CHAPTER 7

WBAN: Driving e-healthcare Beyond Telemedicine to Remote Health Monitoring

Architecture and Protocols

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1 INTRODUCTION

Twenty-first century has been marked as the trendsetter for recent advancements and developments in the area of wireless communications, micro-electromechanical systems (MEMS) technology, and integrated circuits. This has led to the development of low-power, small-sized, cost-efficient, intelligent, invasive/non-invasive micro and nano-technology derived sensor nodes that can be placed strategically inside or outside the human body to be utilized for various applications like health monitoring, etc. This has revolutionized the way healthcare services are implemented and utilized in the real world. The primary focus of modern healthcare services is early detection and prevention of diseases in patients and to deliver best results in almost all situations as compared to traditional healthcare equipment's in terms of treating illness.

The increasing growth of the aging population has triggered the demand for health care and cure, and in all possibility, the trend will continue for the next decades also. According to the latest US Census Bureau data, the number of old people between 65 and 84 years is going to double by 2025 to 70 million [1]. The population could touch 761 million by 2023. During the next 40 years, one-fourth of the population will be over 60. This will put an intense financial burden on the governments. The overall expenditure by the U.S. on healthcare was $9 trillion in 2015 which is expected to triple and touch $27 trillion by 2020. Along with that, the gap between the total population and the number of healthcare professionals will be increasing at an alarming rate. The shortage of doctors and medical personnel will be severed in some particular regions. The increase in the number of doctors has been stagnant for the last few years in many of the regions of some specific countries. The decreased ratio between specialist doctors and general practitioners has made the situation worse. The number of general physicians, in comparison to the specialists, is getting downsized. This has acutely hampered basic healthcare, especially for age-related and chronic diseases.

Traditional healthcare systems suffer from by many shortcomings which can be overcome through new ICT supported healthcare services such as remote and pervasive healthcare [2], healthcare data analytics [3], etc. Advanced ICT-based healthcare systems are able to deliver prompt and efficient services to patients not only in medical intensive care units in hospitals but also in their homes and even workplaces, which in turn is cost-effective and improvises the patient's life quality. The impending health crisis attracts researchers, organizations, and scientists to search for optimal and best health solutions. A term called "eHealth" evolved where healthcare was supported via electronic processes, and now healthcare is extended to becoming mobile known as *mHealth*. In order to fully utilize and optimize wireless technologies, a new type of network has evolved termed as *Wireless Body Area Network* (WBAN) [4].

A WBAN comprises a number of health sensors that collects the information of vital parameters of a human body. The WBAN data sensed by these sensors are

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collected by the remote monitoring application and sent to the appropriate destination for processing and analysis on the basis of which treatment decisions are taken. This enables doctors to continuously monitor patients remotely.

The concept of wireless sensor-based patient monitoring systems via WBAN has evolved and has brought out the revolutionary change in healthcare systems. WBAN technology has been implemented in clinical research laboratories as well as medical test centers. A WBAN system can be deployed at medical care units for old-aged people or at home to act as a source for monitoring without affecting their day to day life activities.

The advancement in sensors, wireless sensor network (WSN), WBAN, and the pervasive systems has taken healthcare to a new height. These technologies are aptly supported by Big Data technologies and different analytics that allows doctors for predictive diagnostics. The patients and medical care units are far more engaged as never before.

Considering the continuous enhancements in this area, WBAN will no longer be utilized in medical but will also move to military based applications, sports training and even for safeguarding human lives. WBAN has become a forefront area of research and development as it offers a huge potential for improvement in health care and monitoring.

The rest of the chapter is organized as follows. The basics of telemedicine and remote health monitoring and their differences are discussed in the next section. Section 3 discusses the components and architecture of WBANs. The difference between WBAN and WSN is also pointed out here. While mentioning the role of WBAN in remote health monitoring, a general architecture of remote health monitoring using WBAN is also illustrated in this section. Section 4 covers the communication architecture of WBAN. It talks about the network structure, topologies, network layers and standards of WBAN. Section 5 explores the WBAN MAC layer while mentioning the importance, properties, channel access and modulation techniques, and traffic adaptive MAC protocols. Several wireless technologies that are used in WBAN and remote health monitoring are reviewed in Section 6. The UWB-based MAC layer protocols and the standard medical radio services are also discussed. Finally, Section 7 concludes the chapter.

2 TELEMEDICINE AND REMOTE HEALTH MONITORING

2.1 Telemedicine

The rise of ICT-based healthcare gave birth to an innovative concept of practicing medicine and clinical services from a distance, using telecommunication, named as *telemedicine*. Telemedicine enables doctors to serve patients remotely by accessing health information through a telecommunication link.

Telemedicine has been a great relief for people in the rural and remote areas where there is a limited medical facility including doctors and infrastructure. Doctors diagnose and consult patients remotely with the help of the local medical staffs who administer the patients directly.

The key enabler of telemedicine is the telecommunication link used in/with different form/technologies such as mobile communication, video conferencing, fax, scanners, etc. for the purpose of communicating and exchanging medical documents (e.g., X-ray and sonography image, infection's photograph, previous prescriptions, pathological report, ECG report, etc.). Based on these documents, doctors assess patients' condition and make recommendations [5]. The widespread and omnipresence of the internet has broadened the scope of telemedicine.

The concept of telemedicine is implemented in the following three ways [6]:

i. Store and forward: This is an asynchronous process and does not need both parties to be in contact or online at the same time. Health information and medical records of the patient are sent to the doctors for assessment. The doctors examine the reports at their convenient time and give feedback/instructions to the local medical staffs.
ii. Remote monitoring: Physician monitors patient's vital statistics remotely.
iii. Real-time interaction: Physician and patient from remote place interact in real-time. As per the patient's convenience, either at home or a nearby medical facility, an interactive schedule with the doctor is pre-arranged [7].

2.2 Remote Health Monitoring

Remote health monitoring is a part of remote healthcare or e-healthcare. It is an approach for automated health monitoring from anywhere. This has been possible thanks to the advancement in sensors and WSN and other newer technologies such as WBAN [8] and IoT [9]. Different health sensors planted within and on the body sense different physiological data like body temperature, heart and pulse readings, blood pressure, blood sugar, brainwave, the oxygen level in blood, etc. [2]. These data are sent to the concerned health professionals who interpret them for assessing a patient's health status, diagnosis, and medication or treatment recommendation. On analyzing the data, it might be decided whether a preventative therapeutic intervention is required or the patient's prescription is needed to be changed. If the monitoring devices are connected to the internet directly, doctors can monitor patients in real-time. Furthermore, integrating the remote monitoring system with sophisticated analytical tools provides physicians with greater visibility and insights into a patient's health status.

2.2.1 Applications of remote health monitoring

With the growing usage of bio-sensors and wearable devices, remote health monitoring is getting very popular and has promoted several health care applications such as diabetes, heart diseases, cancer detection, Parkinson, asthma, Alzheimer, etc. [10,11]. Below some of the most prominent general applications of remote health monitoring are discussed:

Chronic patient care: Number of people suffering from chronic illness is on the rise. Treating chronic diseases in hospitals for longer durations increase the expenses considerably, which many of the times goes beyond the bearing capacity of the patient's family. Instead, taking care of these chronic conditions at home reduces the expense to a great extent. Doctors and nurses continuously keep in touch with the patient and guide, when needed. Remote health monitoring not only makes chronic disease management efficient and less expensive, but also improves the patient's quality of life. Patients enjoy a feeling of independence with the liberty of mobility [12].

Rehabilitating: Rehabilitation can be defined as the restoration of function [13]. In clinical terms, rehabilitation is restoration to a normal life after critical illness, serious injury, or major surgery. Basically, it is the recovering process of getting back to functioning at a level where the patient can live more or less regular lifestyle at home and hopefully at work [14]. Rehabilitation requires constant monitoring of physicians and the remedial professions. The effectiveness of the clinical treatments is strongly dependent on the patient's dedication and sincere adherence to the rehabilitating programs. For a successful rehabilitation, it is of utmost importance to maintain the correct therapy of the prescribed amount and intensity. Deviating from that can affect the rehabilitation process badly. The monitoring device tracks the patient's activity and checks for the adherence to the prescribed rehabilitation session. The relevant statistics about his performance are transmitted to the concerned clinician who can guide the patient if any irregularity is noticed.

Caring elderly people: As mentioned in Section 1, the number of aged people is growing continuously. Nearly half of all hospital treatments pertain to this elderly population. And in most cases, the elderly people are affected not just by one, but by multiple diseases. This results in an escalated frequency of hospitalization which inevitably leads to expensive healthcare. The remote health monitoring systems supporting aged people can significantly reduce the healthcare expenditure while boosting the quality of life and probably the lifespan of the aged people.

2.2.2 Benefits of remote health monitoring

Remote health monitoring exhibits several benefits as follows:

- Remote health monitoring ensures delivering constant and quality care to patients in remote locations.
- Healthcare becomes more available. Remote monitoring allows doctors to reach out to potential patients especially to those people who can't afford to visit a doctor or not been able to go to the hospitals, for certain reasons.
- Offers better quality of life, improved mobility and decrease the mortality rate for the unprivileged populating in terms of healthcare services.
- Reduction in healthcare expenditure by curtailing the long-stay at hospitals and reducing the frequency of re-hospitalization.
- Prevention of the deteriorating health condition through continuous monitoring through advanced and sophisticated devices.
- The pervasive access of patient data allows interdisciplinary collaboration and consultation that helps in the precise and overall better treatment process which leads to increased patient satisfaction and confidence.
- Faster access to relevant patient data enables quick treatment initiation and also shortens treatment duration.
- Doctors and patients both have better access to health information with up-to-date values of the vital parameters. It will be easier for doctors to assess the data collected from the monitoring devices in real-time with the help of visualization tools such as charts and diagrams.
- Monitored data are automatedly fed into the expert systems and advanced data analysis tools for better insight into the patient's health. It is possible to detect the deterioration of non-compliance and a patient's clinical condition early by analyzing the trend of change in physiological parameters [12]. This offers great help to the physicians to proactively manage a patient's treatment.
- Automated monitoring reduces the chance of erroneous diagnosis and incorrect treatment.

- Curtails the possibility of duplicate services (especially diagnostic).
- Automated monitoring can significantly simplify some of the complex clinical tasks such as haemodialysis and diabetes management [15].
- Notification for emergency situations can be set for the physician or family with the help of portable and intelligent devices such as smartphones.
- Real-time data provided by the monitoring devices improve the timeliness of care and boost treatment adherence [16].
- Time-saving for both doctors and patients. The doctors and medical staffs need not be completely preoccupied with a particular patient. They can balance better in attending other patients as well [15].
- Allows healthcare professionals to meet the demand for greater responsibility and accountability from patients and their families.
- Remote monitoring significantly improves the patient follow-up by enabling adjustment of treatment, diet or patient lifestyle.
- The cumbersome burden of patient transportation is avoided.
- Allows hospitals to downsize infrastructure and operational costs.

2.2.3 Challenges in remote health monitoring

To achieve the promised benefits of remote health monitoring, some obstacles, as mentioned below, are needed to be addressed [17].

- The philosophy of remote health monitoring is to provide health services to the people at remote places where there is not enough healthcare infrastructure. But even implementing and using remote monitoring, a minimum technical infrastructure is needed. For example, to process the sensed data, a minimum computing facility is required. Similarly, for communication, good broadband connectivity is needed. Sometimes, these minimum facilities are also not present at small healthcare institutions and in rural areas.
- People are not yet familiar with the wearables. Also, it takes time to be accustomed to implanted devices. The absence of the direct contact of the doctors makes patients skeptical and timid. Treatment based on technology only may upset the patient's confidence. They also might be concerned about the fact that some third parties can get hold of their private health data and use unethically.
- Likewise, healthcare professionals might have apprehension in relying on only technology-based healthcare systems especially for the higher-risk patients. The sensing devices are not errored free. In a recent study on various physical activity tracking wearables, a large variation in accuracy across the devices is observed. The error margins are recorded as high as 25% [18]. To make remote monitoring effective and convincing, imprecision should be eliminated by improving the device accuracy.
- To get the maximum benefit from the remote health monitoring, it should be complemented by suitable efficient software. These software need to be customized for different use cases and should have compatibility with various third-party applications. The remote health monitoring systems should have access to electronic medical record systems (EMRs) from different clinics and hospitals to have an overall visualization of the patients' health history.

