (UWB)</i>	3.1-10.6 GHz	110-480 Mbps	5-10 m (on-body only)	star
<i>ZigBee (IEEE 802.15.4)</i>	868 MHz, 915 MHz, 2.4 GHz ISM	20, 40, 250 Kbps	10-100 m (on-body only)	star, mesh, cluster tree
<i>Near Field Communication (NFC)</i>	13.56 MHz	106, 212, 424 Kbps	Up to 20 cm	Peer-to-Peer
<i>ANT</i>	2.4 GHz ISM	1 Mbps	30 m (on-body only)	star, mesh, peer-to-peer, tree
<i>Sensium</i>	868 MHz, 915 MHz	50 Kbps	1-5 m (on-body only)	star
<i>Zarlink(ZL 70101)</i>	402-405 MHz, 433-434 MHz	200-800 Kbps	2 m (in-body only)	Peer-to-Peer
<i>RuBee (IEEE 1902.1)</i>	131 KHz	9.6 Kbps	30 m	Peer-to-Peer
<i>Z-wave</i>	900 MHz ISM	9.6 Kbps	30 m	Mesh



Nazmus Shaker Nafi (S'14) received the B.Eng. (Hons.) degree in Communication from the International Islamic University Malaysia (IIUM), in 2010, the M.Phil. degree in Computer engineering from the University of Newcastle, Newcastle, NSW, Australia, in 2013, and the PhD degree in Electrical Engineering from the RMIT University in 2017. Currently, he is working as a Lecturer and Higher Education Academic Coordinator at the Victorian Institute of Technology, Melbourne, Australia. His current research interests include Smart Grid communication systems, wireless network architecture, Machine to Machine communication systems, Software Defined Networks and Internet of Things.



Md. Saiful Islam is a Lecturer in the School of Information and Communication Technology, Griffith University, Australia. He has finished his PhD in Computer Science and Software Engineering from Swinburne University of Technology, Australia in February, 2014. He has received his BSc (Hons) and MS degree in Computer Science and Engineering from University of Dhaka, Bangladesh, in 2005 and 2007, respectively. His current research interests are in the areas of database usability, spatial data management and big data analytics.



Khandakar Ahmed (M'11) is a Lecturer at College of Engineering and Science, Victoria University, Melbourne, Australia. Before joining Victoria University, Khandakar was a full-time lecturer with the School of IT and Engineering (SITE) at Melbourne Institute of Technology (MIT) and a researcher at the Australia-India Research Centre for Automation Software Engineering (AICAUSE) at RMIT University. He received his Ph.D. from RMIT University, Melbourne, Australia in December 2014, M.Sc. in Networking and e-Business Centred Computing (NeBCC) from the consortia of University of Reading, UK; Aristotle University of Thessaloniki, Greece; and University of Charles III de Madrid, Spain. Dr. Ahmed has authored or co-authored more than 30 publications in the form of journal Article, peer reviewed conference proceedings, book chapter and book. He has also worked as the reviewer for many Journals including Parallel and Distributed Computing (JPDC), Journal of Computer Networks (ComNet) and Journal of Ad-hoc Networks. His research interest includes Software Defined Wide Area Network, Software Defined Wireless Network, Wireless Sensor Network, Smart- Grid and Cloud Networks.



Khalid Hasan is a PhD candidate at School of Information and Communication Technology, Griffith University, Australia. He received his Master of Science (Radio Communication) from Aalto University, Finland in 2014. He received his Bachelor of Engineering (Communication) from International Islamic University Malaysia in 2010. His current research interests include Wireless Body Area Network, Software Defined Networking, Blockchain and Internet of Things Applications.



Kamanashis Biswas is currently working as a lecturer in Information Technology in the Peter Faber Business School (Sydney), Faculty of Law and Business. He received his Ph.D. degree from School of Information and Communication Technology, Griffith University in 2016. He received his masters in Security Engineering from Blekinge Institute of Technology, Sweden in 2007. His research interests include cryptography, IDS, energy efficient and secure routing, and clustering in WSNs.

The authors declare that there is no conflict of interest.

ACCEPTED MANUSCRIPT