Despite these challenges, remote health monitoring has great potential in changing the traditional way of delivering healthcare services. It is still in its early stage, but it surely will have a promising role in future healthcare. Medical professionals need to pay more effort in effective utilization of remote monitoring and patients need to be motivated to be more engaged as reaping of the benefit of it is very much dependent on patients' ability to use the technologies involved [12]. The establishments providing remote health monitoring and the stakeholders need to adopt standard practices [15].

2.3 Difference Between Telemedicine and Remote Health Monitoring

There are no universal definitions for the terms "telemedicine" and "remote health monitoring". Consequently, there are no agreed and specific differentiating factors between the two. Both refer to the exchange of medical information electronically between two sites [19]. Both aim to help patients remotely. That is why people often use the terms interchangeably. Probably, the involvement of remote operation in both cases is the reason for the misperception.

But, as a matter of fact, they are quite different approaches to e-healthcare. In fact, remote health monitoring is the key differentiating factor between traditional telemedicine and today's e-healthcare which comprises both telemedicine and remote health monitoring. The major differentiating factors are discussed below. Table 7.1 summarizes the differences between telemedicine and remote health monitoring.

- The aim of telemedicine is to enable patients, especially from remote and rural areas, to interact directly with the distant doctors probably seating in a city hospital. Doctors asses the patient's condition by different means with the help of telecommunication and suggest accordingly. The healthcare

TABLE 7.1
Difference Between Telemedicine and Remote Health Monitoring.

	Telemedicine	Remote Health Monitoring
Approach	Reactive	Proactive
Role of doctors and staffs	Highly engaged	Less engaged, only for decision making.
Medical personnel's involvement period in treatment	Short-term and need basis	Continuous monitoring
Health care delivered by	Mainly physicians, with the help of local health technicians.	Physicians and general health professionals including nurses, clinicians, and others.
Scope of real-time patient observation	Less	High
Scope of health prediction	Less scope	Highly possible
Precision medicine	Not aimed for	Possible
Automated health care	No	Yes
Technical sophistication	Less	High
Suitable for high-risk patients	Not really	Yes
Reliability	Depends on the conversing and communing ability of the healthcare personnel at both ends; otherwise reliable.	Depends on the accuracy of the monitoring devices.
Security risk	Low	High
Patients' confidence	High	Low

Continued

TABLE 7.1
Difference Between Telemedicine and Remote Health Monitoring.—cont'd

	Telemedicine	Remote Health Monitoring
Doctor-patient communication	High	Less
Infrastructure needed at the receiver end	Not much	A minimum infrastructure is needed for processing the health data and to transmit it.
Patients responsibility	Not much. Follows the directions of the local medical professionals.	Patients need to be familiar with the devices if operated externally.
Patients' freedom	Less	High
Patients' dependency on healthcare professionals	High	Less
Need for healthcare professionals at the patient's end	Must	Not required
Healthcare service received at	Local clinics	Generally, at home
Pre-scheduling of patient-physician interaction	Most of the cases, must	Not required
Primary communication medium	Telecommunication, Internet	RFID, WBAN, WSN, Internet
Interdisciplinary treatment	Complicated and challenging	Effortless, due to smooth sharing of medical data both historical and real-time.

Continued

TABLE 7.1
Difference Between Telemedicine and Remote Health Monitoring.—cont'd

	Telemedicine	Remote Health Monitoring
Advantageous to elderly people	Not particularly	Very much
Advantageous to rehabilitating patients	Not particularly	Ideally suitable
Tech-savvy healthcare professionals	Not necessarily	Must
Transparency	Low	High

professionals, local to the patient, guide him/her in treatment and medication. In contrast, remote health monitoring is an automated approach for observing and assessing patients' health status remotely. Evaluating the medical data, the physicians and staffs guide the patient directly for taking suitable action.

- In telemedicine, doctors are fully responsible for assessing the patients, making a decision and recommending treatment and medicine. In remote health monitoring, automated monitoring makes the doctor's job much effortless. Using modern analytical tools, the health assessment also somewhat can be automated.
- Monitoring devices capture health data in the continuum, the data recorded over the past could be analyzed for monitoring and predicting future health problem and progress in health fitness. In contrast to this, telemedicine is short time process where physicians in a short session assess a patient's current medical condition and recommend based on the present symptoms. As a result, remote monitoring has many capabilities in overall health care.
- Telemedicine is aftermath but using remote health monitoring doctors can pre-assess the patient's conditions. As monitoring devices constantly assess a person's health, in case of any abnormality, it is immediately reported without waiting for the doctor's check-up schedule. Remote monitoring paves the way for precision medicine.
- Remote monitoring is technological intensive development whereas telemedicine is a human/expert intensive process; doctors diagnose with their expertise.

3 WBAN AND REMOTE HEALTH MONITORING

3.1 What is WBAN?

According to IEEE 802.15 Task Group 6 [20], WBAN is defined as:

> *Low power devices operating in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics/personal entertainment and other.*

A WBAN is a special type of WSN that is associated with the human body, where fewer sensor nodes are deployed on the patient's body as compared to traditional WSNs. The primary requirement of any WBAN is tiny, low-power, wearable or implantable sensor node. A WBAN comprises of a set of heterogeneous sensors and medical devices performing individual roles to perform monitoring of patient's health.

WBAN sensors are capable of monitoring, sampling, processing and communicating all vital signs of a patient's body to the medical server and provide real-time feedback to the user via doctor in a matter of minutes. Various sensors such as temperature sensor, ECG monitor, EMG monitor, heart rate sensor, pulse sensor, blood pressure sensor, etc. can be deployed to form a WBAN system [21]. A WBAN is based on radio frequency wireless technology that interconnects intelligent, low-power and tiny biosensor nodes which can be wearable or implanted on the human body to monitor the vital signs like stress, temperature, the oxygen level in various activities like normal day-to-day operations, sporting or any sort of training [22]. The biosensor nodes create a network with sensors and control device.

WBAN can be used in different types of applications like military, sports, etc., but primarily it is implemented in medical technologies. For medical applications, there is a need for varied sorts of information like heart rate, blood pressure, ECG, EEG and much more and system demands very low latency and high reliability.

A typical WBAN comprises tiny biosensors and gateway node connected to remote locations like hospitals etc. Gateway node can also be called as "Body Control Unit (BCU)" or "Central Control Unit (CCU)" or "Personal Control Unit (PCU)". The collected data can be aggregated and processed locally or they are sent for remote processing, usually to a cloud or a dedicated remote monitoring server [23].

In recent years, it is observed that interest in WBAN applications have increased manifold. According to ABIresearch (Allied Business Intelligence Inc.):

> *Wireless market tends to double in 2020 and market for wireless devices to monitor patient's health is also going to explode and tend to touch $9 billion by 2020.*

A number of the latest research efforts by researchers primarily focus on wearable healthcare systems for patient health monitoring. The latest innovation in WBAN is proposed by MIT Media Lab, where a WBAN based system termed as "MIThril" [24] is proposed, a complete wearable WBAN platform fully equipped with custom and off-the-shelf sensors. In addition to bio-sensors, MIThril is fully equipped with other body monitoring parameters like ECG, skin temperature, and galvanic skin sensors.

WBANs are expected to give a dramatic shift in the medical technology in terms of thinking, utilizing, monitoring and analyzing the patient in different diseases.

The quality of service (QoS) of WBAN depends on the type of applications being used, especially medical applications. For an efficient WBAN system, multiple sensors are required so that data transmission can be reliably transmitted over efficient medium access protocol.

3.2 WBAN Versus WSN

Though WSN has laid the foundation stone of developing WBANs they differ from each other in several aspects. WSNs are used typically in battlefield monitoring, traffic monitoring, environmental monitoring, industrial automation and control and many more. WSNs are regarded as self-organizing, distributed network comprising tons of sensor nodes sensing certain data from varied conditions and giving aggregated information to the base nodes. On the other hand, WBAN is highly short-range, less processing power consuming network and is limited to body parameters sensing only. Table 7.2 enlists the differences between WSN and WBAN based on technical and operational parameters:

TABLE 7.2
Difference Between WSN and WBAN.

	WSN	WBAN
Rate of data transmission	Variable	Variable
Real-time deployment	Random	Fixed
Density	High	Low
Mobility	Absolutely no mobility	Fixed mobility
Range of transmission	Few km	0.01 m to max 2 m
Operational accuracy	Average	High
Homogeneity of nodes	Homogenous	Heterogeneous
Latency	Variable	High
Replacement of nodes	Easy	Implanted sensor nodes are difficult to replace
Network topology	Fixed or static	Variable
Security	Less security	High security to prevent leakage of patient information
Wireless technology backbone	Bluetooth, ZigBee, RF, WLAN	UWB, BLE, ZigBee

3.3 WBAN System Attributes

The primary objective of any WBAN system is to acquire all types of crucial or non-crucial data from patient's different parts of the body and WBAN system should be designed intelligently and with accurate caution to deal with wide range of real-time challenges [25]. In real-time monitoring of the patient, the two most important parameters are "reliability" and "latency". All these parameters depend on the Physical and MAC layer of WBAN. Physical Layer and MAC layer are responsible for determining the energy consumption of WBAN device which is regarded as a foremost issue in the design of any type of WBAN system. The role of the MAC layer is to determine efficiency in network operations and efficient resource utilization. The Physical layer should be designed in such a manner to handle all sorts of transmission issues to transmit the patient's data remotely without any hiccup.

The following points highlight the attributes of a typical WBAN system:

- **Reliability:** WBAN system should be highly reliable in packet transmission and should face minimal delays in packet transmission which is influenced by BER (bit error rate) of channel and MAC layer transmission process. WBAN physical layer should be highly efficient to reduce the BER rate via adaptive modulation and coding techniques to adapt to typical conditions of transmission channels. Reliability of WBAN system also depends on network interference situation.
- **Energy efficiency:** Energy efficient WBAN system are always reliable for precision health monitoring of the patient. MAC layer of WBAN system should be reliable enough by adopting various types of energy efficient techniques in terms of packet scheduling,

channel access so that high rate of packet transmission can be possible for prolonged periods of time.

- **Scalability:** WBAN sensor nodes, deployed on the patient's body, collect vital statistics like physiological data. WBAN systems should be scalable enough to allow WBAN professionals to re-configure the entire WBAN operational system by adding or deleting sensor nodes without any impact on the reliability of WBAN system. It depends on the MAC protocol. Efficient MAC protocol will enable future ready and high scalable WBAN system.

In addition to reliability, energy efficiency, and scalability, WBAN systems should be designed considering the following other attributes [26]:

- WBAN systems should be equipped with fault-tolerant and self-healing capability to ensure secure and efficient transmission of data from wearable and implantable sensors to medical servers or online websites.
- Highly efficient to operate in power constraint environment and WBAN systems should be highly focused more on implantable rather than wearable sensors as implantable sensors are more critical to patient's health.
- Should support data transmission from Kbps to Mbps to transmit a wide range of vital signs data from a patient's body to online servers.
- WBAN systems should be competent enough to have compatibility with QoS parameters in terms of reliable delivery of sensor node data to online servers or mobile apps.
- WBAN systems should have strong coordination with other network nodes operating at different frequency spectrums and have different operational standards.
- The medical data should be secured by means of encryption etc. if the data goes beyond the local network.

3.4 Components of a WBAN System

The following components make up an efficient WBAN system:

- **Sensors:** Biosensors should be incorporated depending on the application of capturing real-world data and should consume very less power and should be equipped with efficient sleep and wake up modes to keep hardware efficient in operation.
- **Data communication:** Wireless communication is the main source of transmission but should be operational in those frequencies bands which are tolerant to interference, and no mix up of frequency can be there during real-time operation.
- **Security:** Protocols of WBAN should be such that, no data can be hacked in between by hackers or intruders and data should be transmitted via the WBAN system to a remote location with strong encryption.
- **Handover mechanism:** It is also desirable to have a handover mechanism in WBAN system using a gateway or router and should not make the design of a node in an overload state.
- **Antenna:** Highly small size antenna should be implemented in WBAN system to operate at high frequencies.
- **Gateway node:** Gateway devices should be designed to interact with wireless networks in medical systems with advanced algorithms having machine learning or deep learning technology so that efficient capturing and re-transmission of data can be made possible.
- **Backup mechanism:** Every WBAN system should be equipped with a backup support system to trigger an alarm on low power or node failure.

3.5 WBAN Sensor Node Categories

Every node in WBAN operate as autonomous device and is fully equipped with a communication system to relay the data back to the medical server. Nodes operating in WBAN are categorized on the basis of functionality, implementation, and roles [27].

On the basis of functionality, the nodes in WBAN are of following different types:

a. **Body control unit (BCU):** It collects all the information from sensors and actuators operating as part of a WBAN system.
b. **Sensors:** WBAN applications range from medical to non-medical applications. Non-medical applications comprise motion and various gestures for detecting one's fitness, social interactions and even medical assistance in varied situations like floods, earthquakes, fires, etc. Medical applications include healthcare-based applications. Depending on situations, varied sensors are available either wearable or implantable to transmit physiological signals.
   Generally, the following body sensors are used for health monitoring (typically termed as biosensors):
   - **Inertial motion sensors**: To measure body posture and movement patterns like accelerometers and gyroscopes.
   - **Bioelectrical sensors**: To measure electrical variations in a patient with regard to the certain activity of organ-like ECG, EMG.
   - **Electrochemical sensors**: Measure some chemical agents of the human body like glucose sensor.

- **Optical sensors**: To determine the degree of absorption of light passing through the patient's blood vessels like the oximetry sensor.
- **Temperature sensors**: Measure the normal body temperature of the patient.

Considering WBAN sensors technology, various wearable and implantable sensors are also available. The following enlists various wearable and implantable biosensors [2]:

- **Wearable sensors:** The primary objective of wearable sensors is to gather all types of physiological and patient's movement data to facilitate remote health monitoring of the patient. Wearable sensors are used both for diagnosing as well as monitoring applications which include biochemical sensing and motion sensing.
  - Electrocardiographic (ECG) sensor: ECG sensor monitors the electrical energy produced during a heartbeat. The changes in electrical energy are detected via two leads and references to a ground signal. All the energy changes are displayed via waveform. ECG Sensor is attached to the patient's body using disposable electrodes on the chest left side and right side. The ECG sensor gives an analogue signal as an output and is converted via ADC (analogue to digital converter) and send to a mobile phone using Bluetooth module.
  - Heart rate sensor: Heart rate sensor measures heart rate in beats per minute using an optical LED source and LED light sensor.
  - Electromyography sensor (EMG) sensor: EMG sensor is used to measure all patient's body muscle's electrical activity. It is used as a control signal for all types of prosthetic devices.
  - Electroencephalography (EEG) sensor: It is primarily used to sense and obtain all electrical activity of the brain. It measures all types of voltage fluctuations resulting via iconic current within brain neurons.
  - Body temperature sensor: It is used to measure the body temperature of the patient. This sensor is highly useful as different diseases create fluctuations in the patient's body temperature. It is used to monitor the patient's in critical conditions to have a precise observation.
  - Photoplethysmography: Often implemented using a pulse sensor or pulse oximeter and is used to measure non-invasive heart rate and also the blood oxygen levels.
- **Implantable sensors:** Implantable sensors are primarily used to determine force, torque, pressure, and temperature inside the human body. Very small in size and have compatibility with human tissue and can withstand all physical forces inside the human body. Implantable sensors have a self-powering mechanism and transmit data wirelessly. Examples of implantable sensors are:
  - Pacemaker: A pacemaker is a tiny device placed at the chest or abdomen to control all sorts of abnormal heart rhythms in a patient's body known as Arrhythmias. A Pacemaker makes use of electrical pulses to enable the heart to beat at normal rates. A pacemaker can control two types of arrhythmias - Tachycardia (fast heartbeat) and Bradycardia (slow heartbeat).
  - Cochlear implants: An electronic device to facilitate the working of inner ear damaged parts to supply sound signals to the brain.
  - Implantable cardioverter-defibrillator (ICD): Wearable device for detecting all sorts of rapid heartbeats and life-threatening situations. During abnormal heartbeats, ICD creates an electrical shock to the heart to restore a normal heartbeat.
  - Deep brain stimulator: Medical device implanted inside the human brain through neurosurgery to supply electrical impulses via implanted electrodes to specific areas of the brain for treating all types of movement and neuropsychiatric disorders.

Fig. 7.1 highlights the various wearable and implantable sensors for making up WBAN:

c. **Actuator:** This device primarily performs the task of interaction with the user on receipt of data via sensors. It provides feedback in the network based on sensor data.

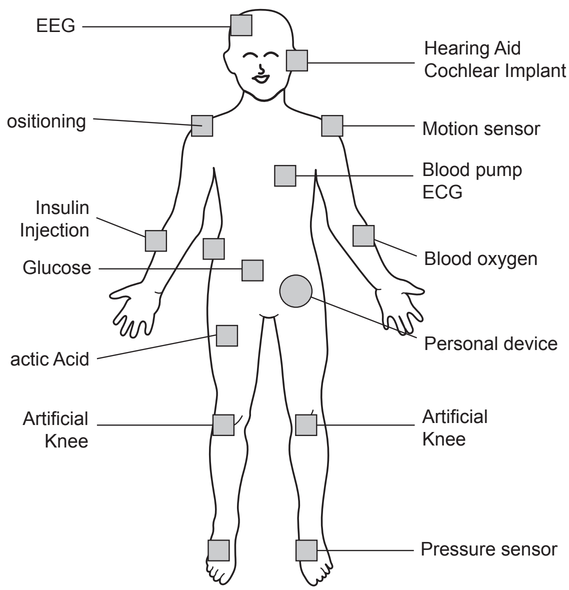

FIG. 7.1 A typical WBAN with attached bio-medical sensors.

On the basis of implementation, WBAN nodes can be classified as follows:

a. **Implant node:** Node implanted inside the human body either underneath the skin or body tissue.
b. **Body surface node:** Node primarily installed on the body surface of the patient.
c. **External node:** Node which doesn't have direct body contact but is placed to about 5−10 cm away from the body.

On the basis of role, WBAN nodes can be classified as follows:

a. **Coordinator node:** Acts as a gateway to the outside world, or another WBAN or Access coordinator.
b. **End node:** Performs certain functions prespecified in WBAN.
c. **Relay node:** Intermediate nodes between parent and child nodes.

3.6 WBAN Architecture

Fig. 7.2 demonstrates a typical WBAN architecture. In this architecture, a mobile phone or laptop are connected to communication access points to transfer the patient's data to secure medical server via wireless technology or the internet. In addition to this, all the access points are connected to patient's emergency family member number, emergency services via alarm notifications and health practitioners for emergency response in case of the critical condition of the patient. A WBAN consists of a three-tier architecture as discussed below:

3.6.1 Sensors/Intra-BAN communication/Tier 1

Sensor nodes are placed on the varied parts of patient's body depending on the patient's monitoring and depends on the disease vital statistics to be monitored. Patients are required to keep the sensors in place to the body to allow the doctors to monitor the patient's health continuously from anywhere and anytime. Sensors come under "Intra-BAN Communications" and are placed at about two meters near to the human body. The design of Intra-BAN is highly important as apatient, and body sensors have direct contact. In addition, MAC protocols should be designed in such a manner to keep the sensors working for long period of time.

3.6.2 Communications module/Inter-BAN communications/Tier 2

Like WSN's autonomous behavior, WBAN systems are required to work in a highly autonomous manner. In terms of WBAN architecture, Inter-BAN Communications are primarily concerned with communication modules. The communications link up the sensors to the Access Point. The access points form a typical part of WBAN infrastructure to connect WBAN with different networks to access in a routine manner like mobile communication networks or the internet. Inter-BAN Communication can operate in two main categories:

- **Infrastructure based:** High bandwidth with the centralized administration is provided, and WBAN system can be termed as highly robust and scalable.
- **Ad hoc based:** Fast deployment can be possible and dynamic architecture, and high mobility can be achieved.

3.6.3 Medical database servers/Beyond-BAN/Tier 3

To facilitate strong bridging of Tier 1 and Tier 2, i.e., Inter-BAN and Intra-BAN, a gateway device like a laptop

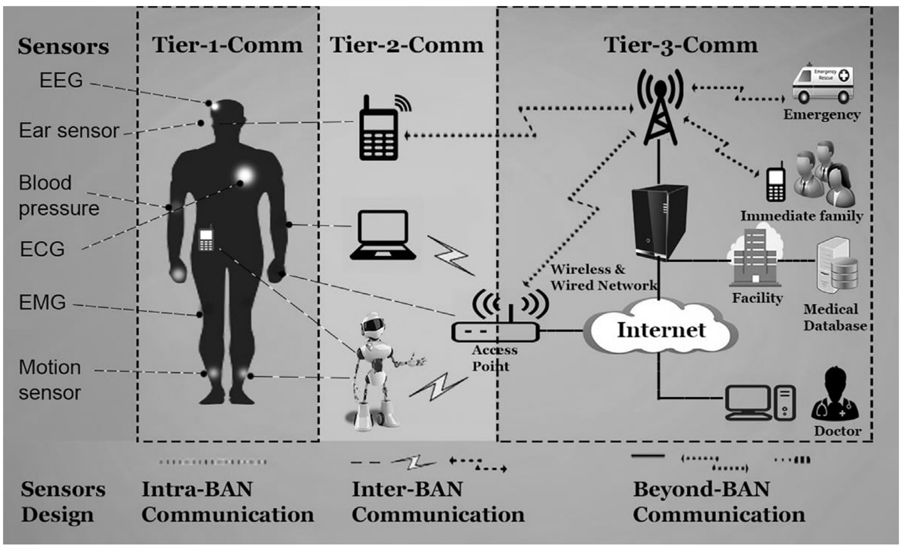

FIG. 7.2 A general architecture of WBAN [8].

or tablet is deployed to create a wireless link between the two. With Tier-2, WBAN system is provided with the power of scalability as the patient's data can be monitored by the doctor either via mobile app or a website or using secure login access to specific files of medical servers.

In beyond-BAN communication, the central point is a database which contains all record of the patient's data in terms of history, current medical status and other personal information. In addition to this, the database and other patient's data can also be accessed by other relatives of the user. The design of the Tier-3 component is based on applications. Mobile applications or IoT-based websites like thingspeak.com can be used to acquire the signal-based data and can be sent to the doctor via email or SMS to alert in case of emergency and also to nearby health services.

3.7 Role of WBAN in Remote Health Monitoring

As per the latest report by the World Health Organization (WHO), about 18 million people died in the year 2008 due to cardiovascular and heart diseases [28]. As per the estimation by WHO, it is predicted that around 25 million people will die due to cardiovascular disease by 2030. One of the instigating factors for cardiovascular diseases is diabetes. Both Type 1 and Type 2 diabetes are linked with cardiovascular diseases, which is also a major cause of deaths in people with diabetes. These statistics lay a strong foundation for the development of remote health monitoring using WBAN technology that can make a contribution toward saving the lives of people from several diseases and enhance the quality of living. Constant health monitoring via WBAN technology plays a crucial role to reduce risk factor of life threats against all types of diseases and early warnings, or critical signs can be reported to medical practitioners at an immediate interval of time.

WBAN is potentially the key enabler of remote health monitoring systems and extends the prospect to take e-healthcare beyond telemedicine [29]. Various health sensors in the WBAN acquire specific physiological parameters from the human body. These data are collected, aggregated, and sent through a central coordinator to the desired destination for effective processing and analysis to obtain reliable and accurate physiological estimations [11]. This helps doctors and medical staffs to diagnose and monitor patients remotely be it offline on in real-time.

WBAN systems are primarily designed for remote monitoring of vital signs of the patients to determine physiological signals and systems are required to have a high degree of reliability and low level of latency. All the sensors transmission rates are low, but with a high degree of energy efficiency will enable the WBAN system to work for a prolonged period of time. Patients can roam freely anywhere with the feeling that WBAN system will do the respective task side by side.

Present remote monitoring systems face several issues. For example, existing remote monitoring systems are location specific, i.e., they should be within reach of the network access points either wired or wireless. Another problem: in the case of short-range wireless communication, Bluetooth and Wi-Fi have been the popular standards for close communications in monitoring systems. But both of them eats up a substantial amount of energy and also cause interference. The WBAN gives remote monitoring systems a better edge than traditional e-monitoring systems in the following aspects:

- Thanks to portable health monitoring devices, patients enjoy the freedom of mobility and flexibility [26]. WBAN has enabled remote monitoring of patients not only when they are on the bed but also while they work, walk or play. Owing to WBAN, along with the wearables and smartphones, now health monitoring is not an additional activity; rather it has been assimilated and dissolved into people's daily life.
- WBAN offers location independent monitoring facility [26]. WBAN can make use of widely deployed mobile data networks, eliminating the dependence on the certain internet access point.
- The old remote monitoring systems, in spite of dedicated wireless link for medical data transmission, do not always guarantee persistent monitoring. A WBAN provides continuous gauging of different physiological parameters that allow a doctor, from a distant location, to make real-time assessment and diagnosis. The real-time monitoring provides faster detection in emergency cases and better revelation in the case of organ failures [11].
- Since WBAN are in general autonomous they are capable of finding a suitable communication network opportunistically. The advancement in the field has enabled WBAN employing cognitive networks [30] for optimal uses of the communication paths.
- WBAN is enriched by some latest power efficient wireless communication protocols such as UWB which makes the sensor batteries last longer [8].
- With the increased popularity of WBAN, the demand of health sensors is also in soaring. The mass

production of these sensors has reduced the cost of WBAN which in turn instigates a cost-effective and affordable healthcare.

In the recent past, WBAN has attracted considerable research interest from people from different domains focusing on issues related to energy aware and miniature sensor design, efficient and optimized sensor circuitry, effective signal processing, energy efficient communications, etc. [8]. As a result, today's remote monitoring systems are enriched with lightweight, tiny, ultra-low-power, and intelligent wearable sensors. The continuous advancement in WBAN and related fields will make remote health monitoring most suitable for delivering affordable, flexible, scalable, and robust health care [31]. The popularity of wearables and portable health sensors as components of WBAN will make the remote monitoring ubiquitous in the true sense by supporting a wide range of health applications.

3.8 A General Architecture of Remote Health Monitoring Using WBAN

A general architecture for the remote health monitoring system is presented in Fig. 7.3. Health attributes that require patients' self-input for collecting their values include weight, blood pressure, blood sugar level, etc. Value of health attributes like heart rate, blood pressure, etc. can be collected/measured using wearable devices like biosensors. All the collected data is sent to the remote patient monitoring server. A remote patient monitoring server is equipped with the necessary hardware and software required for complex analytics on the collected data and generate alerts according to the outcome of the analysis. Depending on the nature of outcomes/alerts, they are sent either to the patient or the attending medical staff (nurse, physician, etc.). In both cases, the output of the monitoring server is computerized feedback that assists the recipient in informed and effective decision making. Broadly, a remote health monitoring system consists of the following three components:

i. Patients' wearable and self-input measurement devices.
ii. A web/mobile interface for the physicians/authorized personnel to monitor patients' data.
iii. A processing and feedback unit called remote patient monitoring server to send alerts for both patients and clinicians.

All the wearable devices and measuring equipment at the patient's end aid accurate and effective data collection. Data collection serves as the basis for further triggering aggregation, processing, and visualization of data for the medical practitioner or the patient. The data collection module of the patient monitoring system further consists of the following components (Fig. 7.4):

- Sensors with connectors
- Application interface for manual data entry
- Pre-processor
- Communication manager

Sensors are the most important components of a remote health monitoring system as they help in collecting consistent data continuously from the patient's body. The network of sensors (WBAN) must be portable, lightweight, low power consuming, and autonomous. These body sensors must be optimized so that they operate on a suitable bandwidth and with latency requirements suitable for accurate collection of values of health attributes. For reducing the signal-to-noize ratio, the number of sensors must be the smallest

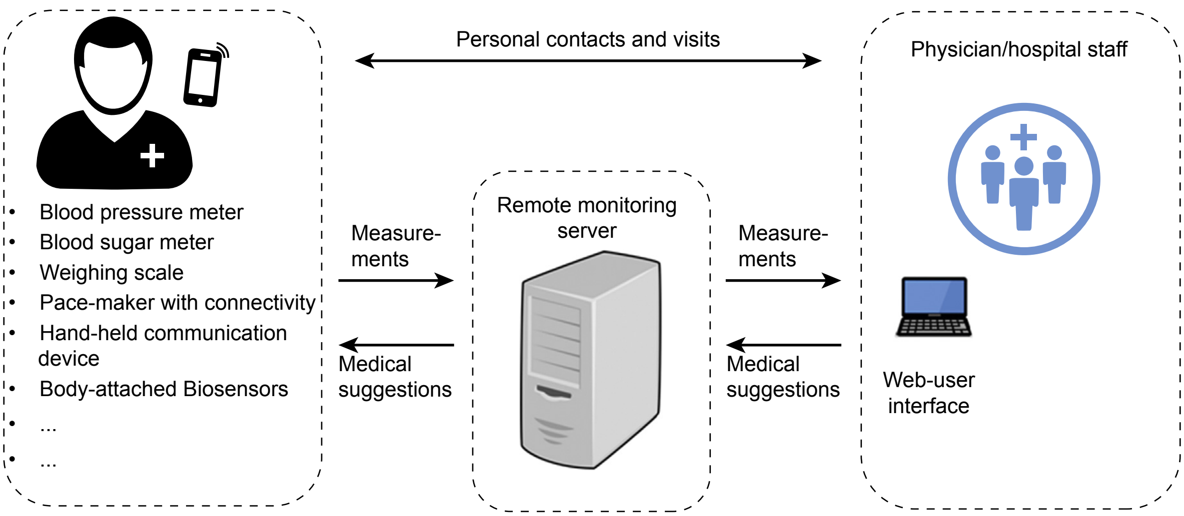

FIG. 7.3 A general architecture of remote monitoring [32].

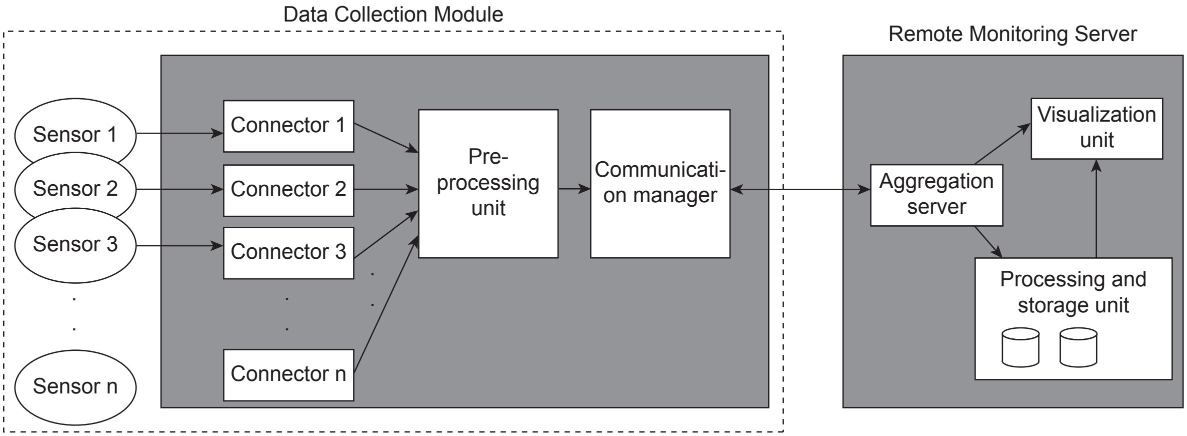

FIG. 7.4 Components of the data collection module and remote monitoring server.

possible. The location of sensors must be planned for accurate collection of health data.

Each sensor or a group of sensors has a connector that manages communication of collected data to the WBAN coordinator. This is often also referred as WBAN controller (WBANC). This controller acts as a sink of the network of sensors attached to the body of the patient. WBANC is responsible for collecting data which further sends collected data to the remote monitoring server over the internet. It is significant that the data collected by the sensors and sent to the WBANC is good in quality and is sent efficiently considering the limited battery power of the sensors nodes. These considerations are met using the appropriate routing techniques and accounting for the quality of service requirements of data transmission. The routing protocol used also determines the overall energy requirements of the network. Routing techniques of the sensor networks used for remote health monitoring are broadly classified into:

i. Flat routing protocols: Each sensor node plays exactly the same role. That is, no sensor node has designated access to more data than other(s).
ii. Hierarchical routing protocols: Each node has a different responsibility. Each node collects different data, and some nodes are dedicated for routing data packets to the controller. Hierarchical routing protocols are designed to achieve QoS-aware data transmission.

Some of the categories of extensively used routing techniques are thermal-aware routing protocols, cluster-based routing protocols, cross layer-based routing protocols, early-aware routing protocols, and delay-tolerant-aware routing protocols.

Though data collection through sensors seems to solve most of the problems, there are health attributes that cannot be captured through the use of sensors. Such attributes include weight, height, blood sugar, etc. To account for such health attributes, the data collection module must also include an application interface for manual data entry by the patient. Data collected from and entered manually by the patient reaches the preprocessing unit of the WBANC that performs integrity checks, groups the data and determines the usability of data through completeness checks. The preprocessor further sends its output to the communication manager that initiates a connection with the remote monitoring server.

The remote monitoring server has three major components (Fig. 7.4):

- Aggregation unit
- Visualization unit
- Processing unit

The data aggregation unit is responsible for collecting data from the patient's communication manager and getting it ready for processing or visualization. Data collected by the aggregation unit can be directly visualized through visualization unit by the doctor or the patient. An aggregation unit is responsible for the cancellation of noise in collected data and for verifying data integrity. Aggregation unit also performs some trivial computations and generate health alerts to both – doctors or the patient through the visualization unit. For example, on input, the weight and height of a patient, the aggregation unit can send the Body Mass Ratio (BMR) to the visualization unit for display. Aggregation unit can store extreme values of health parameters like blood pressure, blood sugar level, etc. Depending on the input value of these parameters, aggregation unit sends to the visualization unit, essential alerts intended for both doctors and patients.

Alternatively, the aggregation unit, after performing integrity and consistency checks, can send the output to the storage and processing unit that is a specialized hardware and software combination that helps carry out complex analyses on data.

Typically, a visualization unit is nothing more than a basic web service that can be accessed by the patient and the medical staff through a web-based application like a web browser or a dedicated mobile phone application. Presentation of results is very important for better understanding and informed decision making. It is required that the complex unrelated details about patient's data be hidden from him. This boosts the usability of the remote health monitoring system. Also, it is required that information that may be relevant for the patient but is trivially interpreted by the doctors were not presented to the medical practitioner. Therefore, it is sometimes the case that there are different visualization units for the patient and the doctors. Alternatively, efficient access management for accessing only relevant information by the respective users — patients and doctors, can also be present.

A processing unit is essentially a specialized hardware and software system that processes data collected by the aggregation unit. The complex pattern recognition and analysis algorithms form an important part of the processing unit. Typically, processing unit concerns detecting certain patterns in values of health parameters of a patient. Also, a processing unit records their current pattern and store them for future learning. A shift in values of health parameters of a patient, when matches a pre-recorded pattern in the database, triggers an alert for the patient and/or the medical staff. For this, the processing unit communicates the results of all the computations to the visualization unit after indicating the intended recipient of the alert. Real-time processing and communication require hardware that is expensive to both purchase and maintains. Therefore, services of a dedicated third-party may be utilized for carrying out complex computation and analysis on patient's preprocessed data. Issues to be taken care of are the data privacy and reliability of results.

One of the early works for architectural advancements of remote health monitoring system was performed in 2001—3 in the form of an integrated platform called MobiHealth [33] which was solely based on communication using GPRS/UMTS. Ever since the development of MobiHealth, numerous other architectures have been developed (see Ref. [34] for the survey). Recently, the focus has shifted from an integrated architecture to a general architecture with scope for efficient inclusion of more advanced analytics as and when needed (see Project SHERPAM [35]). An internet-like multi-layer protocol stack for better and more expressive access policies in each module of the remote health monitoring architecture [36] has also attracted the majority of attention.

4 WBAN COMMUNICATION ARCHITECTURE

4.1 Communication Architecture of WBAN

WBAN communication is divided into three major categories:

- Communication between the node on the body to an outside base station.
- Communication between two nodes on the body surface.
- Communication of node implanted inside the body to outside node.

These three communications are known as off-body communication, on-body communication, and in-body communication. In certain situations, WBAN needs to transmit the data across large distance and range of WBAN can be enhanced via multi-hop network via gateway or router to connect to external network resources. The range should not affect the design of a sensor node as large distance transmission is taken care of by a gateway node; so, a modern approach is required to design an efficient WBAN system.

4.1.1 WBAN network structure

A WBAN network structure consists of several interconnecting networks. There exists communication between sensor nodes and the base node under short-range. The short-range communication is less than 2 m, and sensors are characterized by the following features:

- All the sensor nodes are connected to a gateway node in a typical star topology.
- All sensor nodes have limited capabilities in terms of process and are highly energy efficient.
- Gateway nodes do all sorts of high processing and are equipped with high battery power.
- There is one-way communication between sensor nodes and gateway nodes.

A WBAN system can accommodate various wireless platforms and a multiple WBAN can have multiple wireless links.

The following points elaborate typical requirements of WBAN system:

- Limited range of transmission from less than 0.01 m to max 2 m.
- Ultra-low power consumption especially in sleep mode from 0.1 to 0.5 mW for retaining battery power.
- Data range from 1 Kbps to 10—15 Mbps.

- QoS support for efficiently managing all sorts of physiological signals.
- Low latency and lightweight.

4.1.2 WBAN topologies

In simple terms, topology is defined as a systematic arrangement of the body sensor network in an existing network, which fulfills all the basic requirements of the application. WBANs are generally asymmetric where at least one node is superior to others in the network. The superiority may be in terms of having a larger power supply and more processing power. This node and can take over energy-consuming tasks from the other low-power and inferior sensor nodes [4]. The size of the network size is an important factor for considering suitable topology for WBAN. Unlike environmental sensor networks, a WBAN is inherently small-scale. The maximal distance between two nodes is less than 10 m, and each network has less than 100 nodes. In such a small network, it is more power efficient to use single-hop communication instead of multi-hop. Since the network is small-scale, asymmetric and single-hop, a star topology is suitable, which is used by most WBANs. WBAN topologies are of following different types:

- **Point to point topology:** In a point to point topology, the nodes in a WBAN are connected in direct order and communication takes place via peer to peer.
- **Star topology:** In a star topology, the entire WBAN network is managed by a single node, i.e., Master node. Considering the WBAN network, the master node has larger power capacity as compared to other sensor nodes forming a WBAN network. The entire network is managed by Master node, and under WBAN-star topology, only one node can stay active and transmit data at a particular period of time to avoid any sort of data collisions among other sensor nodes [4]. In a star topology, all the sensor nodes attached to the patient's body communicate via the gateway for transmitting the sensed data. In WBAN systems, star topology is regarded as highly suitable topology for Inter WBAN communication.
- **Peer to peer topology:** A peer-to-peer WBAN network allows multiple hops to route messages from any device to any other device on the network. Such functions can be added at the higher layer, but they are not part of this standard. Each independent PAN selects a unique identifier. This PAN identifier allows communication between devices within a network using short addresses and enables transmissions between devices across independent networks [37].
- **Mesh topology:** In a mesh topology, every device in the radio range can communicate either in a direct fashion or via multi-hopping fashion. Mesh topology can be implemented in those scenarios where there is a high requirement of the reliability of data transmission and communication should be facilitated in a flexible manner as compared to energy utilization and prolonged lifetime.
- **Tree-mesh hybrid:** A tree-mesh hybrid topology is regarded as a combination of tree topology and mesh topology in which nodes at the lower level have dedicated connection with nodes at a higher level and connected via full mesh connectivity. Tree-mesh topology is advantageous in several factors like best coverage, low latency, fault tolerance, and overall high throughput.

4.1.3 Network layers for WBAN

The actual implementation of different communication layers depends on the protocol/technology used for communication. But in general, the proper designing and implementation of the physical (PHY) layer and the media access control (MAC) layer are most important for any WBAN protocol. Because these two layers are combiningly responsible for improving WBAN operations in terms of power consumption, reliability, network efficiency, latency, resource utilization, operating cost, etc. in general, since sensors in WBAN are resource constraint, it is really challenging to design and implement efficient, reliable, and secure protocols for WBAN communication. Table 7.3 summarizes the challenges in each layer.

4.1.3.1 PHY layer. This is the layer that is responsible for providing WBAN with data transmission capabilities. It establishes a reliable physical link between communicating nodes for transmitting binary data. This layer deals with several important factors of communication such as specifying operating bands and channels, modulation and demodulation techniques, the structure of data units, signal encryption, etc. [38]. It also does characterizing the link quality/strength of a received signal known as Link Quality Indication (LQI). PHY layer specifies three different operational states for the devices: transmitting, receiving and sleeping. When the devices in WBAN are not active, they are put into sleep mode. This allows WBAN to save energy which is very crucial for battery operated sensors.

Challenges in WBAN physical layer: Following are some of the challenges related to the physical layer that need to be addressed while designing WBAN [39,40]:

- **Interoperability:** WBAN consists of various devices of different types having different properties and functionalities. Furthermore, they might be made by different vendors. This causes interoperability issues within WBAN devices.

TABLE 7.3
Designing and Implementation Challenges in Different Layers of WBAN Protocols.

Physical Layer	MAC Layer	Network Layer	Transport Layer	Application Layer
• Interoperability • Temperature control • Changing topology • Varying bandwidth needs • Interference • Fault acceptance • Constant signaling • Security • QoS • Varying data rates	• Dynamic channel assignment • Control packets overhead • Protocol overhead • Synchronization • Throughput • Consistency • Over-emitting • Packet scheduling • Error control • Overhearing • Calibration • Fault acceptance • Energy conservation • QoS • Multi-radio and multi-channel design • Data flow control • Idle listening • Security • Delay control	• Optimum routing • Network condition • Real-time streaming • Localization • Mobility • Temperature and heat control • Traffic control • Multi-path routing • Security • QoS • Fault tolerance	• Reliable transport • Congestion control • Self-configuration • Energy awareness • Biased implementation • Constrained addressing	• Efficient interface • Security • Congestion control • Flow control • Bandwidth allocation • Packet-loss recovery • Energy efficiency

- **Varying bandwidth needs:** For different medical applications, the bandwidth requirement depends on the type of data transmitted over a WBAN. So, it is desirable to choose the wireless radio band and the bandwidth wisely that can accommodate a range of application within a single WBAN.
- **Varying data rates:** Since different nodes in a WBAN may have different purposes and execute different tasks they may generate at different rates. WBAN physical layer should be capable of handling these varying data rates in the same network.
- **Temperature control:** The heat and radiation generated from the implanted devices may affect body tissues and other devices in close proximity. Hence, the designing goal of these devices should be taking care of this issue.
- **Changing topology:** The WBAN topology gets changed along with the movement of the body. This makes the connection between the devices unstable. WBAN should be able to accommodate the dynamic topology.
- **Interference:** The working of WBAN devices may be affected due to the interference caused by other surrounding devices, heat and radiation, body tissues, fluid, and chemicals, etc. Such types of interferences should be minimized for the proper functioning of WBAN while co-existing with other devices and networks.
- **Susceptible to faults tolerance:** Different factors such as changing topology, environment influence, transmission power, etc. make WBAN prone to faults. To maintain faultless functioning and seamless connectivity the WBANs need to be fault tolerant.
- **Constant signaling:** Many remote health monitoring cases require continuous and real-time monitoring. The WBAN need to be able to carry out constant signaling task smoothly and seamlessly.
- **Security:** Security threats like eavesdropping, tampering, and jamming are usually targeted at the physical layer. Hence, it is desirable to detect these types of attacks and implement preventive measures at the physical level.
- **QoS:** Since WBAN is related to human health and life it is of utmost importance to maintain QoS in WBAN operations. In the physical layer, QoS is generally determined by communication throughput, reliability, and energy efficiency which can be achieved by adaptive channel coding, power scaling, and effective time slot division.

4.1.3.2 MAC layer. It is usually a part of the Data Link layer that provides the interface between the upper layers and the physical layer and is in charge of transferring data, at a low level, between the nodes within a WBAN. It is responsible for carrying out the jobs such as multiplexing of data streams, data frame detection, medium access and error control, etc. [41]. Both IEEE 802.15.4 and IEEE 802.15.6 standards suggest using *superframe* for MAC layer communication. The superframe is the time gap between one *beacon* to the next beacon. Beacon is a signal that is sent from the coordinator node in WSN to another node within the range. The purpose of using beacon is to synchronizing between the communicating devices, identify the WBAN, describe the superframe structure,[1] inform the WBANC about any pending data, etc. [42]. Basically, the time axis is divided into beacon periods; in other terms, the channel is divided into superframes. A superframe is divided into active and passive regions. If it is in the passive region, a node does not do anything. This inactive period helps in saving energy. If it is in the active region, the node connects to other nodes and transmit data. The active region of a superframe is allocated a number of equal duration slots that are used to transmit the patient's data [43]. The channel time can be bounded (optionally) by the coordinator in a WBAN using a superframe structure. A superframe is bounded by the transmission of equal length beacon frames. The communication can be either in beacon mode or non-beacon mode and with or without superframe boundaries. Section 5 discusses the MAC layer in details.

Challenges in WBAN MAC layer: Similar to the physical layer, there are some challenges that are specific to the MAC layer and need to be addressed. Some of them are as follows [39,40]:

- **Synchronization:** For real-time monitoring and data transmission, perfect synchronization between the two communicating ends are crucial.
- **Throughput:** The exchange of control packets and low duty cycles leads to low throughput in WBANs. Opting for self-adjustable duty cycles in the protocols may solve this issue.
- **Consistency:** The WBAN deals with crucial data. Hence, it is essential to minimize the data loss which directly affects the consistency or reliability of WBAN.
- **Calibration:** Due to several factors such as random noise, sensor node failure, node blockage, damage, random errors, aging, etc. calibration in WBAN is difficult. WBANs need self-calibration mechanisms to surmount this.
- **Packet scheduling:** In medical applications, different packets may have different priorities. For example, some packets may require the earliest delivery but to some packets reliable delivery if more importance. Therefore, MAC layer protocols of WBAN need to adopt efficient scheduling schemes.
- **Dynamic channel assignment:** The presence of noise and interference in the communication channel is the reason for low throughput, high delay, and high data loss. To deal with this, MAC layer protocols should support dynamic channel sharing and efficient bandwidth assignment.
- **Multi-radio and multi-channel design:** In addition to the dynamic channelling, to improve the network capacity as well as the overall WBAN performance, instead of a fixed channel, multiple channels should be used for data transmission, especially for emergency data. The MAC layer protocol should provide this facility.
- **Control packets overhead:** The size of control packets should be as low as possible because they do not carry any medical data but consume a significant amount of energy.
- **Protocol overhead:** Majority of the protocols include extra information, besides actual data, such as the addresses of the source, destination, and, packet type, sensor type, sequence number priority, checksum, message length, timestamp, etc. in each transmitted packet. This leads to transmission overhead and bandwidth consumption. The protocols need to minimize these overheads wherever possible.
- **Idle listening:** Idle listening happens either when a node is expected to receive some packets, but no packets are received or when a node listens to an idle channel. Handling idle listening is very crucial to WBAN because it consumes a lot of power unnecessarily.
- **Over-emitting:** Sometimes, due to lack of synchronization between the source and sink, the generated data gets overflown because the receiving end is not ready to receive data at the same rate. This should be avoided because it causes unnecessary power wastage and makes the channel needlessly busy which, in turn, degrades the overall performance of WBAN.
- **Overhearing:** When a node receives a packet that is destined not for it but for some other node. This involves unnecessary processing and wastage of power which should be avoided.

[1]The superframe structure in IEEE 802.15.4 and IEEE 802.15.6 standards defines the classification of data, frame format and schemes for multiple access of channels.

- **Energy conservation:** Power conservation is very crucial to WBAN. Hence it imperative to make optimum use of energy and take care of all the above-mentioned factors that cause unnecessary power consumption.
- **Data flow control:** As mentioned above, the lack of synchronization between transmitter and receiver causes data flooding at the receiver end. This causes propagation delay and transmission delay. The goal of the MAC layer protocol should be to minimize such delays by controlling the rate of data generation and data flow.
- **Delay control:** In a busy network, low duty cycles cause a delay in packet transmission. To reduce the transmission delay, data can be instantly forwarded instead of buffering.
- **Error control:** Due to several factors, the WBAN operations suffer from errors due to which health data get lost or corrupted. Hence error control schemes are to be adopted for ensuring reliability.
- **Fault tolerant:** In WBAN the fault tolerance in the MAC layer can be achieved by adopting priority management, adding new nodes, having redundant path and resources, etc.
- **Security:** Denial of sleep, spoofing, eavesdropping, sinkhole, sybil, collision, unfairness, exhaustion, etc. are the example of the security attacks specific to the MAC layer. The protocols should have proper security schemes to protect WBAN against these attacks.
- **QoS:** The QoS in the MAC layer can be achieved by the suitable application of adaptive channel coding, power scaling, and time slot division.

***4.1.3.3 Network* layer.** The function of the network layer is to extend communication beyond the BAN. The network layer enables WBAN to be internetworked with external networks such as other WSNs, external servers and data centers, remote monitoring management systems, etc. [41]. Using suitable routing protocols, the WBAN data are sent efficiently to remote destinations fulfilling the purpose of remote health monitoring. The routing protocols and the functioning of the network layer are designed keeping in mind the factors such as low power consumption, data-centric approach, data aggregation and fusion, attribute-based addressing, etc. [44]. Often the routing in WBAN is based on data, not node address. This approach of routing is known as data-centric routing where instead of traditional IP-based global addressing, the attribute-based naming [45,46] is used. This naming scheme is used to query based on the attributes of a certain phenomenon, event or process.

Challenges in WBAN network layer: Following are the challenges that are to be addressed by the network layer of the WBAN protocols [40]:

- **Optimum routing:** Realizing efficient communication in WBAN is challenging mainly due to limited bandwidth that varies with the presence of fading, noise, and interference. Achieving optimum routing efficient and enhanced routing techniques are required.
- **Multi-path routing:** For reliable and robust communication, the routing protocols should adopt multi-path and multi-point routing.
- **Network condition:** For reliable transmission, the network conditions are needed to be stable. Hence it is important to check the issues such as channel, buffer information, priority measurement, etc. periodically.
- **Real-time streaming:** Many of the remote health monitoring scenarios require real-time data transmission. It is the network layers responsibility to make sure that in such cases the packets reach at receiving end in time. In case of delay, the worst transmission time and the probability of it are also should be estimated.
- **Localization:** In WSN the data transmission quality depends on the distance between the transmitting/receiving node and the nearest access point. Since WBAN may be mobile, it is required to adjust the localization of the nodes in operation whenever there is displacement of the nodes with respect to the access point.
- **Mobility:** The mobility in WBAN, especially in case of wearables and fitness devices, poses a challenge for identifying the best suitable route in such dynamic or mobile environment.
- **Traffic control:** To control congestion and transmission rate, designing and adopting efficient traffic control routing protocol is necessary.
- **Security:** The network is prone to several security attacks such as sybil, sink hole, neglect, homing, misdirection, black hole, selective forwarding attacks, etc. The Network layer protocols should be capable of mitigating these attacks.
- **Fault tolerance:** Like other layers in WBAN communication, the networks layer should also be tolerant to fault that is supposed to arise in this layer, e.g., faults in network topologies and routing.
- **QoS:** The QoS in network layer can be improved by addressing the factors such as improving path latency, controlling congestion, robust routing, taking proper action in case of lost and damaged packets contribute to improving QoS.

4.1.3.4 Transport layer. Like the network layer, the transport layer comes into play when there is remote accessing of a WBAN. As usual, the responsibility of the transport layer in the protocols for beyond-BAN are handling congestion control, flow control, fair allocation of bandwidth, reliability, packet-loss recovery, energy efficiency, and heterogeneous application support [41,47]. But contrasting to the traditional transport layer protocols such as TCP and UDP no global addressing is used for the end-to-end communication. Instead, attribute-based naming is considered for addressing the endpoints [44].

Challenges in WBAN transport layer: The designing of the transport layer protocols heavily depends on the specific WBAN application. In this respect, the design and implementation challenges faced by the transport layer are as follows [48]:

- **Reliable transport:** Typically transport layer protocols are responsible for ensuring reliable communication. In WBAN, the sensor data or the events should be reliably transmitted to the receiving end. Similarly, the management or administrative operations and queries on sensors should be reliably delivered to the target sensor node for the proper functioning of WBAN.
- **Congestion control:** Data flooding and channel congestion result in packet loss. Hence, to achieve reliable communication, intelligent congestion control is required for monitoring the channels and regulating the data transmission rate dynamically when congestion is detected or anticipated. It will increase network efficiency as well as conserve network resources.
- **Self-configuration:** The WBAN structure may be changed due to various reasons such as node mobility, node failure, random node deployment, temporary power down, the spatial variation of events, etc. The transport layer protocols must be able to be dynamically adaptive to these changes.
- **Energy awareness:** As usual, the operations (e.g., error and congestion control) in the transport layer also should be power efficient. The transmitting node should be allowed to conserve energy, wherever applicable, by controlling the data transmission rate or putting the sensor in sleep mode.
- **Biased implementation:** Most of the transport layer functionalities should be implemented at the sink (usually the WBANC or the WBAN server) while only the bare minimum portions run on the sensor end. This will be helpful for saving energy consumption at the low-powered sensors.
- **Constrained addressing:** As mentioned above, the transport layer protocols for WBAN use attribute-based naming and data-centric routing instead of end-to-end global addressing. This requires exercising different transport layer approaches.

4.1.3.5 Application layer. This layer provides the interface for managing the WBAN, managing and querying WBAN data, etc. In addition, this layer is also responsible for node localization and time synchronization. The implementation of the application layer in WBAN is application specific. But in the context of WBAN, the most crucial function of application layer is to ensure a secure environment for accessing sensitive medical data remotely. Subject to the purpose, the application layer of a typical WBAN can be divided as following [44]:

i. Sensor Management Protocol (SMP): This is the interface through which the system administrators interact with the WBAN. Using SMP a WBAN administrator should be able to perform the following tasks [48]:
   - Set up rules for attribute-based naming and data aggregation.
   - Assess and inspect sensor status, WBAN configuration.
   - Reconfigure WBAN, if required.
   - Synchronizing health monitoring devices.
   - Move those devices.
   - Turn the monitoring devices on and off as per requirement.
   - Enforce authentication, key distribution, and security in beyond-BAN communications.

ii. Task Assignment and Data Advertisement Protocol (TADAP): Using this protocol users generally express their interest, about a certain phenomenon or an event, to a particular or a group of the sensor device(s) in a WBAN or the whole WBAN. Alternatively, health monitoring devices advertise their corresponding health data, and the users query those data based on their interest.

iii. Sensor Query and Data Dissemination Protocol (SQDDP): This protocol enables users to issue location-based and attribute-based queries to the WBAN as a whole rather than a particular node. Users also can respond to other's queries and can collect incoming replies.

Challenges in WBAN application layer: The main challenge in designing application layer protocols for WBAN is to provide an efficient and swift interface that either can be used by the human or can be interfaced to other devices for automated diagnosis. The application layer is also the first level for enforcing security measures. In addition, most of the functionality of the transport layer protocols are overlapped that of with the application layer protocols. For example, functions like congestion control, flow control, bandwidth allocation, packet-loss recovery, energy efficiency, etc. are at times considered as part of the application layer as well [41]. Hence, designing application layer protocols also faces common challenges as discussed in Section 4.1.3.4.

4.1.4 Desirable properties of a WBAN communication architecture design

Below mentioned are some general properties that should be given importance while designing the communication architecture of any WBAN [26]:

Reliability: Since WBAN deals with very critical and sensitive data, reliability is the most important quality that every WBAN should maintain. The WBAN should ensure no packet loss and minimum noise induction. The WBAN data should be encapsulated from external interferences.

Power efficiency: Another factor of primary importance that every communication protocol in WBAN should take care of. Power usage should be minimized by optimizing the operations in every layer.

Scalability: For the successful application of WBAN in remote health monitoring, the WBAN system should have the flexibility to be scaled as per requirement. The devices in a WBAN may be added, removed or replaced at any point of time. The WBAN should be able to accommodate this change without affecting the usual monitoring process.

4.2 WBAN Standards

IEEE 802 standardization committee is regarded as an international organization whose main task is to propose international standards with regard to wireless communication. Several standards (in the IEEE 802.15 family) have been proposed for different wireless communication technologies. For example, the IEEE 802.15 (WG15) standard especially focus on wireless personal area networks (WPAN) [49]. WG15 has proposed several different wireless standards like IEEE 802.15.1 (Bluetooth); IEEE 802.15.4 (PHY) for low-rate WPAN and is applied to ZigBee; IEEE 802.15.4a (PHY) for ultra-wideband technology; IEEE 802.15.3c (High rate WPAN); IEEE 802.154d (Japanese WPAN); IEEE 802.15.4e (MAC improvement for IEEE 802.15.4), etc.

IEEE 802.15.4 standard was finalized by the 802.15 working group of the IEEE in the year 2003. This standard was specifically designed for low range communications for wireless personal area networks (WPANs) [50,51]. A WPAN essentially deals with communication of locally situated sensors, typically in a small room, among themselves and over the internet. WBANs used WPAN standards in communicating the data collected by the body planted sensors to the central server for storage and processing. Later in 2012, a working group IEEE 802.15.6 was formed for standardizing WBAN communication protocols for sensors that strictly remain inside or on the surface of the human body and communicate over shorter ranges of the order of a few meters [52]. This standard addressed the problem of low range and battery limitations of sensor devices more specifically. Along with the communication efficiency, the standard also addressed security requirements for WBANs by introducing new physical layer (PHY) and MAC protocols for WBANs. A couple of standards that are most suitably applicable to WBAN are briefly discussed below.

4.2.1 IEEE 802.15.4a standard

This is an UWB-based standard on WPAN and an extension of the IEEE 802.15.4 (2006), IEEE 802.15.4a (2007) [53]. It was introduced with the specification of additional PHYs. These new PHYs enriched the newer version with enhanced scalability in data rates (from several Kbps to 10 Mbps) and operational range, lower power consumption, and precision ranging capabilities [54]. The MAC layer of this standard uses a guaranteed time slot (GTS) using which the QoS is achieved in the continuous transmission of vital data in health monitoring applications such as ECG and EEG [55].

4.2.2 IEEE 802.15.6 standard

IEEE 802.15.6 [56] is the first ever standard that exclusively defines the lower tiers of WBAN communication. IEEE 802 Task Group has published this standard that aims to govern the communications inside and around the human body. The objective IEEE 802.15.6 is to provide an international standard for ultra-lower power, short-range and reliable wireless communication within reach of the human body at a data rate up to 10 Mbps for a varied set of applications.

4.2.2.1 IEEE 802.15.6 standard requirements. The following are the main requirements of the IEEE 802.15.6 standard:

- WBAN link rates range in between 10 Kbps to 10 Mbps.
- Nodes removal and addition should be done within 3 s.

- Every WBAN system should be capable of supporting 256 nodes.
- Every sensor node should have reliable communication especially when the patient is moving from one place to another and doing various body movements like sitting, walking, twisting, running, arms and all sorts of leg movements.
- Packet error rate (PER) should be less than 10%. Latency rate should be less than 125 ms in medical and less than 250 ms in non-medical applications.
- Energy saving mechanisms should be integrated into WBAN to make them fully operational in the power-constrained environment.
- WBAN should be fully equipped with UWB technology to allow transmission in all sorts of environments.
- Best QoS features in terms of security and self-healing should be there in WBAN.

The number of communication layers depends on the protocol/technology used for communication. But the physical layer (PHY) and the media access control (MAC) layer are the two most important for any WBAN system. Hence, the IEEE task group obliges this importance and has come out with the specification for these two layers with the IEEE 802.15.6 standard.

4.2.2.2 PHY layer specifications of IEEE 802.15.6. The standard defines three PHY layers:

i. Narrowband (NB) PHY: Purpose of this layer is to handle communication between the sensors on and within the body [38]. It has mainly three responsibilities [56]:
   - Activation/deactivation of the radio transceiver
   - Performing Clear Channel Assessment (CCA)[2] before transmission
   - Transmitting and receiving data

   The working bands of NB PHY includes the 400, 800, 900 MHz and the 2.3 and 2.4 GHz.

ii. Ultra-wideband (UWB) PHY: Purpose of this layer is to provide efficient, power efficient, and robust WBAN communication. uses the 3.111.2 GHz [38]. According to the IEEE 802.15.6 specification, UWB PHY operates in two modes:
   - Default mode
   - High QoS mode

   The data rate of UWB PHY ranges from 0.5 Mbps up to 10 Mbps. The UWB WBAN is discussed in more details in Sections 6.5 and 6.6.

iii. Human body communication (HBC) PHY: HBC is the equivalent of Electrostatic Field Communication (EFC) specification of PHY which is the basis of physical realization. HBC PHY is responsible for dealing with the entire WBAN protocol that may include packet structuring, modulation, preamble/SFD, etc. [56]. The hardware specification has been simplified for optimal usage in WBAN, for example, the transmitters within the sensor nodes in a WBAN system that comply with this standard, do not need antenna; instead, they use a simplified circuit that consists of only one electrode [38]. Similarly, the receiver hardware does not require RF modules which makes the devices power efficient and easier to implement. The communication frequency of the specification conforms within the range of 1050 MHz.

4.2.2.3 MAC layer specifications of IEEE 802.15.6. The patient data in IEEE 802.15.6 specification for WBAN has been categorized as follows:

- Type-I: represents life-critical data
- Type-II: represents normal and regular health monitoring data.

The superframe structure of IEEE 802.15.6 is divided into four access phases [43]:

i. Exclusive access phases (EAP - I & II): EAPs are used to transfer high-priority or emergency traffic, i.e., Type-I data. They offer guaranteed data transfer service.
ii. Random access phases (RAP - I & II): The RAPs are used for nonrecurring traffic and are reserved for transmitting Type-II data.
iii. Managed access phase (MAP): This phase is also used to transfer Type-I data. It guarantees high priority data transfer.
iv. Contention access phase (CAP): This phase is also used for nonrecurring traffic and is reserved for Type-II data.

The IEEE 802.15.6 network operates in one of the following modes [56]:

i. Beacon mode with superframe boundaries: The coordinator in a WBAN transmits beacons in the active region of superframes. The beacon is used for synchronizing the communicating nodes in a WBAN. In between two active superframes, there might be multiple inactive superframes whenever there is no scheduled transmission [43]. CSMA/CA or Slotted Aloha is used for channel allocation in this mode.
ii. Non-beacon mode with superframe boundaries: Here, communicating nodes need not be synchronized with the coordinator. Instead of setting a

[2]CCA is used to determine whether the communication medium is free or not.

superframe boundary by using beacons, the WBANC takes help of polling [26] for scheduling the data transmission of each individual sensor node. This ensures that the communication between the sensors falls within the superframe structure [57]. The non-requirement of synchronization saves energy. But the problem is that the coordinator cannot transmit data directly to the sensor nodes within the WBAN. If a coordinator wants to communicate to a node, it must send an activation alert signal to the recipient to initiate the communication. Another serious issue is there in this mode that at a time only one type of health data is allowed per slot. And since the WBANC operates only during the MAP period in this mode, this exclusion policy might not be ideal for life-critical situations of a patient when different vital status need to be accessed simultaneously by the doctors [58].

iii. Non-beacon mode without superframe boundaries: In this mode, a pre-defined superframe structure is not required. That means the superframe structure does not have any predefined slot allocated to any sensor node for data transmission. The slot allocation is done by contention or post-contention methods. The coordinator opts for polling or posted allocation for data communication where a certain number of timeslots are openly allocated which can be accessed by any sensor node waiting for data transmission. This mode of operation is designed for transmitting Type-II data. The advantage of this mode is that it avoids the unnecessary interruption by the health sensors that are sensing not so critical health status in contention of acquiring communication slots that are required by the sensors that are employed for critical health monitoring [58].

5 WBAN MAC LAYER

5.1 Importance of MAC Layer Protocols for WBANs

In any computer networking system, the protocols adhering to the MAC layer contributes significantly to improving the overall performance of the network as well as extending the network lifetime [59]. The same applies to the MAC layer protocols in WBAN. Different sensors and actuators, implanted on or within the human body, which collects critical and non-critical physiological information throws a major challenge in designing MAC layer protocols in terms of adaptability, dynamicity, flexibility, reliability, and power efficiency [59]. It is essential to adopt an efficient MAC layer protocol for effective implementation and working of WBAN.

5.2 Properties of WBAN MAC Layer Protocols

The inherent challenging environment of WBAN implementation demands the MAC layer protocols to be able to handle these challenges effectually. The working of the MAC layer becomes more challenging in WBAN compared to a regular WSN mainly because of the following facts:

- To save energy consumption, the sensors' radios are usually low-powered, and hence the line of sight is also limited.
- Depending on the position of the sensor (within or on the human body), the line of sight varies significantly. For example, the sensors planted on the chest and the back of a patient find it difficult to communicate. Similarly, in a sitting position (on chair/sofa), communication between sensors planted on the chest and the ankle is not possible.
- If the line of sight is to be improved, the propagation of the radio waves should be broadened. This can be achieved by making the radios more powerful. But that will consume more energy which is not acceptable in WBAN.

The sensor nodes' proximity to the human body, in WBAN, makes the things more complicated. Below, some of the adversities that WBAN MAC layer protocols are expected to address are mentioned.

- **Energy consumption:** The WBAN have small batteries with limited power capabilities, and in most of the cases they are neither rechargeable nor replaceable. That's why power consumption is a major design issue for every protocols and application in WBAN. In the networking stack, MAC is the key layer which can save a great deal of energy consumption by maintaining an optimum ratio of packet delivery and energy efficiency. The major reasons for large power consumption in WBAN communication are [60,61]:
  - Collision between packets: After detecting a collision the transmitting node retransmits the packet that was involved in a collision. This retransmission of data packets causes extra energy consumption.
  - Overhearing of nodes: Sometimes, the sensor nodes receive packets that are not destined for them but some other nodes. On receiving such packets, they are dropped which unnecessarily consumes power.
  - Idle listening to receive possible data packets: Sensor nodes optimistically continue to listen to idle channel in anticipate to receive packets possibly transmitted by other nodes. This also results in needless energy consumption.

- Communication control packet overhead: Usage of control packets in communication results in added energy consumption mainly due to energy wasted in transmitting and receiving those control packets.
- Transceiver state switching: In practice, the transceiver of the sensor nodes is kept in sleep mode when no data to transfer or receive. When required, it is switched on to active mode. This is done to avoid idle listening and overhearing. This may actually decrease the power consumption, but if the switching between the sleep mode and the active mode is frequent, the energy consumption rises sharply. An optimal balance of the number of switching can improve overall energy consumption.

  A good MAC layer protocol can either eliminate or minimize the effects of these sources of power dissipation.

- **Limited bandwidth:** WBANs have limited bandwidth capacity due to the inherent physical constraints. So, the bandwidth requirement of WBAN applications should be low. That is why it is crucial to concentrate on the designing of the applications and services low data generating and transferring rate.
- **Limited device capability:** Due to size constraint, the WBAN nodes have very limited computing and storage capacity. This prevents implementing heavy and complex protocols. That's why the protocols in WBAN need to be lightweight.
- **QoS:** Since WBAN is related to human health, it is crucial to maintaining QoS at each service criteria of WBAN. There are various parameters that determine the QoS such as minimum latency, high reliability, energy efficiency, negligible electromagnetic interface with the human body, and effective communication are to be taken into consideration, etc. [59]. Among these, latency and reliability are the most crucial for patient health monitoring systems. The reliability of a WBAN depends on two factors: transmission delay and packet loss. The MAC protocols play an important role in minimizing both. The proper selection of the medium access technique at the MAC layer significantly influences the reliability. For instance, in the case of TDMA and polling, the packet loss and packet delay are deterministic hence easy to set and adhere to the QoS level. But the accurate transmission time cannot be determined in the case of contention-based media access protocols like CSMA because transmission takes place only when the shared channel is free. Similarly, in the case of other protocols which follow random media access techniques, the packet loss and delay varies from time to time and not predictable [61]. In both cases, QoS is compromised severely.

  QoS is also improved by adopting the MAC layer protocols which come up with optimal packet size, suitable packet re-transmission schemes, and enhanced scheduling schemes.

  Also, many often the different wireless services like Bluetooth, Wi-Fi, and ZigBee coexist in a single band. This results in significant interference. A QoS-aware MAC protocol, essentially, should be able to tackle these conditions.

5.3 Channel Access Techniques for MAC Protocols in WBAN

In general, MAC protocols based on Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA) are not suitable in WSNs mainly because of the requirement of high computing capacity and complex hardware [62]. That's why the MAC protocols for WSNs use either Time Division Multiple Access (TDMA) or CSMA/CA for implementing shared medium access policies. Compared to TDMA the performance of CSMA/CA is much better in dynamic networks. But, in most of the cases, communications in WBANs are not dynamic. Hence, the TDMA approach is preferred in WBANs. However, one drawback of using TDMA-based MAC protocols in WBANs is that TDMA consumes extra energy for synchronization [61].

5.4 Modulation Techniques for MAC Protocols in WBAN

For the same reason as mentioned above, the simple and efficient modulation techniques such as Gaussian FSK (GFSK), Gaussian minimum shift keying (GMSK), differential phase-shift keying (DPSK), offset quadrature phase-shift keying (OQPSK), and phase silence shift keying (PSSK) are preferred in WBAN [63]. These modulation techniques are either bandwidth or power efficient or both.

5.5 Traffic Adaptive MAC Protocols

In WBANs, different sensors are used for various purposes. Some of them require periodical monitoring that results in low but consistent traffic load. Whereas, some sensors produce a huge amount of data suddenly and irregularly. That is why it is important for the MAC protocols for WBANs to be able to adjust the data traffic dynamically according to the varied traffic loads. And because of this quality, these MAC protocols are called traffic adaptive protocols. Surely, designing traffic adaptive MAC protocols are not straightforward.

Below, some of the properties are listed that are required to be considered for designing traffic adaptive MAC protocols [64]:

- **Traffic classification:** In WBAN, for better management, the data traffic is generally be classified into four categories viz. emergency traffic, critical traffic, reliability traffic, delay traffic, and normal traffic. The traffic classification is generally done based on delay and packet delivery ratio. Though, in practice, generally, this classification depends on the context of the traffic.
- **Traffic prioritization:** WBAN includes various implanted nodes with different purposes and priorities which generally access the shared communication path. Hence, it is essential for the MAC protocols to be flexible and dynamic to adjust traffic according to priority. The time slots for data communication are allocated dynamically as per the traffic priority.
  Prioritization of data traffic in WBAN is determined either statically or dynamically. In the first case, priority is set beforehand for each type of data. For example, the emergency traffic is assigned as the highest priority, the critical traffic may be assigned as a second highest priority whereas the normal traffic is assigned as the lowest priority [65]. In the second case, the traffic class value and the data generation rate of the particular WBAN application determines the prioritization of traffic [66].
- **Traffic load estimation:** It is important to carefully estimate the traffic load in a WBAN environment especially where the data traffic is variable. And this estimation process should be light, for a dynamic environment, in terms of the computation required for calculating the traffic load in. Based on the traffic load estimation the variable and heterogeneous traffic loads are adjusted dynamically. There are different approaches for estimating the traffic load in WBAN:
  a. The channel usage of the nodes is measured and communicated to the Body Coordinator (BC) periodically and based on that statistics the BC estimates the traffic load.
  b. The data generation rate is taken into account for each WBAN application, and accordingly, the traffic load is estimated.

Considering the above properties, the traffic adaptive protocols are classified into three categories [64]:

i. Traffic load estimation (TLE) based MAC protocols: The energy efficiency is achieved through attaining low delay by estimating the traffic load.
ii. Adaptive wake-up interval (AWI) based MAC protocols: The sensors remain sleeping by default. When there is a requirement of data transfer, they are awakened either autonomously or by some external entity, generally the coordinator node. This reduces the energy consumption.
iii. Adaptive time slot allocation (ATSA) based MAC protocols: These protocols manage the traffic load diversity dynamically. The traffic allocation is dynamically adjusted based on the traffic load.

6 WIRELESS TECHNOLOGIES FOR REMOTE HEALTH MONITORING

Several wireless technologies are present which are used for communication in remote health monitoring applications. Some of the popular wireless technologies are discussed in this section.

6.1 Bluetooth

Bluetooth [67,68] has been a very popular wireless communication technology for short-range. The Bluetooth protocol enables devices to communicate between them even if they are not in the line-of-sight. Multiple devices (the official claim is 7) can have physical connections simultaneously with a satisfactory data rate (up to 25 Mbps, with the help of WLAN, in Bluetooth 3.0 [69]). Bluetooth has been widely used in wireless health monitoring applications.

Despite the success and popularity, Bluetooth has few serious issues which make it incompetent to be the preferred communication technology for WBAN:

- The major problem is the power consumption. Bluetooth drains the battery very quickly.
- Suffers from frequent connection loss for which frequent pairing and re-pairing is required.
- Does not support automatic network formation. If the master moves away or goes down, the network will collapse.
- The number of simultaneous active connection is very small.
- Connection establishment process is slow.
- Suffers from several security flaws.

6.2 Bluetooth Low Energy (BLE)

As the name suggests, BLE [70,71] is the more energy efficient version of Bluetooth. BLE comes with the package Bluetooth 4.0 that also includes classic Bluetooth and high-speed Bluetooth. BLE addresses some of the drawbacks of classic Bluetooth. In addition to low power consumption, the other advantages of BLE in using WBAN are [72]:

- **Cost efficient:** To minimize cost, BLE technology is optimized for small battery-operated devices. For instance, in BLE, the number of channels is reduced to 40 2-MHz from Bluetooth's 79 1-MHz wide channels.

- **Robust transmission with minimized interference:** In medical applications, it is crucial to have a transmission technology that can provide a transmitting environment that is not affected by the "noisy" RF environments. Alike, Bluetooth, the use of adaptive frequency hopping (AFH) technology enables BLE to achieve this. Due to AFH, BLE also achieves low interference with other wireless transmissions.
- **Extended connection range:** Having a slightly different modulation, in comparison to classic Bluetooth, BLE (with a 10 dBm radio chipset) can cover a range up to 300 m.
- **Ease of use and integration:** In a master-slave arrangement, in Bluetooth, the slave communicates only after initiated by the master. In BLE, a slave can announce itself if it has something to transmit to the master. This is really important in case of an event that occurred at the slave end or if the health sensor (slave) has to send any physiological data to the controller (master).

6.3 ZigBee

ZigBee [73] is a wireless networking protocol suite that defines communication functionality within a personal area network (10–100 m). Zigbee communication relies on small and low-power digital radios. It is based on the IEEE 802.15.4 specification [73]. The ZigBee 3.0 [74] allows interoperability among different applications. Features and advantages of ZigBee are as following [75,76]:

- Short-range operation
- Significantly less power consuming
- Robust and reliable data transfer (its advanced routing feature provides self-healing routes between the communicating devices)
- Reliable data transfer (because it uses mesh topology that has no single point of failure)
- Secure
- Scalable
- Low-cost
- Easy to implement

6.4 WLAN

A wireless local area network (WLAN) [77,78] is a LAN that does not involve physical wired connections. It is standardized by the IEEE 802.11x. Combining WLAN with WBAN can give an effective local communication system for remote monitoring. The WLAN can be used to transmit the health data collected by WBAN to a local centralized server or the nearest internet access point. Since both are defined by different standards, they need to be bridged for working in conjunction [79–81]. Security is the major concern in WLAN because the wireless signal is broadcasted to every reachable and compatible devices.

6.5 Ultra-Wideband (UWB)

UWB [82,83], standardized by IEEE 802.15.3, is a data transmission method in a wireless network that offers, as the name suggests, a very large bandwidth. This high-rate throughput capability is really a great support to WBAN considering the number of wearables and sensors are used for remote monitoring these days. But the winning property of UWB that is applicable in WBAN is the significant power efficiency that it provides. The lower energy consumption increases the sensor operational period and life even transmitting more data.

There are two approaches to implement UWB: i) multi-band (MB) OFDM UWB, and ii) impulse radio (IR) UWB [84]. Characteristically, the second one is more suitable for WBAN because IR-UWB radios are generally of low-complexity by design and consume less power. The reason behind that is, to transmit and receive data, IR-UWB systems use pulses of very short duration (typically 2–3 ns) [85]. That is why they are preferable for the WBAN applications which are energy constrained and require short-range communication. In addition to that, the UWB physical layer is designed to provide WBAN robustness and the capability to implement high-performance operations [38].

UWB suffers from an important drawback. To achieve the short pulse width and power efficient signal transmission, the designing of the front-end circuitry of a UWB receiver is somewhat complex and also consume more power [57].

6.6 UWB-Based MAC Layer Protocols for WBAN

This section highlights some interesting UWB-based MAC layer protocols that can be used in WBAN. For extensive details, interested readers may refer to the book [57] that studies UWB WBAN in particular.

6.6.1 PSMA-based MAC

The PSMA-based MAC protocol is based on Preamble Sense Multiple Access (PSMA) [86] medium access mechanism where a preamble sequence is appended at the starting of a data packet sent by a sensor node to indicate a busy channel condition [57]. For WBAN with a large number of sensors, as the study [87] suggests, PSMA-based MAC protocol has an edge in terms of throughput and energy efficiency in comparison to slotted ALOHA based IEEE 802.15.4a standard.

But the PSMA-based protocols face a problem with the possibility of collision when multiple sensor nodes perform preamble sense simultaneously [57].

6.6.2 UWB^2

The Uncoordinated Wireless Baseborn Access for UWB Networks ((UWB)^2) [88,89] is a multi-channel MAC protocol. A multi-channel protocol divides the overall available resource such as timeslot (TDMA), a frequency band (FDMA) or a code (CDMA) to form separate communication channels. (UWB)^2 is based on CDMA. In comparison to usual multi-channel MAC protocols, it does not require Clear Channel Assessment (CCA) [90,91]. Instead, it uses orthogonal time-hopping (TH) CDMA [92,93] for achieving multiple access in a shared medium. It reduces energy consumption that makes THCDMA a suitable contender for WBAN applications. It is claimed that (UWB)^2 does not require complex mechanisms for interference control and supports a wide range of data rates (hundreds to thousands of bps) and a number of users (tens to hundreds) [88].

(UWB)^2 has a serious reliability loophole. In case of the loss of a Link Control (LC)[3] frame, it does not have any provision for reinitializing the transmission [57]. Also, there are possibilities of collisions in TH CDMA. (UWB)^2 does not address this issue.

6.6.3 Multi-band UWB MAC

In a multi-band approach, the available UWB bandwidth is divided into multiple simultaneously usable bands. Multi-band systems provide more efficient use of the allocated spectrum. In a WBAN system, using multiband UWB MAC [94], the coordinator node can simultaneously communicate to multiple sensors through unique frequency bands allocated to each communication channel. This allows concurrent data transmissions without the possibility of collision. The capability of communicating concurrently results in low latencies and increased throughput, which are important for the WBAN applications demanding high data rate [57].

The considerable drawback of multi-band UWB MAC is that in creating the environment for concurrent communication makes the hardware design complex which may negate its application value in WBAN.

6.6.4 U-MAC

Rather than expending a fixed power level for data transmission, the U-MAC protocol [95] opts for an adaptable approach by adjusting the need for power for the transmission. The sensor node, on receiving data packets from its neighbor, assesses the ranging information of the neighboring device [57]. Based on this information, it determines the power required to transmit data to that particular neighbor and adjust the transmit power levels accordingly. This dynamic adjustment of power expense saves unnecessary energy wastage.

The problem with this approach is that determining the transmitting power requirement of a sensor node and dynamically adjusting to that level involves heavy processing which is an additional overhead as well as more power consuming. In fact, this may overdo the gain of power saving achieved by the U-MAC protocol, especially in WBAN.

6.6.5 DCC-MAC

DCC-MAC [96] allows getting away with the restriction of mutual exclusion in wireless communication where no simultaneous communication is allowed within the same collision domain. It provides a communication environment among sensors where they can simultaneously communicate. This will obviously increase the chance of interference, but that can be mitigated [97,98]. But this mitigation comes at a cost as the physical layer operations become more complex and power consuming.

6.6.6 Transmit-only MAC

Though the above mentioned UWB-based MAC protocols have been successful in minimizing the power consumption, there are still more rooms to do that. In most of the cases, the functioning of the WBAN sensors is limited to data transmission only. The receiver part is redundant. But it consumes power in trying to detect incoming signals continuously. The transmit-only MAC protocol [99,100] supports the sensors which have transmit-only hardware in their design. This saves the power that was otherwise eaten up by the receiver part of the hardware.

The drawback of this protocol is that it is of asynchronous nature which throws the challenge to the receiving devices in terms of synchronization and collision avoidance. To overcome these issues, several remedies have been suggested [57,101].

6.7 Medical Radio Services

All the above mentioned wireless technologies are optimized for short-range communication and designed for general purpose sensor network applications. None of them is specifically designed for medical applications. This section mentions some radio services that are regulated specifically for medical monitoring and applications.

[3]LC message is sent by the coordinator in response to a Link Establishment (LE) request received from a sensor node.

6.7.1 Industrial, scientific and medical (ISM) radio bands

ISM [102] is the first special radio band that is aimed only for industrial, scientific, and medical purposes [103]. Internationally, a subset of radio spectrum has been set aside that is not meant to be used for telecommunications. 2.54 GHz is the commonly accepted band for ISM. The operations in ISM band is defined by the ITU Radio Regulations [104] for global uses, but the actual implementation of this band in different countries depends on the national radio regulations of the individual countries and regions [105]. Though initially, ISM was not meant for telecommunication, recently it is allowed for the same and widely used for short-range wireless communications, e.g., Wi-Fi, Bluetooth, RFID, etc. It, of course, causes interference but the communication technologies and the devices which use ISM band are responsible for mitigating it.

6.7.2 Medical implant communications service (MICS)

MICS [106] is an ultra-low power, short-range (2 m), high-data-rate, unlicensed, mobile radio service recommended by different telecommunication regulatory bodies for transmitting data in implanted medical devices [107]. The 402–405 MHz frequency band is allocated for MICS to operate. The same band is shared by the other primary users of this spectrum - Meteorological Aids Service (Medaids), the Meteorological Satellite Services, and the Earth Satellite Service [108].

Though MICS is designed for supporting diagnostic or therapeutic functions of the implanted medical devices, it is not absolutely free from interferences.

6.7.3 Wireless medical telemetry service (WMTS)

Wireless Medical Telemetry Service (WMTS) [109,110] is a set of specific spectrum bands that are used for remote health monitoring. WMTS was established by the Federal Communications Commission (FCC) [111] in 1999 to safeguard the use of licensed medical telemetry [112]. FCC has allocated dedicated bands in the range of 608–614, 1395–1400, and 1427–1432 MHz which can be used by the licensed physicians, healthcare facilities, and certain trained and supervised technicians. The allocation of the fixed bands allows interference-free operation of medical telemetry systems. The American Society for Healthcare Engineering (ASHE) [113] is in charge as the *Frequency Coordinator* for the WMTS bands and to ensure interference-free operation, it is mandatory for all transmitters operating in the WMTS bands to register with ASHE. In comparison to ISM band, WMTS has a much smaller broadcast arena.

7 CONCLUSION

The traditional healthcare systems are becoming seriously insufficient in the wake of increasing demand for health care. Innovations in ICT is assisting the healthcare sector to efficiently deliver advanced healthcare services. Telemedicine is being one of them has been successfully used to deliver healthcare services to remote locations. But it has its own limitations. Remote health monitoring has emerged as a suitable alternative for many traditional healthcare services. This enhances the quality of patient's life and reduces the number of hospital visits and rehospitalization and, in turn, the medical expenses. Patients can be monitored continuously by the medical staffs from anywhere. Patients and relatives can contact emergency healthcare services in an instant manner. WBAN has high potential to improve the performance of remote health monitoring system and can bring revolution in the healthcare sector as it integrates smart body sensors, latest communication devices, protocols and secured medical server. It significantly reduces the effort and error in diagnosis and prescribing. WBAN technology has significantly improved in recent times with more technological advancements and intelligent sensor integration. The high-end health sensors read different physiological parameters which are sent to medical staffs who take a decision based on those readings. WBAN data (in, on, or outside the human body) is collected, sent to an external medical server where it is processed and analyzed, and the outcome is used for treatment decision making. Since the physical layer and the MAC layer are combiningly responsible for improving WBAN operations in terms of power consumption, reliability, network efficiency, latency, resource utilization, operating cost, etc., they are the two most important part of any WBAN protocol. Because these two layers are Standards like IEEE 802.15.6 has been proposed to develop and standardize physical layer and MAC layer protocols for short-range, low power, highly efficient, and secured wireless communication schemes to operate on, inside, and off the human body. UWB provides high data rates in WSNs without consuming much power. Therefore, this is the preferred communication technology for WBAN. Considering the increasing usage of newer technologies such as the Internet of Nano Things (IoNT) in healthcare, it is expected to witness further advancement in efficient and power efficient WBAN communication technologies.

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